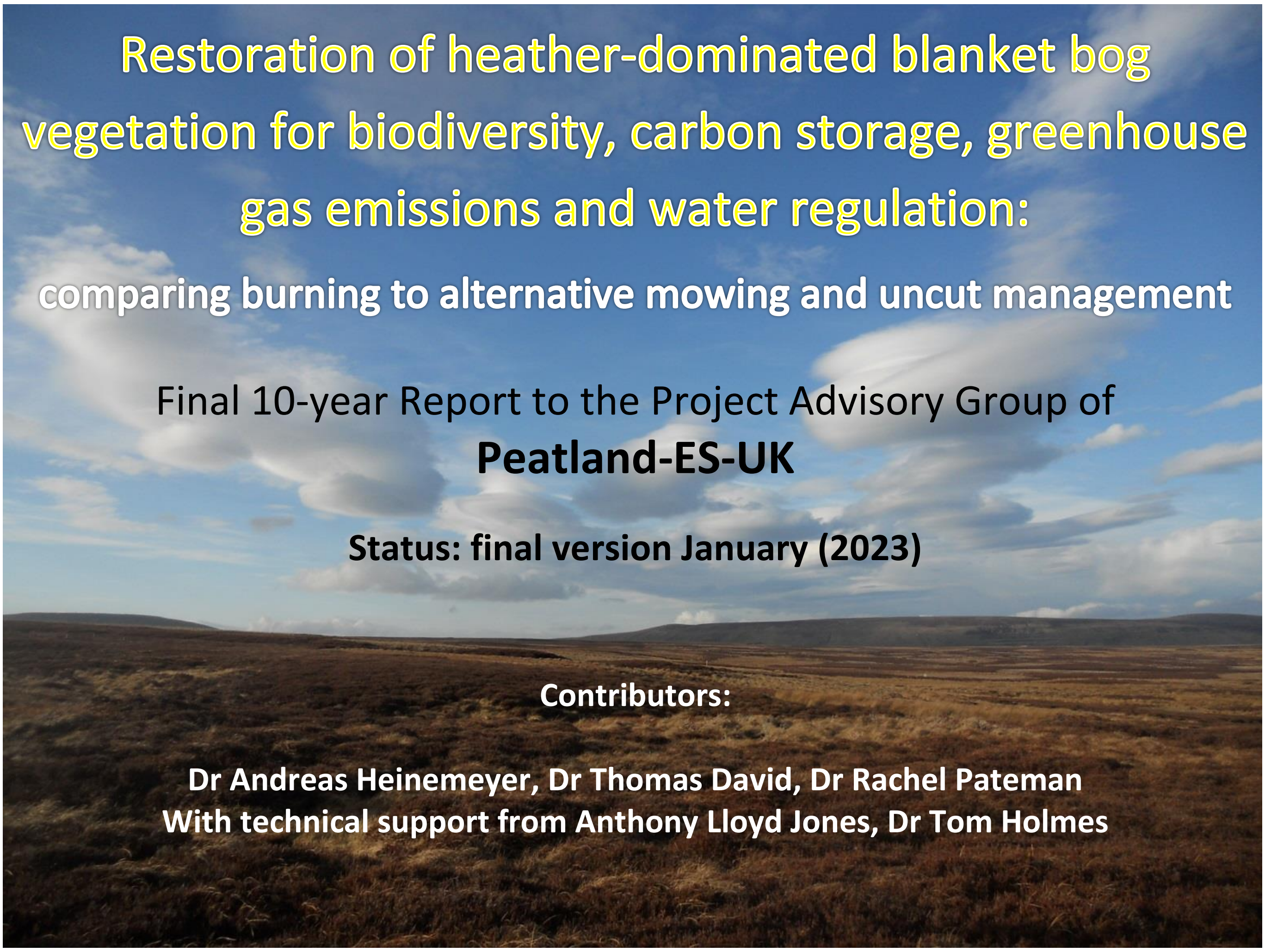

Restoration of heather-dominated blanket bog vegetation for biodiversity, carbon storage, greenhouse gas emissions and water regulation:

comparing burning to alternative mowing and uncut management

Final 10-year Report to the Project Advisory Group of

Peatland-ES-UK

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Background and project aims

Over 25% of the UK land area is covered by uplands, the bulk of which comprise blanket bog, dwarf-shrub heath and acid grassland. Blanket bogs are wetlands which are formed under high precipitation and predominantly cool conditions. The resulting high water tables, together with acid conditions, suppress decomposition of organic matter whilst also promoting the growth of *Sphagnum* mosses. *Sphagnum* moss is a crucial (but not the only) component for active peat formation as it increases the water holding capacity of the peat and produces chemicals which suppress decomposition. Blanket bog development in the UK uplands since the end of the last glaciation, mainly during the last 6,000 to 8,000 years, has resulted in extensive peat cover on all but the more steeply sloping ground. This peat accumulation represents a major UK carbon (C) stock which is linked to a range of other key ecosystem services, particularly flood prevention, drinking water provision and biodiversity aspects. Although 'active' blanket bogs are a long-term C sink due to the predominantly anoxic conditions, their C sink strength tends to decrease with age due to the annual balance between fairly stable C inputs (from vegetation net photosynthesis) and over time increasing C losses (from accumulating peat depth decomposition). Blanket bogs also have the potential to emit large amounts of methane, potentially causing a net positive contribution to greenhouse gas (GHG) emissions and global warming. Moreover, the UK has about 15% of the globally rare blanket bog habitat, containing many specialist species of birds, invertebrates and plants. These habitats also attract many visitors and support local economies including through livestock farming and game management.

In England, only around 12% of designated (i.e. Sites of Special Scientific Interest; SSSI) blanket bogs by area are classed as in a favourable condition (according to Common Standards Monitoring Guidance). About 5-15% (between 0.66 and 1.7 million ha) of the UK upland area, and 30% of UK blanket bog, is managed for red grouse by encouraging heather (*Calluna vulgaris*) cover. Since around 1850, with the onset of driven shoots, grouse moors have been managed by rotational burning to encourage regrowth of nutritious heather shoots and achieve an overall landscape mosaic of age, height and community structures within bog vegetation (partly coinciding with unrelated drainage - notably encouraged by government grants in the 1960/70s). Whilst grouse moors support local economies, their management has been linked to negative impacts on carbon, water and biodiversity. Moreover, other forms of management (including peat cutting and agricultural use) over several millennia are likely to have vastly reduced the current extent of blanket bog. However, there is relatively little, and often conflicting, evidence on the impacts of management, and particularly grouse moor management, on biodiversity and C storage. Furthermore, confounding effects are often not considered in evidence assessments, yet especially drainage likely explains some or most of the negative impacts attributed to prescribed burning. Moreover, climate change poses another challenge, as predicted changes in rainfall patterns together with rising temperatures, particularly the increasing frequency of spring/summer droughts, are a potential threat to future bog development and resilience. Drying poses a triple risk to C storage, stimulating peat decomposition whilst also increasing vegetation water stress limiting C uptake and wildfire risk resulting in potentially vast peat C losses through peat combustion and subsequent erosion from bare peat. Recently, there have been considerable efforts to reverse blanket bog degradation and increase resilience to climate change impacts through a range of restoration measures including restoring hydrology through blocking and re-profiling drainage 'grips' and gullies, revegetating bare peat, re-introducing *Sphagnum* and other scarce or absent mire species, removing trees and scrub, and increasingly so using alternative mowing management, to encourage 'active' blanket bog vegetation.

However, as summarised by Ashby and Heinemeyer (2021) and Heinemeyer & Ashby (2021), despite the ecological and economic importance of blanket bogs there is so far very little evidence on (i) how restoring a peatland's hydrology ensures long-term resilience to wildfires without fuel management (as even wet bogs can become very dry during drought conditions risking deep and smouldering large-scale peat fires as opposed to just small-scale surface vegetation combustion), nor (ii) how heather burning or alternative mowing managements alter key ecosystem services of blanket bogs, such as water and carbon storage, and (iii) if and how mowing and burning differ in their effects on vegetation composition and structure. There are also few robust, long-term datasets available on UK blanket bog C balances, greenhouse gas (GHG) emissions and their controlling factors.

This project was set up by Defra (in 2012) as an *initial* 5-year study (**Phase 1**) with the aim of addressing key evidence gaps, especially in relation to how to reduce heather dominance and support an 'active' peatland status, on the effects of alternative management interventions (excluding assessing grip blocking impacts), as identified in a literature review, through a replicated plot-to-catchment scale multi-year study at three sites in northern England, all on heather-dominated blanket bog under grouse moor management. Contrary to frequent claims (as pointed out by Ashby & Heinemeyer, 2021), the evidence around prescribed fire impacts is far from clear, especially when considering study design (Ashby & Heinemeyer 2019a), nor is there any consensus as outlined in the landmark and multi-author papers by Davies et al. (2016a,b,c). Moreover, impacts of alternatives such as mowing are even less understood, requiring adequate, replicated long-term research, comparing alternative management options at the appropriate temporal and spatial scale (Harper et al., 2018). This project addresses many of the issues highlighted by Davies et al., such as working in a collaborative way (i.e. an advisory group consisting of all major stakeholders overseeing and funding an independent and unbiased research project and monitoring regime) and delivers on the Harper et al. research needs (i.e. replicated plot-to-catchment scale, long-term research with pre-/post-management monitoring across several ecosystem services). Whilst funders have changed over time, the Defra study project aims and monitoring aspects have remained constant (Ashby & Heinemeyer, 2019b). In fact, the co-funding of the second 5-year period (**Phase 2**) provides a crucial extension towards achieving Defra's original long-term project aims, with crucial buy-in from all major stakeholders.

The overall long-term aim of this project was to deliver robust and credible evidence to underpin the development and refinement of possible heather management techniques as alternatives to burning (and not in relation to grouse moor management), for example, applicable through Environmental Stewardship and other agri-environment schemes, to reduce the dominance of *Calluna vulgaris* and support the development of 'active' blanket bog vegetation with a high cover of other peat-forming species, particularly *Sphagnum* mosses. However, this long-term aim requires robust evidence based on long-term monitoring well beyond the initial 5-year project phase (i.e. covering at least a full management rotation with vegetation re-growth to near maturity) as presented in the previous Defra report by Heinemeyer et al. (2019b). Ideally, long-term monitoring following initial management would cover the crucial developmental stages of an initial response (1-3 years) and recovery (3-5 years), intermediate transition (5-10 years) and long-term trajectories (10-25+ years). Therefore, the emphasis for extending the initial **short-term** monitoring in this second 5-year project phase was to focus on the project's objectives of assessing the **intermediate** management impacts on biodiversity, carbon storage, GHG emissions and water. For policy relevance (especially to the government's 25-year plan) clearly the more meaningful **long-term** ecological aspects would need to be captured by future continuation of both research and monitoring.

The three sites chosen for experimental manipulation in this study covered a range of climatic conditions but had a similar average peat depth and plant species composition, and were representative of large areas of heather-dominated upland blanket bog habitat, specifically in Britain. The paired catchment study included a one-year pre-management change period and compares burning to alternative mowing, with several additional plot-level treatments including brash removal, *Sphagnum* addition and an unmanaged (uncut) comparison. However, an unmanaged control scenario (i.e. catchment), although not included in this study, would ideally be considered in future work. Management was carried out after a one-year pre-monitoring, initially on areas including the monitoring plots, but over subsequent years covered an increasing catchment area as part of a usual management plan. However, recent (2021) changes in the UK government's burning on peat regulation meant that the continuation of the catchment-scale management was limited in the final year at one site. The experimental results from site monitoring, together with additional laboratory measurements, allowed impacts on peat properties, biodiversity (including vegetation and craneflies with modelled impacts on key upland bird species), nutrient content, peat hydrology and flow, water quality and elemental export in streams, the magnitude of C balance and net GHG emissions, and their controlling factors, to be quantified. For most parameters a statistical *Before-After Control-Impact* (**BACI**) assessment could be performed, detected pre-existing differences between plots and catchments (i.e. unrelated to management changes), and effect sizes often revealed that highly significant differences are likely ecologically less meaningful.

Site locations

The three study sites are all located in north-west England (**Figure 1**). The names used to identify the sites throughout this report are **Nidderdale**, **Mossdale** and **Whitendale**. Each site offered two adjacent (Nidderdale and Mossdale) or closely located (Whitendale) sub-catchments of similar size (~10 ha), with each being allocated either burning or mowing management after an initial pre-treatment period. Each sub-catchment has one central stream (see **Figure 1**), and their proximity allows all to be reached within one day when necessary. *The three sites represent a spectrum of site wetness and habitat condition with Mossdale being the wettest and least modified site and Nidderdale the driest and most modified and Whitendale the intermediate site*.

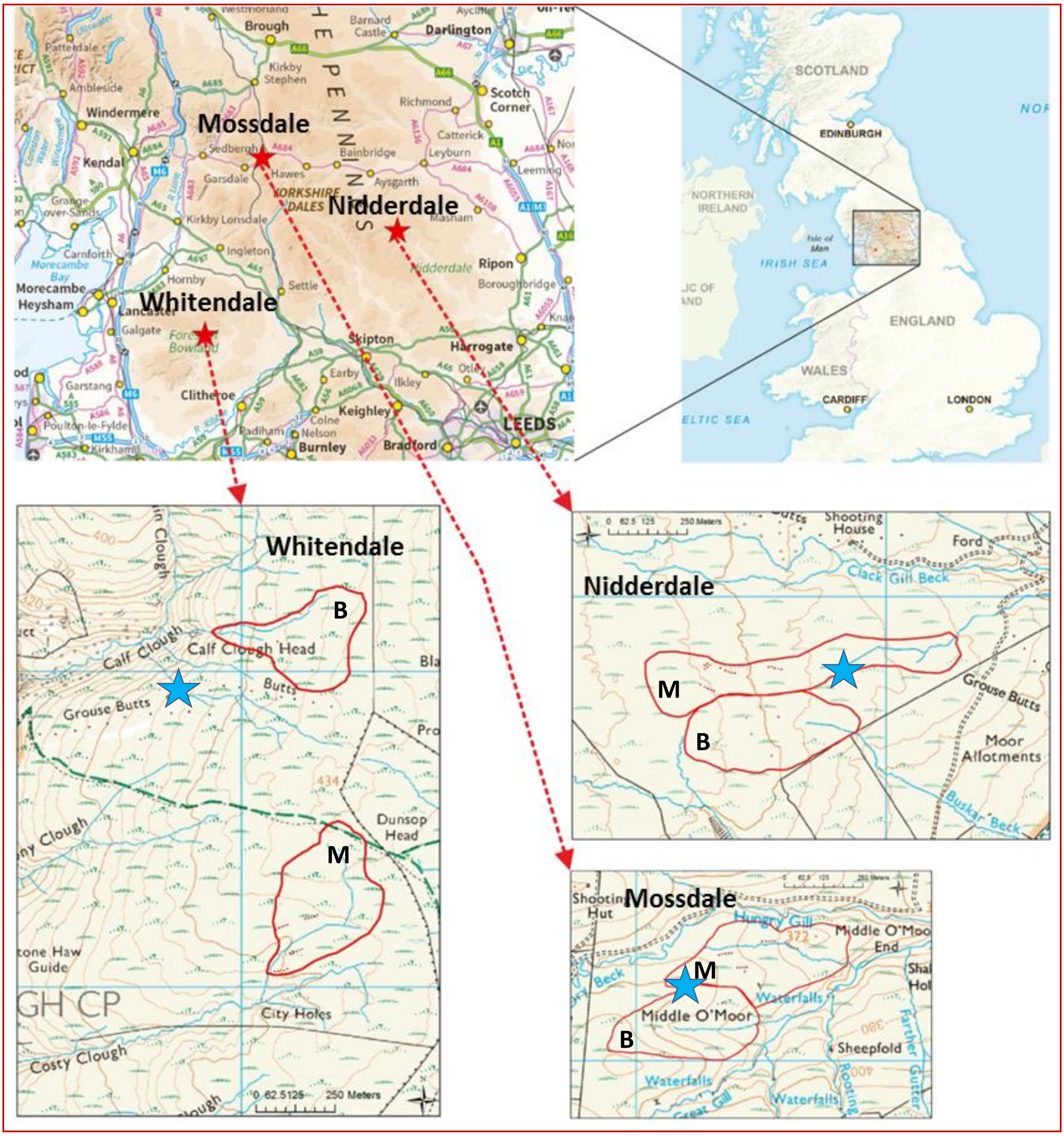


Fig. 1 Location of the three study sites in north-west England (**top maps**, red stars). The catchment boundaries (thick red lines) with the burnt (B) and mown (M) catchments and automated weather station (blue star) are detailed in the **lower maps** for Whitendale, Mossdale and Nidderdale. Source: MiniScale® [TIFF geospatial data], Scale 1:1000000, Tiles: GB, Updated: 3rd December 2015, Ordnance Survey (GB), Using: EDINA Digimap Ordnance Survey Service, http://digimap.edina.ac.uk, Downloaded: 2016-09-09 14:35:01.73. Note the central stream within each sub-catchment.

Site management

The below **Figure 2** shows satellite pictures for the three sites and their two catchments (burnt & mown) outlining the management areas during the four management periods (2013, 2015, 2018 and 2021).

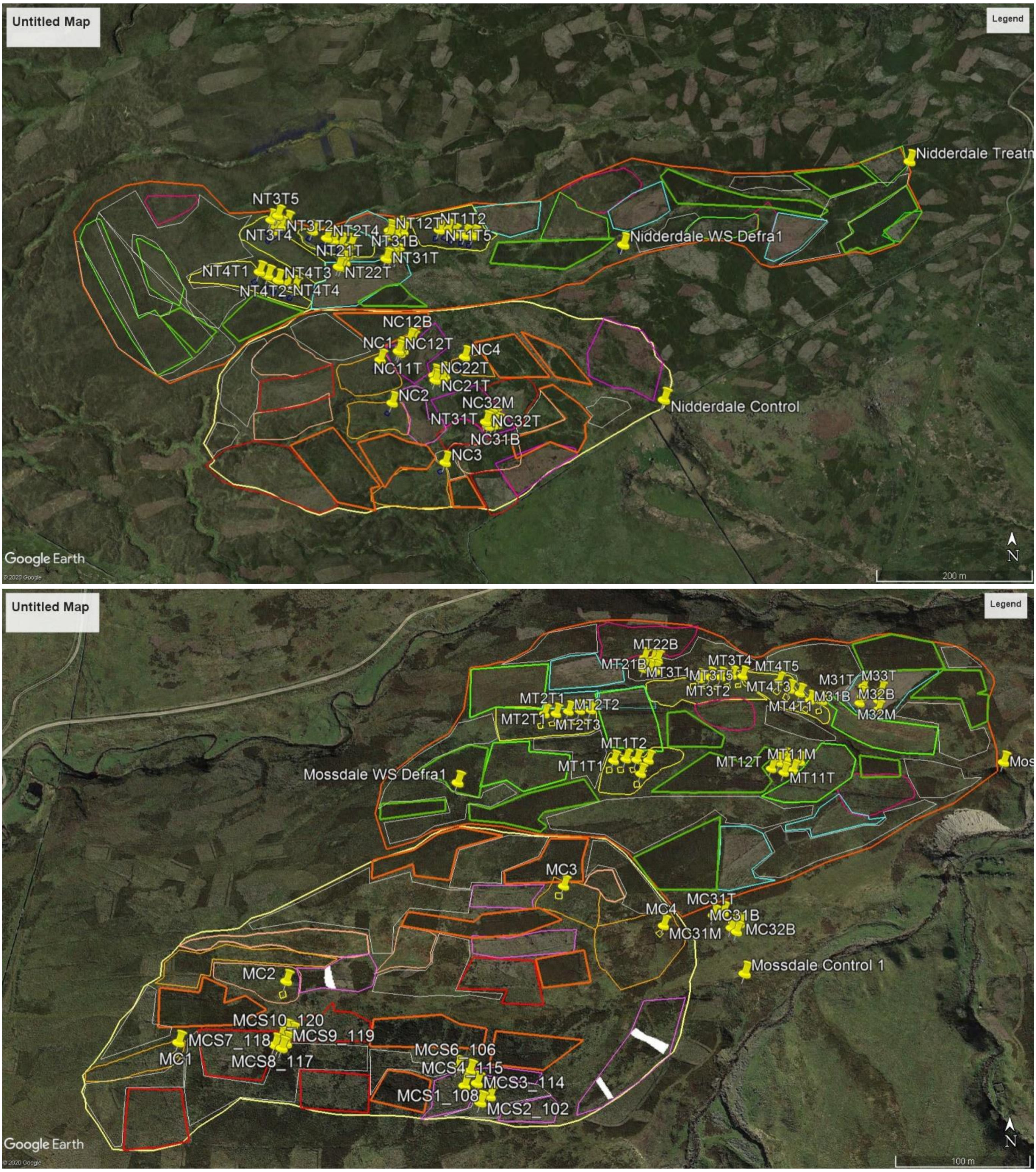


Fig. 2a Outlines for the paired sub-catchments (red = burnt; green = mown) at the two sites: Nidderdale (**top**) and Mossdale (**bottom**) with pictures obtained from Google Earth (2020). Shown are the GIS layers for the large catchment boundaries, the plot (5x5 m) and slope locations (yellow pins) and the burnt and mown areas (small polygons) with orange (containing plots) & skin polygons for burnt and yellow (containing plots) & pink polygons for mown areas in 2013, red (burnt) and light green (mown) polygons for 2015, purple (burnt) and blue (mown) polygons for 2018 and brown (burnt) and dark green (mown) polygons for 2021 management interventions, respectively. Additional areas likely suitable for future management are shown by thin, pale outlines in each catchment. All sites show active grouse moor management (burnt strips). Scale bars (i.e. entire white marker length shown in the bottom right of each picture) are 200 m for Nidderdale and 100 m for Mossdale.

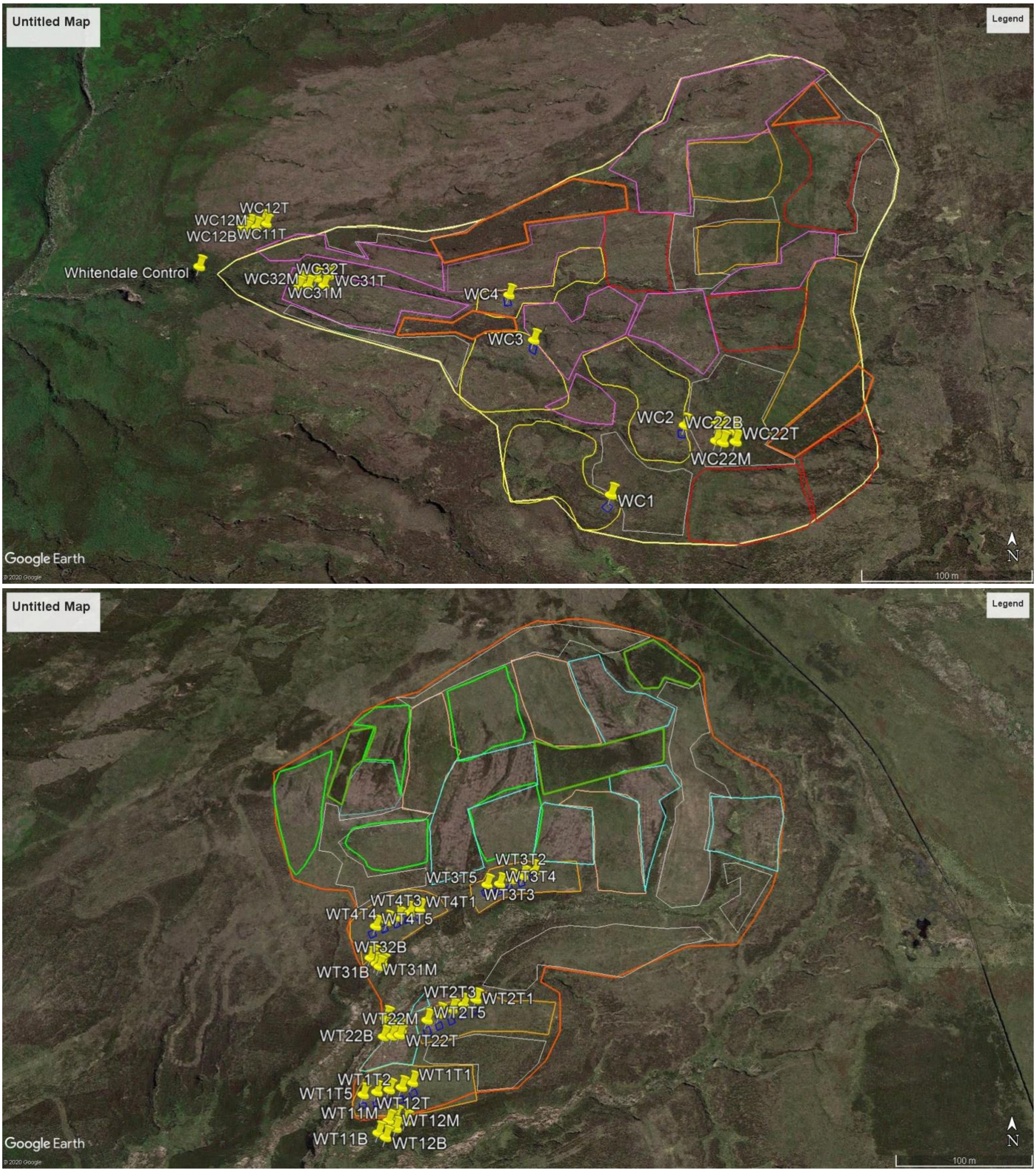


Fig. 2b Outlines for the paired sub-catchments (red = burnt; green = mown) at the Whitendale site: burnt sub-catchment (**top**) and mown sub-catchment (**bottom**) with pictures obtained from Google Earth (2020). Shown are the GIS layers for the large catchment boundaries, the plot (5x5 m) and slope locations (yellow pins) and the burnt and mown areas (small polygons) with yellow (containing plots) & orange polygons for burnt and orange (containing plots) & skin polygons for mown areas in 2013, red (burnt) and bright green (mown) polygons for 2015, purple (burnt) and blue (mown) polygons for 2018 and brown (burnt) and dark green (mown) polygons for 2021 management interventions, respectively. However, no 2021 management was undertaken in either catchment. Additional areas likely suitable for future management are shown by thin, pale outlines in each catchment. Both sub-catchments show some active grouse moor management (burnt areas) and also previously (2009) mown areas (stripes). Note also the additional larger burns (2018), which happened outside the experimental burn catchment area. Scale bars (entire white marker length shown in the bottom right of each picture) are 100 m for both the burnt and mown catchment.

Although the three sites had the same basic setup, landscape features required placing the weather stations in suitable locations within the overall catchment, which coincided with different vegetation and topography. Moreover, although very closely located to each other, the paired catchments also varied slightly in vegetation and topography (slightly steeper in burnt). Finally, individual site management achieved similar burning and mowing results (as in total managed area and reduction in overall heather cover). The pictures below (**Figures 3-6**) show the main characteristics of the three sites, their catchments and management practice.

Fig. 3 The automated weather stations (AWS) at (**from left to right**) Nidderdale, Mossdale and Whitendale. All sites are on heather dominated grouse moors but vegetation at the Mossdale AWS location is shown re-growing after a recent burn. Pictures were taken in December 2016.

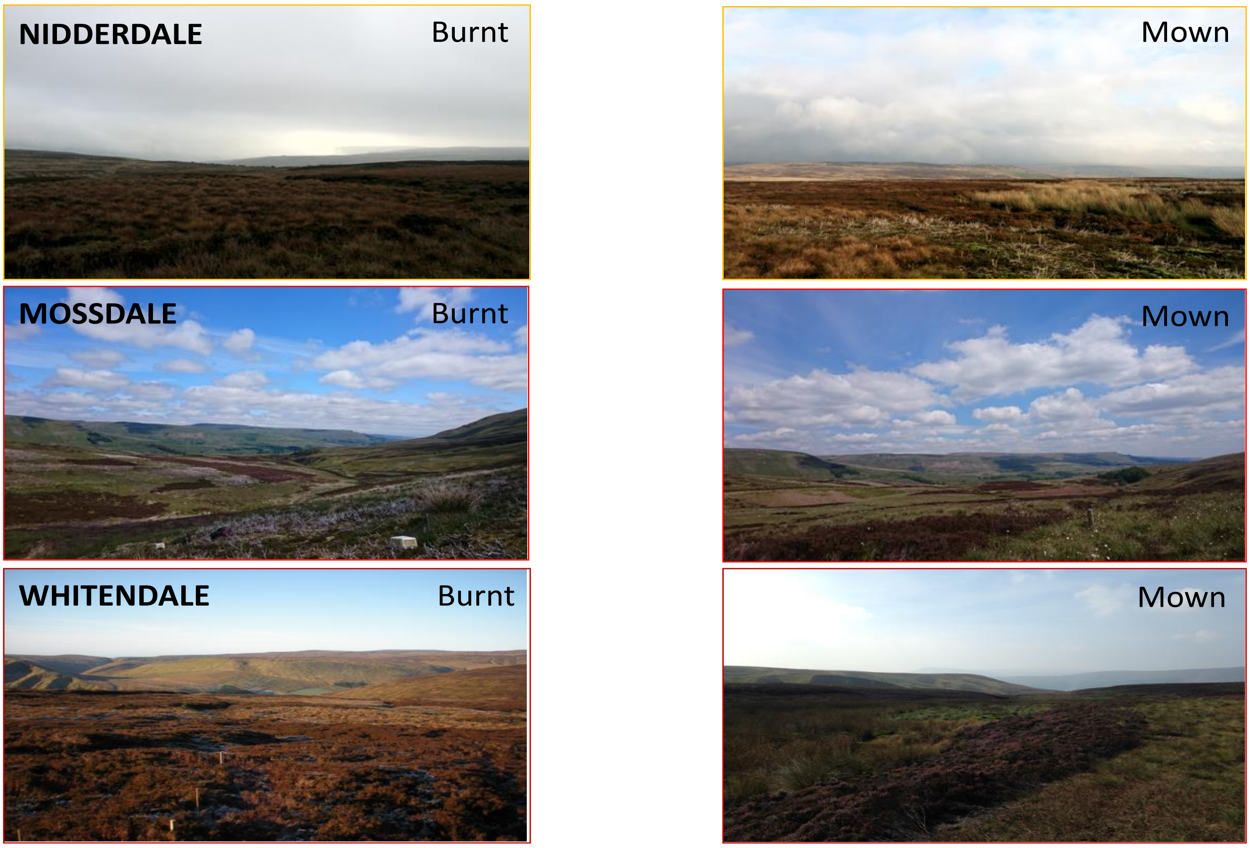


Fig. 4 The six sub-catchments shown from an elevated point. Shown are the pairs of burnt (**left**) and mown (**right**) sub-catchments for Nidderdale (**top**), Mossdale (**middle**) and Whitendale (**bottom**). Pictures were taken in September 2015.

Fig. 5 The six sub-catchments (**from left to right**: Nidderdale, Mossdale, Whitendale) shown during burning (**top row**) and after mowing (**bottom row**) in March/April 2013. Also note the very flat topography and thick brash layers after mowing.

Fig. 6 The three mowing arrangements (**from left to right**): Nidderdale, Mossdale and Whitendale. On average, vegetation was mown about 12 cm above the peat surface and the heather brash returned to the surface was about 5-10 cm long, with the coarsest brash at Nidderdale and the finest at Whitendale. The initial brash layer after mowing was around 5 cm thick. Brash was removed from mown (BR) and mown with added *Sphagnum* (BRSp) plots by manual raking (~4-5 times ca. 50 L brash were collected from the 5x5 m plots in 70 L bags, see picture on the **far right** and deposited in adjacent areas.

The below **Table 1** outlines the managed catchment areas at each site and for the overall average versus the amount of actual heather dominated areas and thus the potential for further, future management; the final column shows the percentage (~72%) of the so far managed area (of the likely total heather-dominated area).

Site Catchment	**Catchment area (ha)**			**Percentage**
	Managed	**Actual Heather**	**Further potential**	**managed**
Nidderdale Burnt	**7.1**	**8.2**	**1.1**	**87**
Nidderdale Mown	**7.1**	**9.9**	**2.8**	**72**
Mossdale Burnt	**4.1**	**6.2**	**2.1**	**66**
Mossdale Mown	**5.3**	**8.0**	**2.7**	**66**
Whitendale Burnt	**5.4**	**7.2**	**1.8**	**75**
Whitendale Mown	**5.5**	**8.2**	**2.7**	**67**
All sites (average)	5.8	7.9	2.2	72

Finally, whilst both catchments at Nidderdale and Mossdale showed historic drainage (mostly naturally infilled), Whitendale only had several gullies (see **Figures 2a,b**). For further site information see Heinemeyer et al. (2019b).

Experimental design

The following sections outline the overall experimental design as per initial Defra project (BD5104; Heinemeyer et al., 2019b). For each site, two similar adjacent sub-catchments were randomly allocated either a burning or mowing management at the catchment scale, with various plot-level managements, including an additional uncut plot-level management within each mown sub-catchment. The entire manipulative experiment was based on a Before-After-Control-Impact (BACI) design, to enable robust statistical analysis of the effects, and therefore included almost a full year of pre-management monitoring. Each site was visited in November 2011 to assess site conditions and determine suitability for the project; an appropriate central point for a weather station (**Figure 7**) was determined between the two sub-catchments, which were of similar size and manifested similar conditions (e.g. vegetation, management, slope, peat depth).

Fig. 7 Argocats enabled accessing remote areas during setup (**left**), away from public footpaths. Weather stations (**middle**) were protected from sheep by a fence with reflective plates to be visible to birds. Individual 5x5 m plots (**right**) were marked by low wooden posts, with uncut plots marked by larger fence posts to ensure about 1 m of unmown edge around the plot.

The experimental design enabled a robust statistical approach, addressing the need for a pre-treatment period (i.e. before a change in management) and providing replication at plot and catchment scales, which is both scientifically rigorous and relevant to practitioners. The paired catchment design allowed for comparison of the main managements (burning and mowing) across sites whilst the plot-level treatments within the sub-catchments could also be compared at each site. This design is unique within a peatland context; it aims to set a precedent for future ecological work and offers a potential long-term research platform of national/international significance.

Sub-catchment boundaries for the three sites were defined based on the watershed, first by defining the rough outline of each catchment using contour lines on a detailed map, and then walking the top of the identified ridge around each sub-catchment using a GPS to accurately record the outline. A V-notch flow weir (with a notch angle of 90°) was constructed from durable PVC at the outflow of each sub-catchment. One sub-catchment of each site was randomly assigned to a business-as-usual burning management with the other being assigned to management by mowing. Within each sub-catchment four blocks each with one plot-level replicate**,** were defined with at least 50 m between blocks (e.g. **Figure 8**). In the burning sub-catchment, each block contained two plots; **FI** plots were solely burnt and **FI+Sp** plots were burnt with *Sphagnum* propagules added. In the mown catchment, each block contained five randomly allocated treatment plots; **LB** plots were mown with the brash left, **BR** plots were mown with the brash removed (see **Figure 6**), **LB+Sp** plots were mown with the brash left and *Sphagnum* propagules added, **BR+Sp** plots were mown with brash removed and *Sphagnum* propagules added and **DN** plots were left uncut as the ‘do nothing’ control.

All **plots were 5 x 5 m**, with a 5 m gap between each plot, and were marked out with wooden corner posts protruding approximately 50 cm from the peat surface. In the lowest corner (flow direction) of each plot (see **Figure 8** for a schematic diagram of a typical plot), a temperature logger (Tinytag Plus 2 – TGP-4017 data logger, Gemini Data Loggers Ltd, Chichester, UK) was placed on the peat surface and covered by a reflective lid secured by plastic mesh and pegs. Another logger unit (TGP-4520) measured the temperature at the peat surface (with the probe covered by 0.5 cm of peat to prevent any direct sunlight heating the sensor) and at 5 cm depth on FI, LB and DN plots only. Above the temperature logger lid, a WTD meter was inserted into a 1 m deep hole cored in the peat and a peat rod (steel; 12 mm diameter) was inserted into the bedrock (to enable measurement of peat surface changes). Additionally, each plot contained a Rhizon sampler (type MOM 10c, 2.5 mm diameter, van Walt, UK) extending to 10 cm peat depth which allowed for periodical sampling of peat pore water. The instruments were covered by a stainless-steel mesh cage which was pegged at the bottom and folded at the top to prevent sheep damage whilst allowing easy access. Circular flux areas for repeated methane (CH_4) and total CO_2 soil respiration (SR), root-free SR (SR_c) and net ecosystem exchange (NEE) measurements were chosen along one side of the plot and marked with metal pegs. A **1 x 1 m sub-plot** was marked in each plot in a different corner to that of the WTD meter for detailed vegetation monitoring (**Figure 8**).

Each sub-catchment contained a further three slope locations between the four main blocks containing the plot-level replicates to capture a range of aspect and slope conditions across the sub-catchments. Each slope location consisted of six plots, set out in two rows down a slope, with each plot containing a WTD meter (measuring to 50 cm depth) and surface temperature loggers and Rhizon samplers (as above). Mean slopes on slope plot locations on Nidderdale, Mossdale and Whitendale were 8°, 10° and 14° ± 4° STDEV, respectively.

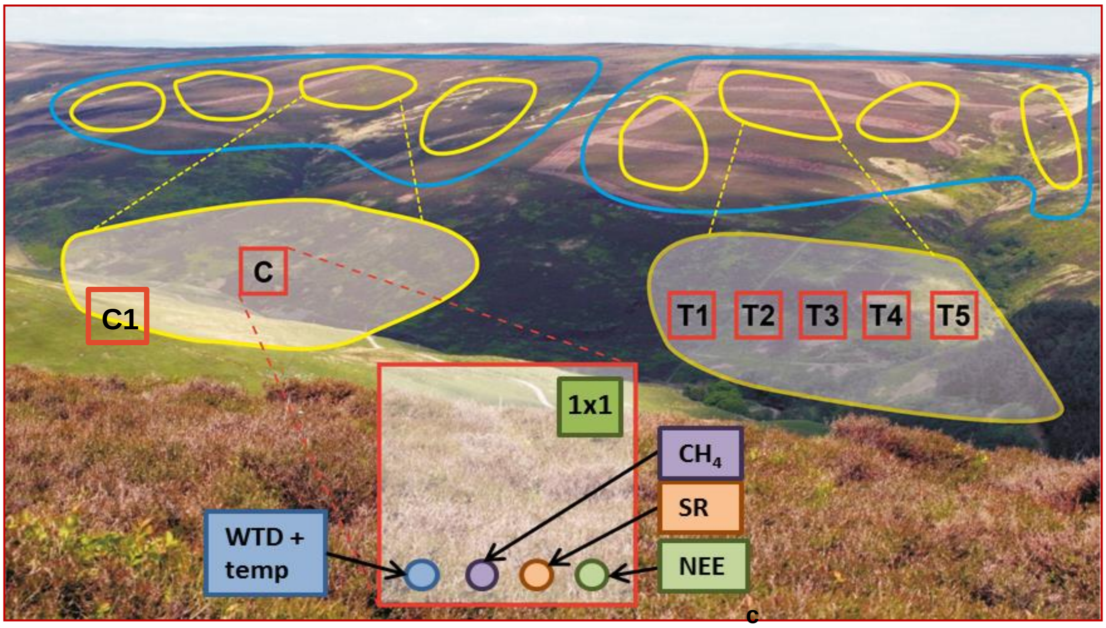


Fig. 8 Typical site layout (i.e. a schematic only and not one of the actual project sites) of the two sub-catchments (blue outlines) with four blocks (yellow outlines) each. Each plot (red outlines) is 5x5 m. Control (C) plots were burnt (FI) and the additional C1 plots were burnt with *Sphagnum* propagules subsequently added (FI+Sp). Treatment (T1-T5; randomly allocated) plots in the mown sub-catchment were either mown with brash left (LB) or brash removed (BR), were mown with *Sphagnum* propagules added (LB+Sp; BR+Sp), or were left uncut as 'do nothing' comparisons (DN). Each plot contained a corner 1x1 m area (green square) for detailed vegetation monitoring, a circle for initial CH_4 [from 2015 onwards CH_4 was measured at NEE plots] and total soil respiration (purple circle), root-free soil respiration (SR_c) areas for decomposition (brown circle), and NEE flux (green circle) measurements and a mesh cage with a dipwell and temperature logger (blue circle). Each sub-catchment also had three slope locations, one positioned between each of the four main blocks (i.e. not shown but located between the yellow outlines).

Management change started with the first management phase in 2013 (see **Figure 2** for polygon outlines), burning (Nidderdale: 5th March; Mossdale: 1st March; Whitendale: 21st February) and mowing (Nidderdale: 11th April; Mossdale: 9th April; Whitendale: 7th March) on all blocks and on three additional areas per sub-catchment (~0.24 ha each). In the second management phase in 2015, five new areas (~0.25 ha each) within the sub-catchments were burnt (Nidderdale: 10th and 14th April; Mossdale: 19th March; Whitendale: 18th March) and mown (Nidderdale: 13th January; Mossdale: 31st March; Whitendale: 13th and 14th March). Further management occurred in 2018 (in each sub-catchment a total of: Nidderdale ~1.7 ha during 15th-25th March; Mossdale ~0.9 ha on 26th February; Whitendale ~2.1 ha during 16th-26th February) and 2021 (total of: Nidderdale ~2.0 ha during 1st-20th March; Mossdale ~1.5 ha on 3rd March; Whitendale 0.0 ha [due to changes in Defra burn regulation]).

Key findings (including updates to the previous Defra report)

The below summaries provide an update of the peer-reviewed Heinemeyer et al. (2019b) report, as such the methods and analyses have been previously peer-reviewed and provided in detail. However, a few aspects were added, notably a (heather) nutrition analysis and peat growth (rod) assessment. Finally, additional appendices provide some more site information, data analyses, outputs and interpretation/contextualisation of results.

Physical management impacts. Despite anticipated compaction from the heavy machinery used for mowing, the peat showed resilience and there was no lasting plot-level impact on either peat depth or bulk density, yet impacts elsewhere, such as from turning and standing machinery, although not assessed, were sometimes severe and long-lasting (compacted and bare peat). Moreover, mowing did affect the plot micro-topography, making it more uniform, by removing the tops of hummocks/tussocks (also damaging *Sphagnum* moss), which could negatively affect ground nesting birds (nesting sites) or other animals (diverse habitat). Indications that mowing and leaving brash on the ground might be beneficial in spreading *Sphagnum* propagules were not found to be long lasting (i.e. similar change in *Sphagnum* cover on burnt and mown plots). Importantly, burning did not result in any large peat surface temperature increases compared to uncut or mown plots, and mowing showed some insulation effects (i.e. lower maxima with left brash). Ground penetrating radar indicated no change in the number of natural peat pipes.

Vegetation assessment. In the immediate post-management period, combined bare and burnt ground cover was higher on burnt than mown plots, whilst brash was higher on mown than burnt plots, but both were transient effects lost after 4 years. Initially, heather re-growth was slower on burnt than mown plots, although after 4 years, heather cover and height was similar on burnt and mown plots. The highest increase in cover was on the driest site, especially on burnt plots, but the greatest increase in height was on the wettest site. However, subsequently, sites significantly suffered from heather beetle setbacks, especially on burnt plots at the wetter sites and mown plots on the driest site. Cotton-grass (*Eriophorum* spp.) cover increased on both burnt and mown plots after management with a greater and continuous increase on mown plots at the two drier sites. Specifically, *Eriophorum vaginatum* cover was significantly greater on mown than burnt plots, but this varied between sites, and to some degree this was also the case in the pre-management period. Grass cover (mainly *Deschampsia flexuosa*) increased to a low extent and mostly on burnt plots. Cover of total non-*Sphagnum* mosses, particularly *Hypnum jutlandicum* and *Campylopus introflexus*, was greater on burnt than on mown plots, but this difference was already present pre-management, and the greatest increase (and an indication of drying) was observed on uncut plots. *Sphagnum* cover increased relatively constantly across time and similarly under all management regimes if considering differences in pre-management cover, although there was a sharp yet only transient increase in total cover on mown plots in the final year of Phase 1. The *Sphagnum* pellet additions only resulted in a minor potential increase of cover at the intermediate site (Whitendale) and only on two burnt plots, which was significant only for *S. capillifolium* out of all three added species (also incl. *S. pallustre* and *S. papillosum*). The increased sedge cover after mowing seems to indicate a possible different long-term trajectory between burnt and mown plots. Overall plant species diversity was low, decreasing from the wettest to the driest site. The driest site had the highest number of *Sphagnum* species, likely reflecting greater habitat variety, but it also had the lowest overall *Sphagnum* cover with the wettest site by far having the highest cover, as would be expected. The initial relative scarcity of *Sphagnum* moss at the drier sites might limit the development towards more 'active' blanket bog with higher *Sphagnum* cover, resulting in heather and non-*Sphagnum* mosses regaining dominance (as indicated by heather and non-*Sphagnum* moss regaining dominance on the driest sites). Unless there is a relatively rapid post-treatment 'natural' increase of *Sphagnum,* the re-introduction of *Sphagnum* propagules or additional heather control (e.g. via repeated mowing) might be required. However, definitions around 'active' or 'intact' status in relation to linking vegetation cover to bog functions are ill-defined and there might also be climatic constraints on the long-term survival of *Sphagnum* moss (i.e. at the driest site). So far, both managements appeared to be supporting 'active' bog vegetation, opening up the heather cover to allow

Sphagnum and other mosses to increase in cover in addition to other shrubs, herbs and sedges. The uncut 'do nothing' option showed some downsides, especially a limited development of a supportive 'peat-forming' bryophyte layer at the driest site, although definitions around 'peat-forming' species remain ill-defined (Ashby & Heinemeyer, 2021), as it is the conditions which are most critical to consider (i.e. water table). Mowing, regardless of brash management, seems to encourage a more sedge-dominated bog community, particularly at the two wetter sites together with an increase in *Sphagnum capillifolium*. The nutrient content of young heather shoots (increased levels of N, P, K, Mn and Zn and less Al) was significantly improved by either management compared to uncut areas (for K this was only on burnt plots with also close to significantly higher Mg). The benefit of management was mostly, and often for longer, observed for burning compared to mowing, with particular importance for C fluxes (key elements for photosynthesis enzymes) and for grouse (P and Mn nutrition). However, nutrient levels became mostly similar over nine years of post-management. Cotton-grass showed significantly increased Mn levels but only on burnt plots, especially in flower heads. Species richness and Shannon diversity significantly increased after burning, and diversity was significantly lower on burnt plots pre-management.

Hydrological impacts. Mean annual water table depth (wtd) was ~12 cm on uncut plots, a threshold in relation to defining 'active' (i.e. peat accumulating) bog as per Evans et al. (2022). Mown plots had slightly (~2 cm) higher (i.e. wetter) wtd, as well as higher soil moisture, during the Phase 1 post-management period compared to burnt plots. These effects were particularly apparent in summer, being significant at two sites during May-July, and when leaving brash, but there were also considerable site and time period differences. The higher WTD on mown plots disappeared in the Phase 2 post-management period yet was reflected in overall ~12% (equal to ~0.14 m^3 h^{-1} ha^{-1}) reduced catchment stream water loss from the generally flatter mown catchments compared to the slightly steeper burnt catchments, but only at the two sites with historic drainage, with these mown catchments showing ~10% lower water loss than the burnt catchments in the first post-management and ~20% reduction in the subsequent period (and not increasing further despite the increased management area). The site without any meaningful change in stream water loss had no historic drainage ditches, had received some previous mowing management in both catchments and indicated some influence of non-peat soil flow versus rainfall behaviour (Clark et al., 2007). Overall, flow reduction over the post-management periods across all three sites was 9% in mown versus burnt catchments. Surprisingly, burnt plots became significantly wetter (~2 cm higher mean WTD) over time, especially during 2017-2021 and in winter, whilst uncut plots with ageing and large/tall heather plants became overall significantly drier by ~2-6 cm at two sites, especially during summer months. Importantly, the previous EMBER report also observed highest WTD on plots burnt 10+ years previously (*cf*. Fig. 4.1 in Brown et al., 2014). Moreover, burnt plots had significantly larger water table ranges than all other managements (drying out/rewetting significantly quicker but only at two sites during the Phase 1 post-management period); whilst not significant overall, two sites indicated a brash infiltration effect in significantly reduced runoff from mown compared to burnt catchments under equally high (near saturation) water table and rainfall conditions. However, runoff/retention from near saturated catchments became similar over time. Management implications on flooding remain unknown, requiring more detailed modelling approaches, but higher water tables (mostly in winter) on the burnt plots led to slightly (and not overall significant) higher stream peak flow volumes, shorter peak lag with a longer peak duration. However, the driest site with greater effect sizes indicated significantly higher stream peak flow (by ~1.2 m^3 h^{-1} ha^{-1}) with less peak lag (of ~1.3 hours) in burnt versus mown catchment and non-significantly lower duration (of ~1.8 hours).

Water quality. Mowing resulted in variable yet nearly 3 times higher stream phosphorous (P) concentrations, but significantly lower lead (Pb) concentrations than burning during the post-management periods. The P effect is likely to be a result of continued leaching from the decomposing brash layer in the mown sub-catchments and could be important for long-term eutrophication in reservoirs. Moreover, stream nitrogen (N) concentrations, which can also promote eutrophication, showed an overall strong relationship between dissolved organic carbon (DOC) and nitrogen (DON), with a DOC/DON ratio of 0.47 (unaffected by management, but with large seasonal and sometimes significant interannual variations) and overall higher (yet not significant) concentrations in burnt catchment streams (especially for nitrate [NO_3] and dissolved total and inorganic N [DIN]). Further, annual by catchment area weighted N export rates were not significantly different between burnt and mown catchment streams (only in 2020 total N and DON export was near significantly higher in burnt vs. mown catchments). However, stream nitrogen was only measured during Phase 2 (no pre-management change monitoring) and burn related losses of N might be beneficial by counteracting elevated N input from atmospheric deposition and thus support nutrient poor bog development. Both peat pore and stream water showed a significant near one unit pH increase over time and indicating a peak during 2016-2018, which was not significantly affected by management but was partly linked to climatic conditions, in particular increased temperatures, and likely a recovery from historic acidification. However, burnt plots showed the strongest and most significant trend of slightly increased pH after management. Stream conductivity (~54 µS/cm) also significantly increased slightly over time, regardless of management. Other stream water quality indicators, including concentration of DOC, varied seasonally and between sites, and did show an increasing management impact, over time becoming higher by ~2 mg L^{-1} in mown catchments (but due to less flow, total monthly export was (weakly significant) lower by ~0.4 gC m^{-2} than in burnt catchments). Moreover, POC concentration significantly increased by 1.8 mg L^{-1} in mown streams, yet POC export as well as stream flow UV spectra colour index values (e.g. SUVA) only differed between sites, seasonally and between years, but not between managements. Peat pore water DOC and UV values showed no significant effect of management overall, but over the first five years were positively correlated with temperature, and, in the case of SUVA, also with sedge and *Sphagnum* cover, whilst they were negatively correlated with heather cover. The entire 9-year post-management period revealed a weak link of DOC and several UV spectra based water quality parameters to vegetation cover (explaining <10% variability) for plots and slopes when comparing across all years and sites. Whereas heather, sedge and herb (and mostly also for grass) showed significant negative relationships with water quality parameters, moss, bare and brash showed significant positive relationships, yet responses to *Sphagnum* moss were weak and varied. Moreover, there were significant overall (at plots and slopes) differences between sites (Nidderdale[N], Mossdale[M], Whitendale[W], respectively) in water quality parameters (E4/E6: N>W>M; DOC: N>W&M; SUVA: N<M&W; UV254, UV465 and UV665: M<W&N. There was no plot management impact for individual years, only a marginally significant (p=0.090) effect in 2020 on UV254 (burnt & mown with brash removal were lower than mown with left brash and uncut). Across slopes, water quality revealed some linkages to past and recent management condition, but this was highly variable between sites and years. Therefore, at the plot level there was no clear evidence of a link of burning to declining water quality but rather a link to vegetation and ground cover. This highlights the need for long-term and replicated wider catchment-scale and detailed process-level assessments covering topographic and vegetation complexity.

Cranefly emergence, abundance and bird population modelling. During the first five years, the increased surface peat moisture in mown compared to burnt areas in the dry year after management, resulted in higher cranefly emergence. However, cranefly emergence on mown areas was reduced in the following two wet years. Cranefly emergence was also consistently lower on the wettest site, particularly in the wetter mown plots. These findings are likely to reflect a lower and upper soil moisture limit for optimum cranefly emergence between about 80% - 97%. However, the upper 97% moisture limit, cranefly species and potential food source switching by birds were all not considered in the current predictive models. Cranefly abundance on transects was overall higher in mown than burnt catchments only during Phase 1. The modelled implications for golden plover fledging production showed that numbers would be higher in mown than burnt areas, this effect being strongest in the relatively dry year of 2014 when cranefly abundance was lowest. Modelling the effects of drier summers, which are predicted to be more likely under climate change, and based on the cranefly emergence and soil moisture data, predicted a greater resilience to future drier summers of upland bird numbers (i.e. dunlin, golden plover and red grouse) under mowing, particularly when leaving brash, than under burning. However, the potential that mowing might make generally wetter sites too wet for cranefly larvae survival (i.e. lower emergence) and micro-topographic management impacts on nesting preferences by birds (i.e. importance of hummocks for dunlin) were not included in the model. In fact, reduced vegetation heights by management were shown to be beneficial to breeding density of golden plover, especially following burning, whereas uncut areas were too tall. Moreover, during Phase 2, where only transects were monitored, this revealed that burnt catchments periodically harboured slightly (yet not significantly) higher cranefly numbers than mown catchments, likely reflecting very wet conditions during several years in Phase 2 negatively impacting cranefly larvae survival in mown catchment areas (wetter). Overall, cranefly numbers were most likely affected by interannual climatic changes, showing a peak in 2017 (5 craneflies per 20 m transect) and subsequent decline (to about 1 per 20 m) after the exceptionally dry summer in 2018.

Soil C cycling and decomposition. Soil respiration rates from decomposition processes were significantly influenced by management intervention in the field, whilst burning and (albeit less so) mowing with brash removal reduced it, mowing with leaving brash increased it. However, such field measurements capture fluxes from the whole peat column, whereas management intervention is most likely to affect only the peat surface layers. Therefore, additional measurements and experiments were conducted on surface peat under controlled, laboratory conditions. These showed that decomposition rates in the surface 5 cm were lower on burnt than on mown plots with (decomposing) brash left. The temperature sensitivity (Q_{10}) of decomposition in the surface 5 cm of peat was also lower on burnt than mown with brash left plots, as was the response to variation in soil moisture. In addition to loss of biomass (via combustion) otherwise available for decomposition and reduced plant-derived labile C inputs available to microbes, charcoal input from burning was identified as a potential additional mechanism explaining this difference. Charcoal was linked to an increase in bulk density and organic C content, with subsequent possible negative effects on microbial activity and hence lower decomposition (i.e. Flannagan et al., 2020). Heather associated mycorrhizal fungi were shown to be able to break down very old peat carbon and hence could affect carbon pools and their longevity, whilst potentially also increasing nutrient uptake rates (as seen in especially increased concentrations of key elements in shoots post burning) and hence enhancing net C uptake and biomass production by stimulating photosynthesis. However, in a controlled pot experiment mycorrhizal fungi could not be linked to any meaningful impacts on DOC concentrations or water quality.

Ecosystem CO_2, fluvial C and methane fluxes. Annual net CO_2 flux balance based on net ecosystem exchange (NEE) chamber CO_2 fluxes for uncut plots showed that the 10-year mean C gain (with considerable inter-annual variation) was greatest at the wettest site, but that the driest site was a small net C source. Both burnt and mown (with leaving brash) plots switched from a net C sink to a net C source after management. Net annual C losses were greater from burnt than mown plots in the year following management. However, 4 years after management intervention, C losses from burnt (excluding losses during combustion) and mown plots, averaged across the three sites, were very similar. Subsequent C sink recovery was quicker on burnt than on mown plots, likely related to significantly higher nutrient levels in heather shoots and lower respiration rates (which were significant for soil but not ecosystem respiration [Reco] fluxes) post burning. However, both managements were affected by heather beetles in the Phase 2 period, causing a switch from C sink to C source on some sites. Trajectories on flux data, excluding periods of heather beetle impacts, indicated a higher C gain for the burnt than mown scenario, with an overall decline in C uptake for uncut, driven by a steady increase in Reco (due to ageing biomass). In fact, the overall increase in Reco of ageing heather, together with a strongly positive temperature impact on Reco and near continuous rise in air temperatures by about 1°C (during the 10-year period apart from a peak in 2014), is a very important factor in determining the overall declining C balance for uncut 'do nothing' plots. Overall C export as DOC was about 20 times higher than as particulate organic carbon (POC), but only DOC export rates increased significantly in burnt catchment streams compared to in mown streams. Both DOC and POC export rates showed a high seasonal variability and a positive correlation with temperature, and annual C budgets highlighted the need to include POC fluxes for the 'modified' peatland category in the IUCN UK's Peatland Code (although the origin and fate of stream DOC and POC are both very uncertain). Methane (CH_4) fluxes increased with higher water tables (wetter), and showed a strongly positive effect of sedge cover, but a negative link to heather (on managed plots) and brash layers and weak positive temperature (warmer) effect. Methane fluxes were much higher over four years following a very warm and wet period in 2014/15, particularly during 2015-2017 and at the wettest and less modified site, and higher fluxes corresponded to rising and higher than average annual soil temperatures, water tables and pH. Over the first five years, plant-mediated transfer contribution (i.e. via sedges) to methane emissions (as compared to soil only emissions) was around 60% and there was no difference between methane fluxes from non-vegetated and vegetated areas of burnt and mown plots. However, methane emissions were overall significantly higher from vegetated areas. Moreover, median methane emissions decreased significantly from uncut to mown to burnt plots, with a highly significant negative brash effect (i.e. the brash layer likely facilitating methane oxidation, reducing emissions by about 25%), and during Phase 2 were overall (but depending on time and site) significantly lower (by ~20%) for all managed plots when measured in the dark (vs. in full light; likely relating to stomatal responses by sedges).

Net ecosystem C balance (NECB) and net greenhouse gas (GHG) emissions. The 10-year mean annual NECB estimate for each site (based on the overall proportional average of unmanaged and managed areas) indicated a clear separation by site wetness, ranging from -6 to +60 gC m^{-2} yr^{-1} with an overall small C gain at the wettest site (Mossdale) and a moderate C loss at the driest site (Nidderdale), although values varied greatly between years, primarily due to variation in net ecosystem exchange of CO_2 (NEE) and methane fluxes. However, when excluding fluvial C losses of around 20 gC m^{-2} yr^{-1} (a very uncertain component and not directly attributable to the monitoring plots as it represents the entire catchment area with steeper slopes, areas of shallow peat and different vegetation), annual NECB improved considerably. Importantly, the three heather-dominated peatland sites, with a range of climatic and hydrological conditions, indicated an overall close link to mean annual water tables defining a switch between net C sink and C source status for NEE C balance and overall NECB values for uncut (old heather) plots of around 12 cm, similar to estimates from other UK peatlands based on high-frequency C flux monitoring (Evans et al., 2021).

After management intervention, mean NECB values across the three sites showed C losses for both managements that were on average 4-6 times larger for burning and mowing, respectively, than the mean C gain of the uncut scenario (~17 gC m^2 yr^{-1}), primarily due to lower values of NEE. The size of the net C source from the burning scenario was higher only over the initial 2-year post-management period than from the mowing scenario, even once the combustion loss of the heather biomass was taken into account (as a proportional annual C loss over a 22-year management cycle as based on peat core charcoal records). Notably, over the entire post-management period the burnt management showed about 32% lower cumulative CO_2 flux losses (including estimated combustion losses and charcoal gains) than after mowing. However, variability between sites and years was high, especially due to heather beetle attacks during most of the second phase affecting NEE (defoliation) on both burnt and mown plots. Moreover, there remains uncertainty in these NECB estimates, not only because of the heather beetle impacts on NEE but also because of long-term brash decomposition losses for mowing, which could not yet be considered fully, uncertainties on the carbon amount and fate from charcoal and charred plant remains, and fluvial C losses included losses from areas with little peat cover, also including erosion from slopes, whereas CO_2 and methane fluxes were measured on predominantly flat areas of monitoring plots on deep peat. Further, uncut NECB showed a declining trend, likely reflecting an optimum C-sink age relationship (Santana et al., 2016), with ageing vegetation becoming less efficient in photosynthesis (lower nutrient concentrations and higher respiration) and thus declining net C uptake and increased wildfire-relevant fuel load (Milligan et al., 2018).

The up-scaled estimates for net GHG emissions (including CO_2, CH_4 and N_2O) expressed as CO_2 equivalents (CO_2-equivalents), also differed considerably between sites. The overall average net GHG emissions for the uncut scenario (based on the 10-year median methane flux) was a net GHG sink (-104 tCO_2eq per km^{-2} yr^{-1}), being positive (i.e. a net source) at the driest but negative (i.e. a net sink) at the two wetter sites with C sink increasing from intermediate to high mean annual water table depths. Mean net GHG emission values for both managements were positive and much greater than the uncut scenario at the dry site, but the burnt scenario was only about half that of the mown scenario (232 vs. 388 tCO_2eq per km^{-2} yr^{-1}, respectively) and whilst for burning the driest site showed lowest emissions, the wettest showed highest emissions. Despite the high global warming potential (GWP) of N_2O, the inclusion of N_2O emissions had little influence on the net GHG emissions, but inclusion of long-term methane fluxes had a large effect; net GHG emissions varied considerably, depending on whether the mean or the more robust median fluxes were used, especially affecting long-term emission calculations. During the study period, the results of the uncut plots agreed fairly well with previous assumptions of the IUCN UK's Peatland Code for 'near intact' blanket bog sites. However, whilst the driest site had higher CO_2 losses and lower methane emissions than on the wettest and least modified site, the intermediate years of very high methane emissions (2015-2017), which could be linked to warmer, wetter and less acidic soil conditions, resulted in much higher net GHG emissions (i.e. the Peatland Code could be underestimating the net GHG emissions of very wet sites). These findings call for caution against the assumption of a “the wetter the better” management approach within a blanket bog GHG emissions context, as overall ranges in methane emissions between sites and over time indicated a possible water table depth threshold in relation to achieving both, a net C sink and a beneficial net GHG balance. Moreover, sedges, mown and uncut management were associated with higher net methane emissions, whilst heather and burnt plots were associated with lower emissions.

Peat C sequestration. Cabon accumulation rates based on dated peat cores for all three field sites under burn rotation management were similar to a previously reported estimate for unburnt management (as part of a burn comparison) when compared over the same time period (Heinemeyer et al., 2018). Whilst chamber CO_2 fluxes suggested an overall large short-term net loss of C on burnt plots when losses from burnt biomass were included, C stock changes in peat cores indicated an ‘active’ peat C accumulation status and that recent C accumulation was actually higher under more frequent burn rotation (on these generally undrained and wet bog conditions). Interestingly, the measured higher accumulation rates related well to the estimated maximum charcoal C inputs (about 56 and 84 gC m^{-2} for charcoal and charred stems, respectively) and highlighted the need to consider positive charcoal impacts on peat bulk density and organic C content. Notably, none of these findings were questioned in critical papers by Young et al. (2019, 2021), where modelling constant deep drainage unsurprisingly impacted on C budgets not relevant to this study (i.e. minimal drainage and their model did not represent fire or charcoal impacts). Moreover, another peat core study at Mossdale (Webb et al., 2022) showed a similar age/depth profile with large recent peat growth, high sedge and consistent heather peat-formation, heather (pollen) cover and a high charcoal (fire) record over thousands of years. This fairly consistent picture of high heather cover with active peat-formation not just being a recent landscape feature is also supported by other studies such as Chambers et al. (2017), where three sites confirmed these aspects, but only a valley bog, likely drained, indicated a recent increase in heather. The discrepancy between C sequestration estimates based on the flux chamber method and those based on the peat stock inventory approach highlights the importance of long-term C flux assessment (so far less than half the time of the previous 22-year management cycle has been measured, resulting in a likely vast underestimation of the actual long-term flux C balance). It also highlights the importance of quantifying processes that are not captured by the flux approach, such as charcoal inputs with slower decomposition and the inclusion of decomposition fluxes arising from deeper and older peat layers. Moreover, peat core surface C stock assessments cannot be used to infer recent C budgets (because of possible losses from deeper peat layers as outlined in Heinemeyer et al., 2018) and need to consider impacts of seasonal moisture changes and charcoal inputs on bulk density and organic C content, which could explain differences between C accumulation estimates between studies. Moreover, peat rods also indicated an overall ‘active’ (i.e. peat growth) status as a small overall positive but not yet significant median peat growth over eight years (0.25 mm yr^{-1}), although variability for managements at each site was high. Whilst there was no overall significant increase yet in measured peat growth for burnt (0.31 mm yr^{-1}) and mown (0.25 mm yr^{-1}) managements, plots at Nidderdale (driest site) and Whitendale (intermediate site) showed highest peat growth of about 0.53 mm yr^{-1} on burnt plots, which was weakly significant for Nidderdale and corresponded to higher net C uptake measured by chamber C fluxes.

At Mossdale (the wettest site with extra rods at additional plots for the three main managements and vegetation types within the wider catchment area) peat surface increased significantly overall by about 0.60 mm yr^{-1} but also showed high variability with median peat depth increasing by about 0.50 mm yr^{-1} on recently managed areas (yet only mown showed a significant increase) and under the mature key vegetation types increasing significantly by about 0.90 mm yr^{-1}. The largest and highly significant increase was measured for *Sphagnum* (1.88 mm yr^{-1}), less and only near significant for heather (1.50 mm yr^{-1}) and least but significant for *Eriophorum* (0.69 mm yr^{-1}) dominated plots. However, whilst measurements capture brash inputs from mowing and litter fall, they do not allow detecting charcoal additions from burning (i.e. the main C input after burning in the short-term). Moreover, mown areas were significantly flatter and thus likely wetter areas, whereas heather, burnt and *Eriophorum* plots also included areas of steeper (and for heather also significantly drier) slopes (which was significant for mown plots versus mature heather plots). The high variability in peat growth likely reflected noise due to differences in overall peat depths and wetness (i.e. significant negative correlations with slope) and peat moisture between the two depths measurements (2014 vs. 2022), localised litter accumulation (patchiness) and highlight the longer time scale needed to more accurately capture overall litter inputs to peat accumulation rates using peat rods.

Synthesis of effects of management interventions to date. A detailed cost-benefit analysis (CBA), including long-term effects on ecosystem services, was still not possible as the experimental plots are still in a transition period and catchment management could not be completed. However, a summary matrix was updated (*cf*. Table 29 at the end of the Defra report; Heinemeyer et al., 2019b) capturing the intermediate management impacts so far on all major measured ecological parameters in relation to ecosystem services and the aim of supporting 'active' blanket bog development and reducing heather dominance through either mowing or burning. Overall, based on 30 parameters, mowing was equally beneficial to burning and beneficial impacts increased more for burning (*cf*. previous count). Mowing had positive effects on 14(8) parameters, compared with 14(6) for burning, and had a similar number of negative effects on 8(7) parameters compared with 9(11) for burning, and both had 7(mown:14; burnt: 13)) 'no change' effects, and one category was not assessed for mowing. In particular: mowing initially tended to support the development of more 'active' bog vegetation, although heather and *Sphagnum* regeneration was not different to burning, shoot nutrient levels (i.e. in relation to photosynthesis) benefited from either management but especially from ash fertilisation after burning; mowing did not cause any overall change in plot-level water quality (UV spectra), although there was an indication of possible contribution to eutrophication via greater stream concentrations for DOC and P (i.e. likely affecting reservoirs) but total C and N export rates were lower; mowing initially raised the water table along with a reduced water table range and increased soil moistures with likely positive impacts on bird populations via cranefly abundance, especially in future drier summer climate scenarios; mowing reduced stream flow rates and peak flow but only at the two sites with historic ditches and steeper burnt catchments (indicating an interaction with drainage and slope); but mowing was much more costly, and although mowing did not cause any significant negative impacts on peat properties it negatively affected micro-topography (and possible nesting ground), led to higher carbon flux losses (especially considering brash decomposition), higher net GHG emissions (especially considering methane), yet less air pollution than burning, when including biomass combustion losses. Moreover, leaving heather unmanaged not only causes a build-up of fuel (wildfire risk) but also a declining C sink (ageing heather with lower nutrient levels), lower water tables with drier peat surface (increasing peat decomposition), reduced vegetation diversity with likely overall reduced biodiversity (lacking habitat diversity) and predicted negative impacts on breeding densities of golden plover (benefitted most after burning). However, the C sink strength of unmanaged heather showed a clear net C uptake (i.e. active status) and a benefit of wetter climate and site conditions (i.e. heather-dominated peat can be a net C sink under wet enough conditions), highlighting the importance of peatland rewetting. Furthermore, impacts on wildfire of unmanaged heather is becoming increasingly important under UK climate change and wildfire risk scenarios (Belcher et al., 2021); Belcher et al. (as well as many others such as Davies et al. 2016a-c and Harper et al., 2018) clearly state a lack in research and clear evidence on management impacts and the need to consider prescribed fire within these peatland ecosystems and to continue vital research to address impacts as well as allowing cost-benefit analysis of alternatives (e.g. cutting). Finally, peat core and peat surface growth increments indicated strong positive peat growth and seemed to relate to measured fluxes and highlighted the importance of considering charcoal impacts on C budget assessments (i.e. peat physical (bulk density), chemical (C content) and biological (decomposition) alongside site condition (e.g. slope/runoff impacts)), but limitations in methods and accuracy (mainly due to time constraints) currently prevent a robust comparison between managements. However, for all these effects, inter-annual and site variability was considerable and long-term trajectories remain unknown and are also influenced by other environmental changes (notably pH, temperature and rainfall). It is noteworthy that the current study focused on comparing different management representative of only about 30% of British blanket bog (mainly the Pennines); ideally a 'no management' scenario, an 'intact' and a shallow peatland site would be included at the same plot-to-catchment scale monitoring level in any future assessment.

In summary, the findings from the different elements of the project are still to be seen as intermediate (as so far only nine years of post-management monitoring have been completed), which indicate that: **1)** the heather-dominated peatlands under previous burn management show clear indication of an overall near 'active' bog and near 'intact' status considering carbon sequestration, water storage and biodiversity with strong links to site climatic conditions, especially wetness and, **2)** whilst burning causes some short-term impacts it can support restoration and 'active' bog functions related to carbon cycling, and water storage and biodiversity and **3)** although mowing could be an appropriate, albeit more costly, alternative to burning of heather dominated blanket bog (e.g. on grouse moors), there are clear trade-offs and so far no change in heather cover, and **4)** leaving mature heather vegetation unmanaged very likely leads to a decline in bog functions, notably C sequestration, water storage and diversity together with an increased wildfire risk (with potentially devastating consequences on not just carbon stocks but all peatland ecosystem services).

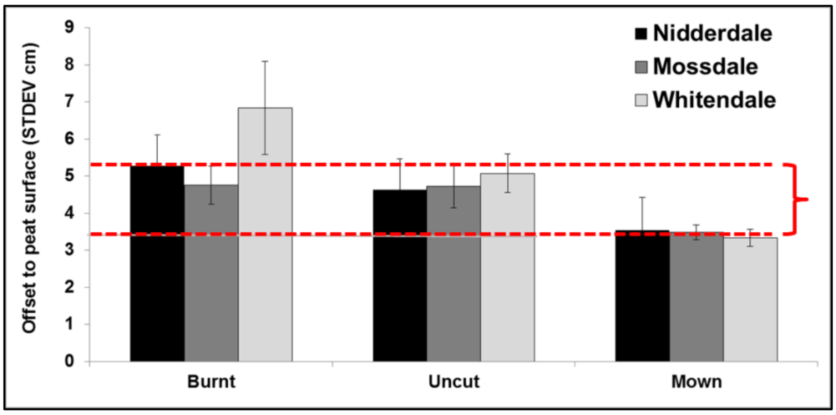
Whilst prescribed burning causes some short-term emissions (which are tiny compared to wildfire peatland emissions; *cf*. Belcher et al., 2021) and initially makes peat drier, it is important to consider long-term rewetting coupled with no management and to compare peat core C accumulation rates to cumulative net C fluxes over the entire management cycle, especially including charcoal as a long-term carbon store. Such a positive C storage effect was predicted by Clay et al. (2011) and Worrall et al. (2013) based on much slower decomposition of charcoal versus litter. Indeed, peat growth rates, although highly variable, also indicated 'active' peat condition with peat growth under either management and mature heather. However, aspects around the total amount of charcoal and charred products (from all vegetation, the litter layer and remaining sticks), their C content and decomposition rates are still very uncertain. Moreover, ash fertilisation seems another crucial component alongside char production. Conversely, whilst mowing is benefiting some key ecosystem services, particularly related to hydrology, it causes damage to the peat surface, might shift vegetation to a more sedge dominated community with important impacts on GHG emissions and seems to result in water quality issues and increased stream nutrient concentrations (although overall DOC and N export was slightly higher for burnt catchments) and might also lead to an overall higher net C lo0ss compared to burning (due to long-term litter decomposition). Notably, many previous negative associations with burning (especially in relation to reduced C storage and water quality) are likely attributable to drainage, an often confounding issue not adequately considered in the evidence base. Other issues in previous studies are likely related to only capturing short-term impacts and not being able to assess pre-management differences (e.g. related to site history, condition, vegetation composition or climate), which is especially the case in Space-for-Time studies, which can only be done robustly in a Before-After Control-Impact design, which should be seen as the 'gold standard' for assessing management impacts.

Although there was no catchment-scale comparison for unmanaged heather, the ageing and tall heather vegetation seems to lead to a drier, more degraded bog with more non-*Sphagnum* moss, decreasing C sink strength and lower plant diversity. Moreover, whilst such old heather habitat is clearly of importance to nesting for some bird species, it likely reduces breeding densities of many others, and it highlights the importance of management to achieve a complex mosaic of vegetation age and composition structure. Further, no management also represents a trajectory of increased wildfire risk due to fuel load build-up, with potentially devastating ecological and socio-economic consequences. However, process-level effects, and the associated long-term impacts on ecosystem services, of a complete change in catchment management practice and vegetation re-growth require time to develop, particularly in cold, wet and thus slow growing upland ecosystems. Overall, comparisons between the managements highlighted the need for continuation over at least a complete management cycle (requiring at least 10 more years; based on previous cycles of ~22 years), possibly together with additional plot-level treatments like repeated mowing and/or *Sphagnum* plug addition, as the long-term (and thus robust and policy relevant) impacts are not yet adequately captured or predictable. For example, damage to *Calluna* can be expected more readily when the plant is under some stress from, for example, rising water tables as was only partly achieved, first by mowing and subsequently also by burning; additional years should also consider the mosaic age/community structure across a managed landscape and generic differences in site conditions, especially wetness. Required time periods for a continuation of monitoring towards providing such policy relevant evidence on key ecosystem parameters (based on catchment-scale management, interannual climate variability and vegetation growth rates and plant community development) can be estimated to require between 10 to 25+ years depending on the parameter, e.g. for C budgets (10+ years; covering at least a full management cycle of ~20 years for managed plots, which would also capture ageing of unmanaged heather), methane emissions (15+ years), water budgets (20+ years) and peat accumulation, vegetation dynamics and biodiversity (25+ years). Moreover, ideally a catchment-scale ‘no management’ scenario and an additional shallow peatland site together with *Sphagnum* plug planting should be considered in future research. Finally, what is of utmost importance is to follow an adaptive management approach, also considering combining management options such as burning and cutting (and thus addressing trade-offs of individual managements), and address our lack of knowledge on the impacts of different management options, especially fuel loads on wildfire risk and large-scale uniform versus small-scale mosaic vegetation age and management structures on the wider biodiversity (i.e. insects, reptiles and birds). Whilst this is only one study of several on the impact of heather management, it is the only BACI and plot to catchment scale study comparing the impacts of alternative managements ‘like for like’; as such this study is of key importance to inform the evidence base underpinning future policy as set out at the start of the Defra project. To achieve its original long-term aim of monitoring a complete management cycle is key to both these aspects.

Selected summary graphs and tables

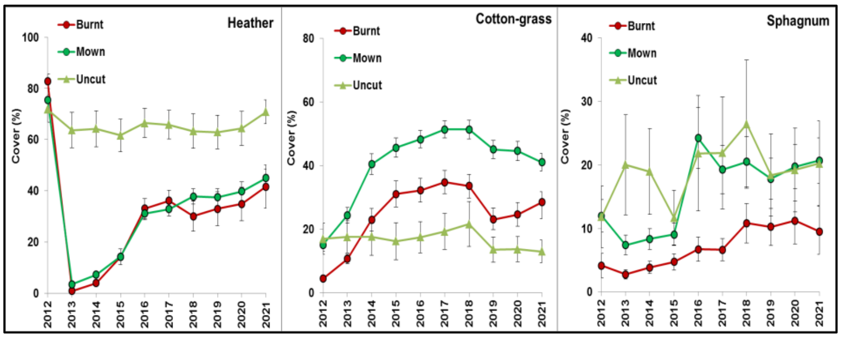
Below is a selection of key graphs and tables in relation to the above key findings sections. Only brief summary texts are provided outlining the main findings and additional information to be considered in the interpretation.

Peat surface micro-topography (Heinemeyer et al., 2019a)



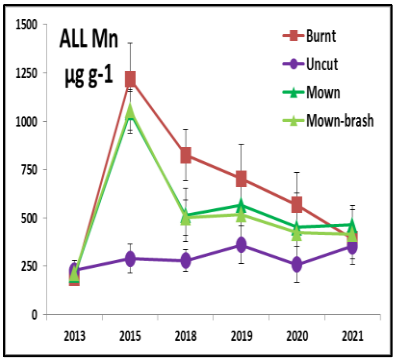
Peat surface micro-topography was similar across the three sites between burnt and uncut plots, but **mown plots showed greatly reduced surface variability** in height (several centimetres) due to the mowing equipment chopping off hummocks and tussocks (uncut plots are the controls within mown areas). This possibly negatively affects suitable habitat for ground nesting birds (less dry spots).

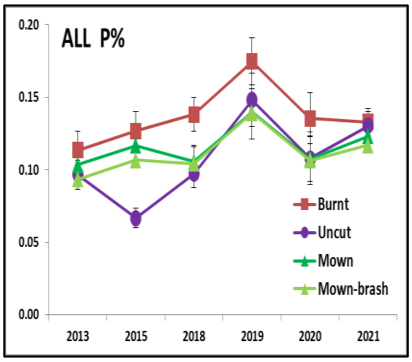
Vegetation composition



Heather cover was equally reduced by management. However, **heather beetle reduced heather cover mainly on burnt plots. Cotton-grass (sedge) increased more on mown plots. *Sphagnum* moss cover increased generally and equally for both managements** but was more variable in mown and uncut plots.

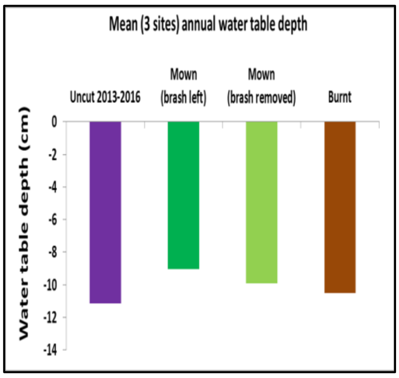
Heather shoots nutrient content

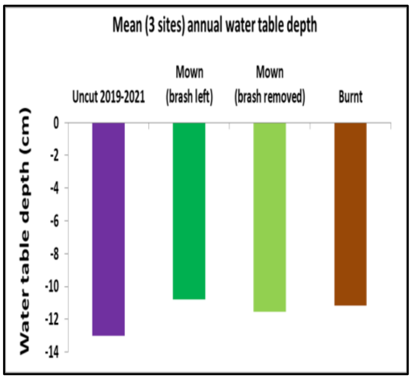




Nutrient contents in heather increased post-management, especially for nitrogen, potassium, manganese (Mn) and phosphorus (P). The increase was highest in the years following management (2013 is pre-management – all tall heather) and declined over time. **Especially for Mn and P, burnt plots showed larger and longer lasting impacts than mown plots**.

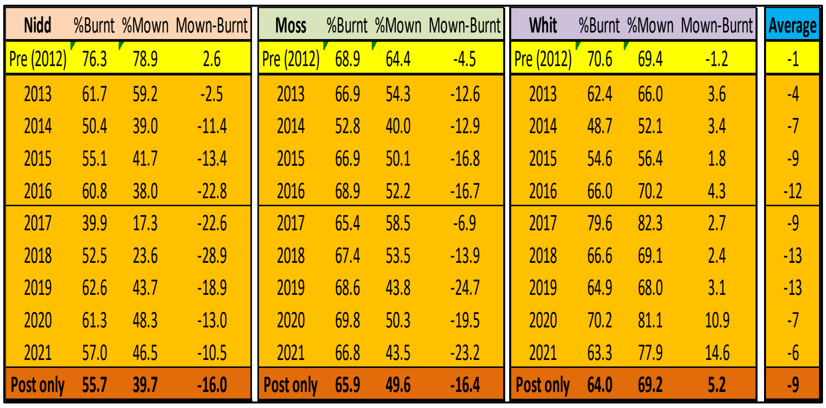
Plot water tables





Mown plots with leaving brash initially became wettest after management (2013-2016), raising water tables by 2-3 cm. However, this effect disappeared, whereas **burnt plots became wetter over time** (2019-2021). Over time **uncut plots with most biomass became drier, showing the lowest water tables post-management** (2013-2021).

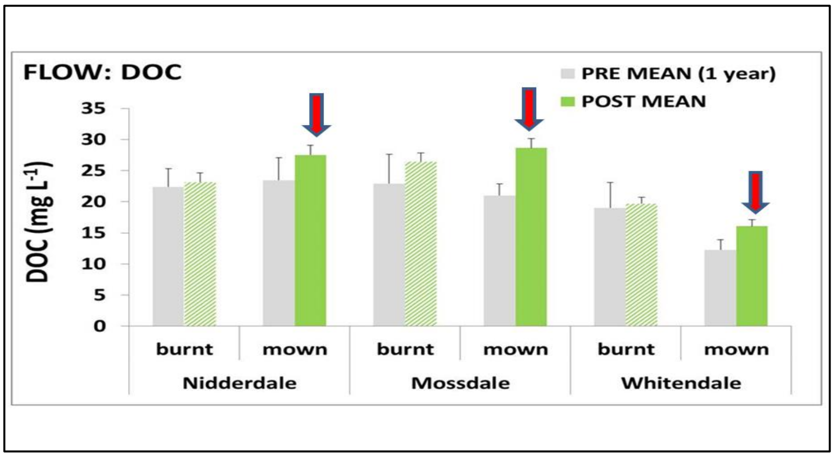
Stream flow budget



Nidd	%Burnt	%Mown	Mown-Burnt	Moss	%Burnt	%Mown	Mown-Burnt	Whit	%Burnt	%Mown	Mown-Burnt	Average
Pre (2012)	76.3	78.9	2.6	Pre (2012)	68.9	64.4	-4.5	Pre (2012)	70.6	69.4	-1.2	-1
2013	61.7	59.2	-2.5	2013	66.9	54.3	-12.6	2013	62.4	66.0	3.6	-4
2014	50.4	39.0	-11.4	2014	52.8	40.0	-12.9	2014	48.7	52.1	3.4	-7
2015	55.1	41.7	-13.4	2015	66.9	50.1	-16.8	2015	54.6	56.4	1.8	-9
2016	60.8	38.0	-22.8	2016	68.9	52.2	-16.7	2016	66.0	70.2	4.3	-12
2017	39.9	17.3	-22.6	2017	65.4	58.5	-6.9	2017	79.6	82.3	2.7	-9
2018	52.5	23.6	-28.9	2018	67.4	53.5	-13.9	2018	66.6	69.1	2.4	-13
2019	62.6	43.7	-18.9	2019	68.6	43.8	-24.7	2019	64.9	68.0	3.1	-13
2020	61.3	48.3	-13.0	2020	69.8	50.3	-19.5	2020	70.2	81.1	10.9	-7
2021	57.0	46.5	-10.5	2021	66.8	43.5	-23.2	2021	63.3	77.9	14.6	-6
Post only	55.7	39.7	-16.0	Post only	65.9	49.6	-16.4	Post only	64.0	69.2	5.2	-9

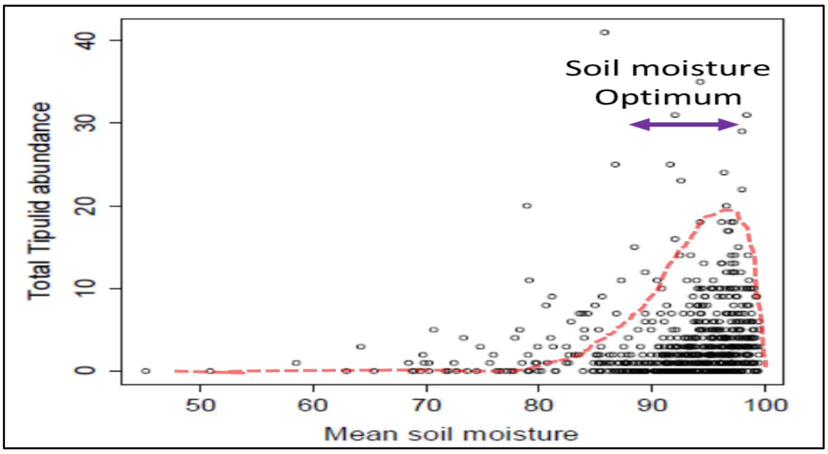
Flow rates were reduced in the mown catchments (during the post-management period compared to the burnt ones) but only at two sites (with historic drainage). The stream flow budget (area weighted flow vs rainfall) reduction at those two sites was around 15-20%, increasing after management and declining over time. **The overall impact was around 10% reduced flow for mown vs burnt**.

Water quality



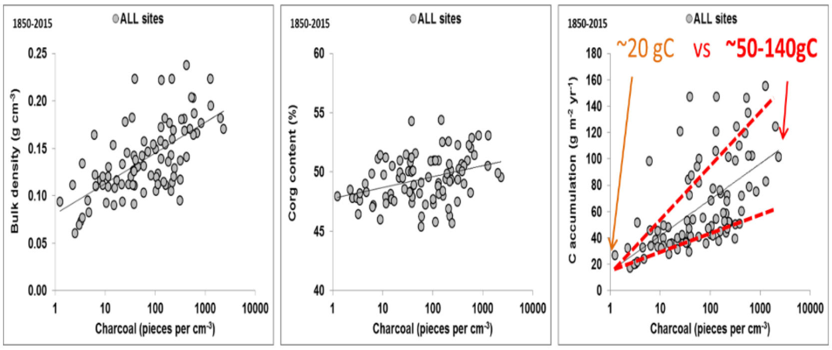
The total export of carbon in streams was higher in burnt than mown catchments. However, **concentrations of dissolved organic carbon (DOC)** (figure on left) **increased more over time in the mown catchments** (see arrows). This likely represents a concentration effect due to lower flow volumes in mown catchments (previous table). **Measured DOC did not differ between managements at the plot level**. (Post period: 2013-2021).

Cranefly abundance



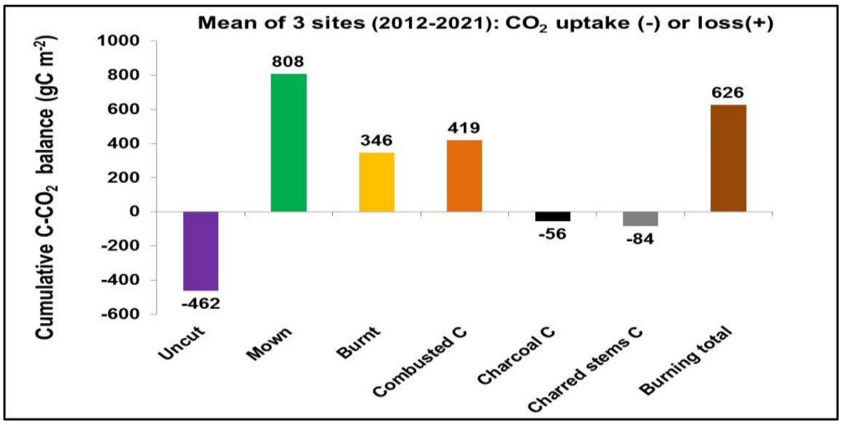
Cranefly numbers responded strongly to soil moisture. **Cranefly abundance showed an optimum peat soil moisture range between ~85-95%.** Lower moistures likely cause desiccation whilst higher moisture indicates possible drowning of larvae (manually drawn red line). **Thus mowing can be beneficial on drier sites but could potentially cause a decline in already wet sites**, especially when considering reduced micro-topography (see above graph).

Historic peat carbon accumulation rates (Heinemeyer et al., 2018)



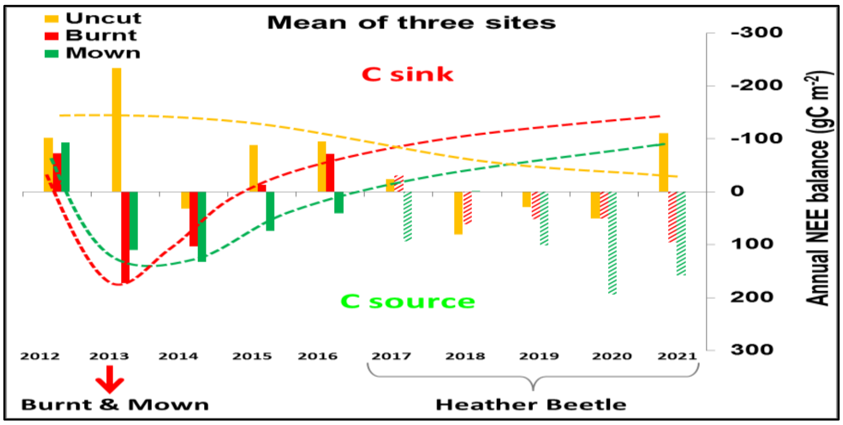
Peat cores revealed a strong relationship between bulk density, organic carbon (%Corg) and charcoal. **Accumulation of peat C** (not a C budget) **was higher in sections with more charcoal**. High recent C accumulation reflects undecomposed peat. The **historic burn frequency was about 22 years** since ca. 1700.

Cumulative ecosystem CO_2 flux balance



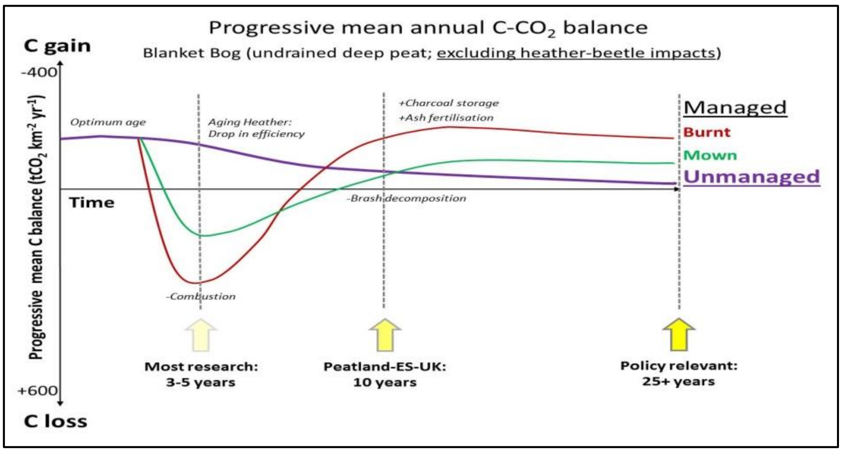
The cumulative 10-year CO_2-flux balance based on annual chamber-based net carbon fluxes shows a **strong (but declining, see next graph) C-sink for uncut plots**, whilst **both burnt and mown are a net C-source**. However, **burnt plots are a much smaller C-source** even accounting for combustion losses and did include C losses due to <u>severe heather beetle</u> impacts (see next graph).

Net ecosystem exchange (NEE) heather beetle impact



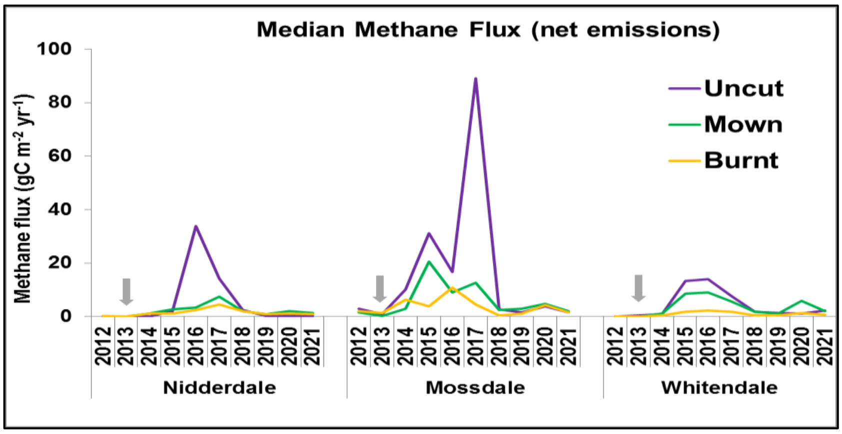
The annual chamber-based carbon flux (NEE) C-balance estimates, outlining the expected trajectories (dashed lines; <u>without heather beetle damage</u>) versus the actual **annual NEE balance (bars), which was reduced on burnt and mown plots** (shaded bars) <u>due to heather beetle</u> damage (2017-2021). **Burnt plots showed quicker net C-uptake recovery partly due to ash fertilisation** (see nutrients).

Carbon balance scenarios



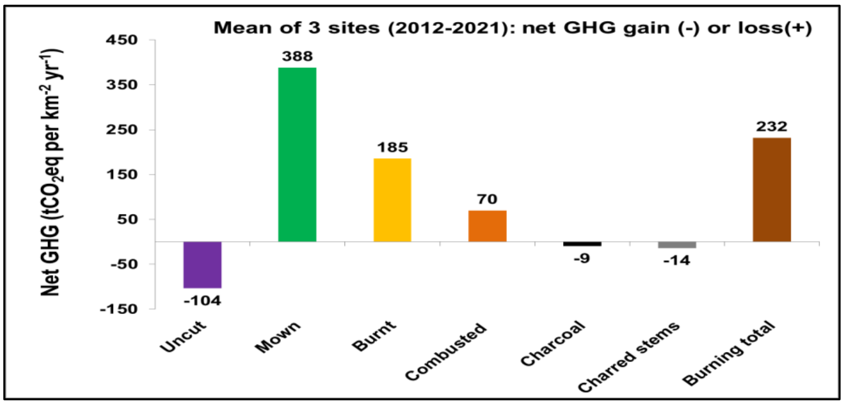
Scenarios of progressive mean annual C balance (for NEE fluxes and including combustion and brash decomposition losses) on <u>undrained deep peat</u>. Data over 10 years are based on the Peatland-ES-UK project (but without heather beetle impacts; see above). Predictions are **uncut to become a declining C-sink** (ageing) and **burnt to sequester more** (charcoal & ash effects) **than mown** (long-term brash decomposition C loss).

Methane emissions



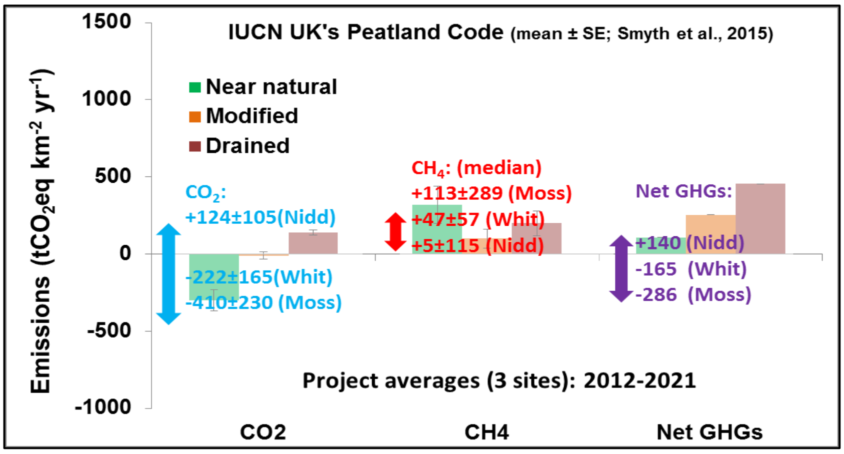
The chamber based net methane flux indicated overall low emissions apart from an **emissions spike in 2015-2017** (<u>coinciding with a rise in pH</u>). **Uncut plots were highest emitters followed by mown plots** (wetter and more sedges, shunt species letting methane escape via aerenchyma). **Burnt plots had lowest emissions** (drier and less sedges). Arrows indicate initial plot management (2013).

Greenhouse gas (GHG) emissions



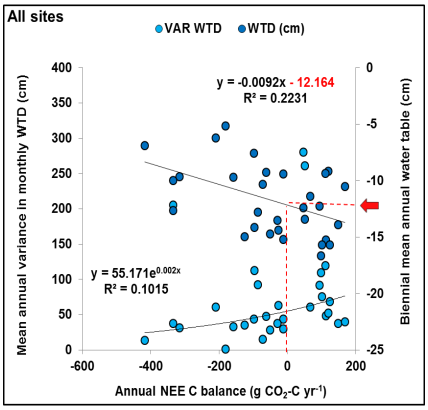
Whilst **uncut management showed a net cooling effect** (negative value), mown and burnt showed a net warming effect. However, the **burn effect was much less than mown**, <u>even when including the combustion emissions</u> (which are partly offset by charcoal gains). The burn management was nearly half of the **mown management with more sedges and higher methane emissions**.

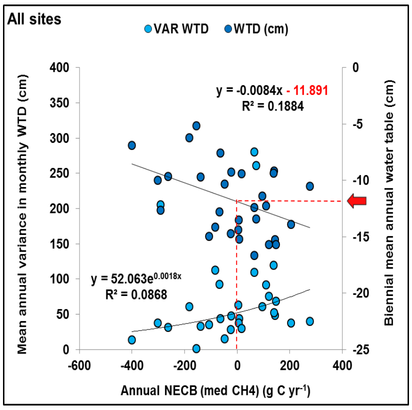
Comparison to IUCN UK Peatland Programme



The 10-year means were compared to the IUCN UK Peatland Code (Smyth et al.; cf. Table 1). The **uncut plots aligned with the 'near natural' category**. However, the driest site (Nidderdale) aligned with the modified category. There is **considerable variability between sites linked to site wetness** (but likely also to management history) and also between years (linked to climatic conditions, especially wetness – see next graph).

Carbon balance versus water tables





CO_2-flux (NEE) carbon balance and net ecosystem C balance (NECB) both show relationships with mean annual water table depth (WTD) and its monthly variance (VAR) (over a 2-year period). **The WTD threshold between positive (drier; more variable) and negative (wetter; less variable) C balance is around -12 cm** (see red arrows), very similar to a recent finding by Evans et al. (2021).

Peat C sequestration

Peat growth (mm/yr)	ALL Sites	
	Median	SE
Uncut	0.31	± 0.09
Burnt	0.31	± 0.09
Mown	0.25	± 0.03

Peat growth (mm/yr) Mossdale			
Category	Median		SE
Burnt	0.37	±	0.41
Mown	0.63	±	0.22
Calluna	1.50	±	0.57
Eriophorum	0.69	±	0.22
Sphagnum	1.88	±	0.41
All	0.6	±	0.1

Peat accumulation over 8-years using fixed peat rods (within different management and mature vegetation areas). **All sites showed active peat growth**, <u>less so at the monitoring plots</u> (~0.3 mm/yr) due to less litter production and interception (by a protective mesh), <u>more so (~0.6 mm/yr) within mature vegetation</u> (most under *Sphagnum*).

Appendices (providing more detailed information on key aspects and measured parameters)

Appendix 1 (climatic information)

The below **Table A1.1** outlines key climatic parameters measured by the automated Skye weather stations at the three sites: Nidderdale (driest), Whitendale (intermediate) and Mossdale (wettest). Shown are the annual total sum of photosynthetic active radiation (PAR; in moles per square meter), total rainfall (rain in millimetres), mean air temperature (Tair; with max and min range), soil temperature (Tsoil; at 5 cm depth) and relative humidity (RH). 2012 data were gap filled (Jan-March) by modelling available site data vs Moor House (CEH) data.

Table A1.1 Annual totals or means of key environmental parameters with 2012-2021 averages for the three sites.

				Nidderdale			
Year	PAR (mol m-2)	Rain (mm)	Tair (°C)	Tair (max)	Tair (min)	Tsoil (°C)	RH (%)
2012	6178	1871	6.8	23.4	-11.6	7.1	93
2013	6858	1318	6.8	25.3	-6.2	7.4	97
2014	6438	1520	7.9	23.1	-3.0	8.8	94
2015	6965	1777	7.3	27.2	-4.5	7.8	91
2016	6663	1335	7.4	26.9	-4.7	8.0	95
2017	6830	1159	7.7	24.8	-5.0	8.0	94
2018	7255	1056	7.6	26.0	-8.2	7.8	92
2019	6837	1477	7.6	29.1	-6.1	7.7	91
2020	7092	1619	7.6	28.2	-3.9	7.6	91
2021	7301	1124	7.5	25.8	-5.9	7.4	91
2012-2021	**6842**	**1426**	**7.4**	**26.0**	**-5.9**	**7.8**	**93**

				Whitendale			
Year	PAR (mol m-2)	Rain (mm)	Tair (°C)	Tair (max)	Tair (min)	Tsoil (°C)	RH (%)
2012	5946	2076	7.3	24.4	-10.7	8.4	94
2013	6608	1393	7.2	26.4	-5.7	7.7	97
2014	6126	1714	8.4	23.1	-1.9	9.0	92
2015	6337	2136	7.6	27.9	-3.9	7.9	89
2016	6568	1839	7.8	28.2	-3.3	8.6	90
2017	6166	1835	7.9	25.6	-4.7	8.6	89
2018	7093	1304	8.0	27.1	-7.4	8.3	86
2019	6677	1872	7.8	29.7	-5.7	8.4	88
2020	6878	2018	8.1	29.8	-3.6	8.4	87
2021	7190	1763	7.9	26.2	-6.0	8.3	89
2012-2021	**6559**	**1795**	**7.8**	**26.8**	**-5.3**	**8.4**	**90**

				Mossdale			
Year	PAR (mol m-2)	Rain (mm)	Tair (°C)	Tair (max)	Tair (min)	Tsoil (°C)	RH (%)
2012	6006	2179	6.9	24.7	-11.1	7.7	93
2013	6581	1708	6.9	25.1	-6.3	7.9	97
2014	6205	1943	8.0	23.1	-4.2	8.8	91
2015	6529	2437	7.2	27.8	-5.7	7.9	88
2016	6576	1685	7.3	26.8	-5.5	8.4	89
2017	6383	1969	7.5	24.6	-6.5	8.3	89
2018	7001	1437	7.4	25.9	-7.9	8.1	89
2019	6552	1917	7.4	29.3	-7.3	8.1	91
2020	6706	2298	7.7	28.0	-4.2	8.1	93
2021	7047	1547	7.6	26.2	-6.6	8.1	96
2012-2021	**6559**	**1912**	**7.4**	**26.2**	**-6.5**	**8.1**	**92**

Annual means were compared in mixed-effects models with least-square means post-hoc tests to compare between sites. Significant differences were at p<0.001 (***). The following parameters were assessed:

PAR: Highest at Nidderdale, greater than at both other sites (***); no difference between Mossdale or Whitendale.

Tsoil: Lowest at Nidderdale, lower than both other sites (***); no difference between Mossdale or Whitendale.

Tair: Highest at Whitendale, greater than both other sites (***); no difference between Mossdale or Nidderdale.

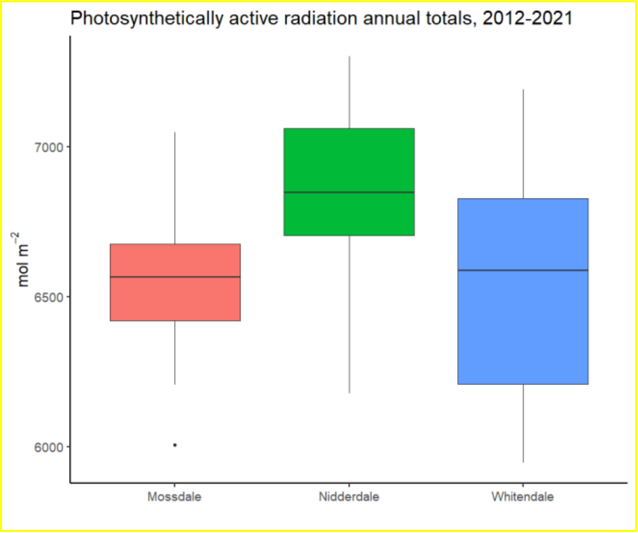
Rain: Lowest at Nidderdale (***); no difference between Mossdale or Whitendale.

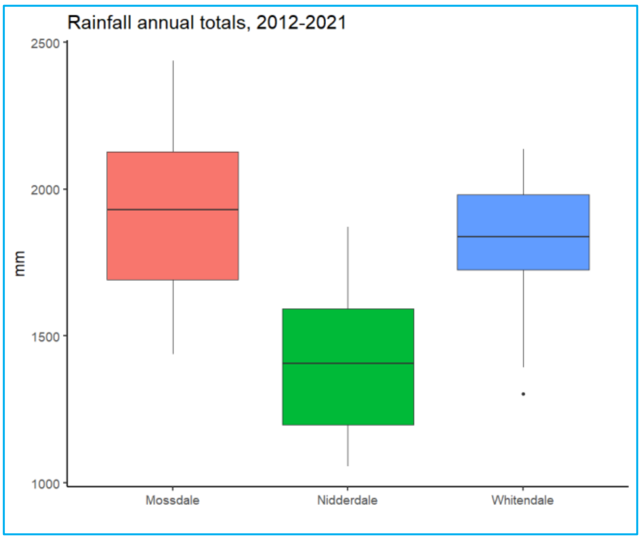
RH: Nidderdale significantly higher than Whitendale (***); Mossdale intermediary, not significantly different from either site.

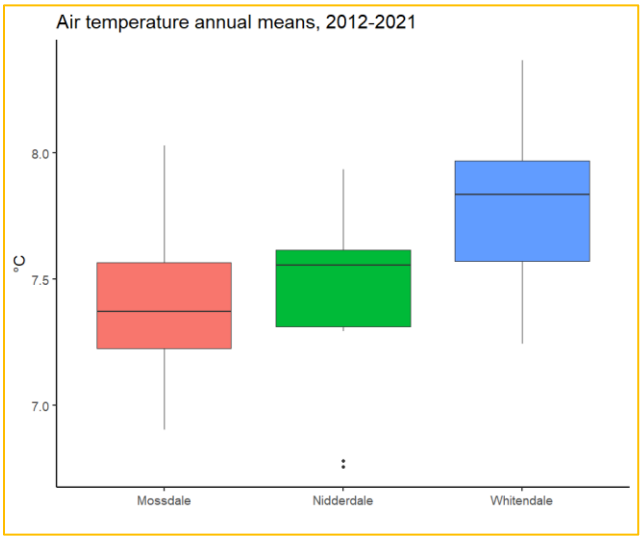
Air pressure: All sites were significantly different (***); Whitendale had highest air pressure (***) and Nidderdale had lowest (***).

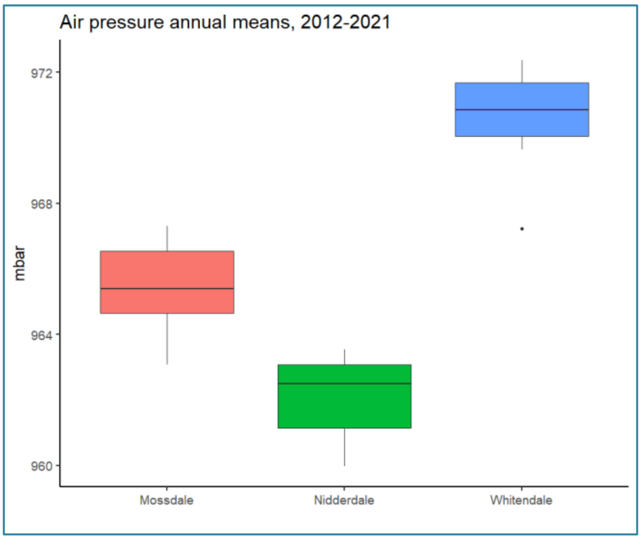
Wind speed: Lowest at Whitendale (***); no difference between Mossdale or Nidderdale.

The below **Figure A1.1** shows the box plots (minimum score, lower quartile, median, upper quartile, maximum score and outliers [1.5*inter quartile range] indicated by dots) for annual total photosynthetic active radiation (PAR), total rainfall, mean air temperature (Tair) and mean air pressure at the three sites.

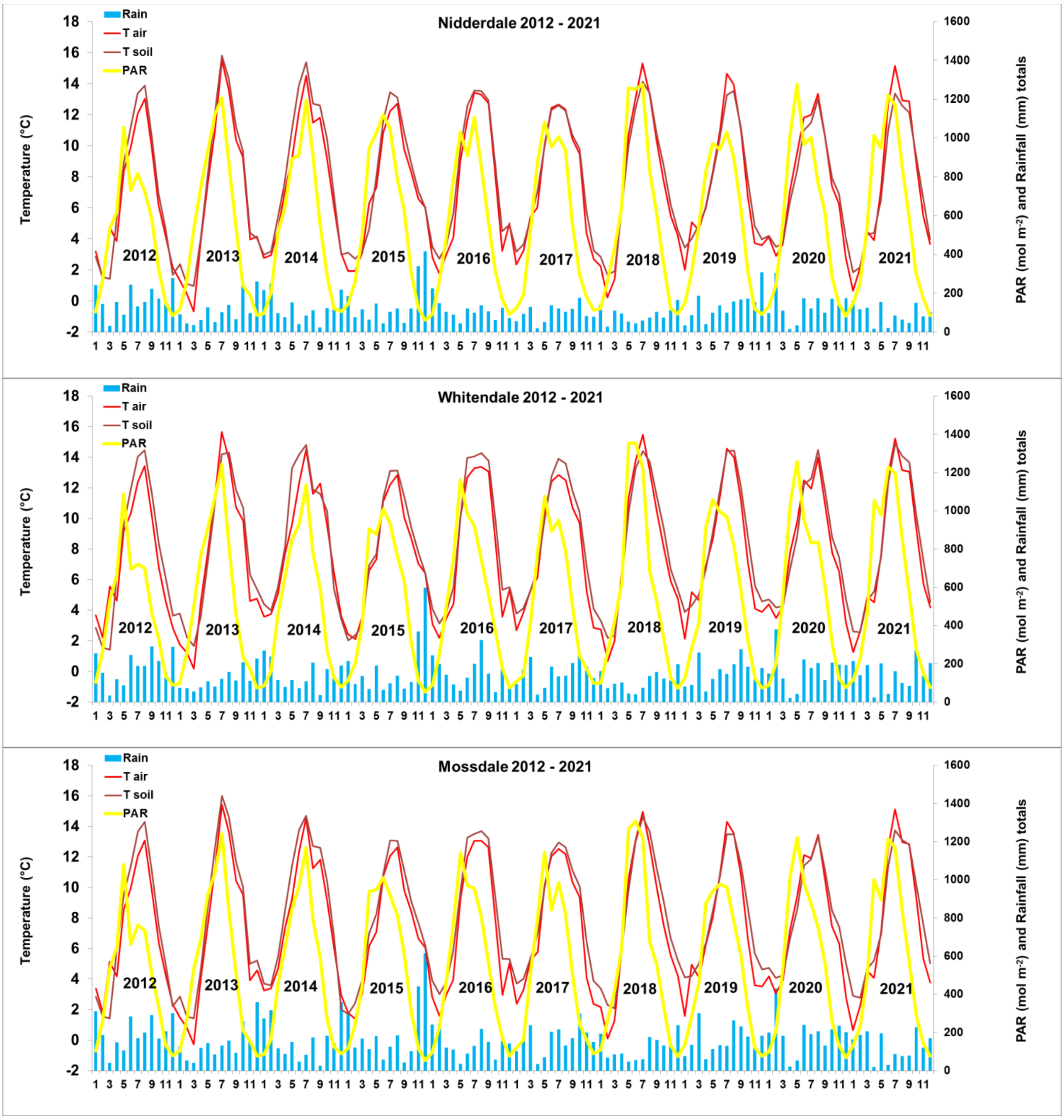




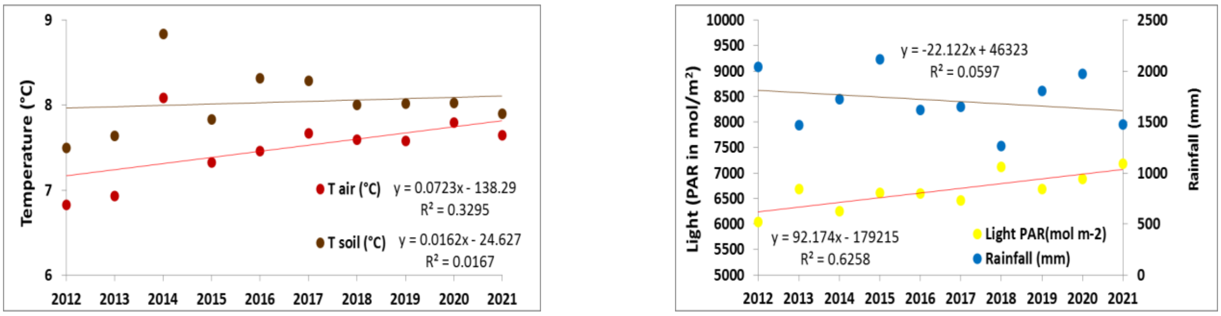




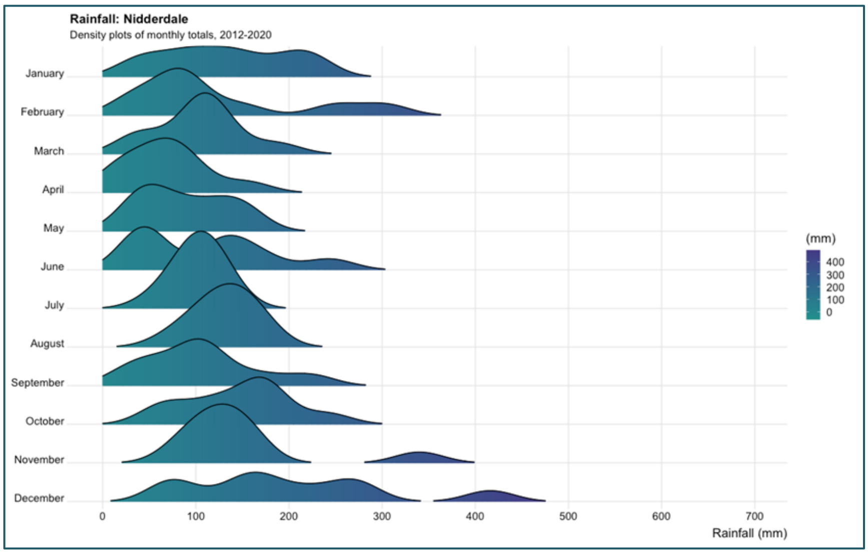
The below **Figure A1.2** shows the monthly time series for rainfall (total Rain), air and soil temperatures (mean Tair & Tsoil, respectively) and photosynthetic active radiation (sum of PAR) over time for the three study sites Nidderdale (driest), Whitendale (intermediate), Mossdale (wettest).

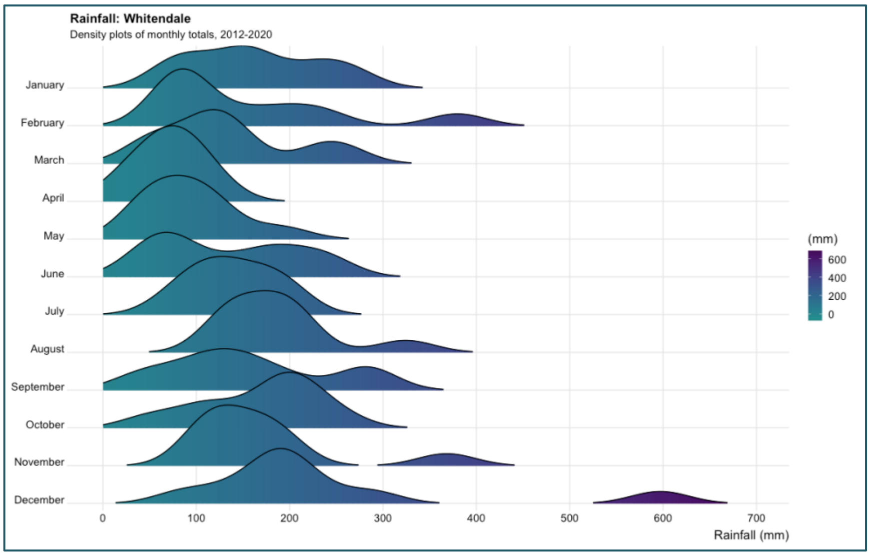


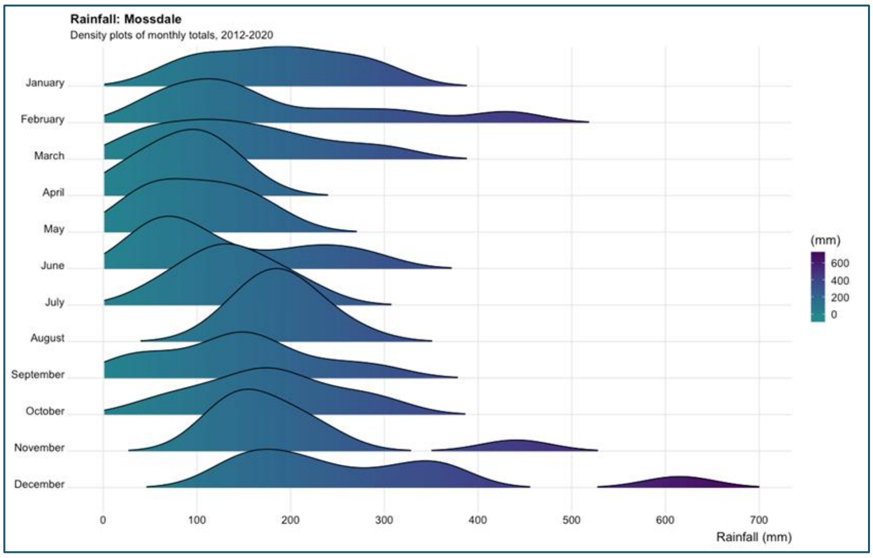
The below **Figure A1.3** outlines the change in average air and soil temperatures (mean Tair & Tsoil, respectively) versus changes in total rainfall and light (total photosynthetic active radiation; PAR) over time. Simple regression lines are shown together with the linear equations, indicating a larger increase in Tair than in Tsoil and an increase in light levels but a slight decline in rainfall. Note the very warm year 2014 followed by a very wet 2015.



The below **Figure A1.4** shows the ridge density plots for monthly rainfall amounts for the driest (Nidderdale), intermediate (Whitendale) and wettest (Mossdale) site. Note the much broader distribution at the wettest site.

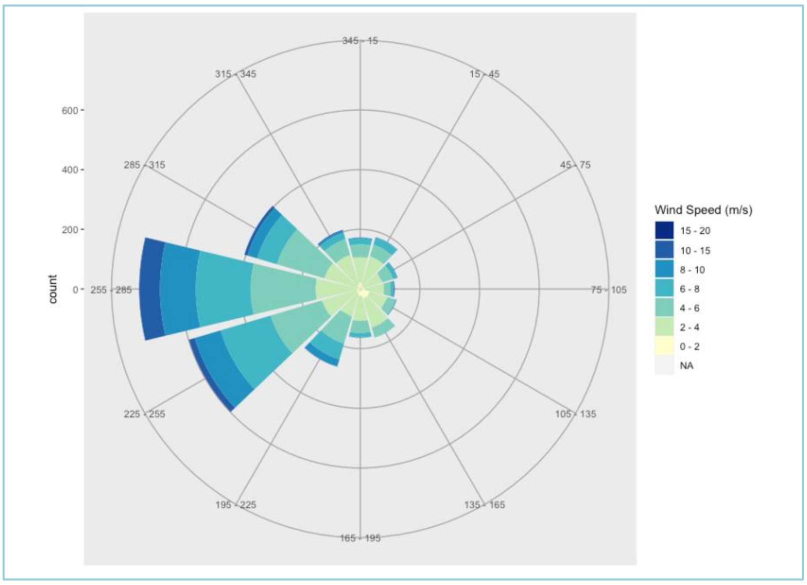




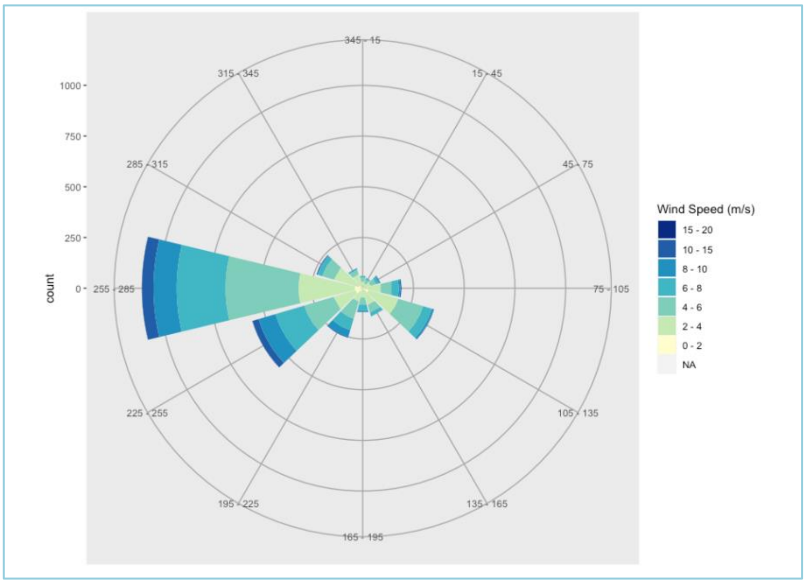


The below **Figure A1.5** shows wind direction (degrees), speed (meters per second) based on daily means for the three sites Nidderdale, Mossdale and Whitendale.

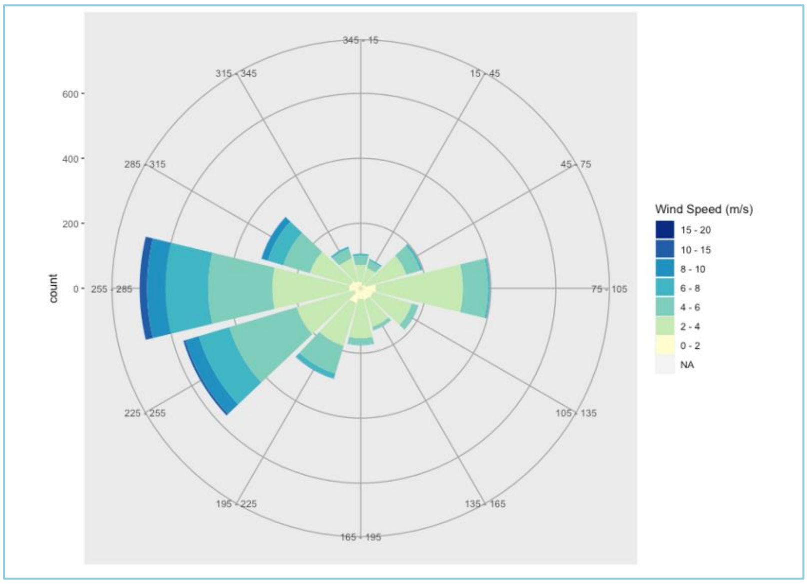
Nidderdale:



Mossdale:

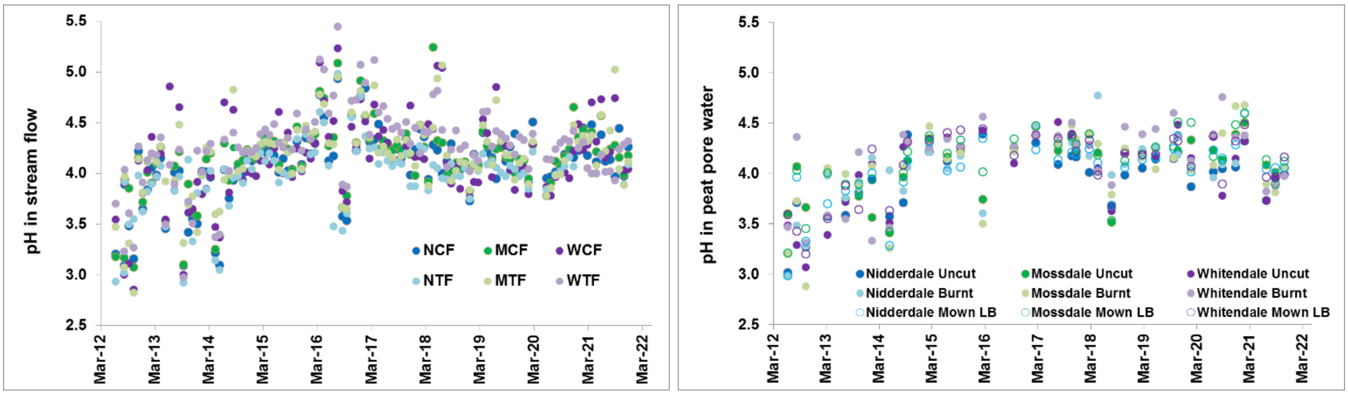


Whitendale:



Appendix 2 (pH & conductivity)

The below **Figure A2.1** shows the pH water samples taken from stream flow (left) and peat pore water (right) during the study period (mostly monthly for flow and seasonal for pore water). The patterns show a general recovery (from acidification) over time fluctuations due to seasonal and interannual effects. Notably higher pH was observed during the period 2015 – 2017. Statistical analysis for flow and pore water showed a significant increase in time without any management effect (linear mixed effect model with site as a random effect).

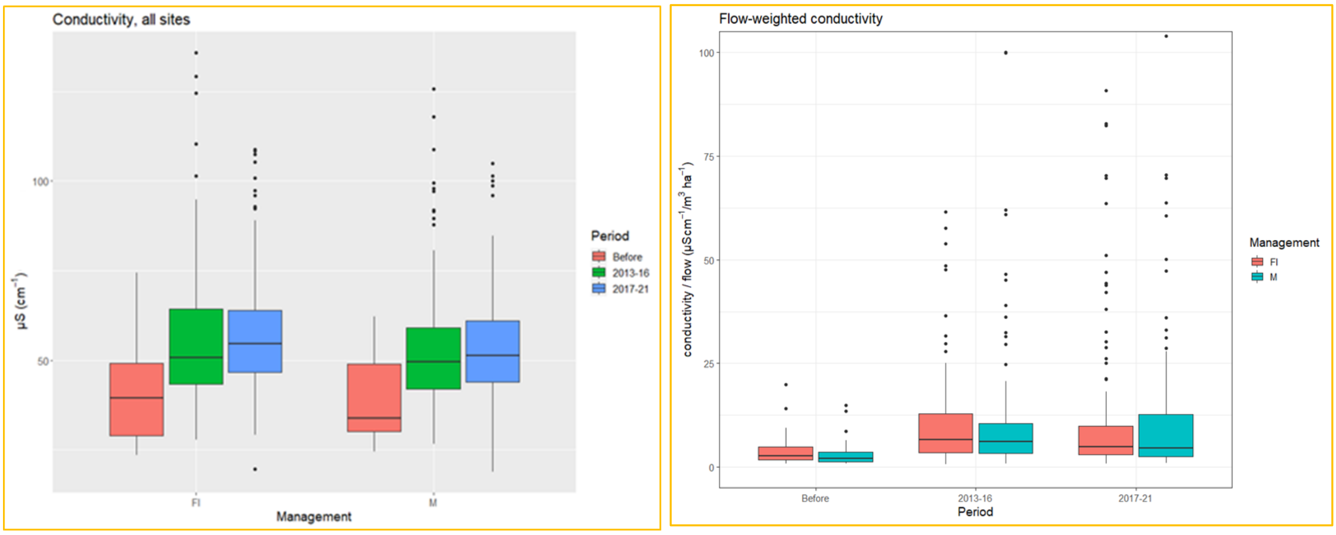


The below **Table A2.1** shows the predicted means of pH in peat pore water samples. All post-management periods (DN = uncut; LB – mown left brash; BR = Mown brash removed) were significantly higher than before, but highest significance (P<0.001; ***) was observed only for burnt (FI) plots.

Peat pore water (plots) pH: all sites – predicted means

	DN	FI	LB	BR
Before	3.49 ± 0.155	3.43 ± 0.154	3.47 ± 0.150	3.54 ± 0.149
2013-16	4.05 ± 0.079	4.10 ± 0.079	4.10 ± 0.077	4.13 ± 0.076
2017-21	4.16 ± 0.068	4.26 ± 0.068	4.18 ± 0.066	4.20 ± 0.065

Additionally, conductivity in (monthly) flow samples showed changes over time and seasonal fluctuations but no differences between managements (see below **Figure A2.2;** left raw vs. right flow weighted conductivity). Overall, conductivity was significantly (based on a generalised mixed effect model that utilised the Gamma family and a log link) lower before management change (during 2012/13) compared to the post-management period (Phase 1: 2013-2016; Phase 2: 2017-2021). However, this difference was due to no early season samples (which tend to be much higher due to higher flow rates) included in the pre-management change period. Moreover, correcting for flow rates resulted in a flow weighted conductivity measure, which did not reveal any significant post-management differences or any differences between catchments (linear mixed-effect model with log-transformed response variable, BACI fixed effect structure, and site and date as random effects).



Appendix 3 (vegetation)

The vegetation differed significantly between sites and also showed marked pre-management differences. The below **Figure A3.1** (Nidderdale) **Figure A3.2** (Mossdale) and **Figure A3.3** (Whitendale) show the total cover (upper and under storey) main vegetation cover for the three sites. Note that the y-axes (% cover) are sometimes different (reflecting low cover). Non-Sph moss stands for all other non-*Sphagnum* moss and bare/brash/burnt combines those categories (with burnt only applicable immediately after the burn management).

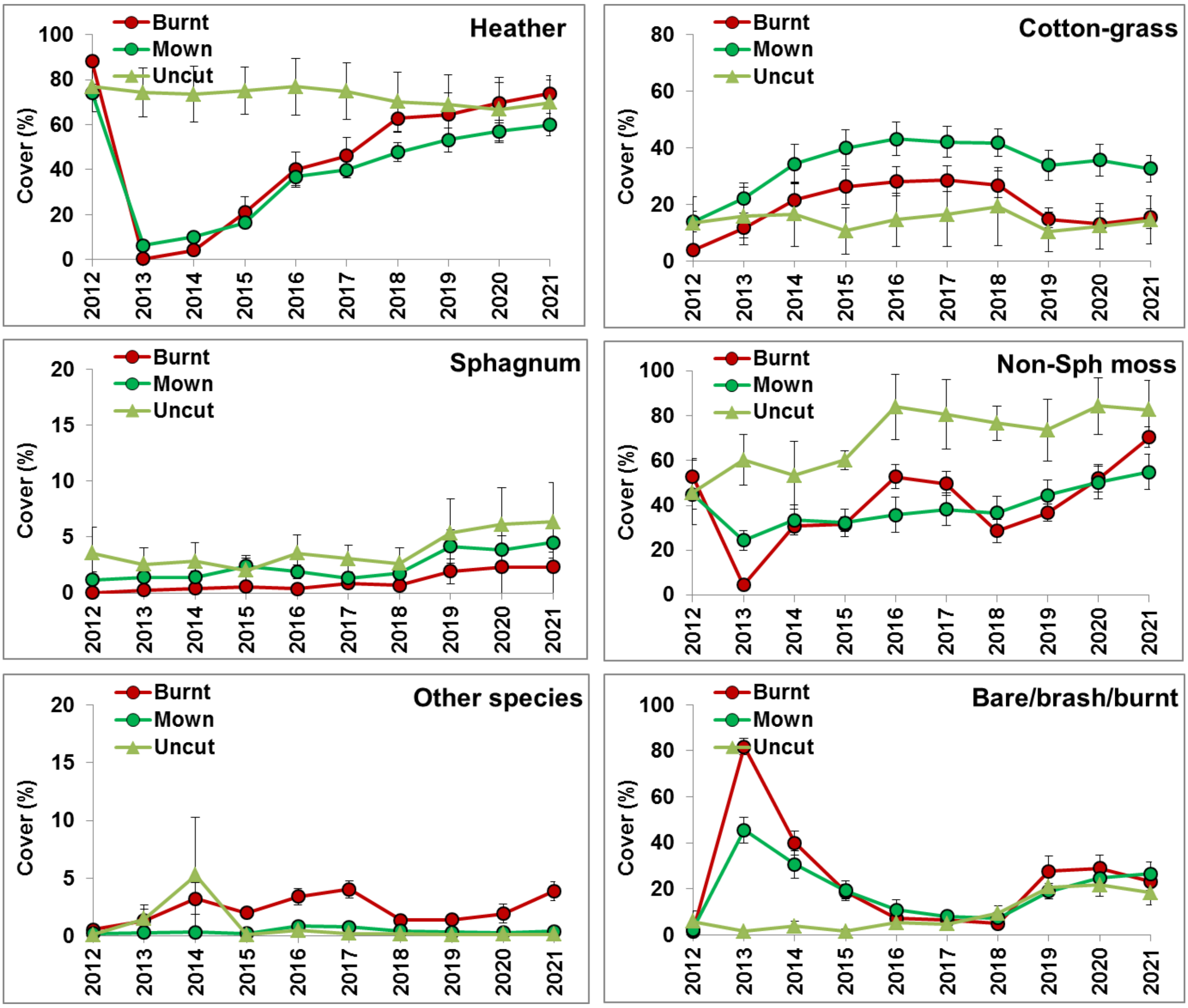


Figure A3.1 (Nidderdale) Note the higher and very steady heather cover on the burnt plots (i.e. no heather beetle) versus that of mown plots (some heather beetle damage 2017/18).

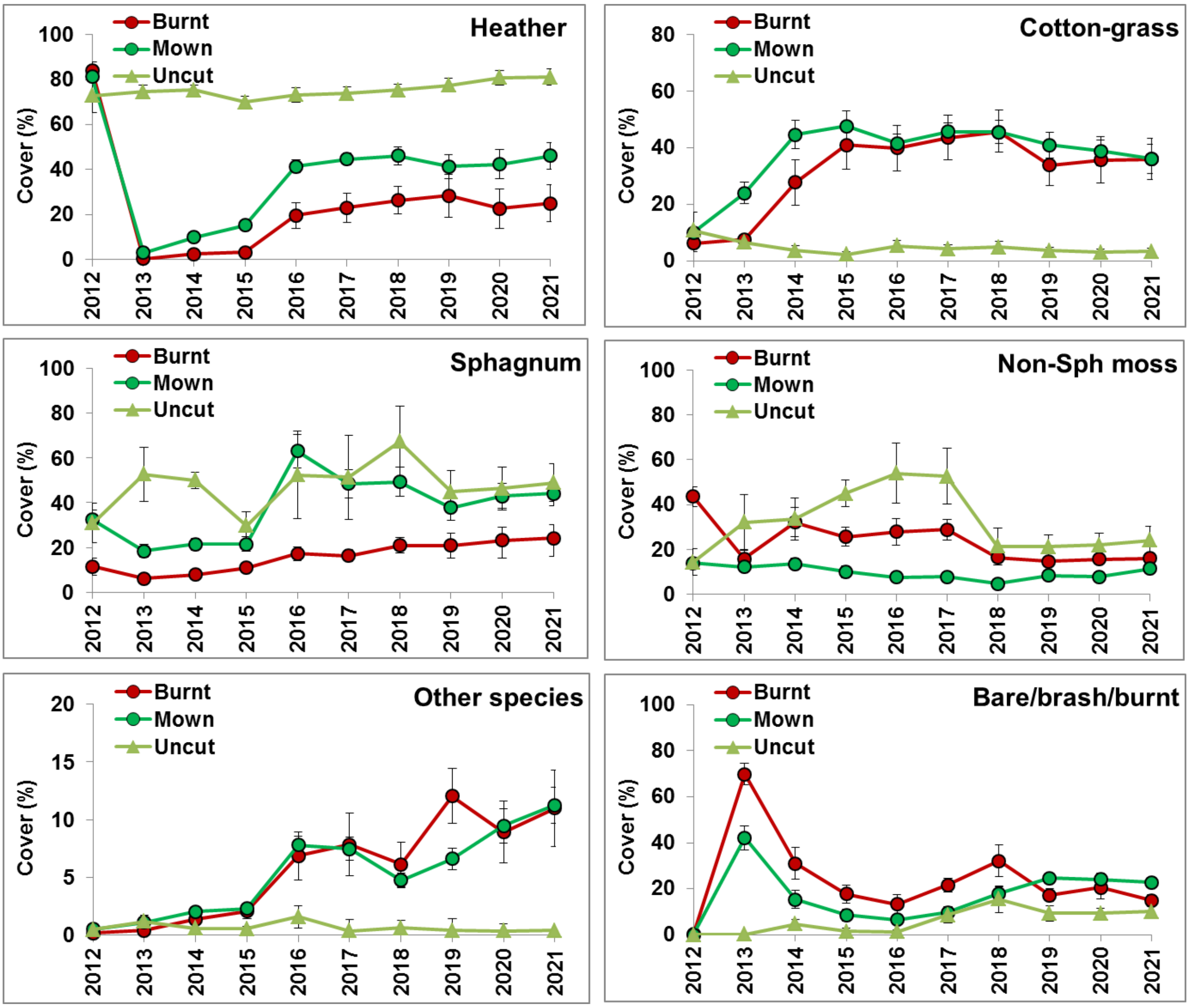


Figure A3.2 (Mossdale) Note the dampened initial heather cover recovery on burnt plots (i.e. heather beetle damage in 2015/16).

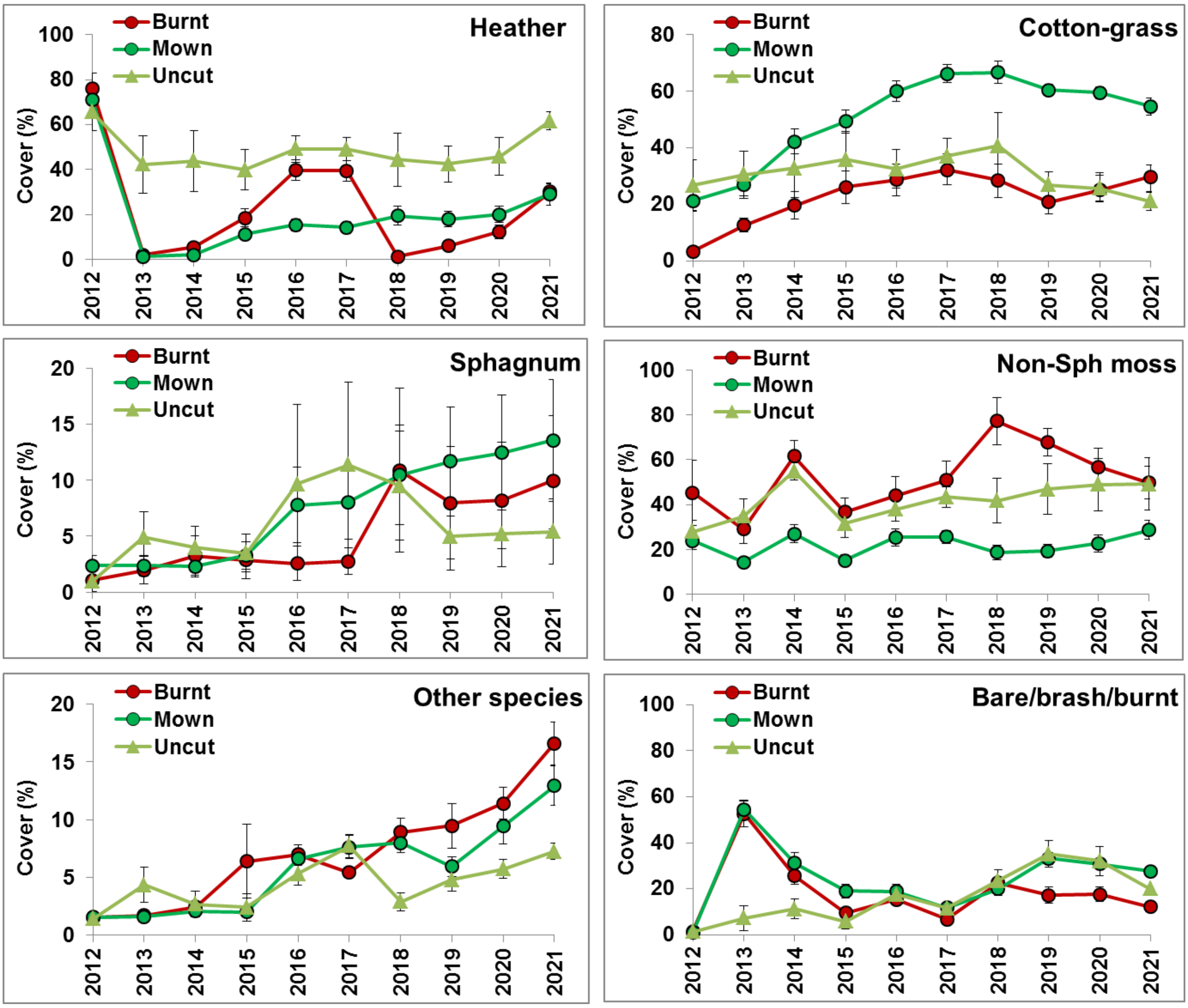


Figure A3.3 (Whitendale) Note the abrupt heather cover decline on burnt plots (i.e. heather beetle damage in 2017/18).

The below **Figure A3.4** summarises the average (across all plots) *Sphagnum* species cover for the pre- and two post-management periods for all three sites (Nidderdale, Mossdale, Whitendale). The legend is also shown enlarged (top to bottom representing a gradient from ‘ombrotrophic bog’ to ‘minerotrophic fen' with a threshold at *S. cuspidatum*; according to Richard Lindsay – in Heinemeyer et al., 2019b). The *Sphagnum* composition separates the dry Nidderdale (mostly *S. subnitens* & *S. fallax*), from the intermediate Whitendale (mostly *S. subnitens* & *S. pallustre*) and wet Mossdale (mostly *S. capillifolium* & *S. fallax*) site.

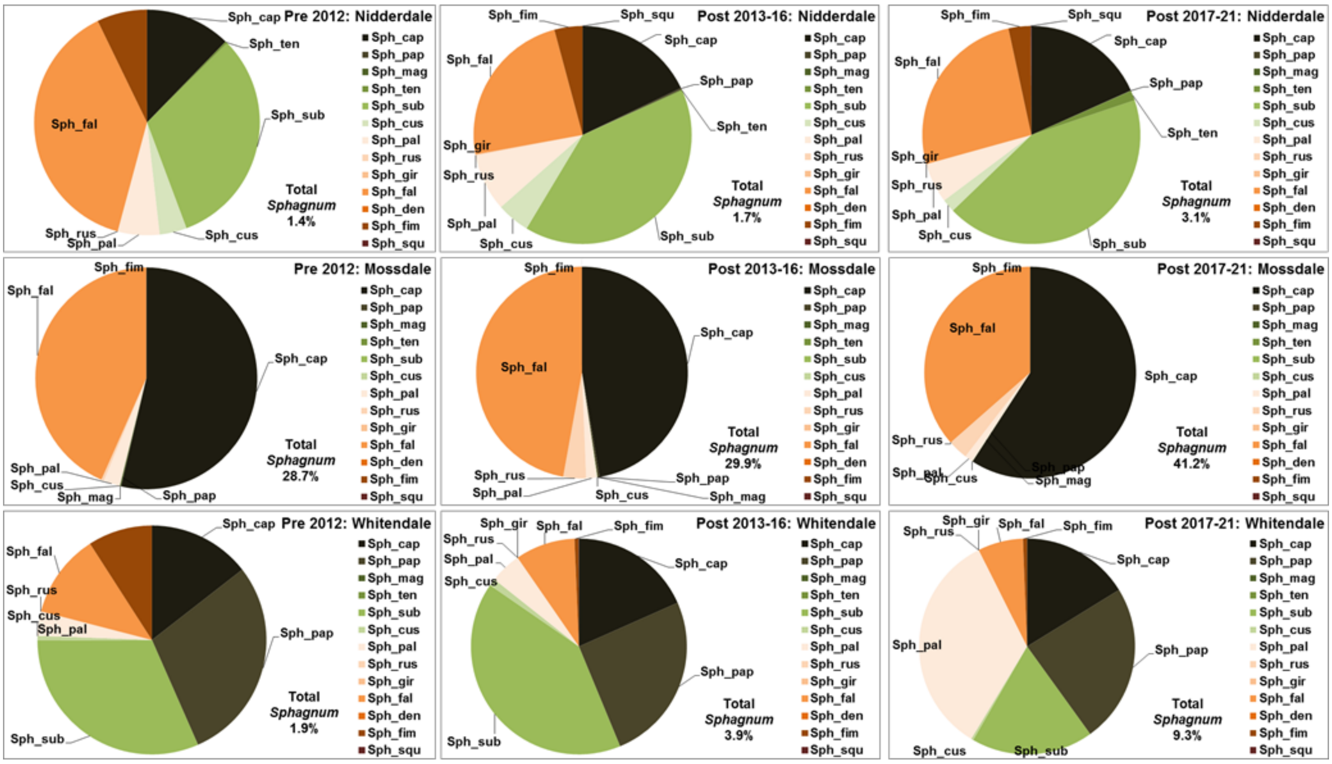


Figure A3.4 *Sphagnum* cover across all three sites (for all plots combined) for the pre- (2012) and two post-management periods (2013-2016 & 2017-2021). The total Sphagnum cover is shown inside each graph.

Heather heights recovered quickly after management, the following figures provide the height development over time for the main managements (DN = uncut [do nothing]; LB = mown with left brash; BR = mown with brash removal; FI = burnt) at 1x1 m plots (**Figure A3.5**) and 5x5 m (**Figure A3.6**). The white bars separate Phase 1 (2012-2016) from Phase 2 (2017-2021). Slower heights on burnt plots at the start reflect germination regrowth.

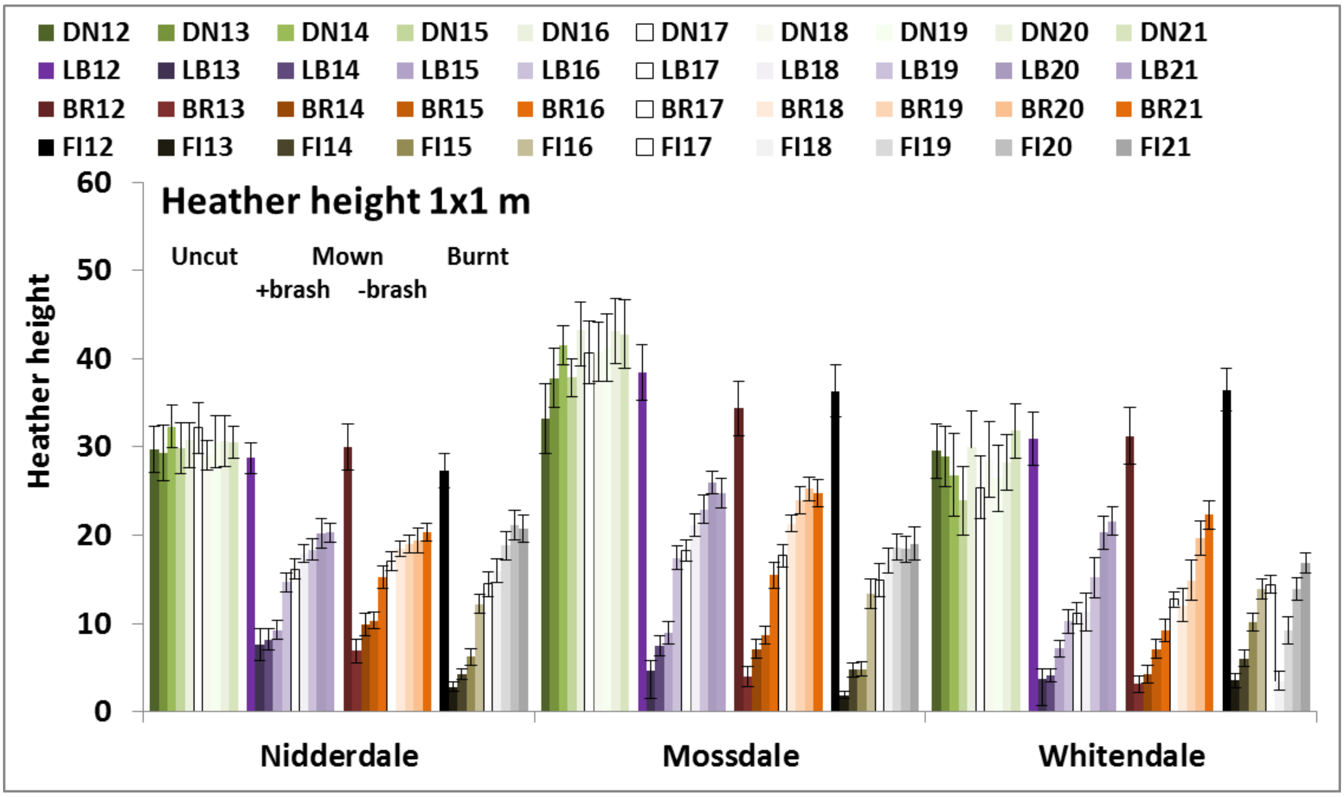


Figure A3.5 heather heights within the 1x1 m plots. Note the reduced heights post 2017 on burnt plots at Mossdale and Whitendale (heather beetle damage).

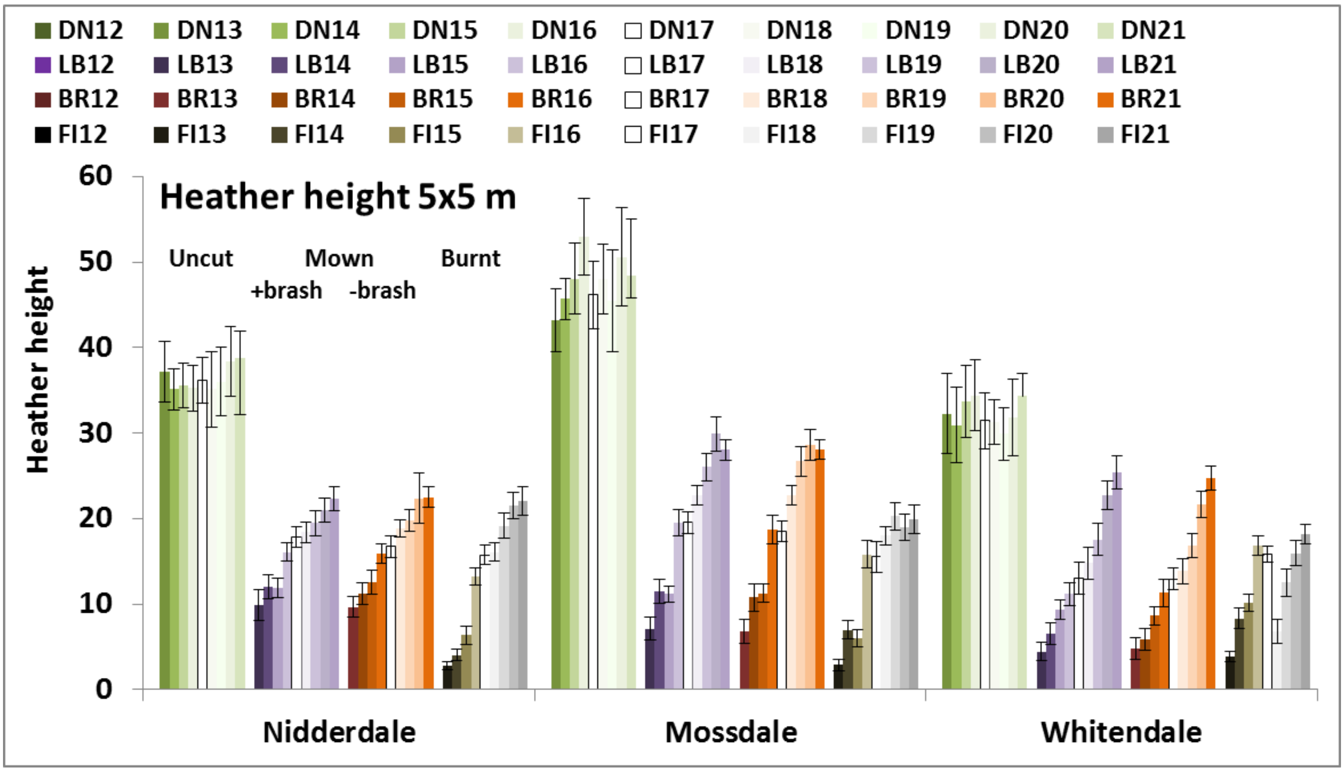


Figure A3.6 heather heights within the 5x5 m plots. Note the reduced heights post 2017 on burnt plots at Mossdale and Whitendale (heather beetle damage).

Shannon's diversity index and species richness were calculated for each data point from the vegetation cover data with combined data from the two quadrat sizes (1x1 m & 5x5 m), but the vegetation layer (total vs. exposed) was maintained. These two response variables were modelled individually using BACI structure. Mixed-effect models and least square models were compared to find the best fitting model for statistical analyses. Models were compared using AIC and log likelihood scores, and through checking diagnostic plots of the models. In all cases, the mixed-effect model performed better than the generalised least square models, so were used for the following analyses. Models also incorporated random block effects. The progressive change BACIPS method, proposed by Thiault et al. (Progressive-Change BACIPS: a flexible approach for environmental impact assessment - Thiault - 2017 - Methods in Ecology and Evolution - Wiley Online Library), was used to identify the pattern of response to management, and where an alternative approach to the standard BACI model was required. The statistical analysis of species richness required studying progressive change through time, so the interaction of management and continuous year was used. Of the four managements, FI (burn) management was taken as the control, thus a significant effect of management means that the management causes a significantly different effect than FI. The only management that increased Shannon's diversity score, with statistical significance supported in post-hoc tests, was the FI management; when separating the 'After' period into short-term (2013-2016) and long-term (2017-2021), the response was similar across both 'After' periods. The BACI effect sizes show at least 'medium' effect sizes for the 'Impact' managements. Shannon diversity is shown in the below **Table A3.1** for the combined sites (Nidderdale, Mossdale, Whitendale).

Table A3.1 Shannon diversity (all sites combined).

Year	1 m² quadrat								5 m² quadrat							
	Total vegetation				Exposed vegetation				Total vegetation				Exposed vegetation			
	FI	BR	LB	DN	FI	BR	LB	DN	FI	BR	LB	DN	FI	BR	LB	DN
2012	0.738	1.123	1.088	1.119	0.439	0.857	0.790	0.822	0.934	1.048	1.056	1.057	0.566	0.660	0.682	0.733
2013	1.025	1.098	1.136	1.316	1.025	1.075	1.127	1.062	1.333	1.246	1.374	1.256	1.333	1.247	1.373	0.930
2014	1.082	1.166	1.204	1.250	1.100	1.128	1.176	0.878	1.296	1.120	1.309	1.235	1.330	1.184	1.267	0.812
2015	1.175	1.215	1.208	1.161	1.158	1.155	1.177	0.884	1.329	1.240	1.259	1.173	1.327	1.220	1.258	0.923
2016	1.410	1.419	1.429	1.312	1.210	1.183	1.182	0.867	1.578	1.384	1.491	1.295	1.411	1.165	1.226	0.879
2017	1.373	1.425	1.361	1.324	1.198	1.164	1.104	0.864	1.585	1.406	1.493	1.327	1.421	1.167	1.211	0.873
2018	1.262	1.375	1.297	1.268	1.084	0.976	0.935	0.843	1.409	1.399	1.388	1.262	1.269	1.008	1.007	0.822
2019	1.242	1.380	1.291	1.263	1.097	1.034	0.956	0.938	1.449	1.401	1.435	1.254	1.295	1.066	1.059	0.876
2020	1.305	1.405	1.353	1.246	1.135	1.026	0.968	0.870	1.495	1.426	1.470	1.256	1.309	1.043	1.063	0.867
2021	1.452	1.465	1.450	1.292	1.239	1.079	1.053	0.841	1.610	1.470	1.549	1.270	1.389	1.063	1.120	0.823

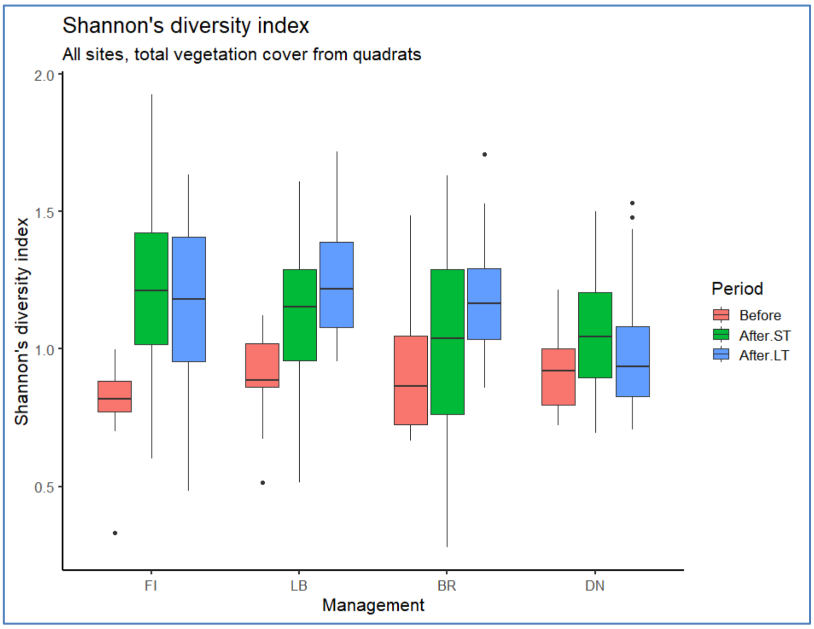


Figure A3.7 Shannon's diversity index across all managements (FI = burnt; LB = mown with left brash; BR = mown with brash removal; DN = uncut [do nothing] and combined for all sites. Before (2012) versus the two after post-management periods (2013-2016 & 2017-2021) are shown.

The linear model regressed species richness against the management*year interaction and included the random effect structure (e.g. block). This model showed a significant interaction of management and year for all three 'impact' managements. All three managements had a much less steep increase in species richness than FI management. The different trends of species richness under these managements were confirmed with estimated marginal means post-hoc test. The contrast between burnt (FI) plots before and overall after management were close to statistical significance (p=0.090) and was strongest compared to uncut (DN) but only marginally significant (p=0.075). Post-hoc tests found a single significant contrast, between FI before management and FI long-term, further emphasising the long-term increases in species richness with burn management (**Figure A3.8**).

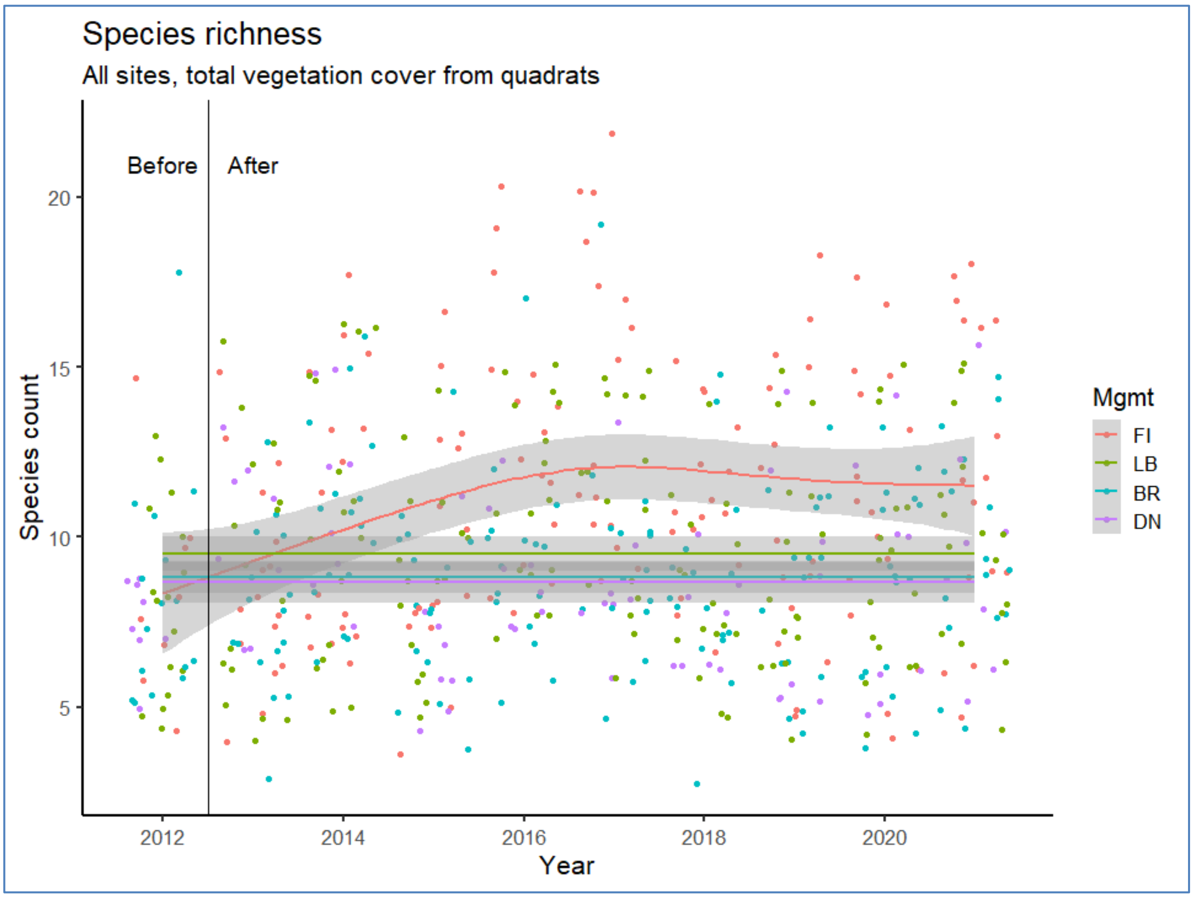
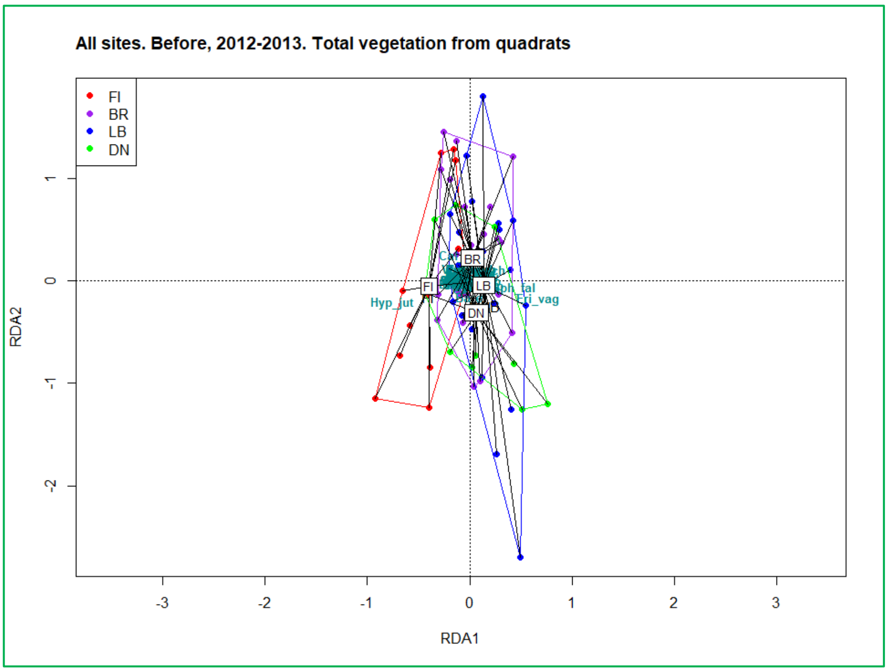
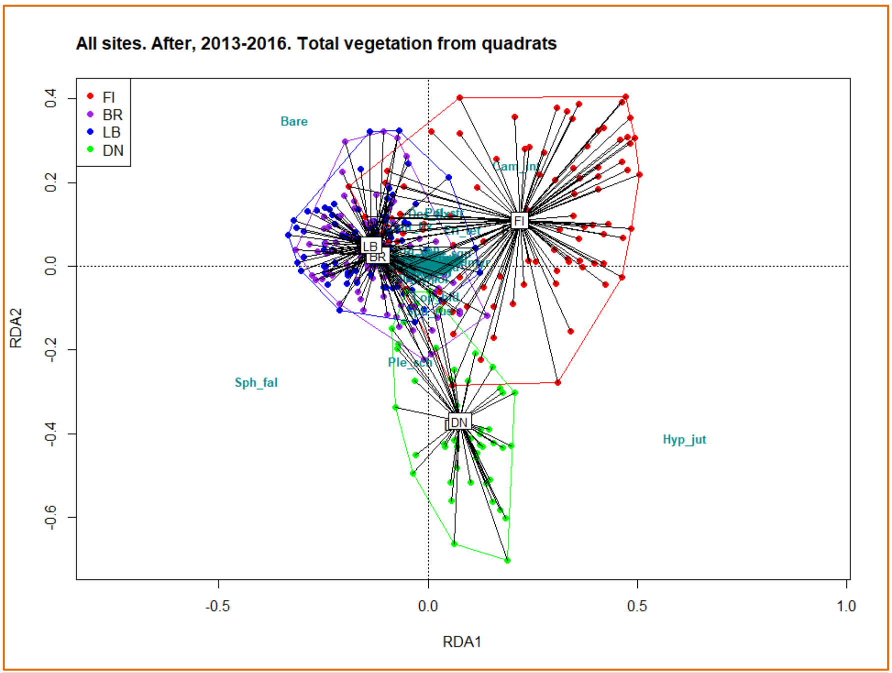
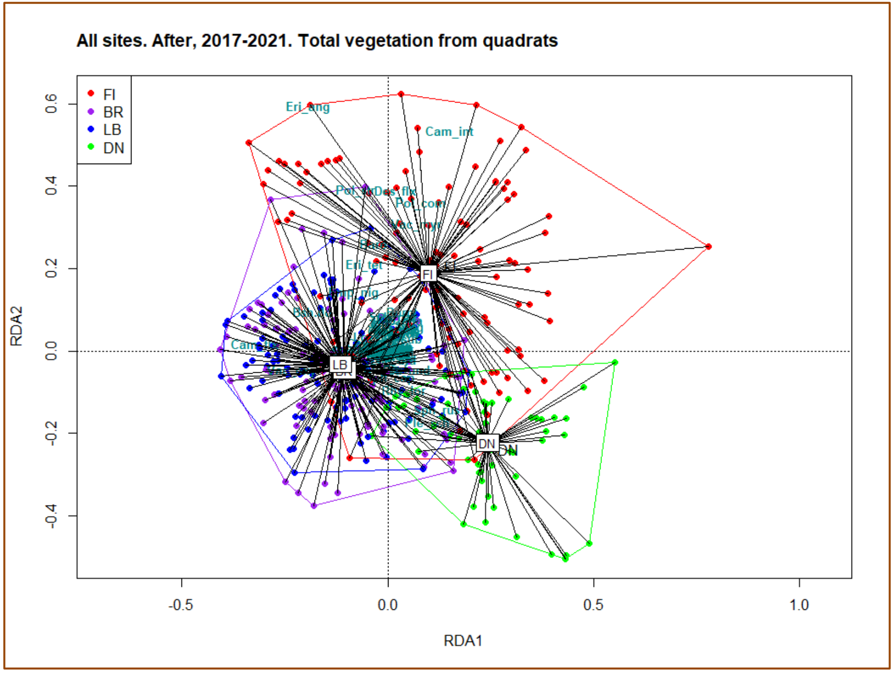


Figure A3.8 Species richness across the plots for the main managements (FI = burnt; LB = mown with left brash; BR = mown with brash removal; DN = uncut [do nothing]) combined across all three sites and split into before (2012) and after post-management (2013-2021) periods.

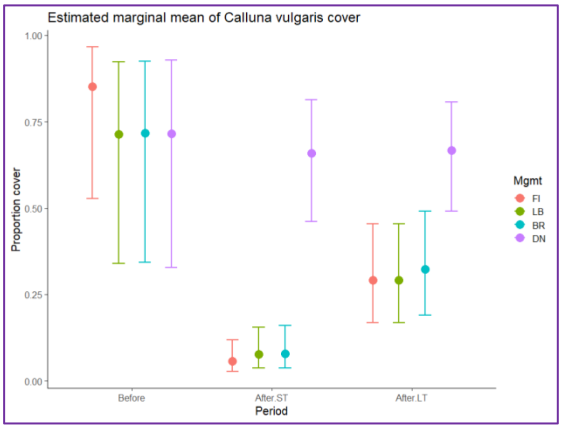
It was very clear that diversity and species richness was lowest pre-management which was maintained under DN management. Furthermore, an overall principle component analysis (RDA) revealed a close similarity across all management plots before management (2012) across all sites. Subsequently, the vegetation community structure of burnt (FI), mown with brash left (LB) and brash removal (BR) and uncut (DN) plots separated, especially in relation to cover of bare/brash/burnt ground, *Sphagnum fallax* and *Hypnum jutlandicum*), in the first post-management period (2013-2016) following management in 2013, which was maintained in the second post-management period (2017-2021) albeit with some changes, relating especially to the non-Sphagnum mosses *Campylopus* spp. and *Pleurozium shreberi*, the cotton-grass *Eriophorum angustifolium* , the grass *Deschampsia flexuosa* and *Empetrum nigrum*. The following **Figure A3.9** outlines these changes over time. Note that the two mown managements overlap closely in both post-management periods and overall managed plots became closer to uncut plots over time.


All sites. Before, 2012-2013. Total vegetation from quadrats

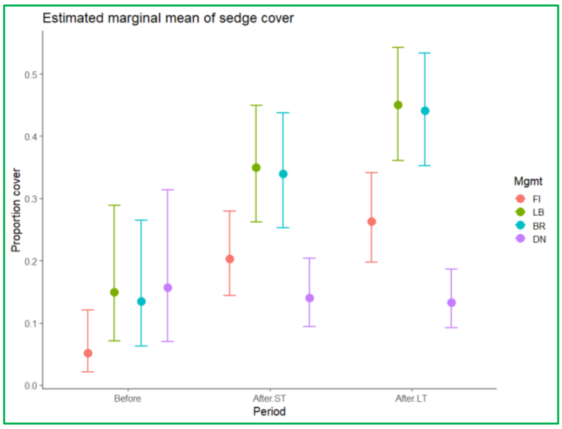

All sites. After, 2013-2016. Total vegetation from quadrats


All sites. After, 2017-2021. Total vegetation from quadrats

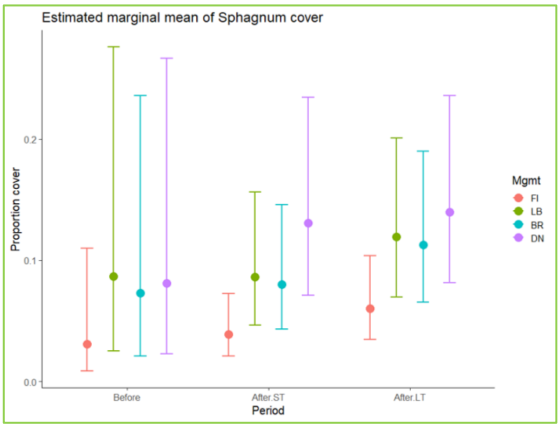
The vegetation cover was analysed using the glmmTMB R-package with generalised mixed-effect models (GLMM). The percentages were converted to proportional data and a beta regression was used to account for the distribution of this response variable (it better accounts for a variety of distribution curves). For each plant group, a model selection step was done, using the progressive change BACIPS approach suggested by Thiault et al. (also see section 3 above). This helped to identify where linear responses occurred, for which BACI analysis a continuous year variable instead of BA would be more useful, or where a traditional BACI model was more appropriate (i.e. for step responses). The models was: y ~ Management * BA + (1|Year/Site/Block/Plot/Quadrat), where y is the response variable (each plant group) and BA is management period (Before (2012), After; Before, Short-term (ST: 2013-2016), Long-term (LT: 2017-2021) or year of study. 'Heather like' included *Erica tetralix*, *Vaccinium myrtillus*, *V. oxycoccus*, *Empetrum nigrum* and *Andromeda polifolia*. This statistical model also accounted for the random variance caused by year, site, block, plot, and quadrat size. Estimated marginal means post-hoc tests were conducted on models to verify the statistical significance of differences between managements. The burn (FI) management was taken as the control [vs uncut (DN), mown with or without brash removal (BR & LB, respectively)] as it represented the historic management at the sites; the following results therefore show the effect of the mown (LB & BR) and uncut (DN) managements compared to the FI management. The below **Figures A3.10a-h** show the modelled marginal means for proportion cover for the main vegetation / cover types comparing before (2012) to the two post-management periods (ST: 2013-2016 & LT: 2017-2021).



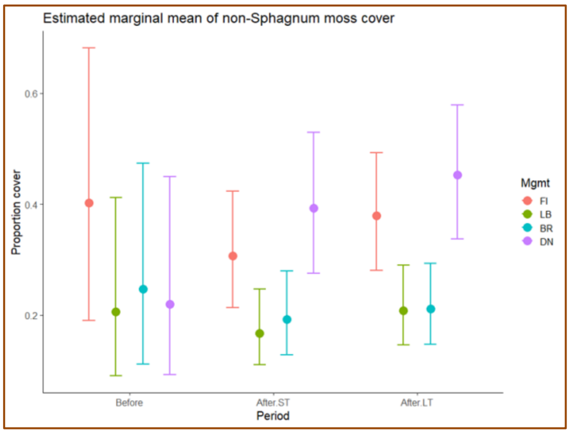
a) Heather: decreased highly significantly (***) with BR, LB, and FI management after management in 2013-16, the difference versus DN declined significantly over the two post-management periods. The sharp decline is unsurprising as it is a direct result of the heather management takin off the above round vegetation. What is surprising is the fairly similar recovery over time regardless of burning or mowing. However, brash removal (BR) recovered faster as seen in a higher BACI significance (**) than LB (*) vs FI over the post-management period. Other 'heather like' cover increased over time mostly on burnt and mown plots.



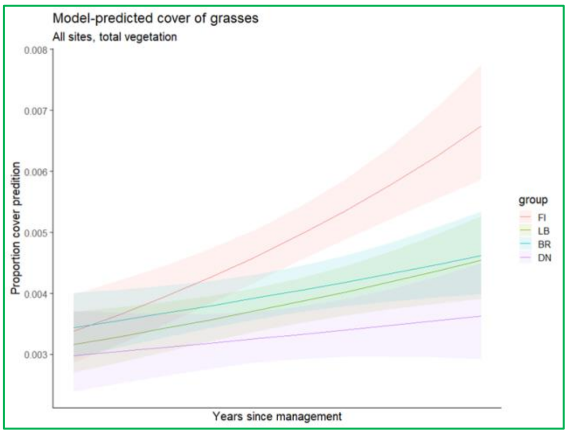
b) Sedges (cotton-grass): increased with FI, BR, and LB management. The GLMM analyses found a significant BACI interaction for DN management, with sedge cover not increasing for DN management. Sedge cover was significantly (*) lower in FI plots than other plots during pre-management (Before) and higher (*) in the Long-term (2017-21) than pre-management with FI, LB and BR management and was higher (***) in LB and BR plots than in FI plots during the Short-term (2013-16) and Lon-term (2017-2021) periods.



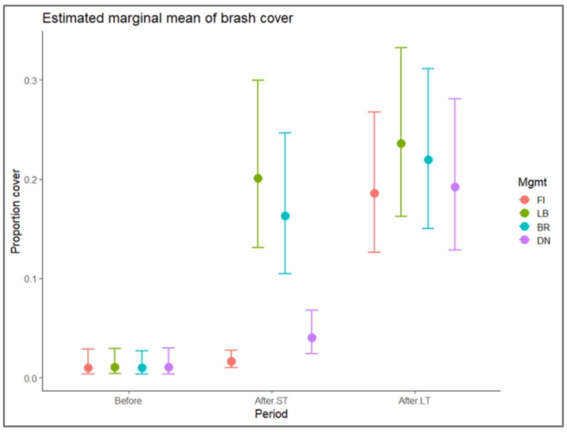
c) *Sphagnum* moss: did not reveal differences in BACI analyses using management periods between FI management and the three alternative managements and neither were interactions significant for the before versus after analysis or for the analysis incorporating short-term and long-term. Therefore, there is not enough evidence to clearly be sure that the three alternative managements (LB, BR, DN) effect *Sphagnum* moss cover differently than FI management. There was a significant interaction (*) of DN management with year, but a post-hoc did not show a statistically significant contrast between FI and DN.



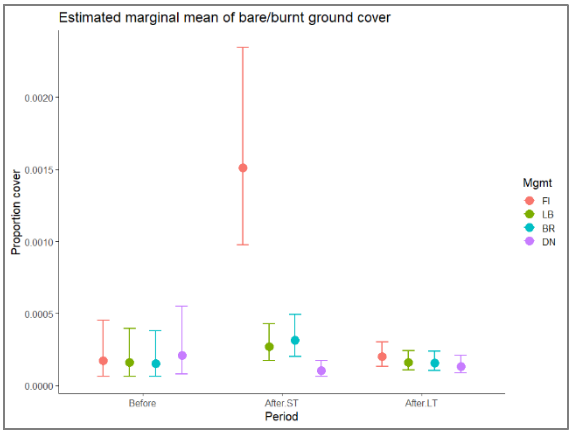
d) Non-*Sphagnum* moss: showed a significant (*) BACI interaction for DN management, which was verified by the post-hoc test. This means that FI and DN management caused different responses in non-*Sphagnum* moss cover. Non-*Sphagnum* moss cover was higher in DN plots than FI plots following management and this was the case in both the short-term period and long-term periods. Non-*Sphagnum* moss cover was also significantly (***) higher in DN plots than LB and BR plots during both post-management periods. Notably, burnt plots already had higher non-*Sphagnum* cover pre-management.



f) Grass: mainly representing *Deschampsia flexuosa*, revealed no statistically significant BACI interactions by the standard BACI analyses using Before and After periods, or when using short-term and long-term levels. However, the BACIPS model selection found a significant (***) likelihood of linear response and the interaction of management and year showed a statistically significant (***) interaction of the three alternative managements with year as a continuous variable, which was confirmed by post hoc tests that showed a faster increase in grasses on FI plots versus the three alternative managements.



g) Brash: showed that both mown managements immediately increased the cover of brash. There were significant (***) BACI interactions for LB and BR in the standard BACI analysis, and significant (***) interactions with the short-term period in the expanded BACI analysis. However, brash cover in DN and FI plots also significantly (***) increased over time, especially in the long-term period (2017-21), so that there were no significant differences between management plots during the second post-management period 2017-21.



h) Bare/burnt: revealed significant interactions for all three alternative managements, which were further verified by post-hoc tests. The small cover of bare and burnt ground was higher (***) in FI plots during 2013-21 than the other management plots, as expected (i.e. burn patches exposing the peat/litter layer). However, the BACI analysis with 'After' period divided into short- and long-term revealed a significant decrease on FI plots in 2017-21, with no significant differences to the other managements in this latter post-management phase. Post-hoc tests also revealed that bare/burnt ground cover was lower (***) in DN plots than LB or BR plots following management.

Appendix 4 (elemental content)

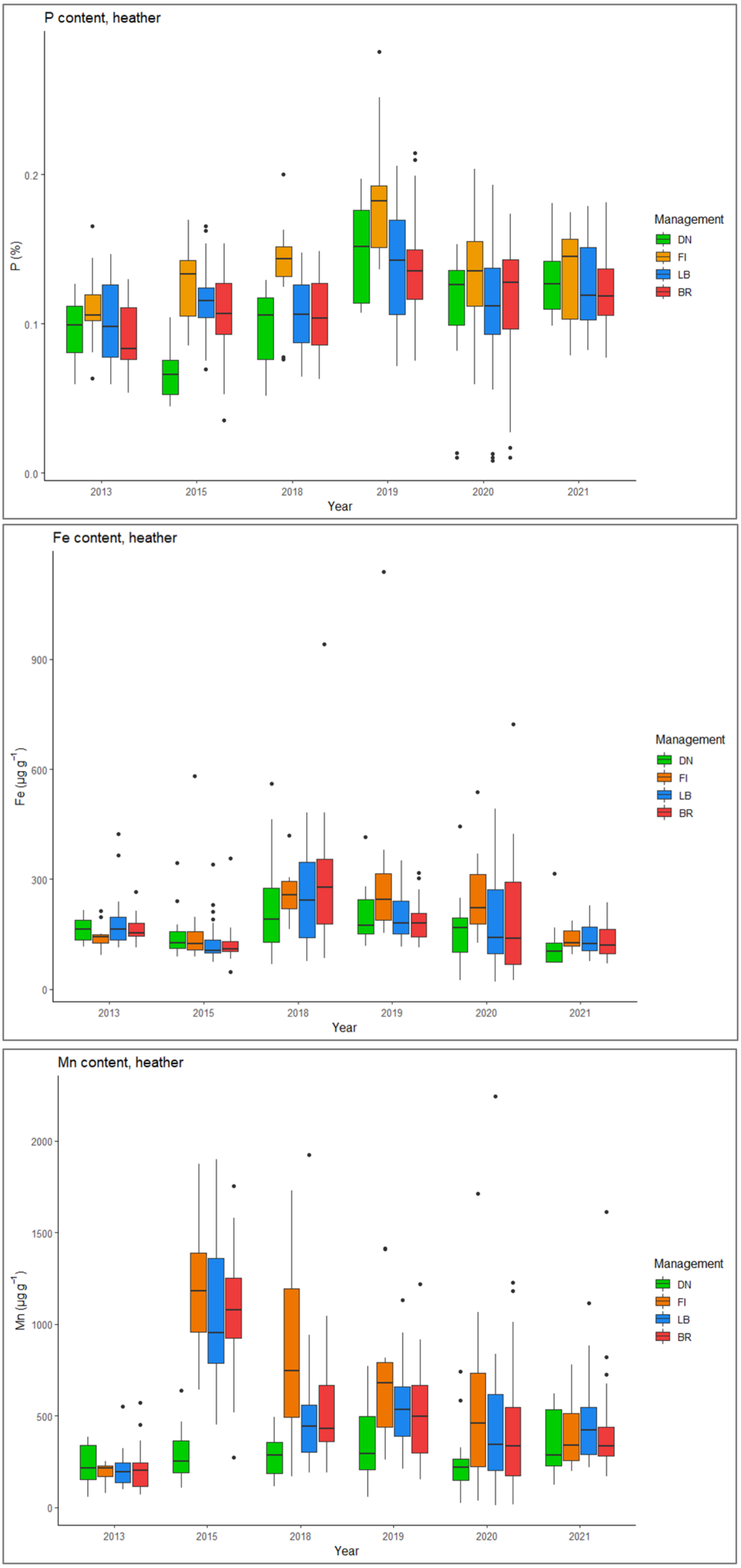
The statistical models were chosen by consulting diagnostic plots and checking AIC and deviance scores to select the best statistical model. The analysis of C, P, K, Na, Mg, Ca, Al and Si were done with linear mixed modelling, whereas the analysis of N, Fe, Mn, and Zn were done with generalised linear mixed modelling using a Gamma family distribution (in the GLMMTMB R package; this was because of a slight right skew in the data and residuals), and the analysis of Cu was done with a generalised linear mixed modelling using a Gamma family distribution and a log link, due to a few extremely high outliers. Before-After Control-Impact (BACI) analyses were performed for all elements (but Si for which no pre-management data were available), albeit using years as a categorical variable (2013 vs 2015, 2018, 2019, 2020, 2021) instead of Before vs After. Whereas 2013 was the control year, DN was the control management. BACI analysis were done relative of this control with random effects as block nested in site.

The below **Table A4.1** summarises the statistical output for heather shoots, indicating the direction and statistical significance terms (i.e. $p<0.05$*; $p<0.01$**; $p<0.001$***) with **A)** uncut (DN) vs. **B)** with burnt (FI) as the control.

A)	**(vs. DN)**	**C**	**N**	**P**	**K**	**Na**	**Mg**	**Ca**	**Fe**	**Al**	**Mn**	**Zn**	**Cu**
FI	2015		↑ ***	↑ *	↑ *	↑ **				↓ *	↑ ***	↑ *	
	2018					↑ *				↑ *	↑ ***	↑ *	↑ ***
	2019					↑ .			↑ *		↑ **	↑ .	
	2020					↑ *			↑ *		↑ ***	↑ *	
	2021		↓ *			↑ *							
LB	2015		↑ ***	↑ **		↑ **				↓ *	↑ ***		
	2018										↑ **	↑ *	
	2019										↑ *	↑ *	
	2020										↑ **	↑ *	
	2021					↑ .						↑ .	
BR	2015		↑ ***	↑ **		↑ **				↓ *	↑ ***		
	2018					↑ *					↑ **	↑ *	
	2019										↑ .		
	2020										↑ *	↑ *	
	2021		↓ **			↑ *							

B)	**(vs. FI)**	**C**	**N**	**P**	**K**	**Na**	**Mg**	**Ca**	**Fe**	**Al**	**Mn**	**Zn**	**Cu**
LB	2015												
	2018		↑ *							↓ **	↓ *		↓ ***
	2019		↓ .	↓ *					↓ **	↓ **		↓ *	
	2020				↓ *	↓ *			↓ *	↓ .			↓ *
	2021		↑ *										
BR	2015				↓ .								
	2018		↑ *							↓ .	↓ *		↓ ***
	2019			↓ .					↓ *	↓ **	↓ .	↓ *	
	2020				↓ *	↓ *			↓ *		↓ *		
	2021												

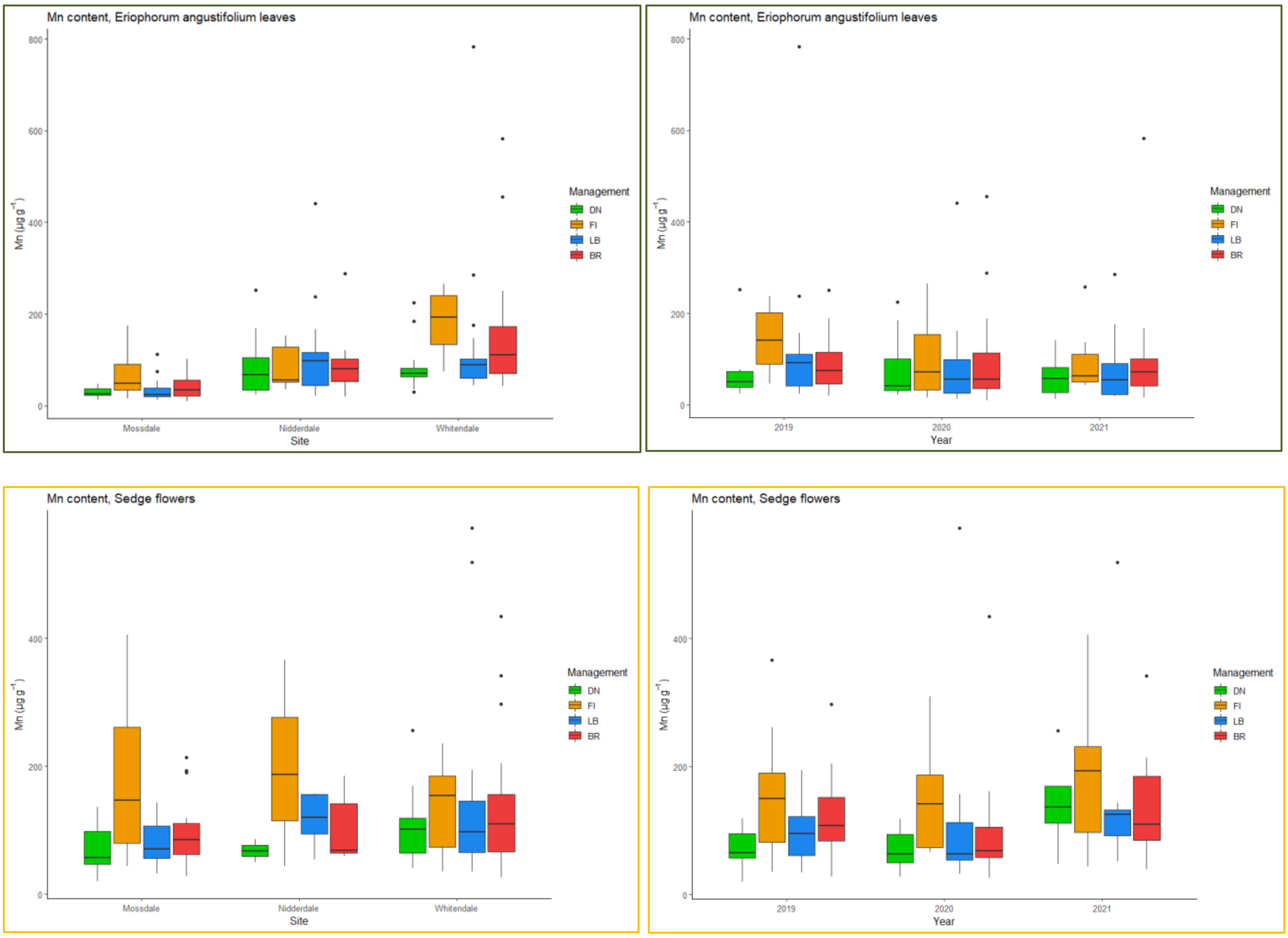
The below **Figure A4.1** shows examples for the elemental phosphorus (P), iron (Fe) and manganese (Mn) concentration in heather shoots with a marked management impact, especially on burnt plots. Note that these elements all play a crucial part for plant growth and C uptake (i.e. photosynthesis).



The below **Table A4.2** summarises the statistical output for cotton-grass (*Eriophorum*) shoots and flower heads, indicating the direction and statistical significance terms (i.e. p<0.05*; p<0.01**; p<0.001***) with uncut (DN) as the control vs. burnt (FI) and mown with left brash (LB) and brash removal (BR).

	<u>Leaves</u>: Eriophorum angustifolium			<u>Leaves</u>: *E. vaginatum*			<u>Flowers</u>: *E.* spp.		
	FI	**LB**	**BR**	**FI**	**LB**	**BR**	**FI**	**LB**	**BR**
P	↓ .								
K	↓								
Na							↑ *	↑ **	↑ .
Mg									
Ca									
Si									↓ **
Fe									↓ .
Al									↓ .
Mn	↑ *			↑ *			↑ **		↑ .
Zn									
Cu									↓ .

The below **Figure A4.2** shows the elemental Manganese (Mn) concentration in cotton-grass (*Eriophorum angustifolium*) shoots (top row left: per site and right: over time) with a marked management impact, especially on burnt plots (*). Note that Mn plays a crucial part for plant growth and C uptake (i.e. photosynthesis). The same increase was observed for *E. vaginatum* leaves (*). Moreover, the flower heads also showed this increased (**) Mn concentration in FI plots (bottom row left: per site and right: over time).



The following tables (**Table A4.3** – **Table A4.10**) summarise the elemental content in heather shoot and sedge (*E. vaginatum* and *E. angustifolium*) shoot and flower/seed head samples. For further information and methods see Heinemeyer et al. (2019b).

Table A4.3 Means ±STDEV for all heather shoot samples (including very high values) from the 5x5 m plots at the three sites and their main managements during pre- (sampled in Spring 2013) and post-management (sampled in late summer during 2015-2021) periods (macronutrients as percentages and micronutrients in weight per weight). Missing data (silica) indicate no analysis was done during Phase 1. For comparison relevant literature values from Allen (1989) and Nordlokken et al. (2015) are also shown (however, different sampling times, locations and site conditions likely explain differences).

	HEATHER	%								µg g-1				
		C	N	P	K	Na	Mg	Ca	Si	Fe	Al	Mn	Zn	Cu
	Allen (1989)		**1.2**	**0.1**	**0.72**	**0.07**	**0.16**	**0.33**	**0.4**	**190**	**200**	**600**	**25**	**12**
	Nordlokken et al. (2015)			**0.09**	**0.55**	**0.028**	**0.11**	**0.27**	**0**	**56**	**30**	**320**	**26**	**8**
2013	Pre Nidderdale Burnt	51.9 ± 0.4	1.20 ± 0.04	0.11 ± 0.01	0.16 ± 0.01	0.06 ± 0.00	0.18 ± 0.01	0.44 ± 0.03		145 ± 3	103 ± 4	212 ± 23	62 ± 13	12 ± 0.0
	Pre Nidderdale Uncut	52.2 ± 0.3	1.20 ± 0.08	0.08 ± 0.01	0.17 ± 0.02	0.06 ± 0.01	0.16 ± 0.02	0.42 ± 0.05		177 ± 22	112 ± 9	284 ± 43	61 ± 15	14 ± 1.0
	Pre Nidderdale Mown	52.3 ± 0.2	1.23 ± 0.05	0.10 ± 0.01	0.16 ± 0.01	0.05 ± 0.01	0.16 ± 0.01	0.41 ± 0.04		163 ± 9	108 ± 3	194 ± 18	41 ± 2	13 ± 0.0
	Pre Nidderdale Mown -brash	52.3 ± 0.3	1.26 ± 0.05	0.09 ± 0.01	0.17 ± 0.01	0.06 ± 0.01	0.16 ± 0.01	0.37 ± 0.03		156 ± 10	108 ± 3	200 ± 33	47 ± 6	12 ± 1.0
	Pre Mossdale Burnt	52.8 ± 0.2	1.06 ± 0.02	0.10 ± 0.01	0.17 ± 0.02	0.08 ± 0.01	0.19 ± 0.01	0.38 ± 0.02		155 ± 29	122 ± 16	204 ± 13	38 ± 2	10 ± 1.0
	Pre Mossdale Uncut	52.2 ± 0.3	1.05 ± 0.03	0.10 ± 0.01	0.19 ± 0.01	0.18 ± 0.04	0.17 ± 0.01	0.39 ± 0.02		145 ± 12	105 ± 1	238 ± 45	42 ± 3	12 ± 0.0
	Pre Mossdale Mown	52.1 ± 0.2	1.04 ± 0.03	0.10 ± 0.01	0.19 ± 0.01	0.15 ± 0.02	0.18 ± 0.01	0.38 ± 0.02		135 ± 5	105 ± 2	212 ± 26	31 ± 2	12 ± 0.0
	Pre Mossdale Mown -brash	52.2 ± 0.2	1.10 ± 0.02	0.10 ± 0.01	0.19 ± 0.01	0.14 ± 0.02	0.17 ± 0.00	0.38 ± 0.01		145 ± 6	108 ± 3	199 ± 28	38 ± 4	11 ± 0.0
	Pre Whitendale Burnt	51.4 ± 0.3	1.37 ± 0.05	0.13 ± 0.02	0.25 ± 0.01	0.12 ± 0.01	0.17 ± 0.01	0.26 ± 0.02		129 ± 12	105 ± 4	151 ± 39	30 ± 1	12 ± 1.0
	Pre Whitendale Uncut	52.6 ± 0.3	1.35 ± 0.05	0.11 ± 0.01	0.17 ± 0.02	0.05 ± 0.00	0.13 ± 0.01	0.23 ± 0.02		169 ± 21	122 ± 10	160 ± 75	52 ± 8	14 ± 1.0
	Pre Whitendale Mown	52.3 ± 0.2	1.46 ± 0.06	0.11 ± 0.01	0.18 ± 0.01	0.07 ± 0.01	0.14 ± 0.01	0.27 ± 0.01		202 ± 8	157 ± 16	211 ± 53	45 ± 2	15 ± 1.0
	Pre Whitendale Mown -brash	52.6 ± 0.2	1.39 ± 0.05	0.09 ± 0.01	0.18 ± 0.01	0.08 ± 0.01	0.14 ± 0.00	0.28 ± 0.03		191 ± 13	129 ± 6	245 ± 62	40 ± 2	13 ± 1.0
2015	Post Nidderdale Burnt	50.7 ± 0.2	1.91 ± 0.10	0.11 ± 0.01	0.45 ± 0.04	0.15 ± 0.03	0.26 ± 0.02	0.45 ± 0.03		171 ± 13	64 ± 10	1173 ± 62	95 ± 17	13 ± 1.0
	Post Nidderdale Uncut	52.4 ± 0.1	1.34 ± 0.17	0.07 ± 0.01	0.37 ± 0.05	0.07 ± 0.01	0.22 ± 0.02	0.43 ± 0.03		139 ± 16	79 ± 22	370 ± 112	51 ± 3	12 ± 0.0
	Post Nidderdale Mown	51.2 ± 0.3	1.96 ± 0.10	0.12 ± 0.01	0.41 ± 0.04	0.11 ± 0.01	0.27 ± 0.01	0.41 ± 0.03		142 ± 22	51 ± 8	998 ± 82	58 ± 10	12 ± 1.0
	Post Nidderdale Mown -brash	51.8 ± 0.3	1.95 ± 0.16	0.10 ± 0.01	0.39 ± 0.05	0.12 ± 0.02	0.25 ± 0.01	0.43 ± 0.02		115 ± 12	46 ± 7	940 ± 158	46 ± 7	11 ± 1.0
	Post Mossdale Burnt	50.0 ± 0.8	2.21 ± 0.07	0.14 ± 0.01	0.66 ± 0.08	0.12 ± 0.02	0.31 ± 0.02	0.46 ± 0.04		121 ± 10	34 ± 3	1367 ± 283	40 ± 4	12 ± 1.0
	Post Mossdale Uncut	52.5 ± 0.4	1.23 ± 0.16	0.06 ± 0.01	0.31 ± 0.02	0.07 ± 0.02	0.20 ± 0.01	0.38 ± 0.02		105 ± 7	49 ± 4	254 ± 63	33 ± 1	11 ± 0.0
	Post Mossdale Mown	51.3 ± 0.5	1.77 ± 0.07	0.12 ± 0.01	0.44 ± 0.02	0.13 ± 0.01	0.25 ± 0.01	0.39 ± 0.02		99 ± 4	35 ± 3	1318 ± 144	38 ± 2	13 ± 1.0
	Post Mossdale Mown -brash	51.0 ± 0.5	1.93 ± 0.18	0.12 ± 0.01	0.47 ± 0.04	0.14 ± 0.01	0.27 ± 0.01	0.40 ± 0.01		95 ± 5	37 ± 3	1237 ± 73	39 ± 4	12 ± 1.0
	Post Whitendale Burnt	51.9 ± 0.8	2.35 ± 0.14	0.13 ± 0.02	0.54 ± 0.06	0.13 ± 0.03	0.30 ± 0.02	0.56 ± 0.03		104 ± 9	46 ± 6	1114 ± 210	59 ± 5	13 ± 1.0
	Post Whitendale Uncut	52.8 ± 0.6	1.42 ± 0.04	0.07 ± 0.00	0.31 ± 0.03	0.11 ± 0.01	0.22 ± 0.01	0.39 ± 0.02		213 ± 51	116 ± 29	245 ± 52	67 ± 19	13 ± 1.0
	Post Whitendale Mown	51.3 ± 0.6	2.06 ± 0.11	0.11 ± 0.01	0.42 ± 0.02	0.14 ± 0.02	0.29 ± 0.02	0.41 ± 0.02		157 ± 29	60 ± 9	820 ± 94	39 ± 3	12 ± 0.0
	Post Whitendale Mown -brash	51.1 ± 0.8	2.07 ± 0.12	0.10 ± 0.01	0.38 ± 0.03	0.11 ± 0.01	0.27 ± 0.02	0.45 ± 0.02		154 ± 29	61 ± 8	1002 ± 88	49 ± 3	12 ± 1.0
2018	Post Nidderdale Burnt	52.4 ± 0.3	1.45 ± 0.12	0.11 ± 0.02	0.32 ± 0.07	0.09 ± 0.01	0.28 ± 0.01	0.49 ± 0.04	0.01 ± 0.00	278 ± 54	119 ± 25	531 ± 98	36 ± 3	292 ± 167.1
	Post Nidderdale Uncut	50.7 ± 2.0	2.29 ± 0.59	0.12 ± 0.01	0.70 ± 0.08	0.09 ± 0.02	0.39 ± 0.02	0.65 ± 0.05	0.02 ± 0.00	398 ± 69	90 ± 8	265 ± 44	41 ± 2	31 ± 12.1
	Post Nidderdale Mown	53.2 ± 0.3	2.35 ± 0.33	0.10 ± 0.01	0.48 ± 0.08	0.11 ± 0.01	0.38 ± 0.05	0.70 ± 0.08	0.02 ± 0.01	336 ± 49	91 ± 19	646 ± 224	45 ± 7	15 ± 1.7
	Post Nidderdale Mown -brash	53.1 ± 0.5	2.43 ± 0.40	0.11 ± 0.01	0.49 ± 0.08	0.15 ± 0.04	0.39 ± 0.04	0.70 ± 0.06	0.02 ± 0.00	418 ± 97	80 ± 6	545 ± 85	48 ± 5	18 ± 2.9
	Post Mossdale Burnt	52.3 ± 0.2	1.95 ± 0.38	0.14 ± 0.01	0.43 ± 0.02	0.11 ± 0.03	0.40 ± 0.03	0.57 ± 0.05	0.01 ± 0.00	230 ± 18	42 ± 1	558 ± 171	53 ± 5	11 ± 0.8
	Post Mossdale Uncut	53.9 ± 0.5	1.74 ± 0.26	0.11 ± 0.01	0.48 ± 0.06	0.05 ± 0.00	0.29 ± 0.02	0.57 ± 0.01	0.01 ± 0.00	186 ± 18	36 ± 4	350 ± 62	34 ± 3	12 ± 0.7
	Post Mossdale Mown	53.5 ± 0.4	1.97 ± 0.17	0.12 ± 0.01	0.47 ± 0.05	0.08 ± 0.01	0.34 ± 0.03	0.61 ± 0.04	0.02 ± 0.00	254 ± 29	43 ± 3	453 ± 82	40 ± 3	27 ± 14.7
	Post Mossdale Mown -brash	53.7 ± 0.5	2.10 ± 0.32	0.11 ± 0.01	0.49 ± 0.04	0.09 ± 0.02	0.36 ± 0.03	0.68 ± 0.04	0.01 ± 0.00	305 ± 35	56 ± 7	547 ± 133	43 ± 4	13 ± 0.8
	Post Whitendale Burnt	51.7 ± 0.3	2.14 ± 0.11	0.17 ± 0.01	0.94 ± 0.08	0.09 ± 0.00	0.31 ± 0.01	0.54 ± 0.06	0.01 ± 0.00	280 ± 17	75 ± 8	1387 ± 122	54 ± 5	16 ± 1.3
	Post Whitendale Uncut	53.3 ± 0.4	2.15 ± 0.21	0.07 ± 0.01	0.24 ± 0.03	0.04 ± 0.01	0.17 ± 0.03	0.29 ± 0.05	0.01 ± 0.00	96 ± 15	23 ± 4	224 ± 66	29 ± 7	8 ± 1.3
	Post Whitendale Mown	53.1 ± 0.3	2.40 ± 0.32	0.10 ± 0.02	0.36 ± 0.05	0.05 ± 0.01	0.24 ± 0.06	0.42 ± 0.11	0.01 ± 0.00	149 ± 54	34 ± 10	446 ± 110	29 ± 7	11 ± 1.8
	Post Whitendale Mown -brash	52.8 ± 0.6	2.28 ± 0.15	0.09 ± 0.01	0.36 ± 0.08	0.06 ± 0.01	0.24 ± 0.04	0.40 ± 0.07	0.01 ± 0.00	154 ± 39	37 ± 6	412 ± 60	28 ± 5	11 ± 1.6
2019	Post Nidderdale Burnt	50.8 ± 0.1	1.49 ± 0.29	0.18 ± 0.01	0.55 ± 0.04	0.07 ± 0.01	0.30 ± 0.02	0.73 ± 0.06	0.01 ± 0.00	533 ± 203	142 ± 11	488 ± 87	57 ± 9	15 ± 1.3
	Post Nidderdale Uncut	50.6 ± 0.1	1.30 ± 0.15	0.15 ± 0.02	0.60 ± 0.06	0.06 ± 0.01	0.31 ± 0.02	0.73 ± 0.05	0.01 ± 0.00	278 ± 46	127 ± 27	307 ± 72	54 ± 4	16 ± 1.4
	Post Nidderdale Mown	50.5 ± 0.3	1.42 ± 0.14	0.15 ± 0.01	0.63 ± 0.06	0.08 ± 0.02	0.30 ± 0.03	0.68 ± 0.09	0.01 ± 0.00	237 ± 37	93 ± 17	598 ± 99	53 ± 7	13 ± 1.2
	Post Nidderdale Mown -brash	50.5 ± 0.2	1.50 ± 0.22	0.14 ± 0.01	0.56 ± 0.06	0.08 ± 0.01	0.30 ± 0.01	0.70 ± 0.09	0.01 ± 0.00	225 ± 26	78 ± 8	496 ± 114	45 ± 3	12 ± 1.4
	Post Mossdale Burnt	50.3 ± 0.3	1.46 ± 0.05	0.23 ± 0.02	0.53 ± 0.04	0.10 ± 0.01	0.31 ± 0.02	0.49 ± 0.02	0.00 ± 0.00	218 ± 34	45 ± 5	776 ± 239	45 ± 7	12 ± 1.0
	Post Mossdale Uncut	54.7 ± 3.7	1.28 ± 0.14	0.16 ± 0.02	0.65 ± 0.13	0.06 ± 0.01	0.23 ± 0.04	0.50 ± 0.08	0.01 ± 0.00	188 ± 33	47 ± 10	266 ± 90	189 ± 147	13 ± 0.6
	Post Mossdale Mown	50.9 ± 0.2	1.30 ± 0.20	0.15 ± 0.02	0.55 ± 0.07	0.07 ± 0.01	0.25 ± 0.03	0.52 ± 0.06	0.01 ± 0.00	197 ± 25	50 ± 8	448 ± 110	241 ± 197	13 ± 0.8
	Post Mossdale Mown -brash	50.8 ± 0.1	1.43 ± 0.16	0.16 ± 0.02	0.53 ± 0.10	0.07 ± 0.01	0.23 ± 0.04	0.50 ± 0.08	0.01 ± 0.00	199 ± 23	45 ± 6	489 ± 168	157 ± 79	14 ± 1.1
	Post Whitendale Burnt	50.6 ± 0.9	2.24 ± 0.28	0.15 ± 0.01	0.78 ± 0.05	0.08 ± 0.01	0.22 ± 0.01	0.45 ± 0.02	0.01 ± 0.00	205 ± 24	83 ± 14	843 ± 206	66 ± 6	15 ± 1.1
	Post Whitendale Uncut	48.9 ± 4.1	1.85 ± 0.33	0.14 ± 0.02	0.55 ± 0.08	0.07 ± 0.01	0.20 ± 0.02	0.41 ± 0.04	0.01 ± 0.00	143 ± 11	57 ± 5	510 ± 135	116 ± 65	11 ± 0.7
	Post Whitendale Mown	50.0 ± 0.3	1.51 ± 0.08	0.12 ± 0.02	0.56 ± 0.10	0.07 ± 0.01	0.24 ± 0.03	0.43 ± 0.05	0.01 ± 0.00	158 ± 19	56 ± 5	658 ± 117	200 ± 136	10 ± 0.8
	Post Whitendale Mown -brash	50.2 ± 0.3	2.08 ± 0.36	0.12 ± 0.02	0.52 ± 0.08	0.07 ± 0.00	0.22 ± 0.03	0.38 ± 0.04	0.01 ± 0.00	141 ± 15	54 ± 8	568 ± 156	154 ± 112	10 ± 1.1
2020	Post Nidderdale Burnt	50.3 ± 1.5	1.55 ± 0.10	0.13 ± 0.01	0.57 ± 0.05	0.09 ± 0.02	0.20 ± 0.02	0.35 ± 0.10	0.01 ± 0.00	269 ± 42	47 ± 10	255 ± 106	43 ± 6	15 ± 1.6
	Post Nidderdale Uncut	51.6 ± 0.3	1.64 ± 0.09	0.14 ± 0.01	0.69 ± 0.06	0.10 ± 0.02	0.29 ± 0.03	0.62 ± 0.09	0.00 ± 0.00	209 ± 14	68 ± 6	384 ± 122	46 ± 3	17 ± 1.5
	Post Nidderdale Mown	50.8 ± 0.6	2.14 ± 0.34	0.14 ± 0.01	0.65 ± 0.07	0.09 ± 0.01	0.26 ± 0.02	0.53 ± 0.05	0.01 ± 0.00	268 ± 50	73 ± 15	451 ± 84	60 ± 15	16 ± 1.7
	Post Nidderdale Mown -brash	51.6 ± 0.2	1.93 ± 0.18	0.14 ± 0.01	0.67 ± 0.01	0.10 ± 0.01	0.30 ± 0.02	0.62 ± 0.04	0.01 ± 0.00	339 ± 45	83 ± 5	517 ± 114	53 ± 4	18 ± 0.7
	Post Mossdale Burnt	47.5 ± 3.7	1.74 ± 0.24	0.17 ± 0.02	0.73 ± 0.09	0.12 ± 0.01	0.26 ± 0.02	0.42 ± 0.04	0.01 ± 0.00	197 ± 33	65 ± 9	440 ± 125	37 ± 7	16 ± 1.2
	Post Mossdale Uncut	51.3 ± 0.3	1.85 ± 0.28	0.12 ± 0.01	0.56 ± 0.08	0.08 ± 0.01	0.19 ± 0.03	0.40 ± 0.04	0.00 ± 0.00	121 ± 21	40 ± 5	252 ± 111	29 ± 3	12 ± 1.3
	Post Mossdale Mown	51.2 ± 0.2	1.68 ± 0.12	0.13 ± 0.01	0.53 ± 0.06	0.06 ± 0.01	0.21 ± 0.03	0.42 ± 0.06	0.00 ± 0.00	118 ± 15	40 ± 5	393 ± 93	35 ± 5	13 ± 1.4
	Post Mossdale Mown -brash	51.0 ± 0.2	1.76 ± 0.15	0.12 ± 0.02	0.51 ± 0.05	0.08 ± 0.01	0.22 ± 0.02	0.41 ± 0.05	0.00 ± 0.00	102 ± 22	39 ± 7	516 ± 220	32 ± 4	12 ± 0.8
	Post Whitendale Burnt	51.6 ± 0.7	2.10 ± 0.27	0.11 ± 0.02	0.72 ± 0.15	0.11 ± 0.02	0.26 ± 0.06	0.44 ± 0.08	0.01 ± 0.00	310 ± 86	75 ± 11	1003 ± 277	45 ± 9	17 ± 1.9
	Post Whitendale Uncut	53.6 ± 0.5	2.16 ± 0.32	0.07 ± 0.03	0.33 ± 0.17	0.06 ± 0.04	0.15 ± 0.08	0.21 ± 0.11	0.00 ± 0.00	165 ± 98	30 ± 20	141 ± 50	26 ± 15	14 ± 6.9
	Post Whitendale Mown	53.1 ± 0.6	2.08 ± 0.39	0.06 ± 0.02	0.36 ± 0.16	0.07 ± 0.03	0.18 ± 0.09	0.27 ± 0.13	0.00 ± 0.00	177 ± 97	47 ± 26	511 ± 352	28 ± 12	8 ± 2.7
	Post Whitendale Mown	53.2 ± 0.4	2.05 ± 0.19	0.06 ± 0.03	0.34 ± 0.18	0.05 ± 0.03	0.12 ± 0.06	0.20 ± 0.11	0.00 ± 0.00	166 ± 114	27 ± 15	239 ± 160	21 ± 9	7 ± 2.7
2021	Post Nidderdale Burnt	51.2 ± 0.4	1.22 ± 0.11	0.10 ± 0.01	0.39 ± 0.03	0.07 ± 0.00	0.21 ± 0.01	0.44 ± 0.02	0.01 ± 0.00	122 ± 8	39 ± 2	266 ± 31	28 ± 1	10 ± 0.1
	Post Nidderdale Uncut	50.9 ± 0.1	1.40 ± 0.05	0.11 ± 0.00	0.53 ± 0.04	0.06 ± 0.00	0.21 ± 0.02	0.46 ± 0.08	0.01 ± 0.00	120 ± 16	38 ± 8	408 ± 106	31 ± 2	10 ± 0.5
	Post Nidderdale Mown	50.5 ± 0.2	1.52 ± 0.16	0.12 ± 0.01	0.50 ± 0.04	0.08 ± 0.01	0.22 ± 0.01	0.45 ± 0.05	0.01 ± 0.00	138 ± 21	39 ± 6	442 ± 51	38 ± 4	11 ± 0.8
	Post Nidderdale Mown -brash	50.4 ± 0.2	1.37 ± 0.14	0.12 ± 0.02	0.50 ± 0.04	0.10 ± 0.01	0.24 ± 0.02	0.50 ± 0.02	0.01 ± 0.00	127 ± 15	38 ± 5	368 ± 91	37 ± 4	10 ± 0.5
	Post Mossdale Burnt	50.9 ± 0.3	1.23 ± 0.12	0.15 ± 0.01	0.52 ± 0.02	0.11 ± 0.02	0.24 ± 0.01	0.44 ± 0.03	0.01 ± 0.00	133 ± 16	42 ± 10	524 ± 122	32 ± 3	10 ± 0.9
	Post Mossdale Uncut	51.3 ± 0.2	1.75 ± 0.37	0.15 ± 0.02	0.58 ± 0.04	0.05 ± 0.00	0.21 ± 0.01	0.41 ± 0.01	0.01 ± 0.00	74 ± 1	21 ± 2	267 ± 93	28 ± 4	9 ± 0.1
	Post Mossdale Mown	50.8 ± 0.1	1.66 ± 0.27	0.15 ± 0.01	0.61 ± 0.03	0.09 ± 0.01	0.23 ± 0.01	0.47 ± 0.02	0.01 ± 0.00	102 ± 10	27 ± 4	542 ± 124	34 ± 2	10 ± 0.3
	Post Mossdale Mown -brash	50.3 ± 0.3	1.23 ± 0.17	0.12 ± 0.01	0.59 ± 0.04	0.08 ± 0.00	0.21 ± 0.01	0.48 ± 0.02	0.01 ± 0.00	91 ± 6	31 ± 2	480 ± 227	30 ± 2	10 ± 0.5
	Post Whitendale Burnt	51.1 ± 0.4	1.83 ± 0.22	0.15 ± 0.00	0.66 ± 0.05	0.06 ± 0.01	0.21 ± 0.01	0.43 ± 0.02	0.00 ± 0.00	151 ± 19	26 ± 4	382 ± 53	36 ± 2	10 ± 0.6
	Post Whitendale Uncut	53.3 ± 1.4	2.47 ± 0.70	0.13 ± 0.01	0.57 ± 0.05	0.05 ± 0.00	0.21 ± 0.02	0.42 ± 0.01	0.00 ± 0.00	166 ± 50	28 ± 3	389 ± 89	54 ± 12	10 ± 0.5
	Post Whitendale Mown	49.8 ± 2.3	2.09 ± 0.40	0.11 ± 0.01	0.47 ± 0.04	0.06 ± 0.01	0.21 ± 0.02	0.42 ± 0.02	0.00 ± 0.00	154 ± 23	31 ± 3	404 ± 135	35 ± 3	9 ± 1.0
	Post Whitendale Mown	48.4 ± 7.9	1.40 ± 0.31	0.11 ± 0.01	0.49 ± 0.05	0.07 ± 0.01	0.23 ± 0.01	0.45 ± 0.04	0.00 ± 0.00	180 ± 24	33 ± 3	402 ± 70	34 ± 3	10 ± 0.7

Table A4.4 Means ±STDEV for all heather shoot samples (excluding very high values) from the 5x5 m plots at the three sites and their main managements during pre- (sampled in Spring 2013) and post-management (sampled in late summer during 2015-2021) periods (macronutrients as percentages and micronutrients in weight per weight). Missing data (silica) indicate no analysis was done during Phase 1. For comparison relevant literature values from Allen (1989) and Nordlokken et al. (2015) are also shown (however, different sampling times, locations and site conditions likely explain differences).

	HEATHER	%								µg g-1				
		C	N	P	K	Na	Mg	Ca	Si	Fe	Al	Mn	Zn	Cu
	Allen (1989)		**1.2**	**0.1**	**0.72**	**0.07**	**0.16**	**0.33**	**0.4**	**190**	**200**	**600**	**25**	**12**
	Nordlokken et al. (2015)			**0.09**	**0.55**	**0.028**	**0.11**	**0.27**	**2E-05**	**56**	**30**	**320**	**26**	**8**
2013	Pre Nidderdale Burnt	51.9 ± 0.4	1.20 ± 0.04	0.11 ± 0.01	0.16 ± 0.01	0.06 ± 0.00	0.18 ± 0.01	0.44 ± 0.03		145 ± 3	103 ± 4	212 ± 23	62 ± 13	12 ± 0.0
	Pre Nidderdale Uncut	52.2 ± 0.3	1.20 ± 0.08	0.08 ± 0.01	0.17 ± 0.02	0.06 ± 0.01	0.16 ± 0.02	0.42 ± 0.05		177 ± 22	112 ± 9	284 ± 43	61 ± 15	14 ± 1.0
	Pre Nidderdale Mown	52.3 ± 0.2	1.23 ± 0.05	0.10 ± 0.01	0.16 ± 0.01	0.05 ± 0.01	0.16 ± 0.01	0.41 ± 0.04		163 ± 9	108 ± 3	194 ± 18	41 ± 2	13 ± 0.0
	Pre Nidderdale Mown -brash	52.3 ± 0.3	1.26 ± 0.05	0.09 ± 0.01	0.17 ± 0.01	0.06 ± 0.01	0.16 ± 0.01	0.37 ± 0.03		156 ± 10	108 ± 3	200 ± 33	47 ± 6	12 ± 1.0
	Pre Mossdale Burnt	52.8 ± 0.2	1.06 ± 0.02	0.10 ± 0.01	0.17 ± 0.02	0.08 ± 0.01	0.19 ± 0.01	0.38 ± 0.02		155 ± 29	122 ± 16	204 ± 13	38 ± 2	10 ± 1.0
	Pre Mossdale Uncut	52.2 ± 0.3	1.05 ± 0.03	0.10 ± 0.01	0.19 ± 0.01	0.18 ± 0.04	0.17 ± 0.01	0.39 ± 0.02		145 ± 12	105 ± 1	238 ± 45	42 ± 3	12 ± 0.0
	Pre Mossdale Mown	52.1 ± 0.2	1.04 ± 0.03	0.10 ± 0.01	0.19 ± 0.01	0.15 ± 0.02	0.18 ± 0.01	0.38 ± 0.02		135 ± 5	105 ± 2	212 ± 26	31 ± 2	12 ± 0.0
	Pre Mossdale Mown -brash	52.2 ± 0.2	1.10 ± 0.02	0.10 ± 0.01	0.19 ± 0.01	0.14 ± 0.02	0.17 ± 0.00	0.38 ± 0.01		145 ± 6	108 ± 3	199 ± 28	38 ± 4	11 ± 0.0
	Pre Whitendale Burnt	51.4 ± 0.3	1.37 ± 0.05	0.13 ± 0.02	0.25 ± 0.01	0.12 ± 0.01	0.17 ± 0.01	0.26 ± 0.02		129 ± 12	105 ± 4	151 ± 39	30 ± 1	12 ± 1.0
	Pre Whitendale Uncut	52.6 ± 0.3	1.35 ± 0.05	0.11 ± 0.01	0.17 ± 0.02	0.05 ± 0.00	0.13 ± 0.01	0.23 ± 0.02		169 ± 21	122 ± 10	160 ± 75	52 ± 8	14 ± 1.0
	Pre Whitendale Mown	52.3 ± 0.2	1.46 ± 0.06	0.11 ± 0.01	0.18 ± 0.01	0.07 ± 0.01	0.14 ± 0.01	0.27 ± 0.01		202 ± 8	157 ± 16	211 ± 53	45 ± 2	15 ± 1.0
	Pre Whitendale Mown -brash	52.6 ± 0.2	1.39 ± 0.05	0.09 ± 0.01	0.18 ± 0.01	0.08 ± 0.01	0.14 ± 0.00	0.28 ± 0.03		191 ± 13	129 ± 6	245 ± 62	40 ± 2	13 ± 1.0
2015	Post Nidderdale Burnt	50.7 ± 0.2	1.91 ± 0.10	0.11 ± 0.01	0.45 ± 0.04	0.15 ± 0.03	0.26 ± 0.02	0.45 ± 0.03		171 ± 13	64 ± 10	1173 ± 62	95 ± 17	13 ± 1.0
	Post Nidderdale Uncut	52.4 ± 0.1	1.34 ± 0.17	0.07 ± 0.01	0.37 ± 0.05	0.07 ± 0.01	0.22 ± 0.02	0.43 ± 0.03		139 ± 16	79 ± 22	370 ± 112	51 ± 3	12 ± 0.0
	Post Nidderdale Mown	51.2 ± 0.3	1.96 ± 0.10	0.12 ± 0.01	0.41 ± 0.04	0.11 ± 0.01	0.27 ± 0.01	0.41 ± 0.03		142 ± 22	51 ± 8	998 ± 82	58 ± 10	12 ± 1.0
	Post Nidderdale Mown -brash	51.8 ± 0.3	1.95 ± 0.16	0.10 ± 0.01	0.39 ± 0.05	0.12 ± 0.02	0.25 ± 0.01	0.43 ± 0.02		115 ± 12	46 ± 7	940 ± 158	46 ± 7	11 ± 1.0
	Post Mossdale Burnt	50.0 ± 0.8	2.21 ± 0.07	0.14 ± 0.01	0.66 ± 0.08	0.12 ± 0.02	0.31 ± 0.02	0.46 ± 0.04		121 ± 10	34 ± 3	1367 ± 283	40 ± 4	12 ± 1.0
	Post Mossdale Uncut	52.5 ± 0.4	1.23 ± 0.16	0.06 ± 0.01	0.31 ± 0.02	0.07 ± 0.02	0.20 ± 0.01	0.38 ± 0.02		105 ± 7	49 ± 4	254 ± 63	33 ± 1	11 ± 0.0
	Post Mossdale Mown	51.3 ± 0.5	1.77 ± 0.07	0.12 ± 0.01	0.44 ± 0.02	0.13 ± 0.01	0.25 ± 0.01	0.39 ± 0.02		99 ± 4	35 ± 3	1318 ± 144	38 ± 2	13 ± 1.0
	Post Mossdale Mown -brash	51.0 ± 0.5	1.93 ± 0.18	0.12 ± 0.01	0.47 ± 0.04	0.14 ± 0.01	0.27 ± 0.01	0.40 ± 0.01		95 ± 5	37 ± 3	1237 ± 73	39 ± 4	12 ± 1.0
	Post Whitendale Burnt	51.9 ± 0.8	2.35 ± 0.14	0.13 ± 0.02	0.54 ± 0.06	0.13 ± 0.03	0.30 ± 0.02	0.56 ± 0.03		104 ± 9	46 ± 6	1114 ± 210	59 ± 5	13 ± 1.0
	Post Whitendale Uncut	52.8 ± 0.6	1.42 ± 0.04	0.07 ± 0.00	0.31 ± 0.03	0.11 ± 0.01	0.22 ± 0.01	0.39 ± 0.02		213 ± 51	116 ± 29	245 ± 52	67 ± 19	13 ± 1.0
	Post Whitendale Mown	51.3 ± 0.6	2.06 ± 0.11	0.11 ± 0.01	0.42 ± 0.02	0.14 ± 0.02	0.29 ± 0.02	0.41 ± 0.02		157 ± 29	60 ± 9	820 ± 94	39 ± 3	12 ± 0.0
	Post Whitendale Mown -brash	51.1 ± 0.8	2.07 ± 0.12	0.10 ± 0.01	0.38 ± 0.03	0.11 ± 0.01	0.27 ± 0.02	0.45 ± 0.02		154 ± 29	61 ± 8	1002 ± 88	49 ± 3	12 ± 1.0
2018	Post Nidderdale Burnt	52.4 ± 0.3	1.45 ± 0.12	0.11 ± 0.02	0.32 ± 0.07	0.09 ± 0.01	0.28 ± 0.01	0.49 ± 0.04	0.01 ± 0.00	278 ± 54	119 ± 25	531 ± 98	36 ± 3	13 ± 0.7
	Post Nidderdale Uncut	50.7 ± 2.0	2.29 ± 0.59	0.12 ± 0.01	0.70 ± 0.08	0.09 ± 0.02	0.39 ± 0.02	0.65 ± 0.05	0.02 ± 0.00	398 ± 69	90 ± 8	265 ± 44	41 ± 2	20 ± 2.3
	Post Nidderdale Mown	53.2 ± 0.3	2.35 ± 0.33	0.10 ± 0.01	0.48 ± 0.08	0.11 ± 0.01	0.38 ± 0.05	0.70 ± 0.08	0.02 ± 0.01	336 ± 49	91 ± 19	646 ± 224	45 ± 7	15 ± 1.7
	Post Nidderdale Mown -brash	53.1 ± 0.5	2.43 ± 0.40	0.11 ± 0.01	0.49 ± 0.08	0.15 ± 0.04	0.39 ± 0.04	0.70 ± 0.06	0.02 ± 0.00	418 ± 97	80 ± 6	545 ± 85	48 ± 5	18 ± 2.9
	Post Mossdale Burnt	52.3 ± 0.2	1.95 ± 0.38	0.14 ± 0.01	0.43 ± 0.02	0.11 ± 0.03	0.40 ± 0.03	0.57 ± 0.05	0.01 ± 0.00	230 ± 18	42 ± 1	558 ± 171	53 ± 5	11 ± 0.8
	Post Mossdale Uncut	53.9 ± 0.5	1.74 ± 0.26	0.11 ± 0.01	0.48 ± 0.06	0.05 ± 0.00	0.29 ± 0.02	0.57 ± 0.01	0.01 ± 0.00	186 ± 18	36 ± 4	350 ± 62	34 ± 3	12 ± 0.7
	Post Mossdale Mown	53.5 ± 0.4	1.97 ± 0.17	0.12 ± 0.01	0.47 ± 0.05	0.08 ± 0.01	0.34 ± 0.03	0.61 ± 0.04	0.02 ± 0.00	254 ± 29	43 ± 3	453 ± 82	40 ± 3	13 ± 1.0
	Post Mossdale Mown -brash	53.7 ± 0.5	2.10 ± 0.32	0.11 ± 0.01	0.49 ± 0.04	0.09 ± 0.02	0.36 ± 0.03	0.68 ± 0.04	0.01 ± 0.00	305 ± 35	56 ± 7	547 ± 133	43 ± 4	13 ± 0.8
	Post Whitendale Burnt	51.7 ± 0.3	2.14 ± 0.11	0.17 ± 0.01	0.94 ± 0.08	0.09 ± 0.00	0.31 ± 0.01	0.54 ± 0.06	0.01 ± 0.00	280 ± 17	75 ± 8	1387 ± 122	54 ± 5	16 ± 1.3
	Post Whitendale Uncut	53.3 ± 0.4	2.15 ± 0.21	0.07 ± 0.01	0.24 ± 0.03	0.04 ± 0.01	0.17 ± 0.03	0.29 ± 0.05	0.01 ± 0.00	96 ± 15	23 ± 4	224 ± 66	29 ± 7	8 ± 1.3
	Post Whitendale Mown	53.1 ± 0.3	2.40 ± 0.32	0.10 ± 0.02	0.36 ± 0.05	0.05 ± 0.01	0.24 ± 0.06	0.42 ± 0.11	0.01 ± 0.00	149 ± 54	34 ± 10	446 ± 110	29 ± 7	11 ± 1.8
	Post Whitendale Mown -brash	52.8 ± 0.6	2.28 ± 0.15	0.09 ± 0.01	0.36 ± 0.08	0.06 ± 0.01	0.24 ± 0.04	0.40 ± 0.07	0.01 ± 0.00	154 ± 39	37 ± 6	412 ± 60	28 ± 5	11 ± 1.6
2019	Post Nidderdale Burnt	50.8 ± 0.1	1.49 ± 0.29	0.18 ± 0.01	0.55 ± 0.04	0.07 ± 0.01	0.30 ± 0.02	0.73 ± 0.06	0.01 ± 0.00	533 ± 203	142 ± 11	488 ± 87	57 ± 9	15 ± 1.3
	Post Nidderdale Uncut	50.6 ± 0.1	1.30 ± 0.15	0.15 ± 0.02	0.60 ± 0.06	0.06 ± 0.01	0.31 ± 0.02	0.73 ± 0.05	0.01 ± 0.00	278 ± 46	127 ± 27	307 ± 72	54 ± 4	16 ± 1.4
	Post Nidderdale Mown	50.5 ± 0.3	1.42 ± 0.14	0.15 ± 0.01	0.63 ± 0.06	0.08 ± 0.02	0.30 ± 0.03	0.68 ± 0.09	0.01 ± 0.00	237 ± 37	93 ± 17	598 ± 99	53 ± 7	13 ± 1.2
	Post Nidderdale Mown -brash	50.5 ± 0.2	1.50 ± 0.22	0.14 ± 0.01	0.56 ± 0.06	0.08 ± 0.01	0.30 ± 0.01	0.70 ± 0.09	0.01 ± 0.00	225 ± 26	78 ± 8	496 ± 114	45 ± 3	12 ± 1.4
	Post Mossdale Burnt	50.3 ± 0.3	1.46 ± 0.05	0.23 ± 0.02	0.53 ± 0.04	0.10 ± 0.01	0.31 ± 0.02	0.49 ± 0.02	0.00 ± 0.00	218 ± 34	45 ± 5	776 ± 239	45 ± 7	12 ± 1.0
	Post Mossdale Uncut	54.7 ± 3.7	1.28 ± 0.14	0.16 ± 0.02	0.65 ± 0.13	0.06 ± 0.01	0.23 ± 0.04	0.50 ± 0.08	0.01 ± 0.00	188 ± 33	47 ± 10	266 ± 90	42 ± 2	13 ± 0.6
	Post Mossdale Mown	50.9 ± 0.2	1.30 ± 0.20	0.15 ± 0.02	0.55 ± 0.07	0.07 ± 0.01	0.25 ± 0.03	0.52 ± 0.06	0.01 ± 0.00	197 ± 25	50 ± 8	448 ± 110	44 ± 5	13 ± 0.8
	Post Mossdale Mown -brash	50.8 ± 0.1	1.43 ± 0.16	0.16 ± 0.02	0.53 ± 0.10	0.07 ± 0.01	0.23 ± 0.04	0.50 ± 0.08	0.01 ± 0.00	199 ± 23	45 ± 6	489 ± 168	54 ± 5	14 ± 1.1
	Post Whitendale Burnt	50.6 ± 0.9	2.24 ± 0.28	0.15 ± 0.01	0.78 ± 0.05	0.08 ± 0.01	0.22 ± 0.01	0.45 ± 0.02	0.01 ± 0.00	205 ± 24	83 ± 14	843 ± 206	66 ± 6	15 ± 1.1
	Post Whitendale Uncut	48.9 ± 4.1	1.85 ± 0.33	0.14 ± 0.02	0.55 ± 0.08	0.07 ± 0.01	0.20 ± 0.02	0.41 ± 0.04	0.01 ± 0.00	143 ± 11	57 ± 5	510 ± 135	52 ± 3	11 ± 0.7
	Post Whitendale Mown	50.0 ± 0.3	1.51 ± 0.08	0.12 ± 0.02	0.56 ± 0.10	0.07 ± 0.01	0.24 ± 0.03	0.43 ± 0.05	0.01 ± 0.00	158 ± 19	56 ± 5	658 ± 117	53 ± 9	10 ± 0.8
	Post Whitendale Mown -brash	50.2 ± 0.3	2.08 ± 0.36	0.12 ± 0.02	0.52 ± 0.08	0.07 ± 0.00	0.22 ± 0.03	0.38 ± 0.04	0.01 ± 0.00	141 ± 15	54 ± 8	568 ± 156	42 ± 4	10 ± 1.1
2020	Post Nidderdale Burnt	50.3 ± 1.5	1.55 ± 0.10	0.13 ± 0.01	0.57 ± 0.05	0.09 ± 0.02	0.20 ± 0.02	0.35 ± 0.10	0.01 ± 0.00	269 ± 42	47 ± 10	328 ± 109	43 ± 6	15 ± 1.6
	Post Nidderdale Uncut	51.6 ± 0.3	1.64 ± 0.09	0.14 ± 0.01	0.69 ± 0.06	0.10 ± 0.02	0.29 ± 0.03	0.62 ± 0.09	0.00 ± 0.00	209 ± 14	68 ± 6	384 ± 122	46 ± 3	17 ± 1.5
	Post Nidderdale Mown	50.8 ± 0.6	2.14 ± 0.34	0.14 ± 0.01	0.65 ± 0.07	0.09 ± 0.01	0.26 ± 0.02	0.53 ± 0.05	0.01 ± 0.00	268 ± 50	73 ± 15	451 ± 84	60 ± 15	16 ± 1.7
	Post Nidderdale Mown -brash	51.6 ± 0.2	1.93 ± 0.18	0.14 ± 0.01	0.67 ± 0.01	0.10 ± 0.01	0.30 ± 0.02	0.62 ± 0.04	0.01 ± 0.00	339 ± 45	83 ± 5	517 ± 114	53 ± 4	18 ± 0.7
	Post Mossdale Burnt	47.5 ± 3.7	1.74 ± 0.24	0.17 ± 0.02	0.73 ± 0.09	0.12 ± 0.01	0.26 ± 0.02	0.42 ± 0.04	0.01 ± 0.00	197 ± 33	65 ± 9	440 ± 125	37 ± 7	16 ± 1.2
	Post Mossdale Uncut	51.3 ± 0.3	1.85 ± 0.28	0.12 ± 0.01	0.56 ± 0.08	0.08 ± 0.01	0.19 ± 0.03	0.40 ± 0.04	0.00 ± 0.00	121 ± 21	40 ± 5	252 ± 111	29 ± 3	12 ± 1.3
	Post Mossdale Mown	51.2 ± 0.2	1.68 ± 0.12	0.13 ± 0.01	0.53 ± 0.06	0.06 ± 0.01	0.21 ± 0.03	0.42 ± 0.06	0.00 ± 0.00	118 ± 15	40 ± 5	393 ± 93	35 ± 5	13 ± 1.4
	Post Mossdale Mown -brash	51.0 ± 0.2	1.59 ± 0.15	0.12 ± 0.02	0.51 ± 0.05	0.08 ± 0.01	0.22 ± 0.02	0.41 ± 0.05	0.00 ± 0.00	102 ± 22	39 ± 7	516 ± 220	32 ± 4	12 ± 0.8
	Post Whitendale Burnt	51.6 ± 0.7	2.10 ± 0.27	0.11 ± 0.02	0.72 ± 0.15	0.11 ± 0.02	0.26 ± 0.06	0.44 ± 0.08	0.01 ± 0.00	310 ± 86	75 ± 11	1003 ± 277	45 ± 9	17 ± 1.9
	Post Whitendale Uncut	53.6 ± 0.5	2.16 ± 0.32	0.07 ± 0.03	0.33 ± 0.17	0.06 ± 0.04	0.15 ± 0.08	0.21 ± 0.11	0.00 ± 0.00	165 ± 98	30 ± 20	141 ± 50	26 ± 15	14 ± 6.9
	Post Whitendale Mown	53.1 ± 0.6	2.08 ± 0.39	0.06 ± 0.02	0.36 ± 0.16	0.07 ± 0.03	0.18 ± 0.09	0.27 ± 0.13	0.00 ± 0.00	177 ± 97	47 ± 26	511 ± 352	28 ± 12	8 ± 2.7
	Post Whitendale Mown	53.2 ± 0.4	2.05 ± 0.19	0.06 ± 0.03	0.34 ± 0.18	0.05 ± 0.03	0.12 ± 0.06	0.20 ± 0.11	0.00 ± 0.00	166 ± 114	27 ± 15	239 ± 160	21 ± 9	7 ± 2.7
2021	Post Nidderdale Burnt	51.2 ± 0.4	1.22 ± 0.11	0.10 ± 0.01	0.39 ± 0.03	0.07 ± 0.00	0.21 ± 0.01	0.44 ± 0.02	0.01 ± 0.00	122 ± 8	39 ± 2	266 ± 31	28 ± 1	10 ± 0.1
	Post Nidderdale Uncut	50.9 ± 0.1	1.40 ± 0.05	0.11 ± 0.00	0.53 ± 0.04	0.06 ± 0.00	0.21 ± 0.02	0.46 ± 0.08	0.01 ± 0.00	120 ± 16	38 ± 8	408 ± 106	31 ± 2	10 ± 0.5
	Post Nidderdale Mown	50.5 ± 0.2	1.52 ± 0.16	0.12 ± 0.01	0.50 ± 0.04	0.08 ± 0.01	0.22 ± 0.01	0.45 ± 0.05	0.01 ± 0.00	138 ± 21	39 ± 6	442 ± 51	38 ± 4	11 ± 0.8
	Post Nidderdale Mown -brash	50.4 ± 0.2	1.37 ± 0.14	0.12 ± 0.02	0.50 ± 0.04	0.10 ± 0.01	0.24 ± 0.02	0.50 ± 0.02	0.01 ± 0.00	127 ± 15	38 ± 5	368 ± 91	37 ± 4	10 ± 0.5
	Post Mossdale Burnt	50.9 ± 0.3	1.23 ± 0.12	0.15 ± 0.01	0.52 ± 0.02	0.11 ± 0.02	0.24 ± 0.01	0.44 ± 0.03	0.01 ± 0.00	133 ± 16	42 ± 10	524 ± 122	32 ± 3	10 ± 0.9
	Post Mossdale Uncut	51.3 ± 0.2	1.75 ± 0.37	0.15 ± 0.02	0.58 ± 0.04	0.05 ± 0.00	0.21 ± 0.01	0.41 ± 0.01	0.01 ± 0.00	74 ± 1	21 ± 2	267 ± 93	28 ± 4	9 ± 0.1
	Post Mossdale Mown	50.8 ± 0.1	1.66 ± 0.27	0.15 ± 0.01	0.61 ± 0.03	0.09 ± 0.01	0.23 ± 0.01	0.47 ± 0.02	0.01 ± 0.00	102 ± 10	27 ± 4	542 ± 124	34 ± 2	10 ± 0.3
	Post Mossdale Mown -brash	50.3 ± 0.3	1.23 ± 0.17	0.13 ± 0.01	0.59 ± 0.04	0.08 ± 0.00	0.21 ± 0.01	0.48 ± 0.02	0.01 ± 0.00	91 ± 6	31 ± 2	480 ± 227	30 ± 2	10 ± 0.5
	Post Whitendale Burnt	51.1 ± 0.4	1.83 ± 0.22	0.15 ± 0.00	0.66 ± 0.05	0.06 ± 0.01	0.21 ± 0.01	0.43 ± 0.02	0.00 ± 0.00	151 ± 19	26 ± 4	382 ± 53	36 ± 2	10 ± 0.6
	Post Whitendale Uncut	53.3 ± 1.4	2.47 ± 0.70	0.13 ± 0.01	0.57 ± 0.05	0.05 ± 0.00	0.21 ± 0.02	0.42 ± 0.01	0.00 ± 0.00	166 ± 50	28 ± 3	389 ± 89	54 ± 12	10 ± 0.5
	Post Whitendale Mown	49.8 ± 2.3	2.09 ± 0.40	0.11 ± 0.01	0.47 ± 0.04	0.06 ± 0.01	0.21 ± 0.02	0.42 ± 0.02	0.00 ± 0.00	154 ± 23	31 ± 3	404 ± 135	35 ± 3	9 ± 1.0
	Post Whitendale Mown	48.4 ± 7.9	1.40 ± 0.31	0.11 ± 0.01	0.49 ± 0.05	0.07 ± 0.01	0.23 ± 0.01	0.45 ± 0.04	0.00 ± 0.00	180 ± 24	33 ± 3	402 ± 70	34 ± 3	10 ± 0.7

Table A4.5 Means ±STDEV for sedge (*E. angustifolium*) shoot samples (including very high values) from the 5x5 m plots at the three sites and their main managements during post-management (sampled in late summer during 2019-2021; no pre-management samples were assessed) period (macronutrients as percentages and micronutrients in weight per weight). For comparison relevant literature values from Allen (1989) are also shown (however, different sampling times, locations and site conditions likely explain differences).

	E. angustifolium	**%**						**µg g-1**				
		P	**K**	**Na**	**Mg**	**Ca**	**Si**	**Fe**	**Al**	**Mn**	**Zn**	**Cu**
	Allen, S. E., Ed. (1989)	**0.11**	**1.20**	**0.08**	**0.11**	**0.14**	**0.10**	**60**		**400**	**80**	**3**
2019	Post Nidderdale Burnt	0.14 ± 0.02	0.48 ± 0.05	0.05 ± 0.01	0.09 ± 0.01	0.14 ± 0.02	0.01 ± 0.00	352 ± 79	56 ± 12	99 ± 28	87 ± 15	16 ± 3
	Post Nidderdale Uncut	0.18 ± 0.01	0.74 ± 0.13	0.06 ± 0.02	0.20 ± 0.06	0.23 ± 0.06	0.01 ± 0.00	375 ± 84	65 ± 16	100 ± 52	143 ± 24	15 ± 5
	Post Nidderdale Mown	0.18 ± 0.02	0.68 ± 0.13	0.09 ± 0.01	0.14 ± 0.02	0.23 ± 0.04	0.01 ± 0.00	369 ± 79	48 ± 15	110 ± 33	142 ± 22	12 ± 2
	Post Nidderdale Mown -brash	0.19 ± 0.02	0.56 ± 0.09	0.10 ± 0.02	0.16 ± 0.02	0.17 ± 0.04	0.01 ± 0.00	339 ± 86	36 ± 9	74 ± 16	104 ± 4	11 ± 2
	Post Mossdale Burnt	0.20 ± 0.02	0.49 ± 0.05	0.08 ± 0.03	0.19 ± 0.04	0.25 ± 0.03	0.01 ± 0.00	712 ± 21	25 ± 4	117 ± 33	163 ± 24	15 ± 3
	Post Mossdale Uncut	0.22 ± 0.01	0.81 ± 0.15	0.07 ± 0.01	0.19 ± 0.03	0.23 ± 0.05	0.02 ± 0.00	566 ± 91	25 ± 4	34 ± 5	132 ± 33	34 ± 11
	Post Mossdale Mown	0.18 ± 0.02	0.68 ± 0.13	0.09 ± 0.01	0.14 ± 0.02	0.23 ± 0.04	0.01 ± 0.00	369 ± 79	48 ± 15	110 ± 33	142 ± 22	12 ± 2
	Post Mossdale Mown -brash	0.19 ± 0.02	0.56 ± 0.09	0.10 ± 0.02	0.16 ± 0.02	0.17 ± 0.04	0.01 ± 0.00	339 ± 86	36 ± 9	74 ± 16	104 ± 4	11 ± 2
	Post Whitendale Burnt	0.14 ± 0.02	0.86 ± 0.04	0.04 ± 0.01	0.13 ± 0.02	0.27 ± 0.04	0.01 ± 0.00	275 ± 30	15 ± 1	205 ± 27	165 ± 21	16 ± 2
	Post Whitendale Uncut	0.17 ± 0.02	0.59 ± 0.04	0.05 ± 0.01	0.12 ± 0.01	0.18 ± 0.02	0.01 ± 0.00	162 ± 21	14 ± 1	68 ± 6	123 ± 13	8 ± 0
	Post Whitendale Mown	0.18 ± 0.03	0.78 ± 0.16	0.05 ± 0.01	0.11 ± 0.01	0.19 ± 0.03	0.01 ± 0.00	298 ± 82	20 ± 3	180 ± 96	148 ± 16	11 ± 2
	Post Whitendale Mown -brash	0.16 ± 0.03	0.60 ± 0.06	0.05 ± 0.01	0.12 ± 0.02	0.19 ± 0.02	0.01 ± 0.00	280 ± 67	22 ± 4	153 ± 32	137 ± 15	11 ± 2
2020	Post Nidderdale Burnt	0.10 ± 0.01	0.52 ± 0.03	0.05 ± 0.01	0.09 ± 0.01	0.17 ± 0.04	0.00 ± 0.00	200 ± 55	15 ± 4	74 ± 24	98 ± 13	6 ± 1
	Post Nidderdale Uncut	0.10 ± 0.02	0.63 ± 0.14	0.04 ± 0.02	0.10 ± 0.02	0.19 ± 0.04	0.00 ± 0.00	307 ± 19	12 ± 1	76 ± 33	132 ± 39	6 ± 1
	Post Nidderdale Mown	0.15 ± 0.04	0.76 ± 0.16	0.06 ± 0.02	0.17 ± 0.04	0.23 ± 0.03	0.00 ± 0.00	296 ± 135	24 ± 7	130 ± 60	131 ± 37	11 ± 3
	Post Nidderdale Mown -brash	0.16 ± 0.04	0.78 ± 0.11	0.08 ± 0.02	0.16 ± 0.04	0.23 ± 0.02	0.00 ± 0.00	418 ± 155	19 ± 4	107 ± 34	151 ± 28	9 ± 2
	Post Mossdale Burnt	0.07 ± 0.01	0.24 ± 0.06	0.04 ± 0.01	0.07 ± 0.02	0.11 ± 0.03	0.01 ± 0.00	221 ± 129	11 ± 4	36 ± 15	107 ± 38	9 ± 3
	Post Mossdale Uncut	0.16 ± 0.01	0.92 ± 0.32	0.04 ± 0.02	0.11 ± 0.02	0.12 ± 0.03	0.01 ± 0.00	106 ± 19	8 ± 2	32 ± 6	83 ± 22	15 ± 5
	Post Mossdale Mown	0.09 ± 0.01	0.45 ± 0.12	0.11 ± 0.08	0.07 ± 0.01	0.14 ± 0.03	0.02 ± 0.01	297 ± 98	35 ± 15	23 ± 6	120 ± 51	82 ± 68
	Post Mossdale Mown -brash	0.13 ± 0.03	0.56 ± 0.08	0.05 ± 0.01	0.09 ± 0.02	0.20 ± 0.04	0.01 ± 0.00	195 ± 71	11 ± 3	32 ± 8	107 ± 30	9 ± 2
	Post Whitendale Burnt	0.12 ± 0.03	0.89 ± 0.17	0.05 ± 0.01	0.17 ± 0.02	0.28 ± 0.03	0.00 ± 0.00	388 ± 60	23 ± 3	206 ± 29	205 ± 36	10 ± 1
	Post Whitendale Uncut	0.17 ± 0.04	0.93 ± 0.26	0.07 ± 0.02	0.17 ± 0.05	0.25 ± 0.09	0.01 ± 0.00	439 ± 97	39 ± 9	128 ± 46	171 ± 37	13 ± 2
	Post Whitendale Mown	0.13 ± 0.03	0.80 ± 0.13	0.07 ± 0.01	0.12 ± 0.02	0.20 ± 0.03	0.01 ± 0.00	383 ± 106	35 ± 10	78 ± 9	138 ± 16	12 ± 2
	Post Whitendale Mown -brash	0.13 ± 0.03	0.78 ± 0.06	0.06 ± 0.02	0.13 ± 0.03	0.24 ± 0.05	0.02 ± 0.01	413 ± 153	94 ± 57	141 ± 64	148 ± 33	17 ± 5
2021	Post Nidderdale Burnt	0.11 ± 0.01	0.66 ± 0.12	0.05 ± 0.02	0.12 ± 0.01	0.20 ± 0.01	0.01 ± 0.00	291 ± 48	17 ± 1	69 ± 18	118 ± 10	7 ± 1
	Post Nidderdale Uncut	0.17 ± 0.03	0.78 ± 0.13	0.10 ± 0.03	0.16 ± 0.03	0.25 ± 0.03	0.01 ± 0.00	274 ± 69	10 ± 1	81 ± 23	164 ± 16	7 ± 1
	Post Nidderdale Mown	0.15 ± 0.02	0.71 ± 0.06	0.07 ± 0.02	0.14 ± 0.02	0.21 ± 0.03	0.01 ± 0.00	282 ± 72	12 ± 2	78 ± 22	122 ± 15	7 ± 1
	Post Nidderdale Mown -brash	0.13 ± 0.01	0.62 ± 0.10	0.07 ± 0.02	0.14 ± 0.02	0.22 ± 0.03	0.01 ± 0.00	223 ± 47	14 ± 2	71 ± 17	124 ± 15	6 ± 1
	Post Mossdale Burnt	0.14 ± 0.01	0.49 ± 0.09	0.07 ± 0.02	0.17 ± 0.02	0.22 ± 0.02	0.01 ± 0.00	195 ± 29	13 ± 1	60 ± 14	121 ± 13	7 ± 1
	Post Mossdale Uncut	0.21 ± 0.05	0.78 ± 0.05	0.06 ± 0.03	0.13 ± 0.02	0.16 ± 0.03	0.01 ± 0.00	185 ± 18	9 ± 1	17 ± 3	85 ± 4	7 ± 1
	Post Mossdale Mown	0.13 ± 0.01	0.59 ± 0.07	0.04 ± 0.01	0.11 ± 0.01	0.21 ± 0.01	0.01 ± 0.00	202 ± 30	12 ± 0	26 ± 6	98 ± 8	6 ± 1
	Post Mossdale Mown -brash	0.14 ± 0.02	0.64 ± 0.06	0.04 ± 0.01	0.14 ± 0.03	0.22 ± 0.03	0.01 ± 0.00	250 ± 60	13 ± 1	49 ± 15	114 ± 15	7 ± 1
	Post Whitendale Burnt	0.11 ± 0.02	0.96 ± 0.15	0.03 ± 0.00	0.14 ± 0.01	0.21 ± 0.02	0.01 ± 0.00	194 ± 55	14 ± 1	144 ± 40	151 ± 21	16 ± 4
	Post Whitendale Uncut	0.12 ± 0.01	0.71 ± 0.12	0.04 ± 0.01	0.12 ± 0.02	0.22 ± 0.02	0.01 ± 0.00	154 ± 16	16 ± 2	66 ± 14	133 ± 34	8 ± 1
	Post Whitendale Mown	0.11 ± 0.02	0.80 ± 0.13	0.03 ± 0.01	0.13 ± 0.02	0.24 ± 0.03	0.01 ± 0.00	221 ± 34	17 ± 2	105 ± 43	148 ± 16	11 ± 2
	Post Whitendale Mown -brash	0.12 ± 0.01	0.85 ± 0.06	0.03 ± 0.01	0.14 ± 0.01	0.25 ± 0.02	0.01 ± 0.00	217 ± 34	15 ± 1	154 ± 17	145 ± 13	11 ± 2

Table A4.6 Means ±STDEV for sedge (*E. vaginatum*) shoot samples (including very high values) from the 5x5 m plots at the three sites and their main managements during post-management (sampled in late summer during 2019-2021; no pre-management samples were assessed) period (macronutrients as percentages and micronutrients in weight per weight). For comparison relevant literature values from Allen (1989) are also shown (however, different sampling times, locations and site conditions likely explain differences).

	E. vaginatum	**%**						**µg g-1**				
		P	**K**	**Na**	**Mg**	**Ca**	**Si**	**Fe**	**Al**	**Mn**	**Zn**	**Cu**
	Allen, S. E., Ed. (1989)	**0.15**	**0.90**	**0.03**	**0.12**	**0.13**	**0.10**	**60**	**60**	**180**	**95**	**12**
2019	Post Nidderdale Burnt	0.15 ± 0.03	0.59 ± 0.03	0.05 ± 0.01	0.13 ± 0.02	0.11 ± 0.01	0.02 ± 0.01	388 ± 57	114 ± 21	101 ± 39	109 ± 6	46 ± 13
	Post Nidderdale Uncut	0.18 ± 0.02	0.59 ± 0.06	0.02 ± 0.00	0.17 ± 0.03	0.16 ± 0.02	0.01 ± 0.00	549 ± 194	70 ± 32	40 ± 12	139 ± 19	14 ± 2
	Post Nidderdale Mown	0.18 ± 0.03	0.70 ± 0.05	0.03 ± 0.01	0.16 ± 0.02	0.18 ± 0.02	0.01 ± 0.01	377 ± 142	89 ± 59	71 ± 11	162 ± 52	29 ± 9
	Post Nidderdale Mown -brash	0.21 ± 0.02	0.66 ± 0.06	0.02 ± 0.00	0.19 ± 0.01	0.16 ± 0.02	0.01 ± 0.00	409 ± 156	47 ± 16	60 ± 11	143 ± 26	21 ± 4
	Post Mossdale Burnt	0.18 ± 0.02	0.71 ± 0.03	0.03 ± 0.00	0.19 ± 0.02	0.19 ± 0.01	0.01 ± 0.00	554 ± 107	20 ± 4	205 ± 66	205 ± 74	17 ± 3
	Post Mossdale Uncut	0.24 ± 0.02	0.71 ± 0.11	0.09 ± 0.04	0.15 ± 0.01	0.16 ± 0.04	0.04 ± 0.02	579 ± 194	157 ± 121	35 ± 11	266 ± 103	100 ± 51
	Post Mossdale Mown	0.18 ± 0.03	0.63 ± 0.10	0.04 ± 0.01	0.16 ± 0.02	0.19 ± 0.02	0.02 ± 0.00	835 ± 192	62 ± 31	66 ± 12	339 ± 88	34 ± 6
	Post Mossdale Mown -brash	0.19 ± 0.02	0.58 ± 0.11	0.06 ± 0.01	0.13 ± 0.01	0.15 ± 0.03	0.03 ± 0.01	925 ± 248	49 ± 14	52 ± 8	154 ± 33	52 ± 14
	Post Whitendale Burnt	0.12 ± 0.01	0.70 ± 0.13	0.03 ± 0.01	0.17 ± 0.02	0.18 ± 0.04	0.01 ± 0.00	279 ± 75	23 ± 7	126 ± 68	87 ± 21	20 ± 3
	Post Whitendale Uncut	0.13 ± 0.02	0.82 ± 0.08	0.02 ± 0.00	0.13 ± 0.02	0.12 ± 0.02	0.01 ± 0.00	196 ± 26	10 ± 0	65 ± 18	80 ± 14	14 ± 2
	Post Whitendale Mown	0.20 ± 0.03	0.83 ± 0.04	0.03 ± 0.01	0.18 ± 0.01	0.15 ± 0.02	0.01 ± 0.00	457 ± 81	32 ± 6	175 ± 63	132 ± 13	26 ± 5
	Post Whitendale Mown -brash	0.18 ± 0.05	0.74 ± 0.12	0.03 ± 0.01	0.14 ± 0.03	0.14 ± 0.03	0.01 ± 0.00	267 ± 63	18 ± 3	143 ± 43	97 ± 19	20 ± 5
2020	Post Nidderdale Burnt	0.12 ± 0.01	0.70 ± 0.13	0.03 ± 0.01	0.17 ± 0.02	0.18 ± 0.04	0.01 ± 0.00	279 ± 75	23 ± 7	126 ± 68	87 ± 21	20 ± 3
	Post Nidderdale Uncut	0.13 ± 0.02	0.82 ± 0.08	0.02 ± 0.00	0.13 ± 0.02	0.12 ± 0.02	0.01 ± 0.00	196 ± 26	10 ± 0	65 ± 18	80 ± 14	14 ± 2
	Post Nidderdale Mown	0.13 ± 0.03	0.86 ± 0.21	0.02 ± 0.01	0.14 ± 0.03	0.12 ± 0.02	0.01 ± 0.00	162 ± 31	13 ± 4	71 ± 27	91 ± 14	14 ± 2
	Post Nidderdale Mown -brash	0.11 ± 0.01	0.69 ± 0.10	0.02 ± 0.00	0.13 ± 0.02	0.10 ± 0.02	0.01 ± 0.00	176 ± 87	11 ± 4	39 ± 10	80 ± 12	19 ± 2
	Post Mossdale Burnt	0.21 ± 0.02	0.98 ± 0.11	0.03 ± 0.01	0.26 ± 0.03	0.18 ± 0.02	0.01 ± 0.00	156 ± 15	14 ± 3	147 ± 41	144 ± 21	19 ± 2
	Post Mossdale Uncut	0.19 ± 0.02	1.12 ± 0.15	0.03 ± 0.01	0.18 ± 0.01	0.15 ± 0.02	0.01 ± 0.00	294 ± 69	13 ± 2	35 ± 13	98 ± 6	18 ± 3
	Post Mossdale Mown	0.15 ± 0.02	0.84 ± 0.13	0.02 ± 0.00	0.17 ± 0.04	0.15 ± 0.03	0.00 ± 0.00	122 ± 9	7 ± 1	35 ± 8	89 ± 11	15 ± 1
	Post Mossdale Mown -brash	0.16 ± 0.01	1.01 ± 0.11	0.02 ± 0.00	0.17 ± 0.00	0.17 ± 0.02	0.01 ± 0.00	201 ± 69	22 ± 13	42 ± 16	92 ± 5	14 ± 1
	Post Whitendale Burnt	0.14 ± 0.01	1.11 ± 0.07	0.05 ± 0.01	0.17 ± 0.02	0.18 ± 0.01	0.01 ± 0.00	305 ± 99	23 ± 9	91 ± 5	134 ± 24	23 ± 2
	Post Whitendale Uncut	0.12 ± 0.03	0.82 ± 0.23	0.02 ± 0.01	0.14 ± 0.04	0.16 ± 0.07	0.01 ± 0.00	305 ± 103	22 ± 6	95 ± 47	100 ± 29	42 ± 20
	Post Whitendale Mown	0.12 ± 0.02	0.91 ± 0.16	0.03 ± 0.00	0.15 ± 0.02	0.14 ± 0.02	0.01 ± 0.00	272 ± 93	15 ± 3	101 ± 42	102 ± 26	24 ± 4
	Post Whitendale Mown -brash	0.11 ± 0.03	0.84 ± 0.27	0.03 ± 0.01	0.14 ± 0.04	0.13 ± 0.04	0.01 ± 0.00	351 ± 125	28 ± 10	163 ± 78	99 ± 30	26 ± 4
2021	Post Nidderdale Burnt	0.13 ± 0.01	0.86 ± 0.02	0.03 ± 0.00	0.17 ± 0.02	0.21 ± 0.01	0.01 ± 0.00	269 ± 39	12 ± 1	51 ± 8	122 ± 12	18 ± 2
	Post Nidderdale Uncut	0.15 ± 0.01	0.86 ± 0.07	0.02 ± 0.00	0.18 ± 0.01	0.19 ± 0.01	0.01 ± 0.00	197 ± 70	10 ± 1	65 ± 23	114 ± 7	10 ± 1
	Post Nidderdale Mown	0.14 ± 0.02	0.77 ± 0.07	0.03 ± 0.01	0.18 ± 0.01	0.23 ± 0.02	0.01 ± 0.00	219 ± 49	16 ± 4	88 ± 24	117 ± 22	10 ± 1
	Post Nidderdale Mown -brash	0.16 ± 0.01	0.86 ± 0.09	0.02 ± 0.00	0.23 ± 0.03	0.25 ± 0.02	0.01 ± 0.00	330 ± 83	21 ± 7	59 ± 16	128 ± 11	14 ± 1
	Post Mossdale Burnt	0.16 ± 0.01	0.70 ± 0.03	0.03 ± 0.00	0.20 ± 0.02	0.26 ± 0.01	0.01 ± 0.00	154 ± 7	11 ± 1	152 ± 42	151 ± 1	11 ± 1
	Post Mossdale Uncut	0.18 ± 0.03	0.75 ± 0.09	0.01 ± 0.00	0.21 ± 0.02	0.21 ± 0.01	0.01 ± 0.00	199 ± 48	10 ± 1	27 ± 8	108 ± 15	14 ± 2
	Post Mossdale Mown	0.18 ± 0.03	0.79 ± 0.05	0.01 ± 0.00	0.16 ± 0.03	0.25 ± 0.02	0.01 ± 0.00	184 ± 51	12 ± 2	42 ± 20	100 ± 13	16 ± 2
	Post Mossdale Mown -brash	0.17 ± 0.03	0.85 ± 0.08	0.01 ± 0.00	0.19 ± 0.04	0.26 ± 0.04	0.01 ± 0.00	220 ± 56	11 ± 2	56 ± 17	112 ± 28	15 ± 2
	Post Whitendale Burnt	0.10 ± 0.01	0.81 ± 0.01	0.01 ± 0.00	0.11 ± 0.01	0.20 ± 0.03	0.01 ± 0.00	273 ± 94	17 ± 5	116 ± 26	126 ± 13	25 ± 2
	Post Whitendale Uncut	0.13 ± 0.01	0.61 ± 0.08	0.01 ± 0.00	0.17 ± 0.04	0.16 ± 0.01	0.01 ± 0.00	173 ± 55	12 ± 1	147 ± 68	126 ± 34	20 ± 2
	Post Whitendale Mown	0.11 ± 0.00	0.67 ± 0.05	0.01 ± 0.00	0.12 ± 0.01	0.17 ± 0.02	0.01 ± 0.00	168 ± 31	10 ± 1	79 ± 20	100 ± 18	20 ± 1
	Post Whitendale Mown -brash	0.11 ± 0.01	0.64 ± 0.03	0.02 ± 0.00	0.13 ± 0.01	0.15 ± 0.01	0.01 ± 0.00	174 ± 40	10 ± 1	82 ± 32	97 ± 7	21 ± 1

Table A4.7 Means ±STDEV for sedge (*E. angustifolium*) shoot samples (excluding very high values) from the 5x5 m plots at the three sites and their main managements during post-management (sampled in late summer during 2019-2021; no pre-management samples were assessed) period (macronutrients as percentages and micronutrients in weight per weight). For comparison relevant literature values from Allen (1989) are also shown (however, different sampling times, locations and site conditions likely explain differences).

	E. angustifolium	**%**						**µg g-1**				
		P	**K**	**Na**	**Mg**	**Ca**	**Si**	**Fe**	**Al**	**Mn**	**Zn**	**Cu**
	Allen, S. E., Ed. (1989)	**0.11**	**1.20**	**0.08**	**0.11**	**0.14**	**0.10**	**60**		**400**	**80**	**3**
2019	Post Nidderdale Burnt	0.14 ± 0.02	0.48 ± 0.05	0.05 ± 0.01	0.09 ± 0.01	0.14 ± 0.02	0.01 ± 0.00	352 ± 79	56 ± 12	99 ± 28	87 ± 15	16 ± 3
	Post Nidderdale Uncut	0.18 ± 0.01	0.74 ± 0.13	0.06 ± 0.02	0.20 ± 0.06	0.23 ± 0.06	0.01 ± 0.00	375 ± 84	65 ± 16	100 ± 52	143 ± 24	15 ± 5
	Post Nidderdale Mown	0.18 ± 0.02	0.68 ± 0.13	0.09 ± 0.01	0.14 ± 0.02	0.23 ± 0.04	0.01 ± 0.00	369 ± 79	48 ± 15	110 ± 33	142 ± 22	12 ± 2
	Post Nidderdale Mown -brash	0.19 ± 0.02	0.56 ± 0.09	0.10 ± 0.02	0.16 ± 0.02	0.17 ± 0.04	0.01 ± 0.00	339 ± 86	36 ± 9	74 ± 16	104 ± 4	11 ± 2
	Post Mossdale Burnt	0.20 ± 0.02	0.49 ± 0.05	0.08 ± 0.03	0.19 ± 0.04	0.25 ± 0.03	0.01 ± 0.00	712 ± 21	25 ± 4	117 ± 33	163 ± 24	15 ± 3
	Post Mossdale Uncut	0.22 ± 0.01	0.81 ± 0.15	0.07 ± 0.01	0.19 ± 0.03	0.23 ± 0.05	0.02 ± 0.00	566 ± 91	25 ± 4	34 ± 5	132 ± 33	34 ± 11
	Post Mossdale Mown	0.18 ± 0.02	0.68 ± 0.13	0.09 ± 0.01	0.14 ± 0.02	0.23 ± 0.04	0.01 ± 0.00	369 ± 79	48 ± 15	110 ± 33	142 ± 22	12 ± 2
	Post Mossdale Mown -brash	0.19 ± 0.02	0.56 ± 0.09	0.10 ± 0.02	0.16 ± 0.02	0.17 ± 0.04	0.01 ± 0.00	339 ± 86	36 ± 9	74 ± 16	104 ± 4	11 ± 2
	Post Whitendale Burnt	0.14 ± 0.02	0.86 ± 0.04	0.04 ± 0.01	0.13 ± 0.02	0.27 ± 0.04	0.01 ± 0.00	275 ± 30	15 ± 1	205 ± 27	165 ± 21	16 ± 2
	Post Whitendale Uncut	0.17 ± 0.02	0.59 ± 0.04	0.05 ± 0.01	0.12 ± 0.01	0.18 ± 0.02	0.01 ± 0.00	162 ± 21	14 ± 1	68 ± 6	123 ± 13	8 ± 0
	Post Whitendale Mown	0.18 ± 0.03	0.78 ± 0.16	0.05 ± 0.01	0.11 ± 0.01	0.19 ± 0.03	0.01 ± 0.00	298 ± 82	20 ± 3	180 ± 96	148 ± 16	11 ± 2
	Post Whitendale Mown -brash	0.16 ± 0.03	0.60 ± 0.06	0.05 ± 0.01	0.12 ± 0.02	0.19 ± 0.02	0.01 ± 0.00	280 ± 67	22 ± 4	153 ± 32	137 ± 15	11 ± 2
2020	Post Nidderdale Burnt	0.10 ± 0.01	0.52 ± 0.03	0.05 ± 0.01	0.09 ± 0.01	0.17 ± 0.04	0.00 ± 0.00	200 ± 55	15 ± 4	74 ± 24	98 ± 13	6 ± 1
	Post Nidderdale Uncut	0.10 ± 0.02	0.63 ± 0.14	0.04 ± 0.02	0.10 ± 0.02	0.19 ± 0.04	0.00 ± 0.00	307 ± 19	12 ± 1	76 ± 33	132 ± 39	6 ± 1
	Post Nidderdale Mown	0.15 ± 0.04	0.76 ± 0.16	0.06 ± 0.02	0.17 ± 0.04	0.23 ± 0.03	0.00 ± 0.00	296 ± 135	24 ± 7	130 ± 60	131 ± 37	11 ± 3
	Post Nidderdale Mown -brash	0.16 ± 0.04	0.78 ± 0.11	0.08 ± 0.02	0.16 ± 0.04	0.23 ± 0.02	0.00 ± 0.00	418 ± 155	19 ± 4	107 ± 34	151 ± 28	9 ± 2
	Post Mossdale Burnt	0.07 ± 0.01	0.24 ± 0.06	0.04 ± 0.01	0.07 ± 0.02	0.11 ± 0.03	0.01 ± 0.00	221 ± 129	11 ± 4	36 ± 15	107 ± 38	9 ± 3
	Post Mossdale Uncut	0.16 ± 0.01	0.92 ± 0.32	0.04 ± 0.02	0.11 ± 0.02	0.12 ± 0.03	0.01 ± 0.00	106 ± 19	8 ± 2	32 ± 6	83 ± 22	15 ± 5
	Post Mossdale Mown	0.09 ± 0.01	0.45 ± 0.12	0.11 ± 0.08	0.07 ± 0.01	0.14 ± 0.03	0.02 ± 0.01	297 ± 98	35 ± 15	23 ± 6	120 ± 51	15 ± 5
	Post Mossdale Mown -brash	0.13 ± 0.03	0.56 ± 0.08	0.05 ± 0.01	0.09 ± 0.02	0.20 ± 0.04	0.01 ± 0.00	195 ± 71	11 ± 3	32 ± 8	107 ± 30	9 ± 2
	Post Whitendale Burnt	0.12 ± 0.03	0.89 ± 0.17	0.05 ± 0.01	0.17 ± 0.02	0.28 ± 0.03	0.00 ± 0.00	388 ± 60	23 ± 3	206 ± 29	205 ± 36	10 ± 1
	Post Whitendale Uncut	0.17 ± 0.04	0.93 ± 0.26	0.07 ± 0.02	0.17 ± 0.05	0.25 ± 0.09	0.01 ± 0.00	439 ± 97	39 ± 9	128 ± 46	171 ± 37	13 ± 2
	Post Whitendale Mown	0.13 ± 0.03	0.80 ± 0.13	0.07 ± 0.01	0.12 ± 0.02	0.20 ± 0.03	0.01 ± 0.00	383 ± 106	35 ± 10	78 ± 9	138 ± 16	12 ± 2
	Post Whitendale Mown -brash	0.13 ± 0.03	0.78 ± 0.06	0.06 ± 0.02	0.13 ± 0.03	0.24 ± 0.05	0.02 ± 0.01	413 ± 153	43 ± 16	141 ± 64	148 ± 33	17 ± 5
2021	Post Nidderdale Burnt	0.11 ± 0.01	0.66 ± 0.12	0.05 ± 0.02	0.12 ± 0.01	0.20 ± 0.01	0.01 ± 0.00	291 ± 48	17 ± 1	69 ± 18	118 ± 10	7 ± 1
	Post Nidderdale Uncut	0.17 ± 0.03	0.78 ± 0.13	0.10 ± 0.03	0.16 ± 0.03	0.25 ± 0.03	0.01 ± 0.00	274 ± 69	10 ± 1	81 ± 23	164 ± 16	7 ± 1
	Post Nidderdale Mown	0.15 ± 0.02	0.71 ± 0.06	0.07 ± 0.02	0.14 ± 0.02	0.21 ± 0.03	0.01 ± 0.00	282 ± 72	12 ± 2	78 ± 22	122 ± 15	7 ± 1
	Post Nidderdale Mown -brash	0.13 ± 0.01	0.62 ± 0.10	0.07 ± 0.02	0.14 ± 0.02	0.22 ± 0.03	0.01 ± 0.00	223 ± 47	14 ± 2	71 ± 17	124 ± 15	6 ± 1
	Post Mossdale Burnt	0.14 ± 0.01	0.49 ± 0.09	0.07 ± 0.02	0.17 ± 0.02	0.22 ± 0.02	0.01 ± 0.00	195 ± 29	13 ± 1	60 ± 14	121 ± 13	7 ± 1
	Post Mossdale Uncut	0.21 ± 0.05	0.78 ± 0.05	0.06 ± 0.03	0.13 ± 0.02	0.16 ± 0.03	0.01 ± 0.00	185 ± 18	9 ± 1	17 ± 3	85 ± 4	7 ± 1
	Post Mossdale Mown	0.13 ± 0.01	0.59 ± 0.07	0.04 ± 0.01	0.11 ± 0.01	0.21 ± 0.01	0.01 ± 0.00	202 ± 30	12 ± 0	26 ± 6	98 ± 8	6 ± 1
	Post Mossdale Mown -brash	0.14 ± 0.02	0.64 ± 0.06	0.04 ± 0.01	0.14 ± 0.03	0.22 ± 0.03	0.01 ± 0.00	250 ± 60	13 ± 1	49 ± 15	114 ± 15	7 ± 1
	Post Whitendale Burnt	0.11 ± 0.02	0.96 ± 0.15	0.03 ± 0.00	0.14 ± 0.01	0.21 ± 0.02	0.01 ± 0.00	194 ± 55	14 ± 1	144 ± 40	151 ± 21	16 ± 4
	Post Whitendale Uncut	0.12 ± 0.01	0.71 ± 0.12	0.04 ± 0.01	0.12 ± 0.02	0.22 ± 0.02	0.01 ± 0.00	154 ± 16	16 ± 2	66 ± 14	133 ± 34	8 ± 1
	Post Whitendale Mown	0.11 ± 0.02	0.80 ± 0.13	0.03 ± 0.01	0.13 ± 0.02	0.24 ± 0.03	0.01 ± 0.00	221 ± 34	17 ± 2	105 ± 43	148 ± 16	11 ± 2
	Post Whitendale Mown -brash	0.12 ± 0.01	0.85 ± 0.06	0.03 ± 0.01	0.14 ± 0.01	0.25 ± 0.02	0.01 ± 0.00	217 ± 34	15 ± 1	154 ± 17	145 ± 13	11 ± 2

Table A4.8 Means ±STDEV for sedge (*E. vaginatum*) shoot samples (exluding very high values) from the 5x5 m plots at the three sites and their main managements during post-management (sampled in late summer during 2019-2021; no pre-management samples were assessed) period (macronutrients as percentages and micronutrients in weight per weight). For comparison relevant literature values from Allen (1989) are also shown (however, different sampling times, locations and site conditions likely explain differences).

	E. vaginatum	%						µg g-1				
		P	K	Na	Mg	Ca	Si	Fe	Al	Mn	Zn	Cu
	Allen, S. E., Ed. (1989)	**0.15**	**0.90**	**0.03**	**0.12**	**0.13**	**0.10**	**60**	**60**	**180**	**95**	**12**
2019	Post Nidderdale Burnt	0.15 ± 0.03	0.59 ± 0.03	0.05 ± 0.01	0.13 ± 0.02	0.11 ± 0.01	0.02 ± 0.01	388 ± 57	84 ± 7	101 ± 39	109 ± 6	46 ± 13
	Post Nidderdale Uncut	0.18 ± 0.02	0.59 ± 0.06	0.02 ± 0.00	0.17 ± 0.03	0.16 ± 0.02	0.01 ± 0.00	549 ± 194	44 ± 26	40 ± 12	139 ± 19	14 ± 2
	Post Nidderdale Mown	0.18 ± 0.03	0.70 ± 0.05	0.03 ± 0.01	0.16 ± 0.02	0.18 ± 0.02	0.01 ± 0.01	377 ± 142	33 ± 16	71 ± 11	162 ± 52	29 ± 9
	Post Nidderdale Mown -brash	0.21 ± 0.02	0.66 ± 0.06	0.02 ± 0.00	0.19 ± 0.01	0.16 ± 0.02	0.01 ± 0.00	409 ± 156	47 ± 16	60 ± 11	143 ± 26	21 ± 4
	Post Mossdale Burnt	0.18 ± 0.02	0.71 ± 0.03	0.03 ± 0.00	0.19 ± 0.02	0.19 ± 0.01	0.01 ± 0.00	554 ± 107	20 ± 4	205 ± 66	135 ± 32	17 ± 3
	Post Mossdale Uncut	0.24 ± 0.02	0.71 ± 0.11	0.09 ± 0.04	0.15 ± 0.01	0.16 ± 0.04	0.04 ± 0.02	579 ± 194	36 ± 15	35 ± 11	92 ± 8	100 ± 51
	Post Mossdale Mown	0.18 ± 0.03	0.63 ± 0.10	0.04 ± 0.01	0.16 ± 0.02	0.19 ± 0.02	0.02 ± 0.00	835 ± 192	34 ± 7	66 ± 12	192 ± 12	34 ± 6
	Post Mossdale Mown -brash	0.19 ± 0.02	0.58 ± 0.11	0.06 ± 0.01	0.13 ± 0.01	0.15 ± 0.03	0.03 ± 0.01	925 ± 248	49 ± 14	52 ± 8	154 ± 33	52 ± 14
	Post Whitendale Burnt	0.12 ± 0.01	0.70 ± 0.13	0.03 ± 0.01	0.17 ± 0.02	0.18 ± 0.04	0.01 ± 0.00	279 ± 75	23 ± 7	126 ± 68	87 ± 21	20 ± 3
	Post Whitendale Uncut	0.13 ± 0.02	0.82 ± 0.08	0.02 ± 0.00	0.13 ± 0.02	0.12 ± 0.02	0.01 ± 0.00	196 ± 26	10 ± 0	65 ± 18	80 ± 14	14 ± 2
	Post Whitendale Mown	0.20 ± 0.03	0.83 ± 0.04	0.03 ± 0.01	0.18 ± 0.01	0.15 ± 0.02	0.01 ± 0.00	457 ± 81	32 ± 6	175 ± 63	132 ± 13	26 ± 5
	Post Whitendale Mown -brash	0.18 ± 0.05	0.74 ± 0.12	0.03 ± 0.01	0.14 ± 0.03	0.14 ± 0.03	0.01 ± 0.00	267 ± 63	18 ± 3	143 ± 43	97 ± 19	20 ± 5
2020	Post Nidderdale Burnt	0.12 ± 0.01	0.70 ± 0.13	0.03 ± 0.01	0.17 ± 0.02	0.18 ± 0.04	0.01 ± 0.00	279 ± 75	23 ± 7	126 ± 68	87 ± 21	20 ± 3
	Post Nidderdale Uncut	0.13 ± 0.02	0.82 ± 0.08	0.02 ± 0.00	0.13 ± 0.02	0.12 ± 0.02	0.01 ± 0.00	196 ± 26	10 ± 0	65 ± 18	80 ± 14	14 ± 2
	Post Nidderdale Mown	0.13 ± 0.03	0.86 ± 0.21	0.02 ± 0.01	0.14 ± 0.03	0.12 ± 0.02	0.01 ± 0.00	162 ± 31	13 ± 4	71 ± 27	91 ± 14	14 ± 2
	Post Nidderdale Mown -brash	0.11 ± 0.01	0.69 ± 0.10	0.02 ± 0.00	0.13 ± 0.02	0.10 ± 0.02	0.01 ± 0.00	176 ± 87	11 ± 4	39 ± 10	80 ± 12	19 ± 2
	Post Mossdale Burnt	0.21 ± 0.02	0.98 ± 0.11	0.03 ± 0.01	0.26 ± 0.03	0.18 ± 0.02	0.01 ± 0.00	156 ± 15	14 ± 3	147 ± 41	144 ± 21	19 ± 2
	Post Mossdale Uncut	0.19 ± 0.02	1.12 ± 0.15	0.03 ± 0.01	0.18 ± 0.01	0.15 ± 0.02	0.01 ± 0.00	294 ± 69	13 ± 2	35 ± 13	98 ± 6	18 ± 3
	Post Mossdale Mown	0.15 ± 0.02	0.84 ± 0.13	0.02 ± 0.00	0.17 ± 0.04	0.15 ± 0.03	0.00 ± 0.00	122 ± 9	7 ± 1	35 ± 8	89 ± 11	15 ± 1
	Post Mossdale Mown -brash	0.16 ± 0.01	1.01 ± 0.11	0.02 ± 0.00	0.17 ± 0.00	0.17 ± 0.02	0.01 ± 0.00	201 ± 69	22 ± 13	42 ± 16	92 ± 5	14 ± 1
	Post Whitendale Burnt	0.14 ± 0.01	1.11 ± 0.07	0.05 ± 0.01	0.17 ± 0.02	0.18 ± 0.01	0.01 ± 0.00	305 ± 99	23 ± 9	91 ± 5	134 ± 24	23 ± 2
	Post Whitendale Uncut	0.12 ± 0.03	0.82 ± 0.23	0.02 ± 0.01	0.14 ± 0.04	0.16 ± 0.07	0.01 ± 0.00	305 ± 103	22 ± 6	95 ± 47	100 ± 29	42 ± 20
	Post Whitendale Mown	0.12 ± 0.02	0.91 ± 0.16	0.03 ± 0.00	0.15 ± 0.02	0.14 ± 0.02	0.01 ± 0.00	272 ± 93	15 ± 3	101 ± 42	102 ± 26	24 ± 4
	Post Whitendale Mown -brash	0.11 ± 0.03	0.84 ± 0.27	0.03 ± 0.01	0.14 ± 0.04	0.13 ± 0.04	0.01 ± 0.00	351 ± 125	28 ± 10	163 ± 78	99 ± 30	26 ± 4
2021	Post Nidderdale Burnt	0.13 ± 0.01	0.86 ± 0.02	0.03 ± 0.00	0.17 ± 0.02	0.21 ± 0.01	0.01 ± 0.00	269 ± 39	12 ± 1	51 ± 8	122 ± 12	18 ± 2
	Post Nidderdale Uncut	0.15 ± 0.01	0.86 ± 0.07	0.02 ± 0.00	0.18 ± 0.01	0.19 ± 0.01	0.01 ± 0.00	197 ± 70	10 ± 1	65 ± 23	114 ± 7	10 ± 1
	Post Nidderdale Mown	0.14 ± 0.02	0.77 ± 0.07	0.03 ± 0.01	0.18 ± 0.01	0.23 ± 0.02	0.01 ± 0.00	219 ± 49	16 ± 4	88 ± 24	117 ± 22	10 ± 1
	Post Nidderdale Mown -brash	0.16 ± 0.01	0.86 ± 0.09	0.02 ± 0.00	0.23 ± 0.03	0.25 ± 0.02	0.01 ± 0.00	330 ± 83	21 ± 7	59 ± 16	128 ± 11	14 ± 1
	Post Mossdale Burnt	0.16 ± 0.01	0.70 ± 0.03	0.03 ± 0.00	0.20 ± 0.02	0.26 ± 0.01	0.01 ± 0.00	154 ± 7	11 ± 1	152 ± 42	151 ± 1	11 ± 1
	Post Mossdale Uncut	0.18 ± 0.03	0.75 ± 0.09	0.01 ± 0.00	0.21 ± 0.02	0.21 ± 0.01	0.01 ± 0.00	199 ± 48	10 ± 1	27 ± 8	108 ± 15	14 ± 2
	Post Mossdale Mown	0.18 ± 0.03	0.79 ± 0.05	0.01 ± 0.00	0.16 ± 0.03	0.25 ± 0.02	0.01 ± 0.00	184 ± 51	12 ± 2	42 ± 20	100 ± 13	16 ± 2
	Post Mossdale Mown -brash	0.17 ± 0.03	0.85 ± 0.08	0.01 ± 0.00	0.19 ± 0.04	0.26 ± 0.04	0.01 ± 0.00	220 ± 56	11 ± 2	56 ± 17	112 ± 28	15 ± 2
	Post Whitendale Burnt	0.10 ± 0.01	0.81 ± 0.01	0.01 ± 0.00	0.11 ± 0.01	0.20 ± 0.03	0.01 ± 0.00	273 ± 94	17 ± 5	116 ± 26	126 ± 13	25 ± 2
	Post Whitendale Uncut	0.13 ± 0.01	0.61 ± 0.08	0.01 ± 0.00	0.17 ± 0.04	0.16 ± 0.01	0.01 ± 0.00	173 ± 55	12 ± 1	147 ± 68	126 ± 34	20 ± 2
	Post Whitendale Mown	0.11 ± 0.00	0.67 ± 0.05	0.01 ± 0.00	0.12 ± 0.01	0.17 ± 0.02	0.01 ± 0.00	168 ± 31	10 ± 1	79 ± 20	100 ± 18	20 ± 1
	Post Whitendale Mown -brash	0.11 ± 0.01	0.64 ± 0.03	0.02 ± 0.00	0.13 ± 0.01	0.15 ± 0.01	0.01 ± 0.00	174 ± 40	10 ± 1	82 ± 32	97 ± 7	21 ± 1

Table A4.9 Means ±STDEV for sedge (combined *E. angustifolium* and *E. vaginatum*) flower/seed head samples (including very high values) from the 5x5 m plots at the three sites and their main managements during post-management (sampled in late summer during 2019-2021; no pre-management samples were assessed) period (macronutrients as percentages and micronutrients in weight per weight). Missing values indicate not enough sample material could be collected or that (for standard deviation) only one sample was available.

	Sedge flowers	%						µg g-1				
		P	K	Na	Mg	Ca	Si	Fe	Al	Mn	Zn	Cu
2019	Post Nidderdale Burnt	0.17 ± 0.04	0.48 ± 0.26	0.04 ± 0.00	0.19 ± 0.04	0.16 ± 0.01	0.06 ± 0.01	1527.64 ± 1261.89	384.36 ± 258.14	204.49 ± 161.04	142.84 ± 4.27	33.40 ± 3.14
	Post Nidderdale Uncut	±	±	±	±	±	±	±	±	±	±	±
	Post Nidderdale Mown	±	±	±	±	±	±	±	±	±	±	±
	Post Nidderdale Mown -brash	±	±	±	±	±	±	±	±	±	±	±
	Post Mossdale Burnt	0.24 ± 0.02	0.60 ± 0.04	0.04 ± 0.01	0.24 ± 0.02	0.18 ± 0.02	0.02 ± 0.00	105.18 ± 11.16	56.55 ± 4.27	169.79 ± 38.26	122.85 ± 13.65	22.37 ± 2.22
	Post Mossdale Uncut	0.22 ± 0.01	1.05 ± 0.11	0.01 ± 0.01	0.23 ± 0.02	0.18 ± 0.02	0.05 ± 0.01	182.32 ± 10.39	75.53 ± 6.72	61.24 ± 18.83	149.87 ± 14.15	37.32 ± 7.03
	Post Mossdale Mown	0.22 ± 0.02	0.67 ± 0.05	0.03 ± 0.01	0.21 ± 0.02	0.14 ± 0.02	0.03 ± 0.01	116.07 ± 27.15	59.96 ± 17.45	65.90 ± 9.58	116.03 ± 8.66	27.00 ± 4.22
	Post Mossdale Mown -brash	0.21 ± 0.04	0.59 ± 0.10	0.03 ± 0.01	0.20 ± 0.04	0.17 ± 0.04	0.03 ± 0.00	122.75 ± 21.09	54.44 ± 9.87	75.67 ± 19.18	119.42 ± 21.46	25.19 ± 3.90
	Post Whitendale Burnt	0.21 ± 0.02	0.60 ± 0.12	0.04 ± 0.02	0.21 ± 0.02	0.13 ± 0.00	0.02 ± 0.01	104.48 ± 20.61	45.70 ± 8.97	115.04 ± 33.66	106.21 ± 7.17	25.20 ± 2.50
	Post Whitendale Uncut	0.14 ± 0.03	1.13 ± 0.33	0.03 ± 0.01	0.19 ± 0.04	0.14 ± 0.01	0.04 ± 0.01	156.06 ± 24.46	73.63 ± 5.52	87.50 ± 16.09	142.24 ± 2.11	30.55 ± 5.98
	Post Whitendale Mown	0.22 ± 0.02	0.68 ± 0.11	0.05 ± 0.01	0.21 ± 0.02	0.13 ± 0.01	0.02 ± 0.00	103.79 ± 12.78	44.31 ± 6.44	135.47 ± 24.11	117.42 ± 4.58	25.05 ± 2.83
	Post Whitendale Mown -brash	0.20 ± 0.01	0.70 ± 0.09	0.04 ± 0.01	0.19 ± 0.01	0.12 ± 0.01	0.02 ± 0.00	115.80 ± 17.18	54.06 ± 7.52	166.33 ± 42.20	107.60 ± 7.18	24.15 ± 1.30
2020	Post Nidderdale Burnt	0.38 ±	1.26 ±	0.04 ±	0.31 ±	0.13 ±	0.01 ±	73.00 ±	20.38 ±	186.79 ±	133.23 ±	45.57 ±
	Post Nidderdale Uncut	0.20 ± 0.02	0.52 ± 0.10	0.02 ± 0.00	0.23 ± 0.02	0.14 ± 0.04	0.05 ± 0.04	185.47 ± 148.25	110.77 ± 96.69	67.73 ± 17.69	107.50 ± 8.53	123.65 ± 94.05
	Post Nidderdale Mown	0.17 ± 0.02	0.58 ± 0.05	0.03 ± 0.01	0.20 ± 0.03	0.14 ± 0.03	0.02 ± 0.01	122.21 ± 41.63	59.02 ± 28.52	114.51 ± 23.70	105.21 ± 11.25	85.50 ± 44.40
	Post Nidderdale Mown -brash	0.22 ± 0.06	0.54 ± 0.09	0.03 ± 0.01	0.23 ± 0.03	0.14 ± 0.02	0.02 ± 0.01	85.62 ± 32.89	34.65 ± 3.70	73.33 ± 10.69	116.27 ± 11.14	48.90 ± 17.19
	Post Mossdale Burnt	0.17 ± 0.03	0.58 ± 0.06	0.05 ± 0.01	0.21 ± 0.03	0.16 ± 0.02	0.02 ± 0.00	125.07 ± 12.39	41.52 ± 10.22	172.39 ± 71.94	118.82 ± 9.52	61.42 ± 11.40
	Post Mossdale Uncut	0.20 ± 0.02	0.52 ± 0.10	0.02 ± 0.00	0.23 ± 0.02	0.14 ± 0.04	0.05 ± 0.04	185.47 ± 148.25	110.77 ± 96.69	67.73 ± 17.69	107.50 ± 8.53	123.65 ± 94.05
	Post Mossdale Mown	0.23 ± 0.01	0.74 ± 0.13	0.04 ± 0.01	0.24 ± 0.02	0.16 ± 0.01	0.01 ± 0.00	80.45 ± 15.76	27.61 ± 5.83	62.47 ± 11.12	126.51 ± 14.43	43.25 ± 8.29
	Post Mossdale Mown -brash	0.22 ± 0.02	0.59 ± 0.12	0.04 ± 0.01	0.23 ± 0.02	0.18 ± 0.03	0.01 ± 0.00	80.89 ± 12.74	25.48 ± 3.98	67.68 ± 17.07	122.77 ± 9.46	41.80 ± 7.34
	Post Whitendale Burnt	0.10 ±	0.14 ±	0.02 ±	0.08 ±	0.07 ±	0.02 ±	61.96 ±	74.34 ±	73.82 ±	48.57 ±	141.92 ±
	Post Whitendale Uncut	0.15 ± 0.04	0.33 ± 0.11	0.03 ± 0.00	0.19 ± 0.03	0.10 ± 0.01	0.01 ± 0.00	93.96 ± 18.90	18.10 ± 4.47	80.82 ± 17.66	93.17 ± 7.25	48.62 ± 6.72
	Post Whitendale Mown	0.17 ± 0.05	0.56 ± 0.16	0.04 ± 0.01	0.18 ± 0.06	0.10 ± 0.03	0.01 ± 0.00	47.43 ± 9.17	17.47 ± 6.57	151.08 ± 99.45	81.86 ± 17.91	34.86 ± 6.14
	Post Whitendale Mown -brash	0.16 ± 0.03	0.54 ± 0.11	0.05 ± 0.01	0.16 ± 0.03	0.09 ± 0.01	0.01 ± 0.00	63.04 ± 22.78	14.93 ± 3.01	117.45 ± 57.08	74.56 ± 13.14	31.84 ± 6.46
2021	Post Nidderdale Burnt	±	±	±	±	±	±	±	±	±	±	±
	Post Nidderdale Uncut	±	±	±	±	±	±	±	±	±	±	±
	Post Nidderdale Mown	±	±	±	±	±	±	±	±	±	±	±
	Post Nidderdale Mown -brash	0.09 ±	0.53 ±	0.02 ±	0.16 ±	0.10 ±	0.00 ±	29.53 ±	10.66 ±	92.43 ±	90.20 ±	19.50 ±
	Post Mossdale Burnt	0.25 ± 0.10	1.08 ± 0.50	0.11 ± 0.09	0.31 ± 0.14	0.40 ± 0.28	0.04 ± 0.04	185.54 ± 166.01	43.82 ± 31.71	133.15 ± 54.89	165.19 ± 89.71	126.43 ± 116.72
	Post Mossdale Uncut	0.22 ±	0.75 ±	0.02 ±	0.23 ±	0.17 ±	0.01 ±	55.93 ±	10.86 ±	136.20 ±	91.78 ±	40.81 ±
	Post Mossdale Mown	0.28 ± 0.01	1.25 ± 0.17	0.09 ± 0.05	0.34 ± 0.03	0.38 ± 0.10	0.03 ± 0.02	160.46 ± 85.78	44.66 ± 20.22	122.64 ± 10.99	160.05 ± 33.17	97.51 ± 59.39
	Post Mossdale Mown -brash	0.32 ± 0.06	1.16 ± 0.21	0.04 ± 0.01	0.34 ± 0.09	0.29 ± 0.07	0.01 ± 0.01	89.15 ± 28.02	28.86 ± 10.08	127.00 ± 41.20	140.36 ± 27.50	56.88 ± 21.41
	Post Whitendale Burnt	0.23 ± 0.02	0.97 ± 0.13	0.05 ± 0.01	0.26 ± 0.03	0.22 ± 0.02	0.01 ± 0.00	63.06 ± 7.06	41.07 ± 7.03	173.66 ± 36.39	129.62 ± 14.06	32.58 ± 3.42
	Post Whitendale Uncut	0.18 ± 0.02	0.64 ± 0.14	0.04 ± 0.01	0.21 ± 0.05	0.16 ± 0.02	0.01 ± 0.00	71.85 ± 25.27	25.80 ± 7.39	146.16 ± 44.17	88.13 ± 19.23	30.51 ± 6.10
	Post Whitendale Mown	0.18 ± 0.04	0.66 ± 0.14	0.05 ± 0.01	0.17 ± 0.04	0.18 ± 0.04	0.01 ± 0.00	77.34 ± 20.86	26.89 ± 7.37	147.39 ± 74.69	91.30 ± 19.54	33.03 ± 7.68
	Post Whitendale Mown -brash	0.21 ± 0.03	0.81 ± 0.12	0.04 ± 0.01	0.22 ± 0.02	0.19 ± 0.02	0.01 ± 0.00	61.58 ± 8.40	25.88 ± 5.15	133.26 ± 43.38	109.97 ± 10.27	32.68 ± 1.73

Table A4.10 Means ±STDEV for sedge (combined *E. angustifolium* and *E. vaginatum*) flower/seed head samples (excluding very high values) from the 5x5 m plots at the three sites and their main managements during post-management (sampled in late summer during 2019-2021; no pre-management samples were assessed) period (macronutrients as percentages and micronutrients in weight per weight). Missing values indicate not enough sample material could be collected or that (for standard deviation) only one sample was available.

	Sedge flowers	%						µg g-1				
		P	K	Na	Mg	Ca	Si	Fe	Al	Mn	Zn	Cu
2019	Post Nidderdale Burnt	0.17 ± 0.04	0.48 ± 0.26	0.04 ± 0.00	0.19 ± 0.04	0.16 ± 0.01	0.06 ± 0.01	1527.64 ± 1261.89	384.36 ± 258.14	204.49 ± 161.04	142.84 ± 4.27	33.40 ± 3.14
	Post Nidderdale Uncut	±	±	±	±	±	±	±	±	±	±	±
	Post Nidderdale Mown	±	±	±	±	±	±	±	±	±	±	±
	Post Nidderdale Mown -brash	±	±	±	±	±	±	±	±	±	±	±
	Post Mossdale Burnt	0.24 ± 0.02	0.60 ± 0.04	0.04 ± 0.01	0.24 ± 0.02	0.18 ± 0.02	0.02 ± 0.00	105.18 ± 11.16	56.55 ± 4.27	169.79 ± 38.26	122.85 ± 13.65	22.37 ± 2.22
	Post Mossdale Uncut	0.22 ± 0.01	1.05 ± 0.11	0.01 ± 0.01	0.23 ± 0.02	0.18 ± 0.02	0.05 ± 0.01	182.32 ± 10.39	75.53 ± 6.72	61.24 ± 18.83	149.87 ± 14.15	37.32 ± 7.03
	Post Mossdale Mown	0.22 ± 0.02	0.67 ± 0.05	0.03 ± 0.01	0.21 ± 0.02	0.14 ± 0.02	0.03 ± 0.01	116.07 ± 27.15	59.96 ± 17.45	65.90 ± 9.58	116.03 ± 8.66	27.00 ± 4.22
	Post Mossdale Mown -brash	0.21 ± 0.04	0.59 ± 0.10	0.03 ± 0.01	0.20 ± 0.04	0.17 ± 0.04	0.03 ± 0.00	122.75 ± 21.09	54.44 ± 9.87	75.67 ± 19.18	119.42 ± 21.46	25.19 ± 3.90
	Post Whitendale Burnt	0.21 ± 0.02	0.60 ± 0.12	0.04 ± 0.02	0.21 ± 0.02	0.13 ± 0.00	0.02 ± 0.01	104.48 ± 20.61	45.70 ± 8.97	115.04 ± 33.66	106.21 ± 7.17	25.20 ± 2.50
	Post Whitendale Uncut	0.14 ± 0.03	1.13 ± 0.33	0.03 ± 0.01	0.19 ± 0.04	0.14 ± 0.01	0.04 ± 0.01	156.06 ± 24.46	73.63 ± 5.52	87.50 ± 16.09	142.24 ± 2.11	30.55 ± 5.98
	Post Whitendale Mown	0.22 ± 0.02	0.68 ± 0.11	0.05 ± 0.01	0.21 ± 0.02	0.13 ± 0.01	0.02 ± 0.00	103.79 ± 12.78	44.31 ± 6.44	135.47 ± 24.11	117.42 ± 4.58	25.05 ± 2.83
	Post Whitendale Mown -brash	0.20 ± 0.01	0.70 ± 0.09	0.04 ± 0.01	0.19 ± 0.01	0.12 ± 0.01	0.02 ± 0.00	115.80 ± 17.18	54.06 ± 7.52	166.33 ± 42.20	107.60 ± 7.18	24.15 ± 1.30
2020	Post Nidderdale Burnt	0.38 ±	1.26 ±	0.04 ±	0.31 ±	0.13 ±	0.01 ±	73.00 ±	20.38 ±	186.79 ±	133.23 ±	45.57 ±
	Post Nidderdale Uncut	0.20 ± 0.02	0.52 ± 0.10	0.02 ± 0.00	0.23 ± 0.02	0.14 ± 0.04	0.05 ± 0.04	185.47 ± 148.25	110.77 ± 96.69	67.73 ± 17.69	107.50 ± 8.53	123.65 ± 94.05
	Post Nidderdale Mown	0.17 ± 0.02	0.58 ± 0.05	0.03 ± 0.01	0.20 ± 0.03	0.14 ± 0.03	0.02 ± 0.01	122.21 ± 41.63	59.02 ± 28.52	114.51 ± 23.70	105.21 ± 11.25	85.50 ± 44.40
	Post Nidderdale Mown -brash	0.22 ± 0.06	0.54 ± 0.09	0.03 ± 0.01	0.23 ± 0.03	0.14 ± 0.02	0.02 ± 0.01	85.62 ± 32.89	34.65 ± 3.70	73.33 ± 10.69	116.27 ± 11.14	48.90 ± 17.19
	Post Mossdale Burnt	0.17 ± 0.03	0.58 ± 0.06	0.05 ± 0.01	0.21 ± 0.03	0.16 ± 0.02	0.02 ± 0.00	125.07 ± 12.39	41.52 ± 10.22	172.39 ± 71.94	118.82 ± 9.52	61.42 ± 11.40
	Post Mossdale Uncut	0.20 ± 0.02	0.52 ± 0.10	0.02 ± 0.00	0.23 ± 0.02	0.14 ± 0.04	0.05 ± 0.04	185.47 ± 148.25	110.77 ± 96.69	67.73 ± 17.69	107.50 ± 8.53	123.65 ± 94.05
	Post Mossdale Mown	0.23 ± 0.01	0.74 ± 0.13	0.04 ± 0.01	0.24 ± 0.02	0.16 ± 0.01	0.01 ± 0.00	80.45 ± 15.76	27.61 ± 5.83	62.47 ± 11.12	126.51 ± 14.43	43.25 ± 8.29
	Post Mossdale Mown -brash	0.22 ± 0.02	0.59 ± 0.12	0.04 ± 0.01	0.23 ± 0.02	0.18 ± 0.03	0.01 ± 0.00	80.89 ± 12.74	25.48 ± 3.98	67.68 ± 17.07	122.77 ± 9.46	41.80 ± 7.34
	Post Whitendale Burnt	0.10 ±	0.14 ±	0.02 ±	0.08 ±	0.07 ±	0.02 ±	61.96 ±	74.34 ±	73.82 ±	48.57 ±	141.92 ±
	Post Whitendale Uncut	0.15 ± 0.04	0.33 ± 0.11	0.03 ± 0.00	0.19 ± 0.03	0.10 ± 0.01	0.01 ± 0.00	93.96 ± 18.90	18.10 ± 4.47	80.82 ± 17.66	93.17 ± 7.25	48.62 ± 6.72
	Post Whitendale Mown	0.17 ± 0.05	0.56 ± 0.16	0.04 ± 0.01	0.18 ± 0.06	0.10 ± 0.03	0.01 ± 0.00	47.43 ± 9.17	17.47 ± 6.57	151.08 ± 99.45	81.86 ± 17.91	34.86 ± 6.14
	Post Whitendale Mown -brash	0.16 ± 0.03	0.54 ± 0.11	0.05 ± 0.01	0.16 ± 0.03	0.09 ± 0.01	0.01 ± 0.00	63.04 ± 22.78	14.93 ± 3.01	117.45 ± 57.08	74.56 ± 13.14	31.84 ± 6.46
2021	Post Nidderdale Burnt	±	±	±	±	±	±	±	±	±	±	±
	Post Nidderdale Uncut	±	±	±	±	±	±	±	±	±	±	±
	Post Nidderdale Mown	±	±	±	±	±	±	±	±	±	±	±
	Post Nidderdale Mown -brash	0.09 ±	0.53 ±	0.02 ±	0.16 ±	0.10 ±	0.00 ±	29.53 ±	10.66 ±	92.43 ±	90.20 ±	19.50 ±
	Post Mossdale Burnt	0.25 ± 0.10	1.08 ± 0.50	0.11 ± 0.09	0.31 ± 0.14	0.40 ± 0.28	0.04 ± 0.04	185.54 ± 166.01	43.82 ± 31.71	133.15 ± 54.89	165.19 ± 89.71	126.43 ± 116.72
	Post Mossdale Uncut	0.22 ±	0.75 ±	0.02 ±	0.23 ±	0.17 ±	0.01 ±	55.93 ±	10.86 ±	136.20 ±	91.78 ±	40.81 ±
	Post Mossdale Mown	0.28 ± 0.01	1.25 ± 0.17	0.09 ± 0.05	0.34 ± 0.03	0.38 ± 0.10	0.03 ± 0.02	160.46 ± 85.78	44.66 ± 20.22	122.64 ± 10.99	160.05 ± 33.17	97.51 ± 59.39
	Post Mossdale Mown -brash	0.32 ± 0.06	1.16 ± 0.21	0.04 ± 0.01	0.34 ± 0.09	0.29 ± 0.07	0.01 ± 0.01	89.15 ± 28.02	28.86 ± 10.08	127.00 ± 41.20	140.36 ± 27.50	56.88 ± 21.41
	Post Whitendale Burnt	0.23 ± 0.02	0.97 ± 0.13	0.05 ± 0.01	0.26 ± 0.03	0.22 ± 0.02	0.01 ± 0.00	63.06 ± 7.06	41.07 ± 7.03	173.66 ± 36.39	129.62 ± 14.06	32.58 ± 3.42
	Post Whitendale Uncut	0.18 ± 0.02	0.64 ± 0.14	0.04 ± 0.01	0.21 ± 0.05	0.16 ± 0.02	0.01 ± 0.00	71.85 ± 25.27	25.80 ± 7.39	146.16 ± 44.17	88.13 ± 19.23	30.51 ± 6.10
	Post Whitendale Mown	0.18 ± 0.04	0.66 ± 0.14	0.05 ± 0.01	0.17 ± 0.04	0.18 ± 0.04	0.01 ± 0.00	77.34 ± 20.86	26.89 ± 7.37	147.39 ± 74.69	91.30 ± 19.54	33.03 ± 7.68
	Post Whitendale Mown -brash	0.21 ± 0.03	0.81 ± 0.12	0.04 ± 0.01	0.22 ± 0.02	0.19 ± 0.02	0.01 ± 0.00	61.58 ± 8.40	25.88 ± 5.15	133.26 ± 43.38	109.97 ± 10.27	32.68 ± 1.73

Appendix 5 (water tables)

The data was analysed using mixed-effect models. The structure of the statistical models for **daily** means were, Response ~ BA * CI + (1|Site/Block/Plot) + ar1(Date|1); BA is the Before/After term, which was divided into three levels: Before, After short-term, After long-term. These equate to 2012-13, 2013-17, and 2017-21. CI is the Management term. FI management was taken as the control, LB, BR, and DN as the alternative 'impact' managements. Site was included as a random effect when combining all sites together. Plot was nested within Block, nested within Site. An autoregressive correlation function was used on Date, to account for the autocorrelation between days. The recordings begin from 17/04/2012, so the 'Before' period is 17/04/2012 – 16/04/2013. By extension, the 2013-17 period includes data from 17/4/2013 – 16/04/2017, and the 2017-21 period includes data from 17/04/2017. Effect sizes of the raw data (every 6 hours) were also calculated. Finally, Whitendale plot 4 was omitted, due to peat pipes draining the WTD to very low depth unrelated to management.

The following table (**Table A5.1**) shows the model output. 'Interactive term' is the BACI interaction. 'Estimate' is the predicted impact caused by the BACI interaction, i.e. the difference in WTD (cm) from FI management for the specific management and time-period. 'Std. Err' shows the standard error of the estimate. 'Z-value' is the test statistic of the GLMM model, from which significance is calculated. 'P value signif' denotes the level of significance of the BACI interaction. '95% Conf.Int' shows the 95 confidence interval of the impact, calculated from the estimate and standard error. Mown: LB = left brash vs. BR = brash removed; DN = uncut (do nothing).

All sites – model output – daily means for the mixed-effect models.

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	2013-17	-0.2485	0.2416	-1.028	0.3037	-0.7220 – 0.2250
LB	**2017-22**	**-2.7187**	**0.2378**	**-11.432**	**<2e-16 *****	**-3.1848 – -2.2526**
BR	2013-17	-0.1182	0.2416	-0.489	0.6247	-0.5917 – 0.3554
BR	**2017-22**	**-1.8882**	**0.2378**	**-7.940**	**2.02e-15 *****	**-2.3543 – -1.4221**
DN	**2013-17**	**-0.5557**	**0.2770**	**-2.006**	**0.0448 ***	**-1.0986 – -0.0129**
DN	**2017-22**	**-1.6407**	**0.2726**	**-6.018**	**1.77e-09 *****	**-2.1750 – -1.1063**

Nidderdale – model output – daily means

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	2013-17	0.3893	0.4701	0.956	0.339	-0.4087 – 1.1872
LB	**2017-22**	**-1.6725**	**0.4007**	**-4.174**	**3.00e-05 *****	**-2.4580 – -0.8871**
BR	2013-17	-0.4347	0.4071	-1.068	0.286	-1.2327 – 0.3632
BR	**2017-22**	**-1.8257**	**0.4007**	**-4.556**	**5.22e-06 *****	**-2.6111 – -1.0403**
DN	**2013-17**	**-1.0110**	**0.4701**	**-2.150**	**0.0315 ***	**-1.9323 – -0.0896**
DN	**2017-22**	**-1.6291**	**0.4627**	**-3.521**	**0.000431 *****	**-2.5360 – -0.7222**

Mossdale – model output – daily means

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**1.0557**	**0.3337**	**3.164**	**0.00156 ****	**0.4016 – 1.7097**
LB	**2017-22**	**-2.1582**	**0.3285**	**-6.571**	**5.01e-11 *****	**-2.8019 – -1.5144**
BR	**2013-17**	**1.1972**	**0.3337**	**3.588**	**0.000334 *****	**0.5432 – 1.8513**
BR	**2017-22**	**-2.0627**	**0.3285**	**-6.280**	**3.38e-10 *****	**-2.7065 – -1.4190**
DN	**2013-17**	**-1.7082**	**0.3853**	**-4.433**	**9.28e-06 *****	**-2.4634 – -0.9530**
DN	**2017-22**	**-4.8983**	**0.3793**	**-12.915**	**<2e-16 *****	**-5.6417 – -4.1550**

Whitendale – model output – daily means

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**-2.9558**	**0.5177**	**-5.710**	**1.13e-08 *****	**-3.9705 – -1.9412**
LB	**2017-22**	**-4.7124**	**0.5095**	**-9.249**	**<2e-16 *****	**-5.7110 – -3.7137**
BR	**2013-17**	**-1.8846**	**0.5177**	**-3.640**	**0.000272 *****	**-2.8992 – -0.8699**
BR	**2017-22**	**-2.1658**	**0.5095**	**-4.251**	**2.13e-05 *****	**-3.1645 – -0.1672**
DN	2013-17	-0.2841	0.5840	-0.486	0.627	-0.8606 – 1.4286
DN	**2017-22**	**1.2152**	**0.5748**	**2.114**	**0.0345 ***	**0.0886 – 2.3418**

Accordingly (see **Table A5.1**), the LB, BR, and DN managements impacted daily mean water table depth (WTD) differently to the control FI management. Analysis of all sites together, incorporating site as a random effect, showed that LB, BR, and DN managements led to lower WTD than FI management during the 2017-22 period (5+ years after management). During 2017-22, LB management led to mean WTD depth 2.77 ± 0.24 cm lower than FI management and BR management led to mean WTD depth 1.88 ± 0.24 cm lower than FI management. The mown managements, LB and BR, did not significantly change WTD compared to FI management during 2013-17. The DN management did lead to lower WTD than FI management across the full post-management period, with a steeper drop occurring in 2017-22 than in 2013-17 (1.64 ± 0.27 cm in 2017-22, 0.56 ± 0.28 cm in 2013-17).

The LB mown management led to lower WTD than FI management in all three sites during the 2017-22 period, 1.68 ± 0.40 cm lower at Nidderdale, 2.16 ± 0.33 cm lower at Mossdale, and 4.71 ± 0.51 cm lower at Whitendale. The immediate impact of LB management during 2013-17 was site-specific. At Mossdale, LB management led to higher WTD than FI management during 2013-17, by 1.06 ± 0.33 cm (preceding the lower WTD during 2017-21). At Whitendale, WTD was significantly lower with LB management compared to FI throughout the post-management phase. There was a non-significant increase compared with FI at Nidderdale during 2013-17.

The BR mown management affected WTD in a similar way to LB management: higher WTD than FI at Mossdale in 2013-17 preceding lower WTD in 2017-22, lower WTD than FI across the post-management period at Whitendale, and non-significant impacts followed by lower WTD at Nidderdale. The impact of BR relative to FI was of a similar magnitude to the impact of LB at Nidderdale and Mossdale. At Whitendale, BR was less impactful than LB compared with the FI control management. The difference in WTD between BR and FI was 1.88 ± 0.52 cm in 2013-17 and 2.17 ± 0.51 cm in 2017-22.

Mean WTD on DN management plots was lower than FI management throughout the post-management period at Nidderdale and Mossdale, with notably large difference occurring at Mossdale during 2017-22 (4.89 ± 0.38 cm lower for DN, very large effect size). Results differed at Whitendale, during 2017-22 WTD was 1.22 ± 0.57 cm higher with DN management than FI management, and there was a non-significant decline in WTD during 2013-17.

The effect sizes (ES) emphasise the increased difference between managements from 2013-17 to 2017-22. The ES of all managements increased between the time periods at Nidderdale and Mossdale and for DN management at Whitendale. There were 'medium' ES of LB management lowering WTD (compared to FI management) at all three sites during 2017-22. The ES of LB management during 2013-17 differed between sites: 'very small' negative ES at Nidderdale, 'small' positive ES at Mossdale, and 'medium' ES at Whitendale. BR management ES at Nidderdale increased from '< very small' positive ES to 'small' negative ES from 2013-17 to 2017-22. At Mossdale, BR management had a 'small' positive ES during 2013-17 followed by a 'medium' negative ES during 2017-22. At Whitendale, the ES of BR management decreased from 'small' to '<very small' between the two time periods. The ES of DN management was negative at all sites and increased in magnitude from 2013-17 to 2017-22. The ES was notably large at Mossdale, 'medium' in 2013-17 and 'very high' in 2017-22.

The structure of the statistical models for **monthly** mean summary statistics were, Response ~ BA * CI + (1|Site/Block/Plot) + (1|Year/Month); the structure of the model is the same, but autoregressive correlation was not necessary. Month nested in Year was a random effect. The following tables (**Table A5.2 a-d**) show the model output. 'Interactive term' is the BACI interaction. 'Estimate' is the predicted impact caused by the BACI interaction, i.e. the difference in WTD (cm) from FI management for the specific management and time-period. 'Std. Err' shows the standard error of the estimate. 'Z-value' is the test statistic of the GLMM model, from which significance is calculated. 'P value signif' denotes the level of significance of the BACI interaction. '95% Conf.Int' shows the 95 confidence interval of the impact, calculated from the estimate and standard error. Mown: LB = left brash vs. BR = brash removed; DN = uncut (do nothing).

Table A5.2a MONTHLY MINIMA

All sites – model output – monthly minima

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	2013-17	0.864	0.716	1.206	0.228	-0.540 – 2.268
LB	**2017-22**	**-2.670**	**0.704**	**-3.791**	**0.000150 *****	**-4.051 – -1.290**
BR	**2013-17**	**1.631**	**0.716**	**2.277**	**0.0228 ***	**0.227 – 3.034**
BR	2017-22	-1.376	0.704	-1.953	0.0509 .	-2.756 – 0.005
DN	2013-17	1.264	0.821	1.539	0.124	-0.345 – 2.873
DN	2017-22	-0.544	0.808	-0.674	0.500	-2.127 – 1.039

Nidderdale – model output – monthly minima

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**6.961**	**1.140**	**6.107**	**1.01e-09 *****	**4.727 – 9.195**
LB	2017-22	1.274	1.121	1.137	0.256	-0.923 – 3.472
BR	**2013-17**	**5.557**	**1.140**	**4.875**	**1.09e-06 *****	**3.323 – 7.791**
BR	2017-22	-0.123	1.121	-0.110	0.912	-2.231 – 2.074
DN	**2013-17**	**7.625**	**1.316**	**5.793**	**6.90e-09 *****	**5.045 – 10.204**
DN	**2017-22**	**3.323**	**1.295**	**2.567**	**0.0103 ***	**0.785 – 5.860**

Mossdale – model output – monthly minima

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**1.451**	**0.650**	**2.232**	**0.0256 ***	**0.177 – 2.725**
LB	**2017-22**	**-1.750**	**0.639**	**-2.737**	**0.00621 ****	**-3.003 – -0.497**
BR	**2013-17**	**2.857**	**0.650**	**4.395**	**1.11e-05 *****	**1.583 – 4.131**
BR	2017-22	-1.022	0.639	-1.598	0.110	-2.275 – 0.231
DN	2013-17	0.501	0.751	0.668	0.504	-0.970 – 1.972
DN	**2017-22**	**-4.513**	**0.738**	**-6.112**	**9.84e-10 *****	**-5.960 – -3.066**

Whitendale – model output – monthly minima

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**-7.112**	**1.420**	**-5.011**	**5.42e-07 *****	**-13.2465 – -0.9855**
LB	**2017-22**	**-7.885**	**1.396**	**-5.647**	**1.63e-08 *****	**-13.9174 – -1.8575**
BR	**2013-17**	**-4.815**	**1.420**	**-3.392**	**0.000693 *****	**-10.9514 – 1.3096**
BR	**2017-22**	**-3.331**	**1.396**	**-2.385**	**0.0171 ***	**-9.3655 – 2.6945**
DN	**2013-17**	**-5.627**	**1.601**	**-3.513**	**0.000442 *****	**-12.5456 – 1.2867**
DN	2017-22	-0.791	1.575	-0.502	0.616	-7.5960 – 6.0094

Table A5.2b MONTHLY MAXIMA

All sites – model output – monthly maxima

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**-1.760**	**0.388**	**-4.536**	**5.73e-06 *****	**-2.520 – -0.999**
LB	**2017-22**	**-3.231**	**0.382**	**-8.468**	**< 2e-16 *****	**-3.978 – -2.483**
BR	**2013-17**	**-1.410**	**0.388**	**-3.636**	**0.000277 *****	**-2.170 – -0.650**
BR	**2017-22**	**-2.156**	**0.382**	**-5.652**	**1.58e-08 *****	**-2.904 – -1.409**
DN	**2013-17**	**-1.972**	**0.445**	**-4.425**	**9.22e-06 *****	**-2.843 – -1.100**
DN	**2017-22**	**-2.372**	**0.437**	**-5.423**	**5.86e-08 *****	**-3.229 – -1.515**

Nidderdale – model output – monthly maxima

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**-5.684**	**0.685**	**-8.296**	**< 2e-16 *****	**-7.027 – -4.341**
LB	**2017-22**	**-5.423**	**0.674**	**-8.047**	**8.47e-16 *****	**-6.744 – -4.102**
BR	**2013-17**	**-4.156**	**0.685**	**-6.066**	**1.31e-09 *****	**-5.499 – -2.813**
BR	**2017-22**	**-2.783**	**0.674**	**-4.130**	**3.63-05 *****	**-4.104 – -1.462**
DN	**2013-17**	**-6.820**	**0.791**	**-8.621**	**< 2e-16 *****	**-8.371 – -5.270**
DN	**2017-22**	**-5.809**	**0.778**	**-7.466**	**8.28e-14 *****	**-7.334 – -4.284**

Mossdale – model output – monthly maxima

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**2.258**	**0.422**	**5.352**	**8.72e-08 *****	**1.431 – 3.086**
LB	**2017-22**	**-1.113**	**0.415**	**-2.681**	**0.00734 ****	**-1.926 – -0.299**
BR	**2013-17**	**1.291**	**0.422**	**3.059**	**0.00222 ****	**0.464 – 2.118**
BR	**2017-22**	**-1.273**	**0.415**	**-3.066**	**0.00217 ****	**-2.086 – -0.459**
DN	2013-17	-0.748	0.487	-1.534	0.125	-1.703 – 0.207
DN	**2017-22**	**-2.537**	**0.479**	**-5.292**	**1.21e-07 *****	**-3.476 – -1.597**

Whitendale – model output – monthly maxima

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**-2.330**	**0.658**	**-3.544**	**0.000394 *****	**-3.619 – -1.042**
LB	**2017-22**	**-3.629**	**0.647**	**-5.612**	**2.00e-08 *****	**-4.897 – -2.362**
BR	**2013-17**	**-1.843**	**0.658**	**-2.803**	**0.00508 ****	**-3.132 – -0.555**
BR	**2017-22**	**-2.887**	**0.647**	**-4.464**	**8.06e-06 *****	**-4.154 – -1.619**
DN	2013-17	1.175	0.742	1.584	0.113	-0.279 – 2.629
DN	2017-22	0.757	0.730	1.037	0.230	-0.673 – 2.187

Table A5.2c MONTHLY RANGE

All sites – model output – monthly range

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**-2.624**	**0.728**	**-3.607**	**0.000310 *****	**-4.050 – -1.198**
LB	2017-22	-0.561	0.716	-0.784	0.433	-1.963 – 0.842
BR	**2013-17**	**-3.041**	**0.728**	**-4.180**	**2.91e-05 *****	**-4.467 – -1.615**
BR	2017-22	-0.781	0.716	-1.092	0.275	-2.184 – 0.621
DN	**2013-17**	**-3.237**	**0.834**	**-3.881**	**0.000104 *****	**-4.871 – -1.602**
DN	**2017-22**	**-1.828**	**0.820**	**-2.229**	**0.0257 ***	**-3.436 – -0.221**

Nidderdale – model output – monthly range

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**-12.645**	**1.220**	**-10.365**	**< 2e-16 *****	**-15.036 – -10.254**
LB	**2017-22**	**-6.698**	**1.200**	**-5.582**	**2.38e-08 *****	**-9.050 – -4.346**
BR	**2013-17**	**-9.713**	**1.220**	**-7.962**	**1.70e-15 *****	**-12.104 – -7.322**
BR	**2017-22**	**-2.660**	**1.200**	**-2.217**	**0.0266 ***	**-5.012 – 0.308**
DN	**2013-17**	**-14.446**	**1.409**	**-10.254**	**< 2e-16 *****	**-17.207 – -11.685**
DN	**2017-22**	**-9.132**	**1.386**	**-6.591**	**4.37e-11 *****	**-11.848 – -6.417**

Mossdale – model output – monthly range

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	2013-17	0.807	0.664	1.216	0.224	-0.494 – 2.109
LB	2017-22	0.637	0.653	0.975	0.329	-0.643 – 1.917
BR	**2013-17**	**-1.566**	**0.664**	**-2.358**	**0.0184 ***	**-2.868 – -0.264**
BR	2017-22	-0.251	0.653	-0.384	0.701	-1.531 – 1.029
DN	2013-17	-1.249	0.767	-1.629	0.103	-2.752 – 0.254
DN	**2017-22**	**1.976**	**0.754**	**2.620**	**0.00879 ****	**0.498 – 3.455**

Whitendale – model output – monthly range

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**4.783**	**1.353**	**3.534**	**0.000410 *****	**2.130 – 7.435**
LB	**2017-22**	**4.256**	**1.331**	**3.197**	**0.00139 ****	**1.646 – 6.865**
BR	**2013-17**	**2.972**	**1.353**	**2.196**	**0.0281 ***	**0.319 – 5.625**
BR	2017-22	0.444	1.331	0.333	0.739	-2.166 – 3.053
DN	**2013-17**	**6.802**	**1.527**	**4.455**	**8.40e-06 ***	**3.809 – 9.794**
DN	2017-22	1.548	1.502	1.030	0.303	-1.396 – 4.491

Table A5.2d MONTHLY STANDARD DEVIATION

All sites – model output – monthly standard deviation of means

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**-0.774**	**0.243**	**-3.187**	**0.00144 ****	**-1.251 – 0.298**
LB	2017-22	-0.055	0.239	-0.231	0.817	-0.524 – 0.413
BR	**2013-17**	**-0.939**	**0.243**	**-3.866**	**0.000110 *****	**-1.416 – -0.463**
BR	2017-22	-0.168	0.239	-0.704	0.482	-0.637 – 0.300
DN	**2013-17**	**-1.038**	**0.279**	**-3.725**	**0.000195 *****	**-1.583 – -0.492**
DN	**2017-22**	**-0.555**	**0.274**	**-2.027**	**0.0426 ***	**-1.092 – -0.018**

Nidderdale – model output – monthly standard deviation of means

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**-3.655**	**0.396**	**-9.232**	**< 2e-16 *****	**-4.431 – -2.879**
LB	**2017-22**	**-1.639**	**0.389**	**-4.208**	**2.58e-05 *****	**-2.402 – -0.875**
BR	**2013-17**	**-2.911**	**0.396**	**-7.353**	**1.93e-13 *****	**-3.687 – -2.135**
BR	2017-22	-0.577	0.389	-1.481	0.139	-1.340 – 0.186
DN	**2013-17**	**-4.354**	**0.457**	**-9.523**	**< 2e-16 *****	**-5.250 – -3.458**
DN	**2017-22**	**-2.525**	**0.450**	**-5.616**	**1.95e-08 *****	**-3.407 – -1.644**

Mossdale – model output – monthly standard deviation of means

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	2013-17	0.027	0.205	0.133	0.894	-0.374 – 0.429
LB	2017-22	0.064	0.202	0.317	0.751	-0.331 – 0.459
BR	**2013-17**	**-0.594**	**0.205**	**-2.897**	**0.00377 ****	**-0.995 – -0.192**
BR	2017-22	-0.198	0.202	-0.987	0.326	-0.593 – 0.197
DN	**2013-17**	**-0.594**	**0.237**	**-2.512**	**0.0120 ***	**-1.058 – -0.131**
DN	2017-22	0.259	0.233	1.112	0.266	-0.197 – 0.715

Whitendale – model output – monthly standard deviation of means

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**1.504**	**0.459**	**3.275**	**0.00106 ****	**0.604 – 2.404**
LB	**2017-22**	**1.353**	**0.452**	**2.996**	**0.00274 ****	**0.468 – 2.238**
BR	2013-17	0.886	0.459	1.929	0.0538 .	-0.0143 – 1.786
BR	2017-22	0.214	0.452	0.475	0.635	-0.671 – 1.100
DN	**2013-17**	**2.034**	**0.518**	**3.927**	**8.59e-05 *****	**1.019 – 3.050**
DN	2017-22	0.545	0.510	1.069	0.285	-0.454 – 1.543

Accordingly (see **Table A5.2a-d**), all sites showed significant BACI interactions for all managements (Mown: LB = left brash vs. BR = brash removed; DN = uncut) versus burnt (FI) across both time periods for monthly maxima. The **monthly maxima were lower for LB, BR, and DN managements than FI management across the full post-management period**. The difference in maxima from FI levels were greater during 2017-21 than in 2013-17. **LB** management led to lower minima than FI management during the 2017-22 period. Minima were also lower in 2017-22 for **BR** management, although this was marginally outside statistical significance (p=0.0509). Conversely, minima were greater with **BR** management than FI management during 2013-17. This is the effect found at Mossdale, with BR management leading to higher WTD minima than FI during 2013-17, and lower during 2017-22.

The **range of WTD was lower with LB and BR management than FI management during 2013-17**, the years following management implementation. **DN** management caused **lower WTD range than FI management throughout the post-management period**. This suggests that WTD is possibly more stable with DN rather than FI management, both immediately following management and several years later.

The results of **standard deviation analysis also showed less variation with LB and BR management than FI management during 2013-17**, and **less variation with DN management than FI throughout the post-management period**.

Nidderdale monthly WTD minima were higher with LB, BR, and DN managements than FI management during 2013-17 (higher by 6.96 ± 1.14 cm, 5.56 ± 1.14 cm, and 7.63 ± 1.32 cm, respectively). The elevated monthly minima were sustained for DN management during 2017-22, 3.32 ± 1.30 cm higher than FI minima. There was no significant BACI interaction for LB or BR managements during 2017-22, so the monthly minima were not different from FI management during these years. There were significant BACI interactions for all three managements in both time periods for monthly maxima. Monthly maxima were lower with LB, BR, and DN managements than FI management throughout the post-management period. Consequentially, the range of monthly WTD was lower for LB, BR, and DN managements than FI management throughout the post-management period. The difference in range between managements was particularly high during 2013-17: the monthly WTD range for FI management was greater than LB, BR, and DN managements by 12.65 ± 1.22 cm, 9.71 ± 1.22 cm, and 14.45 ± 1.41 cm respectively. This compares with 6.70 ± 1.20 cm, 2.66 ± 1.20 cm, and 9.13 ± 1.39 cm for LB, BR, and DN respectively during 2017-22. The variance of WTD was also lower for alternative managements compared with FI management. Standard deviation was lower for LB and DN managements throughout the post-management period, and lower for BR managements during 2013-17 (no significant BACI interaction for BR during 2017-22).

Mossdale showed a notable change in the impacts to WTD minima and maxima between 2013-17 and 2017-22 with the direction of impact of the alternative managements changing between the two periods. LB and BR management led to higher WTD minima and maxima during 2013-17. In 2017-22, WTD minima and maxima were lower than FI management for LB and DN management. This pattern of impact is reflected by daily WTD mean and median, which are higher in 2013-17 and lower in 2017-22 for LB and BR management compared with FI (noted in the daily WTD mean results summary). The monthly range of WTD was lower for BR management than FI management during 2013-17 and was higher for DN management than FI management during 2017-22. There were no other significant BACI effects for WTD range. Finally, the standard deviation of WTD was lower for BR and DN management than FI managements during 2013-17, with no significant BACI effects during 2017-22.

Whitendale showed WTD monthly minima and maxima following LB and BR management which were lower than for FI management throughout the post-management period. This lowering of WTD extremities is reflected by the lower daily WTD mean and median. The monthly minima were lower for DN management during 2013-17, but not 2017-22. There was also no significant BACI interaction for DN management on WTD maxima, suggesting similar response to rainfall and wet events for DN and FI managements at Whitendale. Monthly WTD range at Whitendale was higher with all three alternative managements compared with FI management in 2013-17. The high WTD range following LB management was maintained into 2017-22, whereas there were on significant BACI interactions for BR or DN managements during this time period. The standard deviation of WTD showed similar results, with higher variance for LB and DN managements than FI management during 2013-17 (higher variance for BR management in 2013-17 was marginally outside statistical significance (p=0.0538). Variance remained higher in LB plots than FI during 2017-22.

The below **Table A5.3** Provides the BACI output for the two periods **a)** May- July and **b)** November – January. Comparing mown: LB = left brash, BR = brash removed and DN = uncut (do nothing) versus burnt (FI).

a) May- July		LB		BR		DN	
		2013-17	**2017-21**	**2013-17**	**2017-21**	**2013-17**	**2017-21**
Daily mean	All sites	↑ .	↓ ***		↓ ***		↓ **
	Nidderdale	↑ ***		↑ **	↓ ***	↑ **	
	Mossdale	↑ ***		↑ ***	↓ ***		↓ ***
	Whitendale	↓ ***	↓ ***	↓ ***	↓ ***	↓ ***	
b) Nov – Jan		LB		BR		DN	
		2013-17	**2017-21**	**2013-17**	**2017-21**	**2013-17**	**2017-21**
Daily mean	All sites	↓ ***	↓ ***	↓ ***	↓ ***	↓ ***	↓ ***
	Nidderdale	↓ ***	↓ ***	↓ ***	↓ ***	↓ ***	↓ ***
	Mossdale		↓ ***	↑ **	↓ ***	↓ ***	↓ ***
	Whitendale	↓ ***	↓ ***	↓ ***	↓ *	↑ ***	↑ ***

MAY – JULY DAILY MEANS

There were impacts of the alternative managements during the months with lowest WTD and highest PAR. Across all sites overall, significant BACI interactions showed that differences from FI management emerged during 2017-22. **All three alternative managements led to lower mean WTD than FI management**, the mown managements with more substantial drop in WTD than DN. During 2017-22, LB and BR managements led to WTD 2.80 ± 0.29 cm and 2.89 ± 0.29 cm lower than FI management, respectively. DN management led to a lesser drop in WTD, 0.99 ± 0.34 cm lower than FI management during 2017-22.

WTD response to mown managements compared with FI management was similar in **Nidderdale** and **Mossdale**. **WTD was elevated in 2013-17 with LB and BR managements compared with FI management**. LB management elevated WTD 2.60 ± 0.41 cm in Nidderdale and 2.37 ± 0.24 cm in Mossdale during 2013-17. In the same time period, BR management elevated WTD 1.19 ± 0.41 cm in Nidderdale and 1.71 ± 0.24 cm in Mossdale. During 2017-22, WTD was lowered by BR management compared to FI management, by 2.36 ± 0.41 cm in Nidderdale and 1.18 ± 0.24 cm in Mossdale. The impact of LB in 2017-22 compared to FI was a non-significant. Impact of mown managements on WTD differed at **Whitendale**, with **highly significant lowering of WTD by mow relative to FI throughout the post-management period**. The impact of LB relative to FI lowered WTD by 5.28 ± 0.55 cm in 2013-17 and by 9.30 ± 0.54 cm in 2017-22. The impact of BR relative to FI lowered WTD by 5.06 ± 0.55 cm in 2013-17 and by 6.27 ± 0.54 cm in 2017-22. The impact of DN management relative to FI differed across sites. At **Nidderdale**, DN management led to WTD elevation by 1.32 ± 0.48 cm compared with FI management during 2013-17, and no significant impact during 2017-22. At **Mossdale**, WTD was lowered 3.89 ± 0.27 cm by DN management relative to FI in 2017-22, with no significant impact during 2013-17. At **Whitendale**, WTD was lowered 2.37 ± 0.62 cm by DN management relative to FI in 2013-17, with no significant impact during 2017-22.

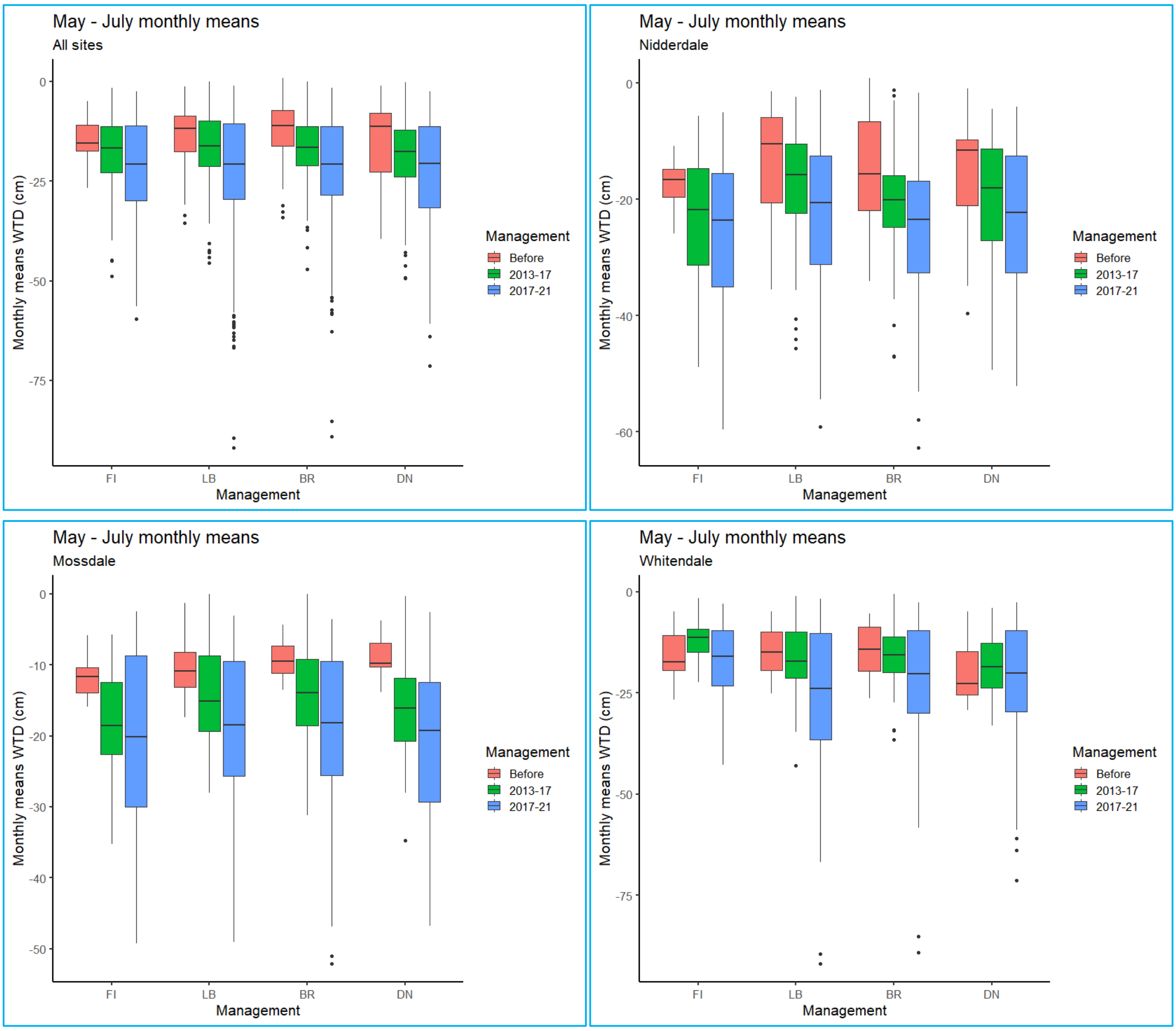
NOVEMBER – JANUARY DAILY MEANS

During the winter months with highest WTD and lowest PAR (November – January), the alternative managements, **LB, BR, and DN, caused lower daily mean WTD than FI management throughout the post-management period 2013-22**. This was highly significant when studying the overall effect across sites. The magnitude of difference between FI management and the alternative managements grew from 2013-17 to 2017-22. Mean WTD was 1.60 ± 0.12 cm lower with LB management than FI management in 2013-17, and 2.97 ± 0.12 cm lower in 2017-22. Mean WTD was 0.92 ± 0.12 cm lower with BR management than FI management in 2013-17, and 1.50 ± 0.12 cm lower in 2017-22. Mean WTD was 1.50 ± 0.14 cm lower with DN management than FI management in 2013-17, and 2.51 ± 0.14 cm lower in 2017-22.

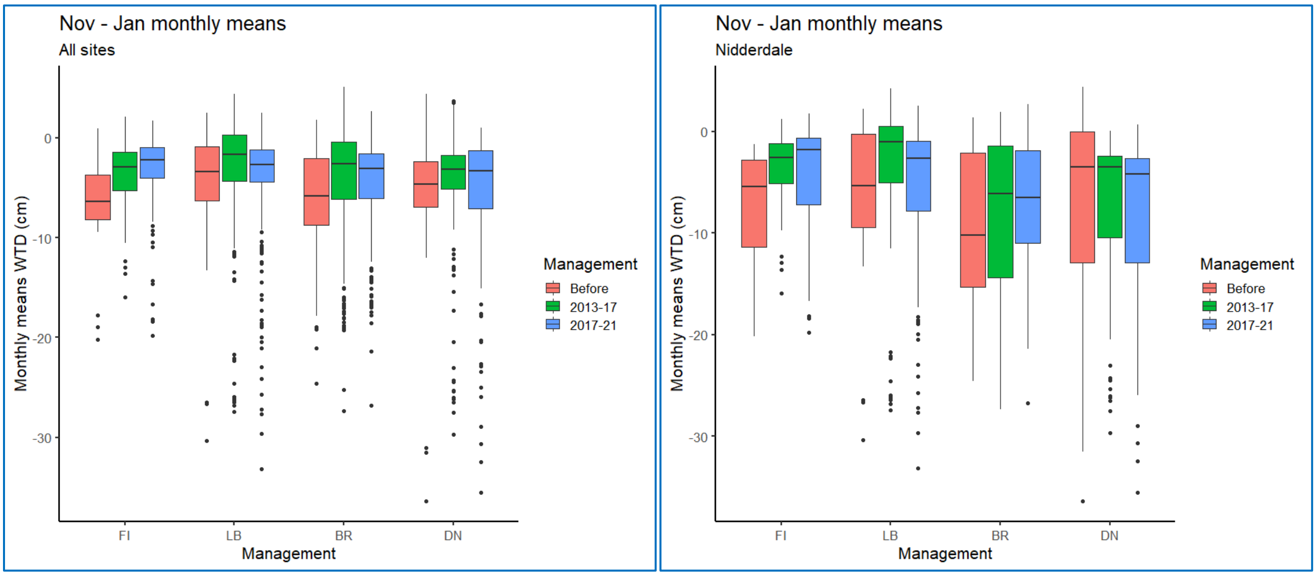
At **Nidderdale**, the alternative managements also had a lowering effect on WTD compared with FI management. The magnitude of WTD lowering compared with FI management increased from 2013-17 to 2017-22 for LB management (1.81 ± 0.22 cm in 2013-17 and 2.31 ± 0.22 cm in 2017-22), but the magnitude decreased for BR management (2.64 ± 0.22 cm in 2013-17 and 1.11 ± 0.22 cm in 2017-22). The lowering of WTD with **DN** management compared to FI management was similar across the two time periods (3.57 ± 0.26 cm in 2013-17 and 3.64 ± 0.25 cm in 2017-22). At **Mossdale, DN** management had a lowering effect on WTD across the post-management period, with magnitude increasing greatly across time periods, from 2.28 ± 0.16 cm in 2013-17 to 5.26 ± 0.16 cm in 2017-22. LB management lowered WTD by 3.92 ± 0.14 cm compared with FI during 2017-22, but there were non-significant impacts during 2013-17. The impact of BR management compared with FI management was dependent on time period. During 2013-17, WTD depth was elevated 0.41 ± 0.14 cm by BR management compared to FI. During 2017-22, WTD depth was lowered 3.12 ± 0.14 cm compared with FI management. At **Whitendale**, WTD was lowered by both mown managements relative to FI management, with a stronger difference between LB and FI than between BR and FI. WTD was 3.18 ± 0.19 cm lower with LB management in 2013-17 and 2.78 ± 0.19 lower in 2017-22. WTD was 0.84 ± 0.19 cm lower with BR management in 2013-17 and 0.38 ± 0.19 lower in 2017-22. WTD was elevated by DN management compared with FI management, by 1.05 ± 0.22 cm in 2013-17 and by 1.25 ± 0.22 cm in 2017-22.

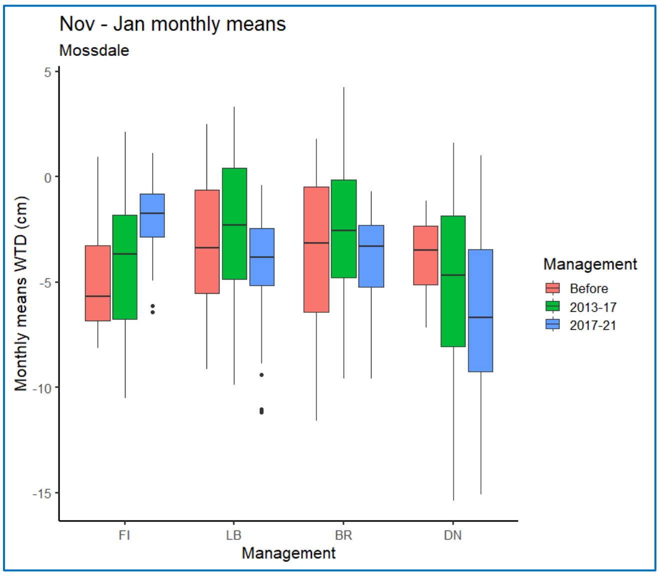
The following **Figure A5.1 a-b** shows the monthly water table depths (WTD) as seasonal averages for **a)** May-July vs **b)** November-January across all sites combined and separately. Comparing burnt (FI; fire), mown with left brash (LB) or brash removed (BR) and uncut (DN; do nothing).

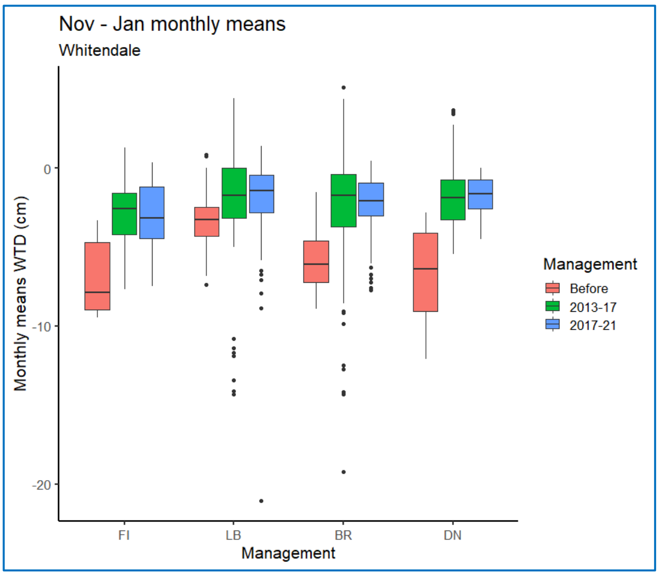
The below **Figure A5.1a** shows May-July mean monthly water table depths



The below **Figure A5.1b** shows November-January mean monthly water table depths







However, there were considerable pre-(before) management differences between sites and treatments, highlighting the importance of a Before-After Control-Impact (BACI) analysis.

The following **Table A5.4** shows the mean annual water table depths (WTD) for all sites (combined and separately) and managements (FI = burnt [fire]; Mown: LB = left brash vs. BR = brash removed; DN = uncut [do nothing]).

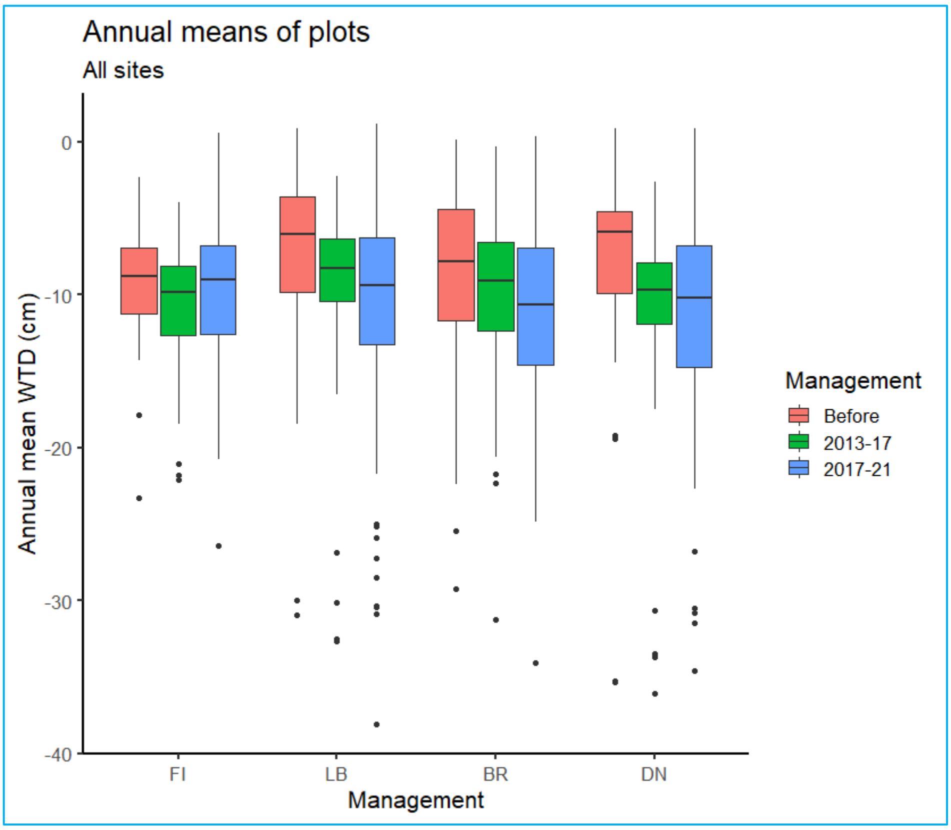
Year	All sites			
	FI	LB	BR	DN
2012-13	-10.15	-8.35	-9.36	-10.38
2013-14	-9.64	-7.73	-8.89	-10.75
2014-15	-11.65	-9.61	-10.77	-12.29
2015-16	-10.69	-8.98	-9.91	-10.96
2016-17	-9.75	-9.20	-9.46	-10.88
2017-18	-7.79	-8.97	-9.08	-9.49
2018-19	-14.33	-16.53	-16.25	-17.15
2019-20	-8.73	-9.46	-9.67	-10.76
2020-21	-9.82	-9.88	-10.14	-11.31
2021-22	-17.54	-17.78	-18.53	-18.62

Year	Nidderdale			
	FI	LB	BR	DN
2012-13	-12.51	-10.31	-12.53	-13.09
2013-14	-11.03	-9.76	-10.99	-14.92
2014-15	-14.17	-10.82	-14.11	-15.57
2015-16	-14.22	-11.20	-15.35	-14.51
2016-17	-12.45	-9.74	-13.23	-13.26
2017-18	-10.31	-11.43	-13.51	-13.66
2018-19	-16.90	-16.57	-18.51	-19.08
2019-20	-10.22	-10.06	-12.24	-13.19
2020-21	-12.32	-11.27	-13.01	-14.20
2021-22	-21.79	-18.98	-23.45	-21.93

Year	Mossdale			
	FI	LB	BR	DN
2012-13	-7.67	-6.41	-6.26	-5.92
2013-14	-9.86	-6.29	-7.19	-8.59
2014-15	-11.50	-8.80	-8.53	-10.75
2015-16	-9.27	-6.30	-5.52	-8.44
2016-17	-9.67	-9.67	-8.62	-12.35
2017-18	-6.50	-7.44	-7.05	-8.75
2018-19	-12.89	-14.14	-13.62	-15.86
2019-20	-7.84	-9.23	-8.62	-11.04
2020-21	-7.79	-8.32	-8.42	-11.39
2021-22	-15.35	-15.55	-15.85	-19.27

Year	Whitendale			
	FI	LB	BR	DN
2012-13	-10.32	-8.33	-9.30	-12.13
2013-14	-7.51	-7.16	-8.50	-8.70
2014-15	-8.51	-9.21	-9.68	-10.55
2015-16	-7.88	-9.44	-8.87	-9.92
2016-17	-6.25	-8.19	-6.52	-7.04
2017-18	-6.14	-8.05	-6.67	-6.07
2018-19	-12.83	-18.89	-16.62	-16.53
2019-20	-7.94	-9.08	-8.14	-8.05
2020-21	-9.20	-10.05	-8.99	-8.35
2021-22	-14.80	-18.80	-16.29	-14.68

The following **Figure A5.2** shows the mean annual water table depths (WTD) for all sites combined per managements (FI = burnt [fire]; Mown: LB = left brash vs. BR = brash removed; DN = uncut [do nothing]).



Overall, the annual Before-After Control-Impact (BACI) analysis revealed:

All Sites: (Means) Significant negative BACI interactions for LB, BR, and DN during 2017-21. These managements led to a lower annual mean WTD than FI management during 2017-21. Median: Similar output to mean, with significant negative BACI interactions for LB, BR, and DN during 2017-21. These managements led to a lower annual median WTD than FI management during 2017-21. Standard deviation: Only significant BACI interaction was BR : 2013-17; BR management led to lower annual variation than FI during 2013-17.

Nidderdale: (Means) No impact of mown managements or DN compared with FI during either post-management period. Median: Negative BACI interactions for LB, BR, and DN during 2017-21. These managements led to drier WTD than FI management during 2017-21. Also, a negative BACI interaction for BR and 2013-17, and slightly outside statistical significance for DN and 2013-17. Drier WTD with these managements than FI during 2013-17. Standard deviation: Significant BACI interactions for all managements in both post-management periods. LB, BR, and DN led to lower annual variance than FI management.

Mossdale: (Mean) Significant negative BACI interactions for LB, BR, and DN during 2017-21. These managements led to a lower annual mean WTD than FI management during 2017-21. Median: Significant negative BACI interactions for LB, BR, and DN during 2017-21. These managements led to a lower annual mean WTD than FI management during 2017-21. Also, a negative BACI interaction for DN and 2013-17. Drier WTD with DN than FI during 2013-17. Standard deviation: Significant negative BACI interactions for BR and both post-management period. BR management led to lower annual variation than FI during the full post-management period.

Whitendale: (Mean) Significant negative BACI interactions for LB and both post-management period. LB management led to lower annual mean WTD than FI during the full post-management period. Median: Significant negative BACI interaction for DN : 2017-21, and slightly outside statistical significance for the DN : 2013-17 interaction. DN management led to higher WTD annual median than FI management. Standard deviation: Significant BACI interactions for LB and both post-management periods, and for BR and DN with 2017-21. Interactions slightly outside statistical significance for BR and DN with 2013-17. All BACI interactions were positive, so higher annual WTD variance associated with LB, BR, and DN compared to FI.

The below **Table A5.5** provides a summary of direction and significance of BACI interactions for the mean annual water table depth for all sites combined and separately for the two post-management periods (compared to the pre-management period and the burnt (FI) management representing the overall control comparison) for the comparison of: Mown: LB = left brash vs. BR = brash removed; DN = uncut [do nothing].

		LB		**BR**		**DN**	
		2013-17	**2017-21**	**2013-17**	**2017-21**	**2013-17**	**2017-21**
Annual mean	All sites		↓ ***		↓ *		↓ *
	Nidderdale						
	Mossdale		↓ ***	↑ .	↓ **		↓ ***
	Whitendale	↓ *	↓ **				
Annual median	All sites		↓ ***		↓ **		↓ **
	Nidderdale		↓ *	↓ *	↓ *	↓ .	↓ *
	Mossdale		↓ ***		↓ ***	↓ **	↓ ***
	Whitendale					↑ .	↑ **
Annual standard deviation	All sites			↓ *			
	Nidderdale	↓ ***	↓*	↓ ***	↓ *	↓ ***	↓ ***
	Mossdale			↓ *	↓ *		
	Whitendale	↑ *	↑ **	↑ *	↑ .	↑ ***	↑ .

The below **Table A5.6** a-b (i.e. Means and Standard Deviation) provides the model output for the annual water table depths (WTD) as outlined in Table A5.2 above.

Table A5.6a ANNUAL MEANS All sites – model output

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	2013-17	-0.1255	0.7736	-0.162	0.871	-1.6418 – 1.3908
LB	**2017-22**	**-2.7318**	**0.7294**	**-3.745**	**0.000180 *****	**-4.1614 – -1.3022**
BR	2013-17	-0.3257	0.7736	-0.421	0.674	-1.1906 – 1.8420
BR	**2017-22**	**-1.5596**	**0.7294**	**-2.138**	**0.0325 ***	**-2.9891 – -0.1300**
DN	2013-17	-0.5163	0.8869	-0.582	0.561	-2.2546 – 1.2220
DN	**2017-22**	**-1.6812**	**0.8362**	**-2.011**	**0.0444 ***	**-3.3208 – -0.0423**

Nidderdale – model output

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	2013-17	0.9413	1.3080	0.720	0.472	-1.6223 – 3.5050
LB	2017-22	-1.7271	1.2332	-1.400	0.161	-4.1441 – 0.6900
BR	2013-17	0.5027	1.3080	0.384	0.701	-2.0609 – 3.0664
BR	2017-22	-1.2957	1.2332	-1.051	0.293	-3.7127 – 1.1214
DN	2013-17	-0.3327	1.5104	-0.220	0.826	-3.2930 – 2.6275
DN	2017-22	-1.1667	1.4240	-0.819	0.412	-3.9577 – 1.6242

Mossdale – model output

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	2013-17	1.1089	0.8581	1.292	0.196	-0.5730 – 2.7908
LB	**2017-22**	**-2.7946**	**0.8090**	**-3.454**	**0.000552 *****	-4.3803 – -1.2089
BR	2013-17	1.5218	0.8581	1.773	0.0762 .	-0.1601 – 3.2036
BR	**2017-22**	**-2.3451**	**0.8090**	**-2.899**	**0.00375 ****	-3.9309 – -0.7594
DN	2013-17	-1.4661	0.9909	-1.480	0.139	-3.4082 – 0.4759
DN	**2017-22**	**-5.4003**	**0.9342**	**-5.781**	**7.44e-09 *****	-7.2313 – -3.5693

Whitendale – model output

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	2013-17	-0.6583	1.4209	-0.463	0.643	-3.4432 – 2.1265
LB	2017-22	-0.9555	1.3296	-0.713	0.476	-3.5811 – 1.6700
BR	2013-17	-0.2974	1.4209	-0.209	0.834	-3.0822 – 2.4874
BR	2017-22	0.6726	1.3396	0.502	0.616	-1.9530 – 3.2982
DN	2013-17	2.9417	1.6029	1.835	0.0665 .	-0.2000 – 6.0834
DN	**2017-22**	**3.9549**	**1.5113**	**2.617**	**0.00887 ****	**0.9928 – 6.9169**

Table A5.6b ANNUAL STANDARD DEVIATIONS All sites – model output

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	2013-17	-1.1028	0.6770	-1.629	0.103	-2.4296 – 0.2241
LB	2017-22	-0.0313	0.6383	-0.049	0.961	-1.2823 – 1.2197
BR	**2013-17**	**-1.7059**	**0.6770**	**-2.520**	**0.0117 ***	**-3.0328 – -0.3790**
BR	2017-22	-0.4565	0.6383	-0.715	0.474	-1.7075 – 0.7945
DN	2013-17	-1.1729	0.7761	-1.511	0.131	-2.6941 – 0.3483
DN	2017-22	-0.7968	0.7318	-1.089	0.276	-2.2310 – 0.6374

Nidderdale – model output

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**-5.1896**	**1.0423**	**-4.979**	**6.39e-07 *****	**-7.2325 – -3.1467**
LB	**2017-22**	**-2.4689**	**0.9287**	**-2.512**	**0.0120 ***	**-4.3950 – -0.5429**
BR	**2013-17**	**-5.6507**	**1.0423**	**-5.421**	**5.92e-08 *****	**-7.6936 – -3.6078**
BR	**2017-22**	**-2.0369**	**0.9287**	**-2.073**	**0.0382 ***	**-3.9630 – -0.1109**
DN	**2013-17**	**-6.0546**	**1.2036**	**-5.031**	**4.89e-07 *****	**-8.4135 – -3.6956**
DN	**2017-22**	**-4.0926**	**1.1347**	**-3.607**	**0.00031 *****	**-6.3166 – -1.8686**

Mossdale – model output

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	2013-17	-0.4248	0.6197	-0.702	0.483	-1.6494 – 0.7798
LB	2017-22	-0.9490	0.5483	-1.624	0.104	-2.0941 – 0.1962
BR	**2013-17**	**-1.3320**	**0.6197**	**-2.149**	**0.0316 ***	**-2.5466 – -0.1174**
BR	**2017-22**	**-1.1696**	**0.5843**	**-2.002**	**0.0453 ***	**-2.3147 – -0.0245**
DN	2013-17	-1.0583	0.7156	-1.479	0.139	-2.4608 – 0.3442
DN	2017-22	-0.2767	0.6746	-0.410	0.682	-1.5989 – 1.0456

Whitendale – model output

Interactive term		Estimate	Std. Err	Z-value	P value signif	95% Conf.Int
LB	**2013-17**	**2.9768**	**1.2665**	**2.350**	**0.0188 ***	**0.4944 – 5.4591**
LB	**2017-22**	**3.5996**	**1.1941**	**3.014**	**0.00257 ****	**1.2592 – 5.9400**
BR	**2013-17**	**2.5255**	**1.2665**	**1.994**	**0.0462 ***	**0.0432 – 5.0079**
BR	2017-22	2.1127	1.1941	1.769	0.0769 .	-0.2277 – 4.4531
DN	**2013-17**	**5.2549**	**1.4289**	**2.978**	**0.00290 ****	**1.4544 – 7.0553**
DN	2017-22	2.2546	1.3471	1.674	0.0942 .	-0.3857 – 4.8949

Appendix 6 (stream flow)

BACI analyses were carried out using the raw hourly data of flow rate, from each site individually and with all sites together. Various statistical model approaches were tested and compared, generalised linear mixed modelling using Gamma and Gaussian distributions, with log and identity link functions, and with and without temporal autoregressive correlation, and generalised least square modelling with and without temporal autoregressive correlation. Autocorrelation function (ACF) and partial autocorrelation function (PACF) plots supported the use of first order autoregressive correlation. The AIC score and other diagnostic plots supported the use of generalised linear mixed modelling with a Gamma distribution and log link function. This is theoretically a logical choice, as the data is left limited with a strong right skew, and the log function enforces a positive response mean value. To account for the '0' values [i.e. no flow during drought conditions] in the response data, a negligible adjustment was used (+ 1e-16), to allow analysis with the log link function. The statistical BACI models used for the analyses were, Flow rate ~ BA * CI + Rain + (1|Site) + AR1(Date-time). The autoregressive correlation term was used on date-time, whilst site was a random effect for the analysis of all sites together. Hourly rainfall was included in the model to account for the strong impact of rainfall on flow and therefore better identify the impact of management. 'BA' is the Before/After term, and 'CI' is the Control/Impact management term.

For these analyses, the burn management is the control management, and the mown management is the impact. Therefore, reported significant BACI interactions show where mown management causes an overall effect over time that is different from burn management (considering BA). Additionally to the standard BA * CI analysis, a BACI analysis that divided the post-management period was conducted (as the overall managed catchment area increased over time). The 2012-21 post-management period was split into 2013-16 ('short-term') and 2017-21 ('long-term'), and for a separate analysis this factor was used in place of the Before/After factor. Estimated marginal means (EM means) post-hoc tests were carried out for each statistical model, giving estimated marginal means and contrasts between BACI interactions levels.

The method for the daily flow data was identical to that of the hourly data. Daily sums of flow rate and rainfall were used as response variables. The statistical models were compared, with diagnostics supporting generalised mixed models with Gamma distribution, log link function, and first order autoregressive correlation of date. Analyses were conducted for unweighted and weighted flow rates (i.e. weighted by catchment area).

Unweighted

Hourly flow data (Table A6.1): BACI analysis of the hourly time-series data showed high levels of significance for BACI interactions at all three sites, indicating different impacts between the two managements. **At Nidderdale and Mossdale, the significance of BACI interactions was extremely high, indicating a clear impact at these sites**. At Nidderdale and Mossdale, mowing caused a lower flow rate than burn management. Contrasting effects occurred at **Whitendale**, with higher flow rates from mowing compared to burn management. **Across the three sites together, the overall impact was decreased flow with mowing compared to burn**, despite the small contrasting effect at Whitendale. The effect sizes of management (**Table A6.2**) illustrate the negligible effect of management treatment on hourly flow rates at Whitendale. Hourly BACI effect sizes at Whitendale (comparing the After period to the Before period) are '< very small'. These are clearly lower than the **'small' hourly effect sizes at Mossdale** and the **'medium' and 'large' hourly effect sizes at Nidderdale**. The effect sizes at Nidderdale were relatively consistent between the short-term and long-term post-management periods. At Mossdale the immediate effect was stronger than the effect during 2017-21.

Daily flow data (Table A6.1): Effect sizes (**Table A6.2**) using daily flow data shows how smaller hourly impacts compound into much larger impact when viewed on larger time scales. The **effect size of management on daily flow rate at Nidderdale was 'very large' throughout 2013-21**. At **Mossdale, there was a 'very large' initial effect during 2013-16, followed by a 'medium' effect during 2017-21**. Again, the overall impact at **Whitendale is shown**

to be 'very small' on average across the full post-management period of 2013-21. Significant BACI interactions occurred for daily flow rates at **Nidderdale and Mossdale, with a lower daily flow rate following mown management compared to burn management**. Significant BACI interactions were recorded for the full 'After' period and when separating the post-management period into short-term and long-term. At **Whitendale, no significant BACI interactions were found for daily flow rate data**. The daily data did not have as much statistical power as the hourly data, which could explain the lack of statistical significance observed at Whitendale. Statistical analysis using **all sites together** showed significant BACI interactions, for the full 'After' period and for the separated short-term and long-term periods. **Mowing overall led to lower daily flow rates than burn management** did.

For each individual site, CI was a significant term in the model. <u>There were statistically significant differences in the flow rate between the burn and mown catchment streams prior to management</u>. BA was also a significant term for each site with hourly data, and for Nidderdale and Whitendale with daily data. **Flow was, on average, lower after (either) management than before management**. Rainfall was higher during 2012-13 than in 2013-16 or 2017-21, which could account for this. **However, the models included rainfall as a term, so the BA effect could indicate that both managements led to decreased flow rates**.

Table A6.1 True means for hourly and daily <u>unweighted</u> flow rates in the burnt (FI) and mown (M) catchments across all three sites (either combined or separately) for the three monitoring periods.

<u>All sites</u>

Study period	**Hourly flow rate (m^3 hr^{-1})**		**Daily flow sum (m^3 day^{-1})**	
	FI	**M**	**FI**	**M**
Before (2012-13)	13.953 ± 0.166	17.319 ± 0.174	334.90 ± 14.62	415.75 ± 15.95
After (2013-16)	11.479 ± 0.092	12.707 ± 0.098	276.16 ± 7.96	305.62 ± 8.74
After (2017-21)	11.949 ± 0.089	13.325 ± 0.102	286.93 ± 7.69	320.07 ± 9.12

<u>Nidderdale</u>

Study period	**Hourly flow rate (m^3 hr^{-1})**		**Daily flow sum (m^3 day^{-1})**	
	FI	**M**	**FI**	**M**
Before (2012-13)	15.684 ± 0.296	19.885 ± 0.329	376.44 ± 27.94	477.30 ± 31.32
After (2013-16)	11.597 ± 0.141	10.901 ± 0.146	279.19 ± 12.93	262.26 ± 13.10
After (2017-21)	10.347 ± 0.115	9.204 ± 0.126	248.39 ± 11.01	220.97 ± 11.66

<u>Mossdale</u>

Study period	**Hourly flow rate (m^3 hr^{-1})**		**Daily flow sum (m^3 day^{-1})**	
	FI	**M**	**FI**	**M**
Before (2012-13)	12.689 ± 0.302	14.258 ± 0.295	304.53 ± 25.34	342.26 ± 26.03
After (2013-16)	13.180 ± 0.193	12.969 ± 0.188	317.11 ± 16.34	312.16 ± 16.44
After (2017-21)	13.248 ± 0.181	12.254 ± 0.164	318.18 ± 15.41	294.42 ± 14.75

<u>Whitendale</u>

Study period	**Hourly flow rate (m^3 hr^{-1})**		**Daily flow sum (m^3 day^{-1})**	
	FI	**M**	**FI**	**M**
Before (2012-13)	13.461 ± 0.260	17.901 ± 0.273	323.11 ± 22.09	429.73 ± 24.44
After (2013-16)	9.661 ± 0.139	14.263 ± 0.173	232.19 ± 11.55	342.74 ± 15.64
After (2017-21)	12.248 ± 0.159	18.416 ± 0.221	294.09 ± 13.12	442.39 ± 19.39

Table A6.2 Effect sizes for the unweighted stream flow rates across the three sites (either combined or separately) for the three monitoring periods. Effect sizes were assigned according to: <0.2 very small; <0.5 small; <0.8 medium; <1.0 large; > 1.2 very large.

All sites

Comparison	Hourly effect size		Daily effect size	
Before vs. After	0.26 ± 0.01	Small	0.39 ± 0.06	Small
Before vs. Short-term	0.37 ± 0.01	Small	0.60 ± 0.06	Medium
Before vs. Long-term	0.22 ± 0.01	Small	0.32 ± 0.06	Small
Short vs. Long-term	0.03 ± 0.01	< Very small	0.05 ± 0.04	< Very small

Nidderdale

Comparison	Hourly effect size		Daily effect size	
Before vs. After	0.78 ± 0.02	Medium	1.30 ± 0.11	Very large
Before vs. Short-term	0.79 ± 0.02	Medium	1.43 ± 0.11	Very large
Before vs. Long-term	0.81 ± 0.02	Large	1.24 ± 0.11	Very large
Short vs. Long-term	0.07 ± 0.01	< Very small	0.12 ± 0.07	Very small

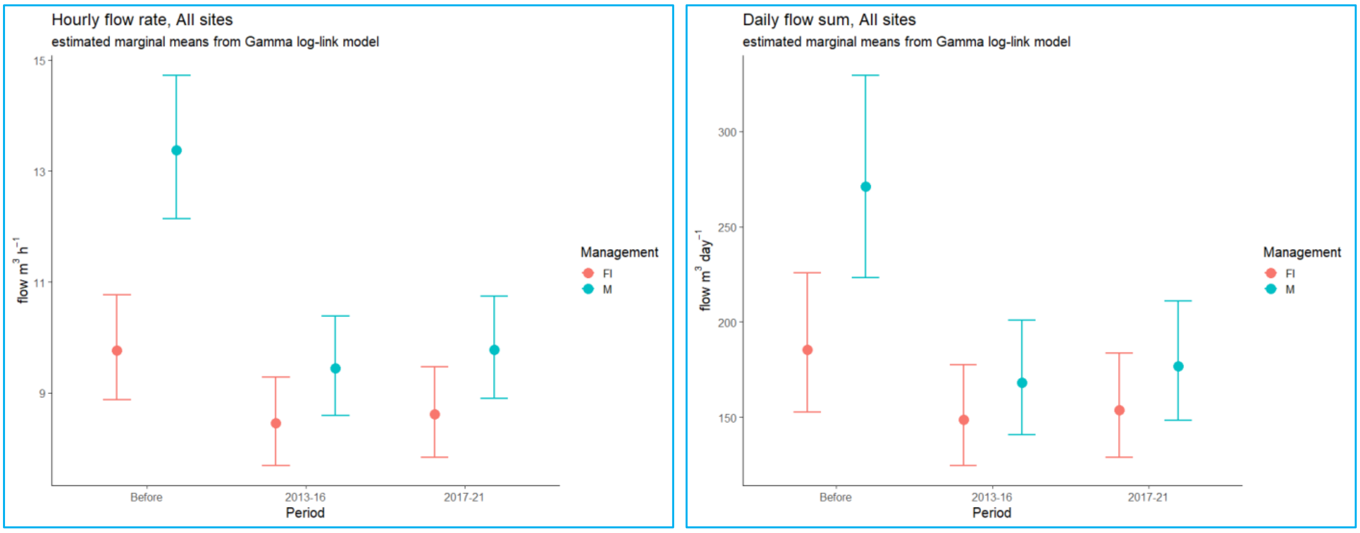
Mossdale

Comparison	Hourly effect size		Daily effect size	
Before vs. After	0.41 ± 0.02	Small	0.81 ± 0.11	Large
Before vs. Short-term	0.48 ± 0.02	Small	1.20 ± 0.11	Very large
Before vs. Long-term	0.39 ± 0.02	Small	0.70 ± 0.11	Medium
Short vs. Long-term	0.04 ± 0.01	< Very small	0.08 ± 0.07	< Very small

Whitendale

Comparison	Hourly effect size		Daily effect size	
Before vs. After	0.03 ± 0.02	< Very small	0.04 ± 0.11	< Very small
Before vs. Short-term	0.06 ± 0.02	< Very small	0.09 ± 0.11	< Very small
Before vs. Long-term	0.08 ± 0.02	< Very small	0.11 ± 0.11	Very small
Short vs. Long-term	0.12 ± 0.01	Very small	0.18 ± 0.07	Very small

The below **Figure A6.1** shows the unweighted flow rates (per hour vs per day) for the three monitoring periods as an average across all three sites comparing the burnt (FI) vs the mown (M) catchments.



<u>All sites</u> (as an example output for <u>unweighted</u> flow rates – individual sites were also investigated and the overall findings are reported above at the start of the section)

- <u>Hourly flow rate data</u>
    - Before vs. After
        - **Significant BACI interaction**
            - BA p < 2e-16 ***
            - CI p < 2e-16 ***
            - Rain p < 2e-16 ***
            - **BACI p < 2e-16 *****
    - Before vs. Short-term/Long-term
        - **Significant BACI interactions at both After periods**
            - BA short-term p < 2e-16 ***
            - BA long-term p < 2e-16 ***
            - CI p < 2e-16 ***
            - Rain p < 2e-16 ***
            - **BACI short-term p < 2e-16 *****
            - **BACI long-term p < 2e-16 *****

- <u>Daily flow rate data</u>
    - Before vs. After
        - **Significant BACI interaction**
            - BA p = 0.000174 ***
            - CI p = 8.16e-08 ***
            - Rain p < 2e-16 ***
            - **BACI p = 0.001036 ****
    - **Before vs. Short-term/Long-term**
        - Significant BACI interactions at both After periods
            - BA short-term p = 0.00012 ***
            - BA long-term p = 0.00091 ***
            - CI p = 8.11e-08 ***
            - Rain p < 2e-16 ***
            - **BACI short-term p = 0.00146 ****
            - **BACI long-term p = 0.00248 ****

- <u>Meaningful significant contrasts for Daily flow rate</u>
    - FI:Before – M:Before (p < 0.0001 ***)
        - Flow rate was higher in mown catchments than before management.
    - FI:Before – FI:Short-term (p = 0.0017 **)
    - FI:Before – FI:Long-term (p = 0.0117 *)
        - Flow rate decreased in burn catchments after management
    - M:Before – M:Short-term (p < 0.0001 ***)
    - M:Before – M:Long-term (p < 0.0001 ***)
        - Flow rate decreased in mown catchments after management
    - FI:Short-term – M:Short-term (p = 0.0192 *)
        - Flow rate was higher in mown catchments than burn catchments during 2013-16.
    - FI:Long-term – M:Long-term (p = 0.0012 **)
        - Flow rate was higher in mown catchments than burn catchments during 2017-21.

Weighted

Hourly flow data

BACI analysis of the catchment area weighted hourly time-series data showed high levels of significance for BACI interactions at all three sites, indicating different impacts between the two managements. **At Nidderdale and Mossdale, the significance of BACI interactions was extremely high, indicating a clear impact at these sites**. At Nidderdale and Mossdale, mowing caused a lower flow rate than burn management. Contrasting effects occurred at **Whitendale**, with higher flow rates from mowing compared to burn management. **Across the three sites together, the overall impact was decreased flow with mowing compared to burn**, despite the small contrasting effect at Whitendale. The effect sizes of management illustrate the negligible effect of management treatment on hourly flow rate at Whitendale. Hourly BACI effect sizes at Whitendale (comparing the After period to the Before period) are '< very small' or 'very small', clearly lower than the effect sizes at Nidderdale or Mossdale. The effect sizes at Nidderdale were relatively consistent between the short-term and long-term post-management periods (0.48 during 2013-16 and 0.52 during 2017-21). At Mossdale the immediate effect was marginally stronger than the effect during 2017-21, albeit the effect size was also relatively constant (0.32 in 2013-16 and 0.27 in 2017-21).

Daily flow data

Effect sizes using catchment area weighted daily flow data shows how smaller hourly impacts compound into much larger impact when viewed on larger time scales. The **effect size of management on daily flow rate at Nidderdale was 'medium' throughout 2013-21**. At **Mossdale, there was a 'medium' initial effect during 2013-16, followed by a 'small' effect between 2017-21**. The overall impact at **Whitendale is less than at Nidderdale or Mossdale, with 'very small' effects across the full post-management period of 2013-21, albeit with a 'small' effect in 2017-21.** Significant BACI interactions occurred for daily flow rate at **Nidderdale and Mossdale, with a lower daily flow rate following mown management compared to burn management**. Significant BACI interactions were recorded for the full 'After' period and when separating the post-management period into short-term and long-term. At **Whitendale, no significant BACI interactions were found for daily flow rate data**. The daily data did not have as much statistical power as the hourly data, which could explain the lack of statistical significance observed at Whitendale. Statistical analysis using **all sites together** showed significant BACI interactions, for the full 'After' period and for the separated short-term and long-term periods. **Mowing overall led to lower daily area weighted flow rates than burn management** did.

At Whitendale, CI was a highly significant term in the model, denoting strong differences in the flow rate of the burnt and mown catchments at this site before management began. The CI term was non-significant at Mossdale. At Nidderdale it had low significance when using hourly resolution, and no significance with daily resolution. BA was also a significant term for each site with hourly data, and for Nidderdale and Whitendale with daily data. **Flow was, on average, lower after management than before management, for both burn and mown managements**. Rainfall was higher during 2012-13 than in 2013-16 or 2017-21, which could account for this. **However, the models included rainfall as a term, so the BA effect could indicate that both managements led to decreased area weighted flow rates**.

Table A6.3 True means for hourly and daily catchment-area weighted flow rates in the burnt (FI) and mown (M) catchments across all three sites (either combined or separately) for the three monitoring periods.

All sites

Study period	**Hourly flow rate (m^3 hr^{-1} ha^{-1})**		**Daily flow sum (m^3 day^{-1} ha^{-1})**	
	FI	**M**	**FI**	**M**
Before (2012-13)	1.517 ± 0.018	1.487 ± 0.015	36.446 ± 1.586	35.725 ± 1.369
After (2013-16)	1.264 ± 0.010	1.124 ± 0.009	30.369 ± 0.892	27.017 ± 0.793
After (2017-21)	1.331 ± 0.010	1.189 ± 0.009	31.976 ± 0.879	28.560 ± 0.829

Nidderdale

Before (2012-13)	**1.425 ± 0.027**	**1.418 ± 0.023**	**34.222 ± 2.540**	**34.093 ± 2.237**
After (2013-16)	1.057 ± 0.013	0.780 ± 0.010	25.381 ± 1.175	18.733 ± 0.935
After (2017-21)	0.940 ± 0.010	0.657 ± 0.009	22.540 ± 1.001	15.783 ± 0.833

Mossdale

Before (2012-13)	**1.509 ± 0.036**	**1.424 ± 0.029**	**36.254 ± 3.017**	**34.226 ± 2.603**
After (2013-16)	1.571 ± 0.023	1.299 ± 0.019	37.751 ± 1.945	31.216 ± 1.644
After (2017-21)	1.577 ± 0.022	1.226 ± 0.016	37.879 ± 1.835	29.442 ± 1.475

Whitendale

Before (2012-13)	**1.621 ± 0.031**	**1.627 ± 0.025**	**38.929 ± 2.662**	**39.067 ± 2.222**
After (2013-16)	1.165 ± 0.017	1.297 ± 0.016	27.975 ± 1.391	31.158 ± 1.421
After (2017-21)	1.475 ± 0.019	1.674 ± 0.020	35.432 ± 1.581	40.217 ± 1.762

Table A6.4 Effect sizes for the catchment-area weighted stream flow rates across the three sites (either combined or separately) for the three monitoring periods. Effect sizes were assigned according to: <0.2 very small; <0.5 small; <0.8 medium; <1.0 large; > 1.2 very large.

All sites

Comparison	Hourly effect size		Daily effect size	
Before vs. After	0.17 ± 0.01	Very small	0.29 ± 0.06	Small
Before vs. Short-term	0.22 ± 0.01	Small	0.41 ± 0.06	Small
Before vs. Long-term	0.15 ± 0.01	Very small	0.24 ± 0.06	Small
Short vs. Long-term	0.02 ± 0.01	< Very small	0.04 ± 0.04	< Very small

Nidderdale

Comparison	Hourly effect size		Daily effect size	
Before vs. After	0.48 ± 0.02	Small	0.70 ± 0.11	Medium
Before vs. Short-term	0.49 ± 0.02	Small	0.76 ± 0.11	Medium
Before vs. Long-term	0.52 ± 0.02	Medium	0.72 ± 0.11	Medium
Short vs. Long-term	0.02 ± 0.01	< Very small	0.03 ± 0.07	< Very small

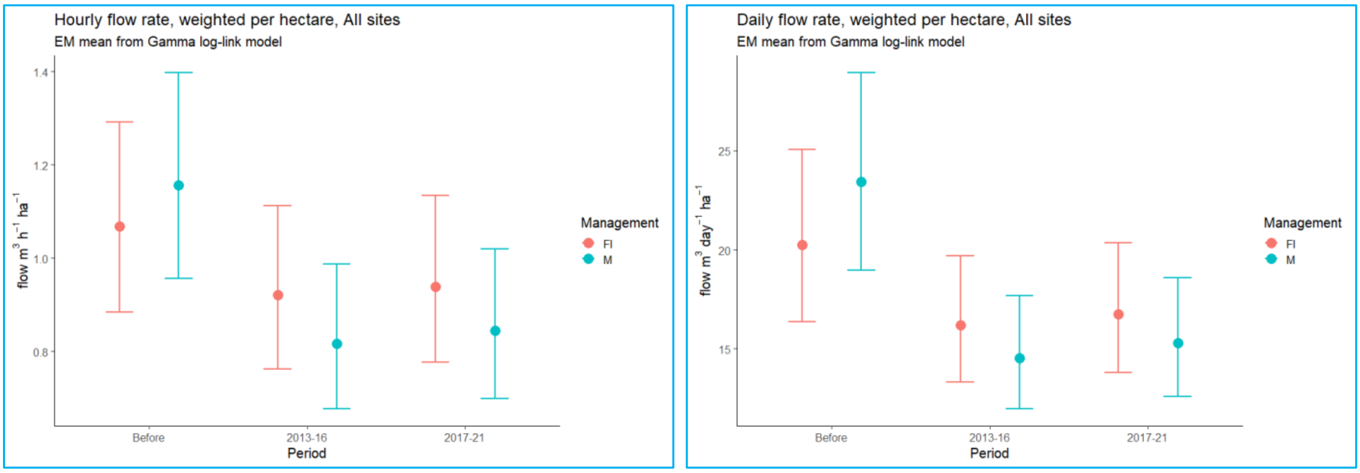
Mossdale

Comparison	Hourly effect size		Daily effect size	
Before vs. After	0.28 ± 0.02	Small	0.49 ± 0.11	Small
Before vs. Short-term	0.32 ± 0.02	Small	0.62 ± 0.11	Medium
Before vs. Long-term	0.27 ± 0.02	Small	0.46 ± 0.11	Small
Short vs. Long-term	0.02 ± 0.01	< Very small	0.04 ± 0.07	< Very small

Whitendale

Comparison	Hourly effect size		Daily effect size	
Before vs. After	0.09 ± 0.02	< Very small	0.17 ± 0.11	Very small
Before vs. Short-term	0.05 ± 0.02	< Very small	0.11 ± 0.11	Very small
Before vs. Long-term	0.11 ± 0.02	Very small	0.20 ± 0.11	Small
Short vs. Long-term	0.09 ± 0.01	< Very small	0.17 ± 0.07	Very small

The below **Figure A6.2** shows the catchment-area weighted flow rates (per hour vs per day) for the three monitoring periods as an average across all three sites comparing the burnt (FI) vs the mown (M) catchments.



All sites (as an example output for area weighted flow rates – individual sites were also investigated and the overall findings are reported above at the start of the section)

- Hourly flow rate data
    - Before vs. After
        - **Significant BACI interaction**
            - BA p < 2e-16 ***
            - CI p = 6.72e-07 ***
            - Rain p < 2e-16 ***
            - **BACI p < 2e-16** ***
    - Before vs. Short-term/Long-term
        - **Significant BACI interactions at both After periods**
            - BA short-term p < 2e-16 ***
            - BA long-term p < 2e-16 ***
            - CI p = 6.74e-07 ***
            - Rain p < 2e-16 ***
            - **BACI short-term p < 2e-16** ***
            - **BACI long-term p < 2e-16** ***
- Daily flow rate data
    - Before vs. After
        - **Significant BACI interaction**
            - BA p = 0.000152 ***
            - CI p = 0.041017 *
            - Rain p < 2e-16 ***
            - **BACI p = 0.001244** **
    - **Before vs. Short-term/Long-term**
        - Significant BACI interactions at both After periods
            - BA short-term p = 0.000106 ***
            - BA long-term p = 0.000818 ***
            - CI p = 0.040952 ***
            - Rain p < 2e-16 ***
            - **BACI short-term p = 0.001808** **
            - **BACI long-term p = 0.002817** **

- Meaningful significant contrasts for Daily flow rate
  - FI:Before – FI:Short-term (p = 0.0015 **)
  - FI:Before – FI:Long-term (p = 0.0106 *)
    - Flow rate **decreased** in **burn** catchments **after** management
  - M:Before – M:Short-term (p < 0.0001 ***)
  - M:Before – M:Long-term (p < 0.0001 ***)
    - Flow rate **decreased** in **mown** catchments **after** management
  - FI:Short-term – M:Short-term (p = 0.0641 .)
    - Flow rate was **lower** in **mown** catchments than **burn** catchments during **2013-16**. This contrast was narrowly **outside statistical significance**.

Peak flow analysis:

The aim of this analysis was to identify **how management treatment affected the nature of flow peak flushes following rainfall events**. The site mean was used as the threshold to find peaks in the rainfall data, and specified a minimum peak distance of 24 hours and then peaks in flow rate that immediately followed the rainfall peaks were identified that were above the 75th percentile. High rainfall and peak flow events were only included in the data when they occurred at both catchments in a site, so as to make a sound comparison between management treatments (the below analysis compares mown to burnt catchments, so a negative value indicates lower values for the mown vs. burnt peak flow rate, lag time, duration). These response variables were studied individually using linear mixed-effect models that incorporated a BACI fixed-effect structure, with Date as a random effect.

The three response variables studied were:

1. Peak flow: the **maximum hourly flow rate** following rainfall events, in m^3 ha^{-1}.
2. Peak lag: the **time lag**, in hours (hr), between peak rainfall and peak flow
3. Peak duration: the **duration**, in hours, for which peak flow remained above the 75th percentile following a peak rainfall event.

Table A6.5: Model output (negative number indicates lower values in mown vs. burnt streams)

		Peak flow (m^3 hr^{-1} ha^{-1})	**Peak lag (hours)**	**Peak duration (hours)**
Nidderdale	2013-16	**-1.168 ± 0.280 *****	**+1.298 ± 0.283 *****	*+0.788 ± 2.643*
	2017-21	**-1.389 ± 0.277 *****	**+1.179 ± 0.280 *****	*+2.708 ± 2.617*
Mossdale	2013-16	*-0.669 ± 1.018*	*-0.257 ± 0.196*	*-0.594 ± 1.879*
	2017-21	**-3.219 ± 1.015 ****	*+0.069 ± 0.196*	*-0.775 ± 1.873*
Whitendale	2013-16	*+1.290 ± 1.127*	**-0.561 ± 0.253 ***	*-1.984 ± 2.011*
	2017-21	**+2.189 ± 1.110 ***	**-0.509 ± 0.249 ***	-3.829 ± 1.981 .
All sites	2013-16	*-0.168 ± 0.833*	*+0.011 ± 0.251*	*-0.802 ± 1.552*
	2017-21	*-0.797 ± 0.826*	*+0.133 ± 0.249*	*-1.000 ± 1.538*

Table A6.5 Effect sizes Effect sizes were assigned according to: <0.2 very small; <0.5 small; <0.8 medium; <1.0 large; > 1.2 very large.

Peak Flow						
	Before vs 2013-16		**Before vs 2017-21**		**2013-16 vs 2017-21**	
Nidderdale	**-0.94 ± 0.37**	**Large**	**-0.83 ± 0.37**	**Large**	-0.12 ± 0.22	Very small
Mossdale	-0.20 ± 0.35	Small	**-0.46 ± 0.35**	**Small**	**-0.43 ± 0.19**	**Small**
Whitendale	**+0.37 ± 0.32**	**Small**	+0.26 ± 0.32	Small	+0.13 ± 0.19	Very small
All sites	-0.06 ± 0.20	< Very small	-0.11 ± 0.20	Very small	-0.10 ± 0.11	Very small

Peak Lag						
	Before vs 2013-16		**Before vs 2017-21**		**2013-16 vs 2017-21**	
Nidderdale	**+0.92 ± 0.37**	**Large**	**+0.78 ± 0.37**	**Medium**	-0.08 ± 0.22	< Very small
Mossdale	-0.23 ± 0.35	Small	+0.06 ± 0.35	< Very small	**+0.28± 0.19**	**Small**
Whitendale	**-0.52 ± 0.32**	**Medium**	-0.28 ± 0.32	Small	+0.03 ± 0.19	< Very small
All sites	+0.00 ± 0.20	< Very small	+0.08 ± 0.20	< Very small	+0.08 ± 0.11	< Very small

Peak Duration						
	Before vs 2013-16		**Before vs 2017-21**		**2013-16 vs 2017-21**	
Nidderdale	+0.03 ± 0.37	< Very small	+0.20 ± 0.37	Small	+0.14 ± 0.22	Very small
Mossdale	-0.06 ± 0.35	< Very small	-0.07 ± 0.35	< Very small	-0.02 ± 0.19	< Very small
Whitendale	-0.16 ± 0.32	Very small	-0.31 ± 0.32	Small	-0.15 ± 0.19	Very small
All sites	-0.07 ± 0.20	< Very small	-0.08 ± 0.20	< Very small	-0.01 ± 0.11	< Very small

Table A6.6 LS means of BACI linear mixed-effect models comparing burnt (FI) to mown (M) catchments

		Peak flow (m^3 hr^{-1} ha^{-1})		**Peak lag (hours)**		**Peak duration (hours)**	
		FI	M	FI	M	FI	M
Nidderdale	Before	8.27 ± 0.91	7.72 ± 0.91	2.86 ± 0.41	2.86 ± 0.41	23.5 ± 2.78	23.5 ± 2.78
	Aft.ST	9.16 ± 0.43	7.45 ± 0.43	2.84 ± 0.20	4.14 ± 0.20	26.6 ± 1.38	27.4 ± 1.38
	Aft.LT	8.12 ± 0.43	6.18 ± 0.43	2.60 ± 0.19	3.78 ± 0.19	30.4 ± 1.31	33.1 ± 1.31
Mossdale	Before	10.85 ± 1.57	7.99 ± 1.57	2.00 ± 0.36	1.89 ± 0.36	23.8 ± 2.72	24.4 ± 2.72
	Aft.ST	15.04 ± 0.64	11.51 ± 0.64	2.93 ± 0.15	2.56 ± 0.15	27.6 ± 1.11	27.7 ± 1.11
	Aft.LT	17.70 ± 0.63	11.62 ± 0.63	2.91 ± 0.14	2.88 ± 0.14	29.8 ± 1.09	29.7 ± 1.09
Whitendale	Before	13.13 ± 1.55	8.85 ± 1.55	2.52 ± 0.34	3.41 ± 0.34	21.5 ± 2.17	25.7 ± 2.17
	Aft.ST	12.84 ± 0.75	9.85 ± 0.75	2.46 ± 0.17	2.79 ± 0.17	25.7 ± 1.04	27.9 ± 1.04
	Aft.LT	17.30 ± 0.68	15.21 ± 0.68	2.75 ± 0.15	3.13 ± 0.15	24.7 ± 0.96	25.0 ± 0.96
All sites	Before	10.59 ± 2.25	7.90 ± 2.25	2.51 ± 0.29	2.82 ± 0.29	22.7 ± 2.04	24.5 ± 2.04
	Aft.ST	11.49 ± 2.03	8.63 ± 2.03	2.81 ± 0.18	3.13 ± 0.18	26.5 ± 1.27	27.5 ± 1.27
	Aft.LT	14.18 ± 2.03	10.69 ± 2.03	2.77 ± 0.18	3.21 ± 0.18	28.9 ± 1.25	29.7 ± 1.25

All sites

Peak flow

- There was **no overall significant BACI term** across all sites.
- Effect sizes were also '< very small' during 2013-16 and 'very small' during 2017-21.
- However, **LS means contrasts reported a significant increase in peak flow in FI catchments during 2017-21**. The peak flow in FI catchments during 2017-21 were 3.59 ± 1.17 m^3 hr^{-1} higher than the pre-management period (p=0.0269 *) and 2.70 ± 0.66 m^3 hr^{-1} higher than the 2013-16 period (p=0.0006 ***). The increases in the M managed catchments were non-significant. Despite these LS means contrasts, **the BACI interactions were non-significant, suggesting no statistically significant difference between the managements across sites overall**.

Peak lag

- There was **not an overall significant BACI term** across all sites.
- Effect sizes were also '< very small' across the post-management period.

Peak duration

- There was **not an overall significant BACI term** across all sites.
- Effect sizes were also '< very small' across the post-management period.

LS means contrasts showed **significant increase in duration from the pre-management to the 2017-21 period by 6.22 ± 1.94 hours for FI catchments** (p=0.178 *). Increased duration from pre-management to 2017-21 for M catchments of 5.22 ± 1.94 hours were narrowly outside statistical significance (0.0794 .)

<u>Nidderdale</u>

Peak flow

- There were significant **BACI interaction for both After periods** (p < 0.0001 ***).
- The statistical model suggests a **1.168 ± 0.280 m^3 ha^{-1} decrease in peak flow with mown management compared to burn management in 2013-16**. This if followed by a **1.389 ± 0.277 m^3 ha^{-1} decrease with mown management compared to burn management in 2017-21.**
- The BACI effect size shows a **'large' effect** of management that is sustained across the full post-management period.
- **Peak flow is higher in FI catchment than M catchment**, which corresponds to the more saturated ground prone to flooding in Nidderdale FI catchment during November – January.

Peak lag

- There was a significant **BACI interaction for both After periods** (p < 0.0001 ***).
- Comparing the least square means suggests **1.298 ± 0.283** hours **increased delay in peak lag with mown management compared to burn management during 2013-16, and increased delay of 1.179 ± 0.280 during 2017-21**.
- The effect size of management on the peak lag was **'large' during 2013-16** and decreased slightly to **'medium' during 2017-21**, remaining statistically significant throughout.

Peak duration

- There was **no significant BACI term**, suggesting **no statistically-significant impact of M management relative to FI management on the duration of peaks**.
- The effect size was **'< very small'** for the 2013-16 period and increased to **'small'** during 2017-21, the effect size was not statistically significant during either period.
- LS means contrasts showed **a significant increase in peak duration for the M catchment during 2017-21**. Peak duration during 2017-21 was 9.56 ± 3.07 hours longer than the pre-management period (p=0.0241 *) and 5.71 ± 1.90 hours longer than during 2013-16 (p=0.0331 *).

<u>Mossdale</u>

Peak flow

- There was a **significant BACI interaction during the 2017-21 period** (p = 0.00161 **), with **peak flow 3.219 ± 1.015 m^3 hr^{-1} lower with M management relative to FI management**.

- There was **no significant BACI interaction during the initial 2013-16 period**.
- The effect sizes reflect the delayed impact of management to peak flow, with **effect size increasing by a statistically significant amount between the two post-management periods**.
- LS mean contrasts showed **significant increases in peak flow in the FI managed catchment from the 'Before' period to the 2017-21 period** (increase of 6.85 ± 1.68 m^3 hr^{-1}, p=0.0008 ***), and also significant increases from the 2013-16 to the 2017-21 period (increase of 2.66 ± 0.90 m^3 hr^{-1}, p=0.0367 *). There were no statistically significant increases through time for the M managed catchment.
- These results also **fit with previously reported results of WTD rising in FI plots during the latter years at Mossdale**.

Peak lag

- There was **no significant BACI term**, suggesting no impact of M management relative to FI management on the lag of flow peaks.
- Effect sizes for the post-management periods compared with the 'Before' period were non-significant. There was, however, a significant effect size between the two post-management periods: a **significant 'small' positive effect size showing increased peak lag with M management relative to FI management between 2013-16 and 2017-21**.

Peak duration

- There was **no significant BACI term**, suggesting no impact of M management relative to FI management on the duration of flow peaks.
- Effect sizes were '< very small' throughout.

Whitendale

Peak flow

- There was a **significant BACI interaction during the 2017-21 period** (p = 0.00161 **), with **peak flow 2.189 ± 1.110 m^3 hr^{-1} higher with M management relative to FI management.**
- There was **no significant BACI interaction during the initial 2013-16 period**.
- However, this was not reflected in the effect sizes, which showed a significant 'small' effect in 2013-16 and a non-significant 'small' effect in 2017-21.
- **LS mean contrasts showed significant increases in both catchments from 2013-16 to 2017-21**. The peak flow in the FI catchment increased by 4.46 ± 1.01 m^3 hr^{-1} during this period (p=0.0002 ***), and the peak flow in the M catchment increased by 5.36 ± 1.01 m^3 hr^{-1} (p<0.0001 ***).

Peak lag

- There were **significant BACI interactions for both post-management periods**.
- Lag was **decreased by M management relative FI management** by 0**.561 ± 0.253 hours during 2013-16** (p=0.0271 *) and by 0**.509 ± 0.249 hours during 2017-21** (p=0.0418 *).
- The BACI effect size reflects that the effect was larger during the 2013-16 period, with a significant 'medium' effect size. The effect size during the 2017-21 period was non-significant and 'small'.

Peak duration

- There was **no significant BACI term**.
- However, the BACI term for 2017-21 was narrowly outside statistical significance (p=0.0538 .), with a decreased peak duration for M managed catchment by 3.829 ± 1.981 hours relative to FI management.
- This is reflected in the effect size, which is '< very small' during 2013-16 and 'small' during 2017-21. The effect size for 2017-21 is also narrowly outside significance.

Flow rate at high WTD and high rainfall:

WTD was measured every 6 hours, whereas rainfall and flow rate were measured every hour and the following steps ensured to amalgamate the datasets. To adjust the WTD data, WTD was rounded down to 6-hour marks (00:00, 06:00, 12:00, 18:00). With the flow data, the initial start date was set to 17/4/2012 06:00 to match the WTD data and the data was then aggregated every 6 hours. The dataframes were then merged by date-time, giving dataframes containing WTD measurements every 6 hours and corresponding rainfall and flow rate sums for the 6 hour period. A lag on the WTD measurements was also defined, to give WTD values that followed the rainfall data for each data-point. From these, WTD rise for each 6-hour period was calculated.

WTD varied between Before vs. After management. Therefore, a percentile threshold was used to standardise the approach of selecting high WTD with high rainfall events, i.e. the selected times when WTD and rainfall were both above their respective 75th percentiles. Moreover, only times for which WTD and rainfall were above the 75th percentile for both catchments in each site (FI and M catchments) were included. At Whitendale, the threshold was lowered to the 70th percentile. This was because the FI catchment had a lower WTD depth than the M catchment, so very few WTD recordings from the FI catchment were above the 75th percentile pre-management. Moreover, plot 4 from Whitendale was omitted from the WTD data, as throughout the previous WTD analyses.

To analyse the data, a linear mixed effects models was used with a BACI structure. The models also incorporated rainfall and WTD, to account for the variation associated with these variables. Datetime was included as a random effect, and site was a random effect when studying all sites.

Flow ~ BA*CI + WTD + rainfall + (1|Datetime)

BACI output all sites overall pre- vs. post-management periods

There were no significant terms in the BACI model when grouping data from all sites together. Furthermore, the effect size showed only a small effect. Different responses were found at the three sites: management at Nidderdale & Mossdale caused significant decreases in flow and there was no effect at Whitendale. This site variation means that overall effects are difficult to discern as shown by no significant BA:CI interaction for all sites combined:

- Non-significant BA:CI interaction (p = 0.115).
    - **Small effect size (0.363).**
- Highly significant effect of rainfall (***) and WTD (***).
- No meaningful significant contrasts given by least-square means post-hoc test

Table A6.7 LS means from the BACI linear mixed-effect models (overall post-management period) which can be derived by subtraction [(FI:After - FI:Before) - (M:After - M:Before)]. For example, for Mossdale, flow increases by 13 in FI catchment, and by 4.4 in M catchment. So the difference between them is 8.6.

		6-hourly flow rate (m^3 ha^{-1}) at high WTD	
		FI (burnt)	M (mown)
Nidderdale	Before	33.9 ± 1.98	32.5 ± 1.98
	After	29.9 ± 0.53	22.7 ± 0.52
Mossdale	Before	41.6 ± 3.59	39.8 ± 3.52
	After	54.6 ± 0.78	44.2 ± 0.78
Whitendale	Before	28.9 ± 4.62	25.8 ± 4.58
	After	31.4 ± 0.70	30.9 ± 0.70
All sites	Before	39.0 ± 4.23	36.6 ± 4.23
	After	36.6 ± 3.62	31.2 ± 3.62

BACI analysis all sites with expanded Before/After structure, including separate management phases

Again, whilst there were significant, albeit contrasting differences at the site level, overall there were no significant management effects when combining all sites.

- **Nidderdale**: Impact of management given by post-hoc least-square means
  - Mown management led to **4.9 m^3 ha^{-1} lower flow at high WTD** than burn management during the 2nd management phase (2015-18). This value is over a 6-hour period.
  - Mown management led to **5.2 m^3 ha^{-1} lower flow at high WTD** than burn management during the 3rd management phase (2018-21). This value is over a 6-hour period.

- **Mossdale**: Impact of management given by post-hoc least-square means
  - Mown management led to **19 m^3 ha^{-1} lower flow at high WTD** than burn management during the 1st management phase (2013-15). This value is over a 6-hour period.
  - Mown management led to **5.3 m^3 ha^{-1} lower flow at high WTD** than burn management during the 2nd management phase (2015-18). This value is over a 6-hour period.
  - Mown management led to **8 m^3 ha^{-1} lower flow at high WTD** than burn management during the 3rd management phase (2018-21). This value is over a 6-hour period.

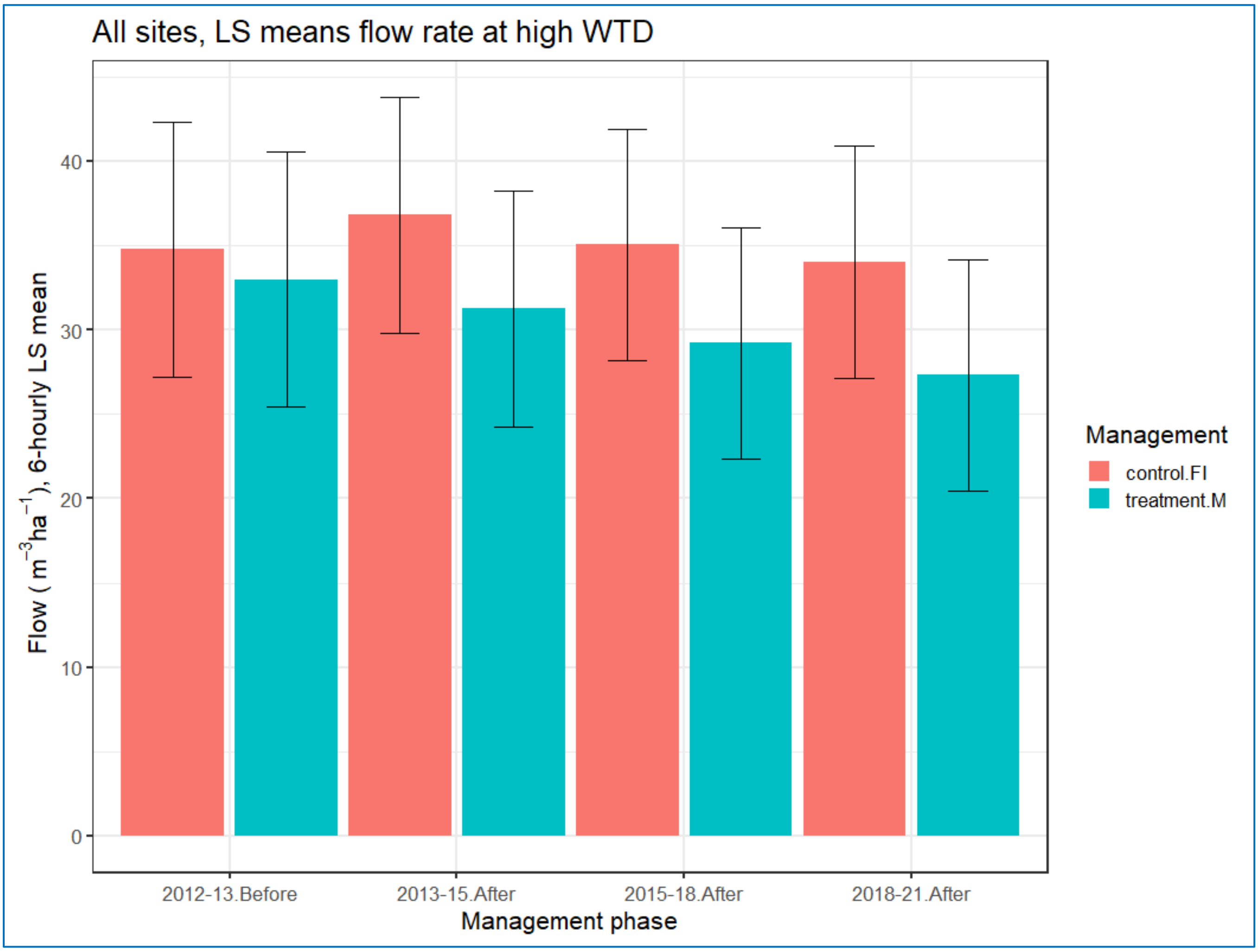
- **Whitendale**: Impact of management given by post-hoc least-square means
  - Mown management led to **4.4 m^3 ha^{-1} higher flow at high WTD** than burn management during the 1st management phase (2013-15). This value is over a 6-hour period.
  - Mown management led to **3.9 m^3 ha^{-1} higher flow at high WTD** than burn management during the 3rd management phase (2018-21). This value is over a 6-hour period.

- **ALL SITES** (Nidderdale, Mossdale, Whitendale combined)
- No significant BA:CI interactions for any management phase
- Significant BA term, with lower flow at high WTD for both management types in all three management phases, 2013-15 (p = 0.0091 **), 2015-18 (p = 0.0023 **), and 2018-21 (p = 0.020 *).
- Rainfall (***) and WTD (***) were also highly significant terms in the model.
- BACI effect sizes comparing each ‘After’ phase with the ‘Before’ phase
  - 1st phase, 2013-15, BACI effect size = **0.392 (small)**
  - 2nd phase, 2015-18, BACI effect size = **0.421 (small)**
  - 3rd phase, 2018-21, BACI effect size = **0.345 (small)**
- Impact of management given by post-hoc least-square means
  - No significant differences
- Meaningful significant contrasts given by least-square means post-hoc test
  - Control.FI:2012-13.B – Control.FI:2015-18.A (p = 0.0467 *)
  - Treatment.M:2012-13.B – Treatment.M:2015-18.A (p = 0.0024 **)
  - Treatment.M:2012-13.B – Treatment.M:2018-21.A (p = 0.0101 *)

Table A6.8 LS means of BACI linear mixed-effect models (separate post-management periods) which can be derived by subtraction [(FI:After - FI:Before) - (M:After - M:Before)].

		6-hourly flow rate (m^3 ha^{-1}) at high WTD	
		FI (burnt)	M (mown)
Nidderdale	Before	37.4 ± 2.12	35.9 ± 2.11
	1.After	26.9 ± 1.20	26.2 ± 1.08
	2.After	27.2 ± 0.91	20.8 ± 0.75
	3.After	31.5 ± 0.79	24.8 ± 0.83
Mossdale	Before	44.5 ± 3.64	42.5 ± 3.62
	1.After	69.8 ± 2.64	48.8 ± 2.60
	2.After	53.8 ± 1.14	46.5 ± 1.14
	3.After	51.6 ± 1.21	41.6 ± 1.16
Whitendale	Before	32.4 ± 4.67	28.0 ± 4.56
	1.After	22.8 ± 1.66	22.8 ± 1.66
	2.After	33.1 ± 1.03	31.5 ± 1.04
	3.After	33.6 ± 1.12	33.1 ± 1.08

The below **Figure A6.3** shows the LS means (model output) for the catchment area weighted flow rate (6-hourly) comparing the burnt (FI) vs. the mown (M) catchment streams across all sites for the pre- and subsequent three post-management periods (management happened in 2013, 2015, 2018 and 2021).



Comparing runoff from saturated versus unsaturated (i.e. burnt vs. mown) catchments:

This analysis was done to test if a catchment management with an already very wet round could exacerbate flooding as storage would likely be limited in a saturated peat (especially as mown catchments were initially wetter).

Analysis of flow when one catchment is wet and the other drier (or less wet)

- Datasets were created for the following conditions
    - Saturated catchment WTD 0 - -5 cm
    - Dry catchment WTD < 5 cm
    - Difference between the catchments WTD > 2 cm
- These datasets were created for when FI was saturated and for when M was saturated.
- Tested with hourly rainfall mean > 5 m^3 ha^{-1} hr^{-1}.
- 6-hourly flow data & daily means were both tested.
- Paired t-tests were used to directly compare the paired flow recordings
- Generalised mixed effect models were used for additional analyses to compare the flow
    - Gamma log-link models were used
- Normal mixed effect models were used to study the change in time of the difference between catchments.

6-hourly data example for rainfall > 5 m^3 ha^{-1} hr^{-1}

- When FI catchment is saturated and M catchment is drier, **flow is higher from the FI catchment**, as would be expected.
- When M catchment is saturated and FI catchment is drier, **flow is still higher from FI catchment than from M catchment**. This shows that M management has superior water retention abilities compared to FI management (likely reflecting a brash layer infiltration/absorption effect).
- However, the **magnitude of the difference in flows between FI and M catchments when M is saturated ($Mwet_d$) decreases over time and moves towards 0**. This suggests that the water retention capabilities of M compared with FI decay over time (as might be expected with loss of brash over time). However, as further areas were managed over time this result is somewhat unexpected and could be related to what areas were managed (less effective at holding back water or causing runoff – distance to streams, slope and or vegetation).

Table A6.9 Paired t-test – these show the difference between burnt (FI) flow and mown (M) flow when FI is wet and when M is wet. In both cases, FI flow is greater than M flow

Log(Ln flow)

Event	Mean of the differences	t statistic	df	p-value	95% Conf.Int
FI wet	0.530	13.66	227	<2.2e-16 ***	0.453 – 0.606
M wet	0.224	4.12	128	6.87e-05 ***	0.116 – 0.332

Back-transformed (m^3 ha^{-1} hr^{-1})

Event	Mean of the differences	95% Conf.Int
FI wet	1.699	1.573 – 1.833
M wet	1.251	1.123 – 1.394

Table A6.10 Output Gamma log link model – these show the output of statistical analyses for burnt (FI) wet scenarios and for mown (M) wet scenarios. In both cases, flow is greater from FI catchments. The difference between catchments is more statistically significant when FI catchment is wet.

FI wet, model output

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	0.974	0.1815	5.366	8.06e-08 ***	0.618 – 1.329
M catch.	-0.366	0.1039	-3.527	0.00042 ***	-0.570 – 0.163

FI wet, back-transformed (m^3 ha^{-1} hr^{-1})

Term	Estimate	95% Conf.Int
Intercept	2.648	1.855 – 3.779
M catch.	-0.812	-1.150 – -0.398

M wet, model output

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	0.477	0.6437	0.741	0.459	-0.785 – 1.739
M catch.	-0.353	0.1430	-2.467	0.0136 *	-0.633 – -0.072

M wet, back-transformed (m^3 ha^{-1} hr^{-1})

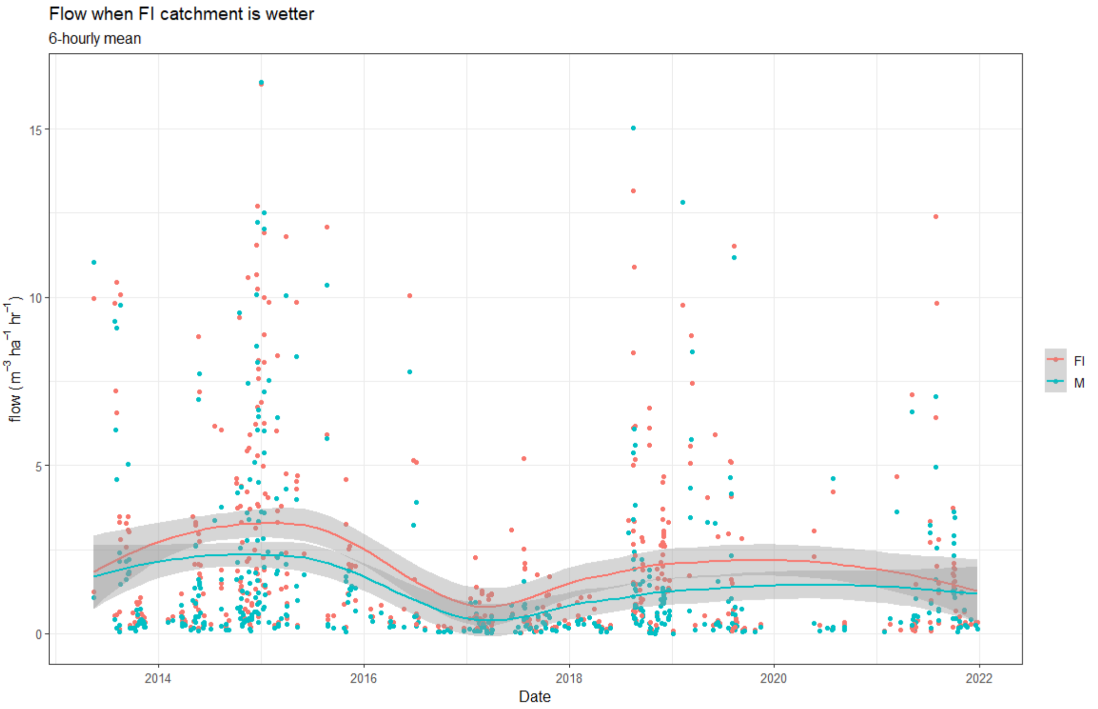
Term	Estimate	95% Conf.Int
Intercept	1.611	0.456 – 5.692
M catch.	-0.479	-0.756 – -0.112

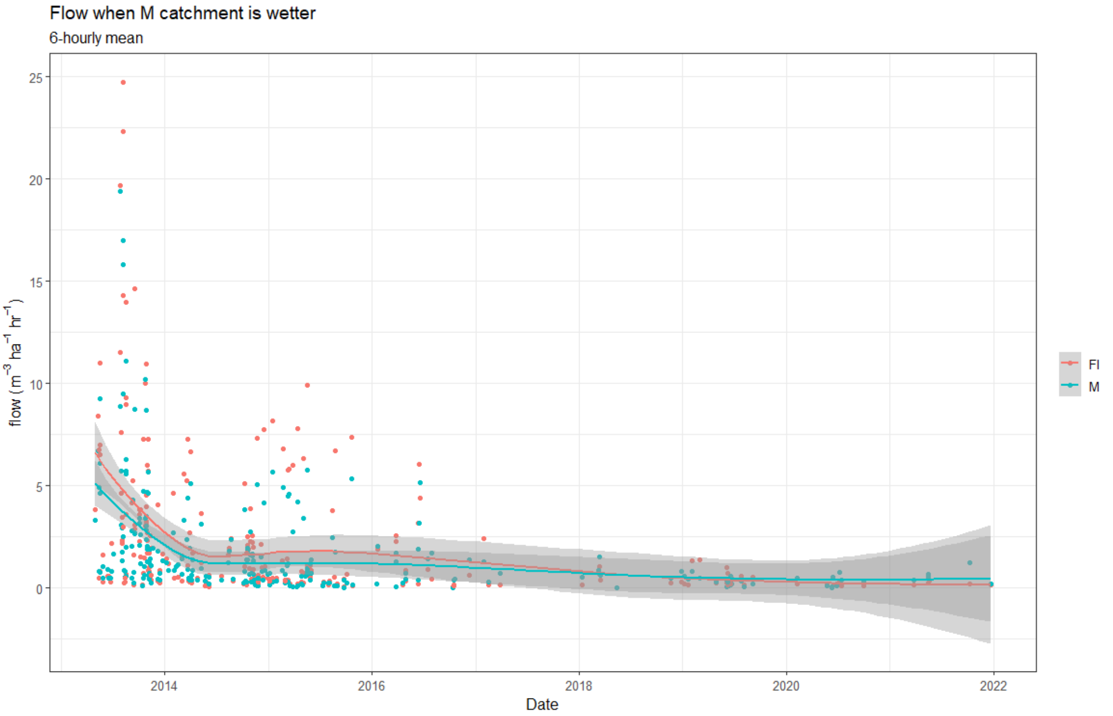
Table A6.11 Analysis of DELTA through time. LMER gaussian model – this shows the change in the difference in flows between burnt (FI) and mown (M) catchments. Only the M wet scenario had a significant change over time. At time point 1, flow was 1.401 m^3 hr^{-1} greater from the FI catchment. The difference between FI and M decreased over time.

M wet

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	-1.401	0.2079	-6.738	5.03e-10 ***	-1.809 – -0.994
M catch.	+0.185	0.0563	3.282	0.00133 **	0.074 – 0.295

The below **Figure A6.4** shows the 6-hourly mean flow rate for each catchment when one is wetter than the other, comparing burnt (FI) vs. mown (M). Management of new areas happened in 2013, 2015, 2018, 2021.





Daily means data example for rainfall > 5 m^3 ha^{-1} hr^{-1}

- When FI catchment is saturated and M catchment is drier, flow is higher from the FI catchment, as would be expected.
- When M catchment is saturated and FI catchment is drier, paired t-tests showed a significantly higher flow rate from FI catchments. However, the Gamma mixed effect model did no support this – the difference between catchments was non-significant, albeit FI flow likely higher than M flow.
- There was no significant difference with rainfall in DELTA through time.

Table A6.11 Paired t-test – daily means comparing flow rates for burnt (FI) and mown (M) catchments when either FI or M is wet.

Log(Ln flow)

Event	Mean of the differences	t statistic	df	p-value	95% Conf.Int
FI wet	0.435	8.85	61	1.54e-12 ***	0.337 – 0.534
M wet	0.236	7.14	31	5.06e-08 ***	0.168 – 0.303

Back-transformed (m^3 ha^{-1} hr^{-1})

Event	Mean of the differences	t statistic	df	p-value	95% Conf.Int
FI wet	0.435	8.85	61	1.54e-12 ***	0.337 – 0.534
M wet	0.236	7.14	31	5.06e-08 ***	0.168 – 0.303

Table A6.12 Output Gamma log link model – daily means comparing flow rates for burnt (FI) and mown (M) catchments when either FI or M is wet.

FI wet, model output

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	1.395	0.0808	17.267	<2e-16 ***	1.236 – 1.553
M catch.	-0.323	0.1142	-2.824	0.00474 **	-0.547 – 0.0986

FI wet, back-transformed (m^3 ha^{-1} hr^{-1})

Term	Estimate	95% Conf.Int
Intercept	4.035	3.442 – 4.726
M catch.	-1.114	-1.700 – -0.379

M wet, model output

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	0.646	0.5388	1.20	0.230	-0.410 – 1.702
M catch.	-0.225	0.1429	-1.57	0.116	-0.505 – 0.0557

M wet, back-transformed (m^3 ha^{-1} hr^{-1})

Term	Estimate	95% Conf.Int
Intercept	1.908	0.664 – 5.485
M catch.	-0.384	-0.756 – 0.109

Table A6.13 Analysis of DELTA through time – daily means comparing flow rates for burnt (FI) and mown (M) catchments when M is wet.

M wet

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	-2.730	1.7974	-1.519	0.270	-6.253 – 0.792
M catch.	+0.153	0.1187	1.288	0.208	-0.0798 – 0.386

Flow rate at high WTD and high rainfall:

The flow rates were also summarised per month in relation to the incoming total rainfall (for further information see Heinemeyer et al., 2019b) as shown in **Table A6.14**, which enabled estimates of annual totals (**Table A6.15**).

Table A6.14 The calculated monthly percentage water loss from each sub-catchment (C = control-burnt; T = treatment-mown) at each site for each year based on monthly totals of incoming rainfall and stream flow rates. Calculations accounted for differences in sub-catchment size. Months in which management applications were carried out are highlighted in green for mowing and in brown for burning. Cells are highlighted grey for pre- and blue for post-management months where a sub-catchment showed water losses which were at least 10% greater than those from the paired sub-catchment (with at least 10% loss in the burnt catchment).

Water loss (%)	Year	2012		2013		2014		2015		2016		2017		2018		2019		2020		2021	
	Month	% loss C	% loss T	% loss C	% loss T	% loss C	% loss T	% loss C	% loss T	% loss C	% loss T	% loss C	% loss T	% loss C	% loss T	% loss C	% loss T	% loss C	% loss T	% loss C	% loss T
Nidderdale	1			101	103	80	64	81	64	96	72	52	25	88	34	65	41	77	54	110	97
	2			133	149	86	74	78	56	84	62	55	23	166	85	81	59	95	79	108	95
	3			103	106	61	50	81	56	83	60	40	15	60	32	82	62	100	75	72	64
	4			56	72	44	33	31	23	53	37	9	4	56	27	13	7	1	1	4	3
	5			42	47	66	45	48	37	17	13	0	0	15	10	40	26	0	0	67	56
	6			3	6	14	13	43	34	39	29	28	10	18	9	57	39	36	31	2	0
	7	119	126	18	14	11	9	16	11	34	26	28	13	5	2	20	16	45	38	8	7
	8	46	49	50	34	20	16	41	32	48	24	38	18	15	7	53	40	56	47	42	26
	9	60	60	31	23	14	9	20	16	43	19	47	19	37	14	67	40	50	35	4	4
	10	69	72	69	50	65	48	59	45	60	28	64	23	43	15	92	61	87	64	62	52
	11	82	86	71	54	73	54	80	62	93	46	58	25	57	22	86	59	88	73	97	76
	12	81	80	64	52	70	54	83	65	78	39	59	31	69	27	96	74	101	83	109	79
Mossdale	1			101	86	85	69	103	75	104	79	78	57	117	108	68	38	86	56	138	92
	2			102	91	87	71	84	64	99	78	75	61	118	97	91	56	105	78	112	76
	3			70	69	64	52	75	60	91	73	80	68	99	80	92	61	96	73	101	72
	4			54	55	48	37	53	39	64	49	13	4	73	57	29	18	1	1	9	5
	5			49	43	52	39	61	45	15	8	12	6	18	11	40	26	4	2	59	46
	6			19	14	29	20	47	35	11	7	56	53	2	0	52	36	57	43	1	0
	7	87	65	39	25	2	1	31	25	51	37	57	57	6	2	30	16	63	45	3	1
	8	47	52	69	43	39	29	62	48	74	58	49	47	47	34	77	48	74	55	19	8
	9	59	58	52	37	8	3	31	18	70	52	75	81	69	55	72	44	63	41	29	15
	10	64	67	80	60	65	48	63	49	59	40	97	90	79	61	89	59	91	64	96	58
	11	71	68	86	64	76	53	91	70	105	83	96	89	82	58	82	55	100	72	120	76
	12	85	76	80	65	79	59	100	75	84	62	95	87	98	79	102	69	96	73	114	72
Whitendale	1			150	155	60	63	84	89	82	81	101	93	114	122	99	111	83	94	124	144
	2			106	111	67	67	67	65	99	94	85	77	119	130	75	94	90	130	93	113
	3			43	43	55	55	64	64	70	66	98	102	85	76	74	88	97	133	80	103
	4			49	49	46	49	45	45	54	53	44	66	82	81	33	26	17	14	15	55
	5			46	48	41	40	54	51	31	32	30	29	28	33	35	23	24	11	42	51
	6			31	35	28	33	42	60	47	45	63	58	10	17	40	40	49	41	6	30
	7	78	86	35	35	8	11	27	26	92	112	50	45	6	7	36	31	87	92	38	30
	8	48	40	48	56	47	56	35	37	59	67	77	80	44	32	56	63	74	72	48	79
	9	68	64	51	52	34	45	32	35	48	53	80	84	66	73	75	70	63	62	39	49
	10	76	75	56	61	51	54	51	37	55	68	102	115	66	70	92	97	81	95	71	77
	11	73	72	69	86	55	55	82	87	80	91	102	105	61	60	76	74	90	125	109	104
	12	80	79	64	62	93	99	74	80	74	81	124	134	118	128	87	99	87	104	95	101

Table A6.15 Annual summary of the percentage of water lost in streams (relative to the total incoming rainfall) from each sub-catchment (see **Table A6.14** for flow volumes) and the calculated difference of water loss between mown and burnt sub-catchments (negative numbers indicate lower losses from mown compared to burnt sub-catchments) for Nidderdale (Nidd), Mossdale (Moss) and Whitendale (Whit). Calculations accounted for differences in sub-catchment size. The pre-management period was in 2012 versus the post-management period from 2013 onwards (i.e. 2013 included a few pre-management change months).

Nidd	%Burnt	%Mown	Mown-Burnt	Moss	%Burnt	%Mown	Mown-Burnt	Whit	%Burnt	%Mown	Mown-Burnt	Average
Pre (2012)	76.3	78.9	2.6	Pre (2012)	68.9	64.4	-4.5	Pre (2012)	70.6	69.4	-1.2	-1
2013	61.7	59.2	-2.5	2013	66.9	54.3	-12.6	2013	62.4	66.0	3.6	-4
2014	50.4	39.0	-11.4	2014	52.8	40.0	-12.9	2014	48.7	52.1	3.4	-7
2015	55.1	41.7	-13.4	2015	66.9	50.1	-16.8	2015	54.6	56.4	1.8	-9
2016	60.8	38.0	-22.8	2016	68.9	52.2	-16.7	2016	66.0	70.2	4.3	-12
2017	39.9	17.3	-22.6	2017	65.4	58.5	-6.9	2017	79.6	82.3	2.7	-9
2018	52.5	23.6	-28.9	2018	67.4	53.5	-13.9	2018	66.6	69.1	2.4	-13
2019	62.6	43.7	-18.9	2019	68.6	43.8	-24.7	2019	64.9	68.0	3.1	-13
2020	61.3	48.3	-13.0	2020	69.8	50.3	-19.5	2020	70.2	81.1	10.9	-7
2021	57.0	46.5	-10.5	2021	66.8	43.5	-23.2	2021	63.3	77.9	14.6	-6
Post only	**55.7**	**39.7**	**-16.0**	**Post only**	**65.9**	**49.6**	**-16.4**	**Post only**	**64.0**	**69.2**	**5.2**	**-9**

Appendix 7 (wet/dry cycles)

To estimate WTD drawdown the dry periods of at least 10 consecutive days with less than 1 mm rainfall each day were located using the site climate data. For each dry period, the following information was used: the WTD at the beginning of the dry period, the WTD at the end of the dry period, the duration in days of the dry period, and the total PAR (mol m^{-2}) during the dry period (as light relates to seasonal differences in evapotranspiration). To investigate WTD rebound with subsequent rainfall, the following wet period of five days after rainfall above 1 mm recommenced were included for each dry period. The total WTD rise and rainfall (mm) in five days was included.

Only data from the post-management period (2013-21) was used, as measurements were more responsive during this period. All plots at all three sites were used for the analysis, with the exception of plot 4 at Whitendale. In total, there were **27 dry periods for Nidderdale, 25 for Mossdale, and 28 for Whitendale**.

Five different response variables were investigated, three for WTD fall and two for WTD rise: **total WTD fall, WTD fall per day, WTD fall per unit PAR** and **total WTD rise, WTD rise per unit rainfall**. These were analysed with mixed effect models. Management was the only fixed effect (FI as control, *LB, BR, DN as impact*). The random effects were date and plot.

Note on reading the model output tables: the model output tables show the output of the mixed effect models. **The estimate shows the predicted impact of managements compared to FI**. The unit of response variables was WTD (cm). Therefore, a positive estimate for models investigating WTD fall does not indicate a greater drop; **a positive estimate indicates a higher (wetter) WTD and therefore a smaller drop in WTD**.

The following summary **Table A7.1** shows the direction and significance of managements (mown with brash left (LB) or brash removal (BR) and uncut (DN)) compared to the burnt (FI) control. The direction of arrows denote higher or lower WTD compared with FI, i.e. upwards arrow means a higher WTD and therefore a lower fall in dry periods or greater rise with rainfall.

		LB			**BR**			**DN**		
		2013-21	**2013-17**	**2017-21**	**2013-21**	**2013-17**	**2017-21**	**2013-21**	**2013-17**	**2017-21**
WTD during drought	All									
	Nidd	↑ .	↑ *			↑ *		↑ .	↑ .	
	Moss	↑ *	↑ *		↑ *	↑ *		↑ **	↑ .	
	Whit	↓ *	↓ *	↓ *		↓ .		↓ .	↓ *	
WTD change per day	All									
	Nidd	↑ .	↑ *			↑ *		↑ .	↑ .	
	Moss	↑ *	↑ *		↑ *	↑ *		↑ **		
	Whit	↓ *	↓ *	↓ *		↓ .		↓ .	↓ *	
WTD change per PAR	All									
	Nidd	↑ *	↑ *			↑ *		↑ *	↑ .	
	Moss	↑ *	↑ **		↑ **	↑ **		↑ *		
	Whit	↓ *	↓ .	↓ *					↓ .	
WTD rise with rain	All									
	Nidd	↓ .	↓ **			↓ *		↓ *	↓ **	
	Moss	↓ *	↓ **			↓ *		↓ **	↓ *	
	Whit	↑ *	↑ *	↑ *				↑ .	↑ *	
WTD rise per rainfall	All									
	Nidd		↓ *			↓ *			↓ *	
	Moss	↓ .						↓ **		
	Whit	↑ *	↑ *	↑ *					↑ *	

All sites

- WTD during dry periods > 10 days
    - **No significant BACI interactions**, likely due to contrasting effects at Whitendale compared with Nidderdale and Mossdale.
- WTD during subsequent rainfall
    - **No significant BACI interactions**, likely due to contrasting effects at Whitendale compared with Nidderdale and Mossdale.

Nidderdale

- WTD during **dry periods** > 10 days
    - **Larger falls in WTD occurred with FI management than LB or BR management in the four years after management (2013-16)**.
    - There was no significant difference between management plots during 2017-21.
    - For the full post-management period (2013-21), there were differences between FI management and LB and DN managements. This was slightly outside statistical significance for the total WTD fall and the fall per dry day.
    - WTD fall per unit PAR showed significant differences for LB and DN managements compared with FI management. LB and DN managements led to lesser drops in WTD per PAR.
    - To summarise, in the years immediately following management, LB and BR led to lesser drops in WTD during dry periods. This is likely due to the protection against solar radiation afforded by vegetation and brash.
- WTD during **subsequent rainfall**
    - The **total rise and rise per rainfall were significantly higher for FI plots than other management plots during 2013-17**.
    - No significant differences between FI and other managements during 2017-21.
- To summarise: **during 2013-17, WTD in FI plots fell more during dry periods and then rebounded more during subsequent rainfall**. There are larger swings in WTD with dry/rainfall events, which is also shown by the significant BACI interactions in the analysis of standard deviation of WTD.

Mossdale

- WTD during **dry periods** > 10 days
    - BACI interactions for the full post-management period (2013-21) showed **smaller falls in WTD for LB, BR, and DN compared with FI**. This was the case for overall WTD changes, WTD changes per day, and WTD changes per unit PAR.
    - The impact of LB and BR, compared with FI, was significant during 2013-16, but not during 2017-21.
- WTD during **subsequent rainfall**
    - The total **rise of WTD with rainfall was higher in FI plots than other management plots during 2013-17**. It was also **higher in FI plots than LB or DN plots for the full post-management study period**.
    - Only **DN management had a lower rise per rainfall than FI**. Possibly because the vegetation prevents more water from making it to the water table (> interception & > evapotranspiration).
- There is an **indication that FI management leads to higher WTD variance**, **with larger drops in WTD during dry periods in 2013-17 and larger rises with subsequent rainfall**. FI management exposes the land more and thus WTD is more affected by climatic influences.

Whitendale

- WTD during **dry periods** > 10 days
  - Whitendale **differed to Nidderdale and Mossdale**, in that <u>WTD fell less with FI management than other managements during dry periods</u>.
  - **LB management was associated with greater drops in WTD than FI management throughout the post-management period** (although the impact to WTD fall per PAR during 2013-16 was outside statistical significance). This is perhaps counter-intuitive, as FI plots should be more exposed to radiation and evapotranspiration, and contrasts with management effects at Nidderdale and Mossdale.
  - There was a **greater overall and daily fall in WTD during 2013-16 dry periods with DN management compared to FI management**. The BACI interaction for DN : 2013-16 on WTD fall per PAR was slightly outside statistical significance.
- WTD during **subsequent rainfall**
  - The total rise of WTD shows the recovery of LB and DN managed plots with rainfall. **WTD of LB plots rose more than FI plots with rainfall following the dry, throughout the post-management period**. WTD of DN-managed plots rose more than FI plots during 2013-21.

Table A7.2 a-e Nidderdale comparing managements (mown with brash left (LB) or brash removal (BR) and uncut (DN)) to the burnt (FI) control across the entire or two separate management periods (2013-2016 & 2017-2021).

a) WTD total fall

2013-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	+4.624	2.626	1.761	0.0936 .	-0.354 – 9.603
BR	+3.817	2.626	1.454	0.1616	-1.161 – 8.796
DN	+5.792	3.033	1.910	0.0706 .	0.043 – 11.541

2013-2016

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+6.557**	**2.872**	**2.283**	**0.0335 ***	**1.122 – 11.992**
BR	**+6.424**	**2.872**	**2.236**	**0.0369 ***	**0.988 – 11.859**
DN	+6.648	3.317	2.004	0.0588 .	0.372 – 12.924

2017-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	+1.726	3.029	0.570	0.5752	-4.038 – 7.489
BR	-0.0916	3.029	-0.030	0.9762	-5.854 – 5.672
DN	+4.509	3.498	1.289	0.2121	-2.146 – 11.164

b) WTD fall per day

2013-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	+0.445	0.248	1.799	0.0872 .	-0.024 – 0.914
BR	+0.390	0.248	1.574	0.1311	-0.079 – 0.859
DN	+0.557	0.286	1.949	0.0655 .	0.015 – 1.099

2013-2016

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+0.667**	**0.307**	**2.171**	**0.0421 ***	**0.085 – 1.248**
BR	**+0.659**	**0.307**	**2.147**	**0.0442 ***	**0.077 – 1.241**
DN	+0.702	0.355	1.980	0.0616 .	0.030 – 1.374

2017-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	+0.113	0.214	0.530	0.602	-0.294 – 0.521
BR	-0.014	0.214	-0.068	0.947	-0.422 – 0.393
DN	+0.340	0.247	1.374	0.185	-0.131 – 0.810

c) WTD fall per PAR

2013-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+0.0221**	**0.0090**	**2.447**	**0.0238 ***	**0.0049 – 0.0393**
BR	+0.0174	0.0090	1.934	0.0674 .	0.0003 – 0.0347
DN	**+0.0222**	**0.0104**	**2.129**	**0.0459 ***	**0.0024 – 0.0420**

2013-2016

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+0.0349**	**0.0126**	**2.765**	**0.0119 ***	**0.0109 – 0.0588**
BR	**+0.0304**	**0.0126**	**2.407**	**0.0259 ***	**0.0064 – 0.0543**
DN	+0.0297	0.0146	2.036	0.0552 .	0.0020 – 0.0573

2017-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	+0.0030	0.0064	0.463	0.6487	-0.0093 – 0.0152
BR	-0.0018	0.0064	-0.286	0.7779	-0.0141 – 0.0104
DN	+0.0110	0.0074	1.490	0.1517	-0.0031 – 0.0252

d) WTD total rise

2013-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	-3.265	1.659	-1.968	0.0631 .	-6.424 – -0.106
BR	-2.409	1.659	-1.452	0.1620	-5.568 – 0.750
DN	**-4.313**	**1.916**	**-2.52**	**0.0357 ***	**-7.691 – -0.665**

2013-2016

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**-7.298**	**2.279**	**-3.202**	**0.0045 ****	**-11.633 – -2.962**
BR	**-5.835**	**2.279**	**-2.560**	**0.0187 ***	**-10.170 – -1.500**
DN	**-7.530**	**2.632**	**-2.862**	**0.0097 ****	**-12.537 – -2.524**

2017-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	+2.784	2.519	1.105	0.282	-2.015 – 7.583
BR	+2.731	2.519	1.084	0.291	-2.069 – 7.530
DN	+0.513	2.908	0.176	0.862	-5.029 – 6.055

e) WTD rise per rainfall

2013-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	+0.0189	0.0739	0.256	0.798	-0.2441 – 0.1636
BR	-0.0201	0.0739	-0.272	0.786	-0.1648 – 0.1247
DN	+0.0159	0.0854	0.186	0.852	-0.1512 – 0.1830

2013-2016

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**-0.1708**	**0.0631**	**-2.706**	**0.0136 ***	**-0.2911 – -0.0506**
BR	**-0.1363**	**0.0631**	**-2.160**	**0.0431 ***	**-0.2566 – -0.0160**
DN	**-0.1842**	**0.0729**	**-2.527**	**0.0201 ***	**-0.3231 – -0.0453**

2017-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	+0.3035	0.1866	1.627	0.119	-0.0520 – 0.6591
BR	+0.1543	0.1866	0.827	0.418	-0.2012 – 0.5098
DN	+0.3160	0.2154	1.467	0.158	-0.0945 – 0.7265

Table A7.3 a-e Mossdale comparing managements (mown with brash left (LB) or brash removal (BR) and uncut (DN)) to the burnt (FI) control across the entire or two separate management periods (2013-2016 & 2017-2021).

a) WTD total fall					
2013-2021					
Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+3.479**	**1.493**	**2.330**	**0.0304 ***	**0.638 – 6.319**
BR	**+3.330**	**1.493**	**2.231**	**0.0373 ***	**0.490 – 6.170**
DN	**+5.237**	**1.724**	**3.038**	**0.0065 ****	**1.957 – 8.517**
2013-2016					
Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+6.469**	**2.761**	**2.343**	**0.0296 ***	**1.231 – 11.706**
BR	**+6.499**	**2.761**	**2.354**	**0.0289 ***	**1.262 – 11.737**
DN	+6.064	3.188	1.902	0.0716 .	0.016 – 12.111
2017-2021					
Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	+2.225	2.936	0.758	0.457	-3.343 – 7.794
BR	+1.041	2.936	0.354	0.727	-4.527 – 6.609
DN	+4.996	3.390	1.473	0.156	-1.434 – 11.425

b) WTD fall per day					
2013-2021					
Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+0.256**	**0.105**	**2.436**	**0.0243 ***	**0.056 – 0.456**
BR	**+0.264**	**0.105**	**2.507**	**0.0209 ***	**0.064 – 0.463**
DN	**+0.373**	**0.121**	**3.074**	**0.0060 ****	**0.142 – 0.604**
2013-2016					
Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+0.567**	**0.265**	**2.141**	**0.0448 ***	**0.064 – 1.070**
BR	**+0.577**	**0.265**	**2.176**	**0.0417 ***	**0.074 – 1.079**
DN	+0.566	0.306	1.849	0.0793 .	-0.015 – 1.146
2017-2021					
Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	+0.176	0.251	0.701	0.492	-0.300 – 0.651
BR	-0.098	0.251	0.389	0.701	-0.378 – 0.573
DN	+0.415	0.289	1.432	0.167	-0.135 – 0.964

c) WTD fall per PAR					
2013-2021					
Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+0.0102**	**0.0044**	**2.324**	**0.0308 ***	**0.0019 – 0.0186**
BR	**+0.0127**	**0.0044**	**2.892**	**0.0090 ****	**0.0044 – 0.0211**
DN	**+0.0142**	**0.0051**	**2.800**	**0.0111 ***	**0.0046 – 0.0239**
2013-2016					
Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+0.0283**	**0.0092**	**3.071**	**0.0060 ****	**0.0108 – 0.0459**
BR	**+0.0268**	**0.0092**	**2.907**	**0.0087 ****	**0.0092 – 0.0443**
DN	+0.0176	0.0106	1.654	0.1140	-0.0027 – 0.0379
2017-2021					
Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	+0.0102	0.0110	0.935	0.361	-0.0106 – 0.0311
BR	+0.0032	0.0110	0.297	0.770	-0.0176 – 0.0241
DN	+0.0194	0.0126	1.537	0.140	-0.0046 – 0.0435

d) WTD total rise

2013-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**-2.620**	**1.193**	**-2.196**	**0.0400 ***	**-4.891 – -0.348**
BR	-1.988	1.193	-1.667	0.1111	-4.260 – 0.283
DN	**-4.881**	**1.377**	**-3.543**	**0.0020 ****	**-7.503 – -2.578**

2013-2016

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**-5.475**	**1.828**	**-2.995**	**0.0072 ****	**-8.088 – -1.993**
BR	**-5.174**	**1.828**	**-2.831**	**0.0103 ***	**-8.656 – -1.692**
DN	**-4.497**	**2.111**	**-2.131**	**0.0457 ***	**-8.519 – -0.476**

2017-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	-0.015	1.656	-0.009	0.9931	-3.168 – 3.140
BR	+0.374	1.656	0.226	0.8237	-2.780 – 3.528
DN	-1.148	1.912	-0.600	0.5550	-4.790 – 2.494

e) WTD rise per rainfall

2013-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	-0.0823	0.0471	-1.747	0.0959 .	-0.1719 – 0.0074
BR	-0.0468	0.0471	-0.994	0.3323	-0.1365 – 0.0429
DN	**-0.1944**	**0.0544**	**-3.574**	**0.0019 ****	**-0.2979 – -0.0908**

2013-2016

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	-0.0727	0.0584	-1.244	0.215	-0.1869 – -0.0415
BR	-0.0871	0.0584	-1.491	0.137	-0.2013 – -0.0271
DN	-0.0665	0.0674	-0.986	0.325	-0.1984 – -0.0654

2017-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	+0.0888	0.0904	0.983	0.338	-0.0833 – 0.2610
BR	+0.0560	0.0904	0.619	0.543	-0.1162 – 0.2282
DN	+0.0310	0.1044	0.297	0.770	-0.1678 – 0.2298

Table A7.4 a-e Whitendale comparing managements (mown with brash left (LB) or brash removal (BR) and uncut (DN)) to the burnt (FI) control across the entire or two separate management periods (2013-2016 & 2017-2021).

a) WTD total fall

2013-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**-8.511**	**3.231**	**-2.634**	**0.0164 ***	**-14.613 – -2.409**
BR	-4.555	3.231	-1.410	0.175	-10.657 – 1.546
DN	-7.322	3.645	-2.009	0.0590 .	-14.206 – -0.438

2013-2016

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**-9.657**	**3.788**	**-2.549**	**0.0196 ***	**-16.818 – -2.496**
BR	-6.852	3.788	-1.809	0.0863 .	-14.013 – 0.309
DN	**-11.645**	**4.274**	**-2.725**	**0.0135 ***	**-19.724 – -3.566**

2017-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**-7.837**	**3.091**	**-2.535**	**0.0202 ***	**-13.695 – -1.979**
BR	-3.204	3.091	-1.037	0.313	-9.062 – 2.654
DN	-4.779	3.488	-1.370	0.187	-11.388 – 1.829

b) WTD fall per day

2013-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**-0.693**	**0.258**	**-2.685**	**0.0147 ***	**-1.180 – -0.205**
BR	-0.379	0.258	-1.469	0.1582	-0.867 – 0.109
DN	-0.589	0.291	-2.022	0.0575 .	-1.139 – -0.0386

2013-2016

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**-0.803**	**0.313**	**-2.569**	**0.0188 ***	**-1.394 – -0.212**
BR	-0.557	0.313	-1.781	0.0910 .	-1.147 – 0.0342
DN	**-0.965**	**0.353**	**-2.737**	**0.0131 ***	**-1.631 – -0.299**

2017-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**-0.628**	**0.240**	**-2.618**	**0.0169 ***	**-1.083 – -0.173**
BR	-0.275	0.240	-1.145	0.266	-0.728 – 0.180
DN	-0.367	0.271	-1.357	0.191	-0.881 – 0.146

c) WTD fall per PAR

2013-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**-0.0220**	**0.0097**	**-2.269**	**0.0351 ***	**-0.0404 – -0.0036**
BR	-0.0111	0.0097	-1.149	0.2650	-0.0295 – 0.0073
DN	-0.0167	0.0109	-1.529	0.1428	-0.0375 – 0.0041

2013-2016

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	-0.0254	0.0133	-1.916	0.0705 .	-0.0506 – -0.0002
BR	-0.0174	0.0133	-1.317	0.2036	-0.0426 – 0.0077
DN	-0.0301	0.0149	-2.014	0.0584 .	-0.0585 – -0.0017

2017-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**-0.0120**	**0.0086**	**-2.330**	**0.0310 ***	**-0.0363 – -0.0037**
BR	-0.0074	0.0086	-0.865	0.3979	-0.0237 – 0.0089
DN	-0.0083	0.0097	-0.913	0.3728	-0.0272 – 0.0096

d) WTD total rise

2013-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+5.249**	**2.139**	**2.454**	**0.0240 ***	**1.182 – 9.316**
BR	+2.677	2.139	1.251	0.2260	-1.390 – 6.734
DN	+4.300	2.413	1.782	0.0908 .	-0.288 – 8.888

2013-2016

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+5.973**	**2.649**	**2.255**	**0.0361 ***	**0.934 – 11.012**
BR	+4.020	2.649	1.518	0.1456	-1.019 – 9.059
DN	**+7.314**	**2.988**	**2.448**	**0.0243 ***	**1.630 – 12.999**

2017-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+4.823**	**1.973**	**2.444**	**0.0245 ***	**1.069 – 8.578**
BR	+1.886	1.973	0.956	0.3512	-1.868 – 5.641
DN	+2.527	2.226	1.135	0.2705	-1.709 – 6.763

e) WTD rise per rainfall

2013-2021

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+0.1325**	**0.0515**	**2.572**	**0.0187 ***	**0.0345 – 0.2305**
BR	+0.0444	0.0515	0.863	0.3991	-0.0536 – 0.1424
DN	+0.0961	0.0581	1.653	0.1147	-0.0145 – 0.2066

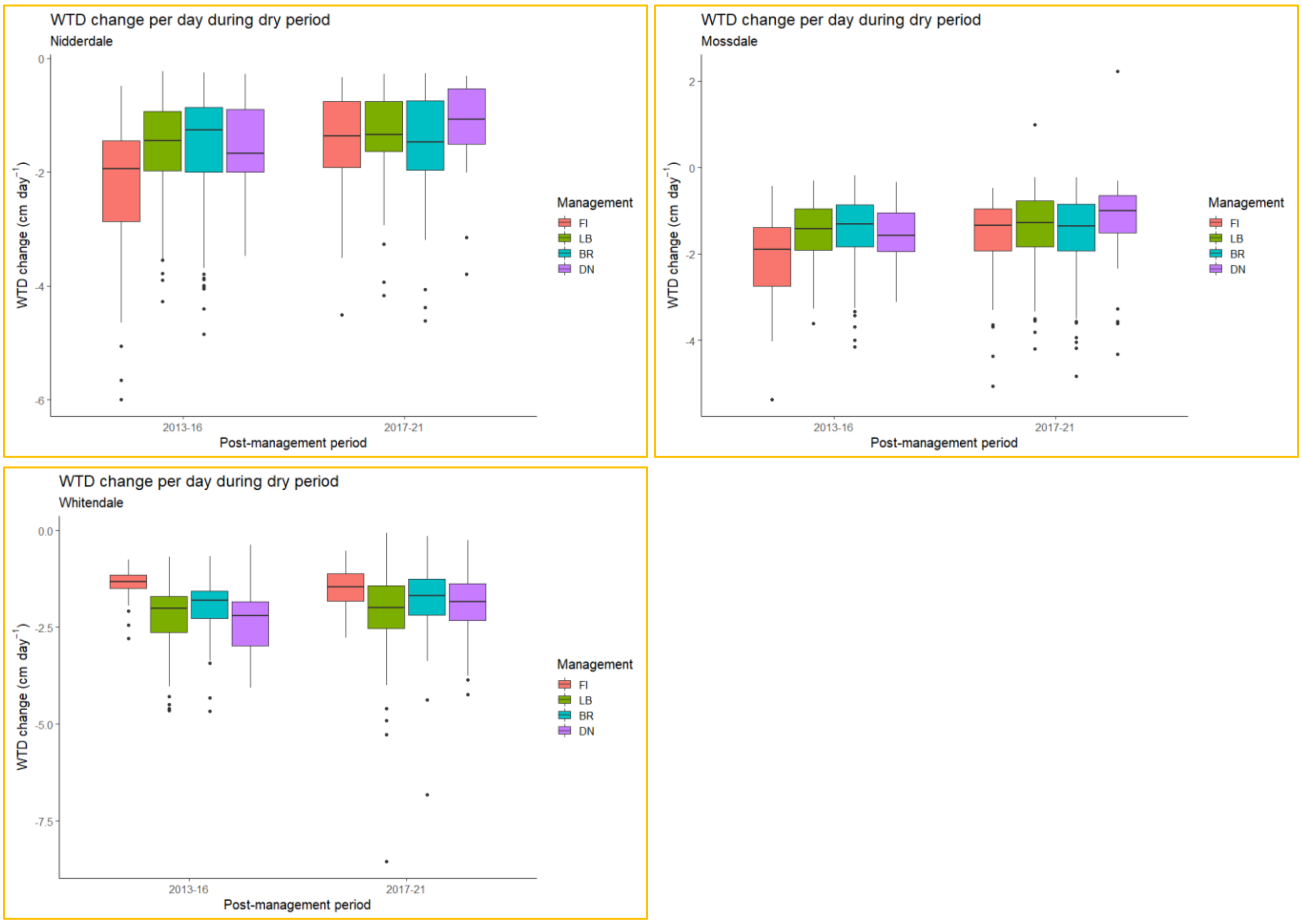
2013-2016

Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+0.1661**	**0.0692**	**2.399**	**0.0268 ***	**0.0344 – 0.2977**
BR	+0.1021	0.0692	1.476	0.1564	-0.0295 – 0.2338
DN	**+0.1932**	**0.0781**	**2.474**	**0.0230 ***	**0.0447 – 0.3417**

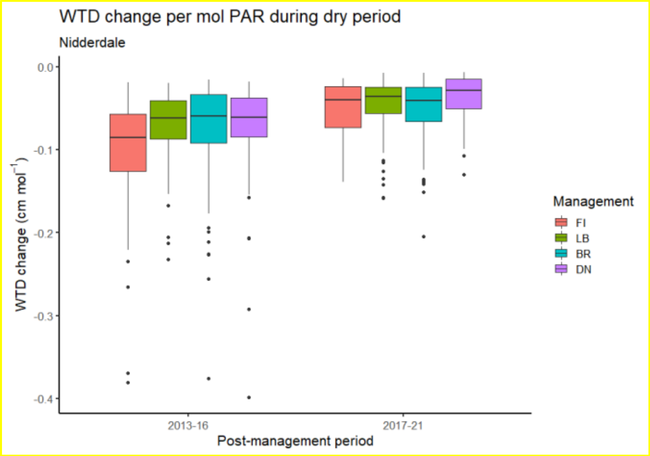
2017-2021

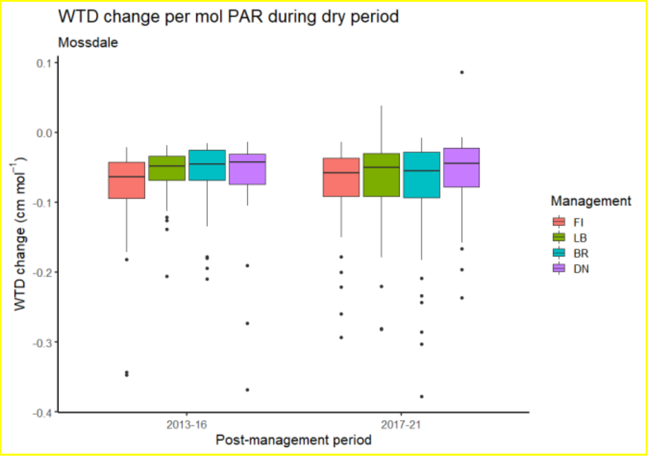
Management	Estimate	Std. Err	t-value	P value signif	95% Conf.Int
LB	**+0.1128**	**0.0475**	**2.374**	**0.0283 ***	**0.0250 – 0.2005**
BR	+0.0105	0.0475	0.221	0.8274	-0.0772 – 0.0982
DN	+0.0390	0.0536	0.727	0.4760	-0.0600 – 0.1379

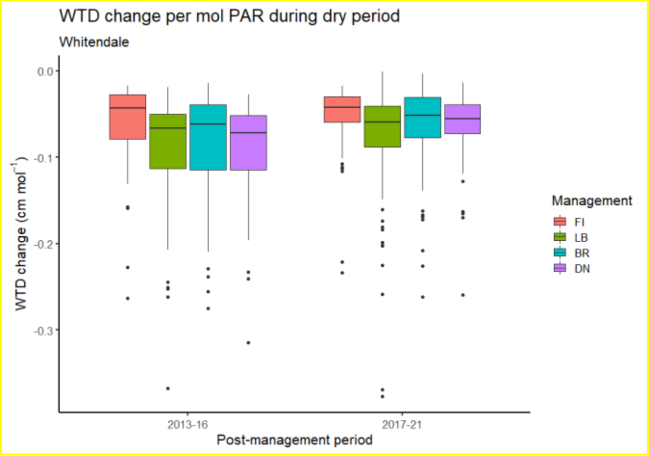
The below **Figure A7.1** shows the water table depth (WTD) change (in cm per day) during dry post-management periods (2013-2016 vs 2017-2021) for the three sites, Nidderdale, Mossdale and Whitendale per management (FI = burnt[fire]; Mown: LB = brash left vs BR = brash removal; DN = uncut[do nothing]). A more positive estimate indicates a higher (wetter) WTD and therefore a smaller drop in WTD.



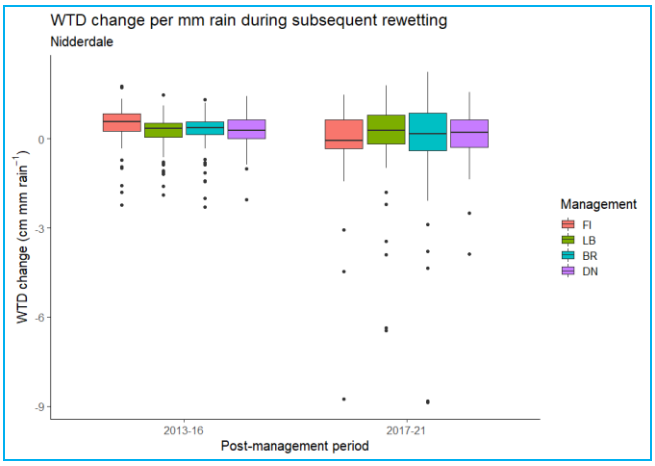
The below **Figure A7.2** shows the water table depth (WTD) change in relation to photosynthetic active radiation (PAR) (in cm per mol) received during dry post-management periods (2013-2016 vs 2017-2021) for the three sites, Nidderdale, Mossdale and Whitendale per management (FI = burnt[fire]; Mown: LB = brash left vs BR = brash removal; DN = uncut[do nothing]). A more positive estimate indicates a higher (wetter) WTD and therefore a smaller drop in WTD.

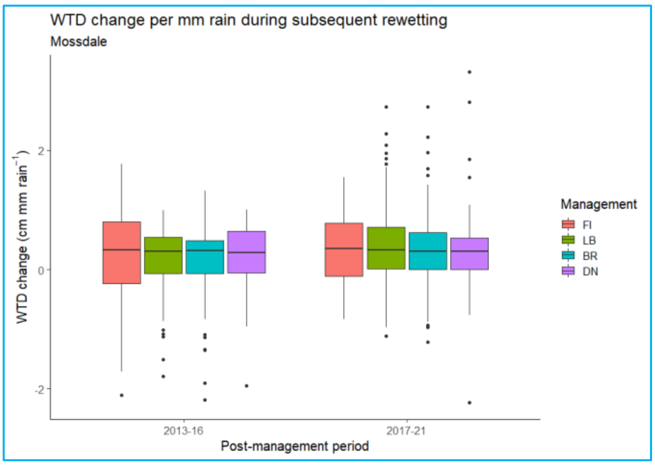


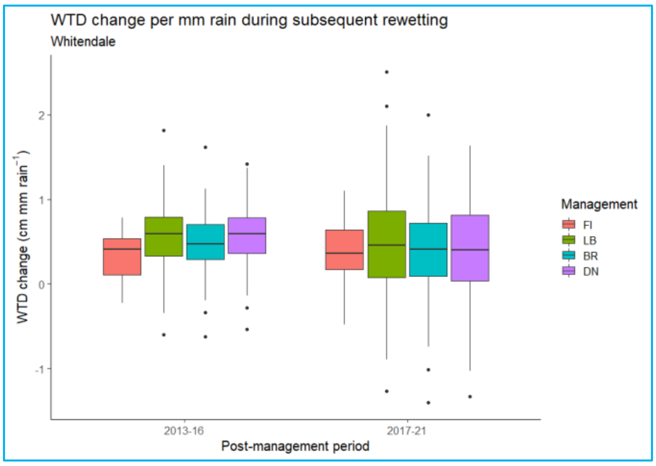




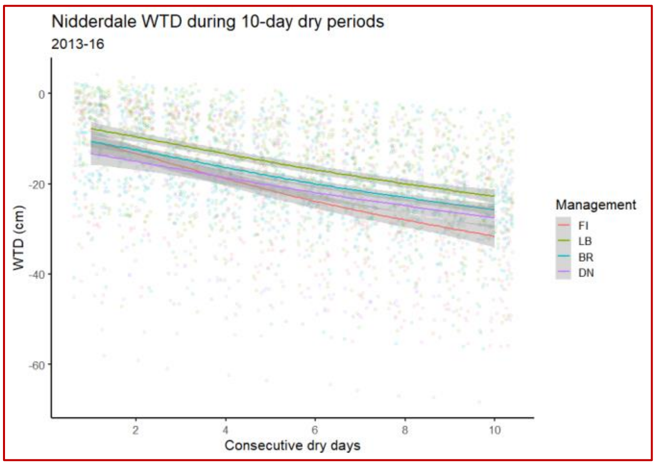
The below **Figure A7.3** shows the water table depth (WTD) change (in cm per day) during dry post-management periods (2013-2016 vs 2017-2021) for the three sites, Nidderdale, Mossdale and Whitendale per management (FI = burnt[fire]; Mown: LB = brash left vs BR = brash removal; DN = uncut[do nothing]). A more positive estimate indicates a higher (wetter) WTD and therefore a smaller drop in WTD.

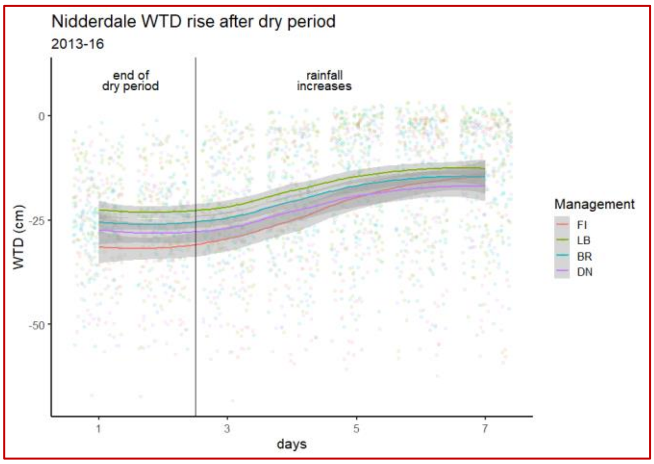


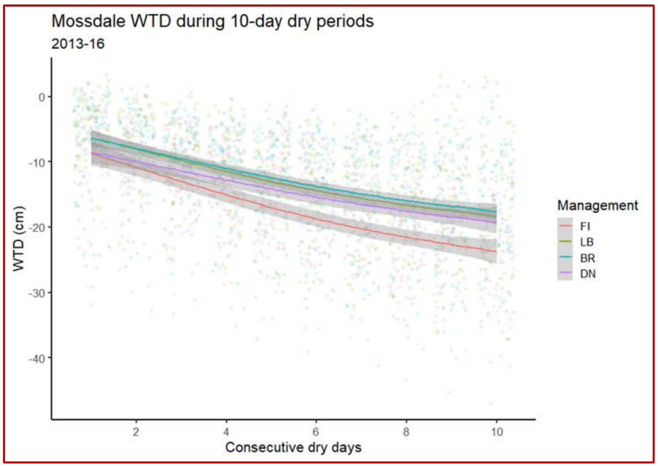


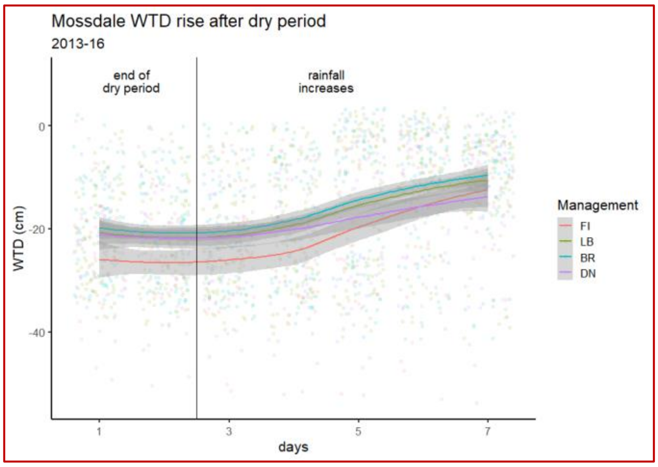


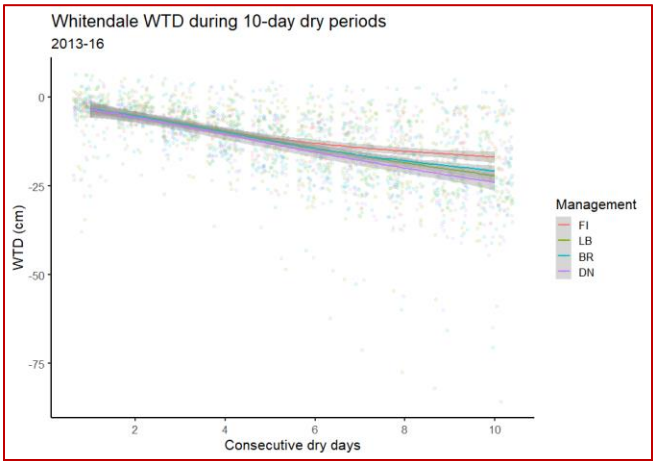
The below **Figure A7.4** shows the water table depth (WTD) change (in cm per day) over 10 consecutive days of (left) dry and (right) rewetting periods (following the end of dry periods after rainfall increase) during the first post-management period (2013-2016; the period with more difference between managements) for the three sites, Nidderdale, Mossdale and Whitendale per management (FI = burnt[fire]; Mown: LB = brash left vs BR = brash removal; DN = uncut[do nothing]). A more positive estimate indicates a higher (wetter) WTD.

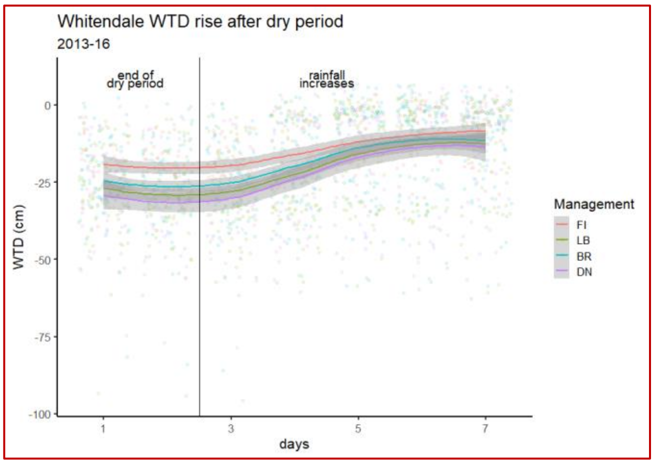












Appendix 8 (water quality for plots & slopes and flow)

The assessment of water quality involved measuring dissolved organic carbon (DOC) and various UV spectra (UV254, UV400, UV465 and UV665) and their relationships to each other (i.e. Hazen, E4/E6 and SUVA). Moreover, for plots water quality parameters were also assessed versus vegetation cover (heather[*Calluna vulgaris*], sedge [*Eriohporum angustifolium* & *E. vaginatum*], *Sphagnum* moss, non-*Sphagnum* moss, herb[mainly *Vaccinium myrtillus*], brash and bare), whilst for flow both DOC and particulate organic carbon (POC) concentrations as well as flow weighted export rates were considered. Finally, flow analyses also considered elemental export (concentrations) of key elements in streams (for all analyses see the relevant sections and their corresponding Appendices in Heinemeyer et al., 2019b); the below sections only provide a selective update on the main findings outlined in the Defra report covering Phase 1.

Plots & Slopes

Non-metric multidimensional scaling (NMDS) analysis did not reveal any separation between the managements at either plot or slopes based on water quality (**Figure A8.1**). Whilst plots revealed a slightly larger range for burnt (FI) and mown plots, slopes revealed a larger range on burnt areas, especially on past burn areas (i.e. previous burn rotation areas). However, past burn areas on the slopes represented areas of steeper slopes (and as such lower water tables and shallower peat) than the other managed monitoring plots; further interpretation of any differences would require a more in depth analysis of environmental differences between the sample locations.

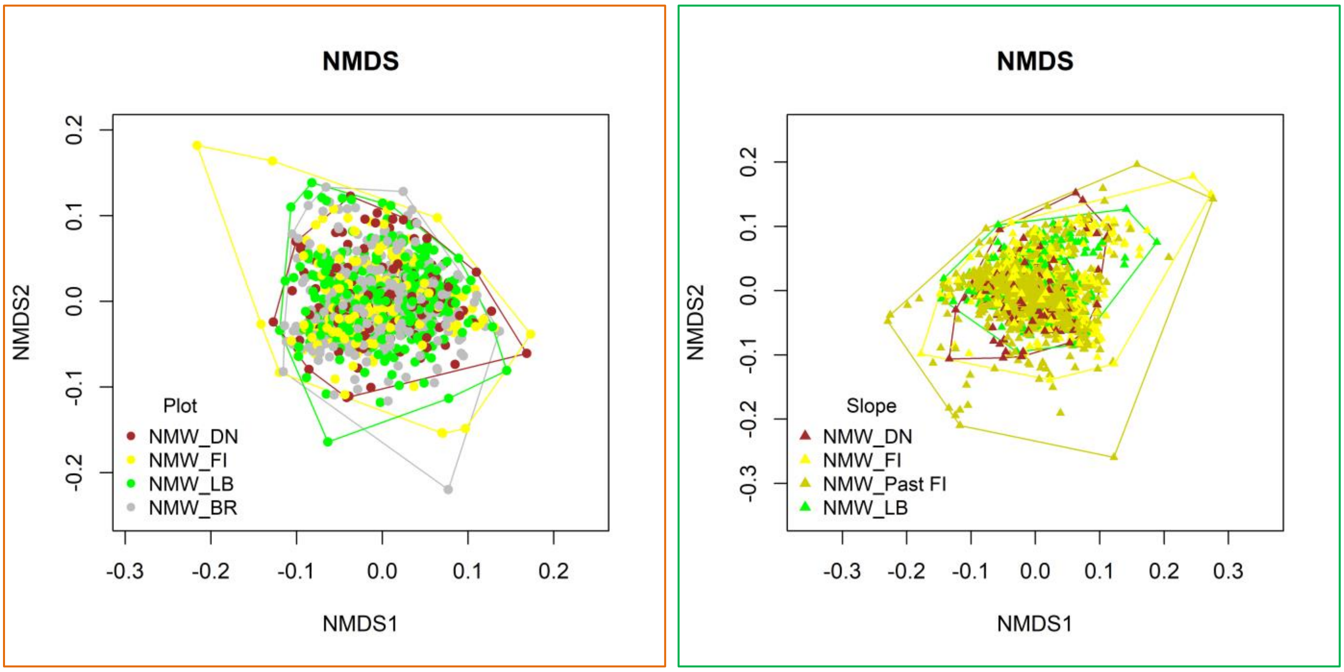


Figure A8.1 Non-metric multidimensional scaling (NMDS) for plots (left) and slopes (right) based on inclusion of all water quality parameters obtained from peat pore water samples as annual averages per sample location for all three sites (Nidderdale, Mossdale, Whitendale) during 2016-2021. Plot and slope level management included no management (DN[do nothing]), burnt (FI[fire]), past burns (Past FI) and mown with either left brash (LB) or brash removal (BR).

The below figures show the mean annual water quality parameters for Hazen (UV400*12), UV254, DOC, SUVA (UV254/DOC) and E4/E6 (ratio of UV465/UV665), which were included in the NMDS analysis (**Figure A8.1**) for the three sites (Nidderdale[Nidd], Mossdale[Moss], Whitendale[Whit]) per management at the plots (**Figure A8.2**) and slopes (**Figure A8.3**). Repeated measures ANOVA for plots revealed only significant overall site differences (E4/E6: Nidd>Whit>Moss; DOC: Nidd>Whit&Moss; SUVA: Nidd<Moss&Whit; UV254, UV465 and UV665: Moss<Whit&Nidd. A non-parametric Kruskal-Wallis test confirmed no management impact for individual years, only indicating a marginally significant (0.090) effect in 2020 on UV254 (FI & BR lower than LB and DN).

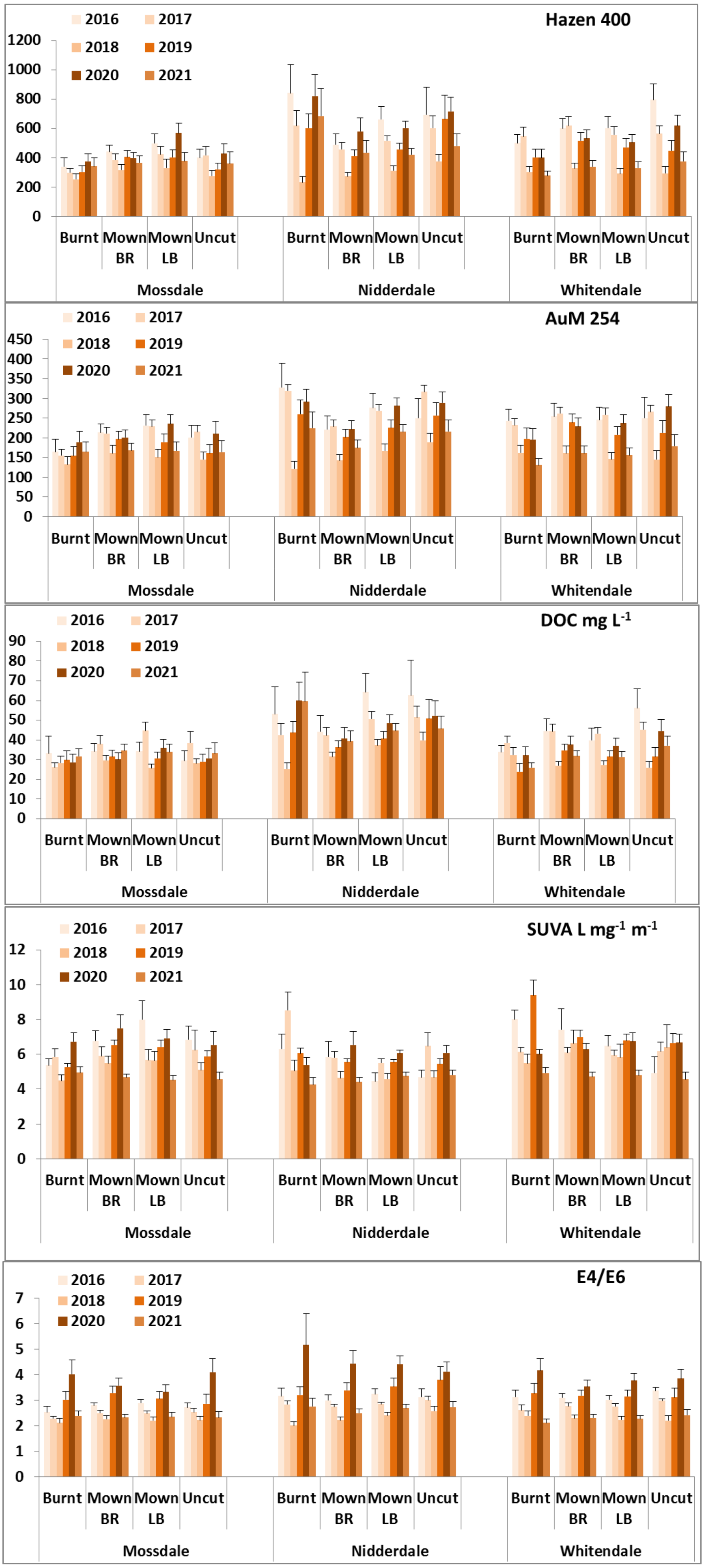


Figure A8.2 Mean annual (±SE) water quality parameters measured at the management plots (BR = brash removal; LB = left brash) at the three sites (Nidderdale, Mossdale, Whitendale) during 2016-2021.

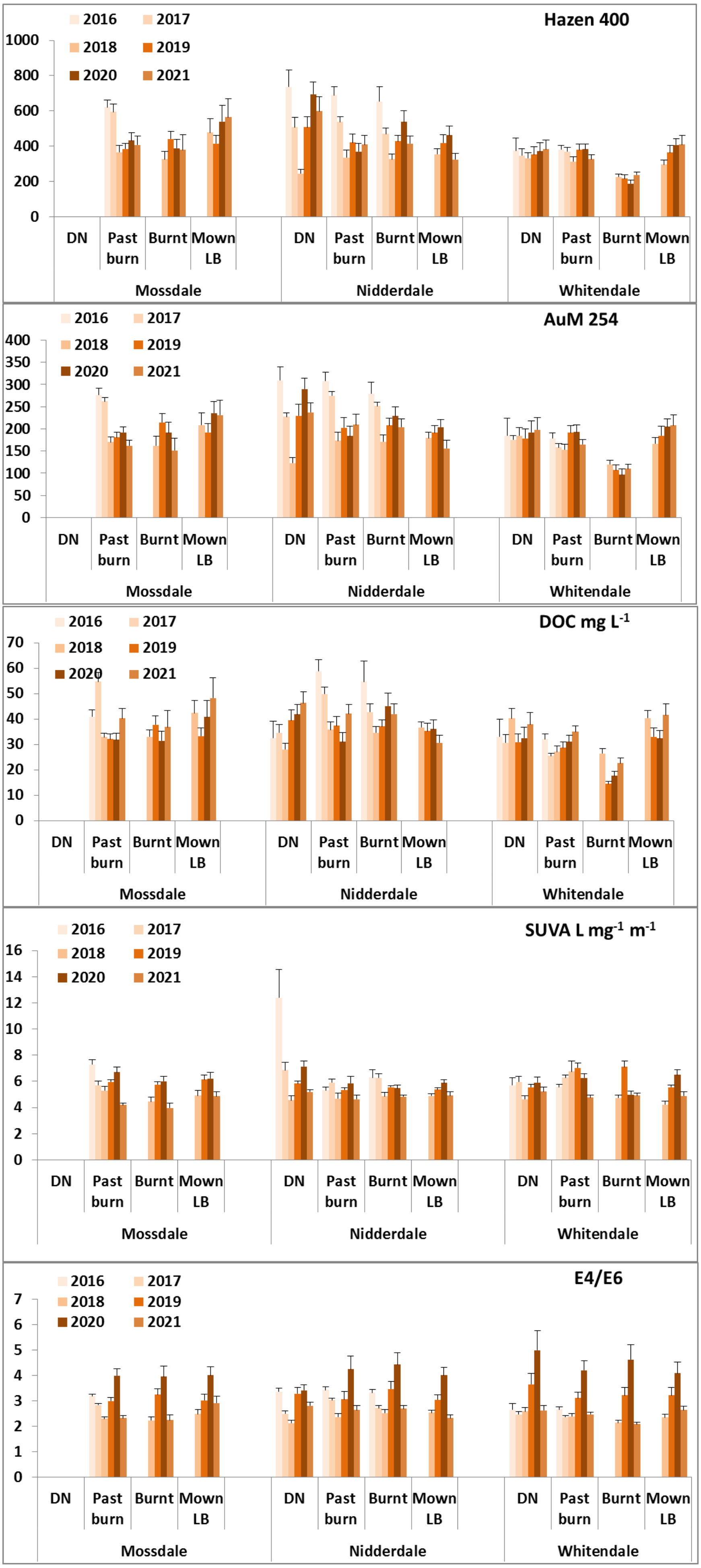


Figure A8.3 Mean annual (±SE) water quality parameters measured at the slopes (DN = no management[do nothing], LB = left brash) at the three sites (Nidderdale, Mossdale, Whitendale) during 2016-2021.

A Kruskal-Wallis test on the slope water quality data revealed some differences during 2017-2019 (2017: SUVA unmanaged lower than past burns (p=0.036); 2018: UV665 mown less than burnt (p=0.027) similarly for DOC and also versus past burns (for both p=0.001); 2019: E4/E6 no management was greater for mown (p=0.014) and past burns (p=0.002)) and most differences during 2020 and 2021. Whilst during 2020 burnt plots were significantly lower than unmanaged locations for Hazen (p=0.006), UV254 (p=0.01), UV465 (p=0.004), UV665 (p=0.015), DOC (p=0.016) and SUVA (p=0.002), in 2021 burnt plots were significantly lower than unmanaged locations Hazen (p=0.003), UV254 (p=0.002), UV465 (p=0.007), E4/E6 (p=0.006), DOC (p=0.01) and SUVA (p=0.005).

Moreover, water quality parameters did not reveal any considerable link to vegetation cover for either plots or plots and slopes combined (less than 5 or 10% of variance was explained by the two axes, respectively) when comparing across all years and sites as indicated by redundancy analysis (RDA) outputs (**Figure A8.4**). A comparison for the individual years (2016-2021) for plot and slopes combined did not reveal any meaningful differences as all RDAs indicated less than 10% of variance explained by the two axes.

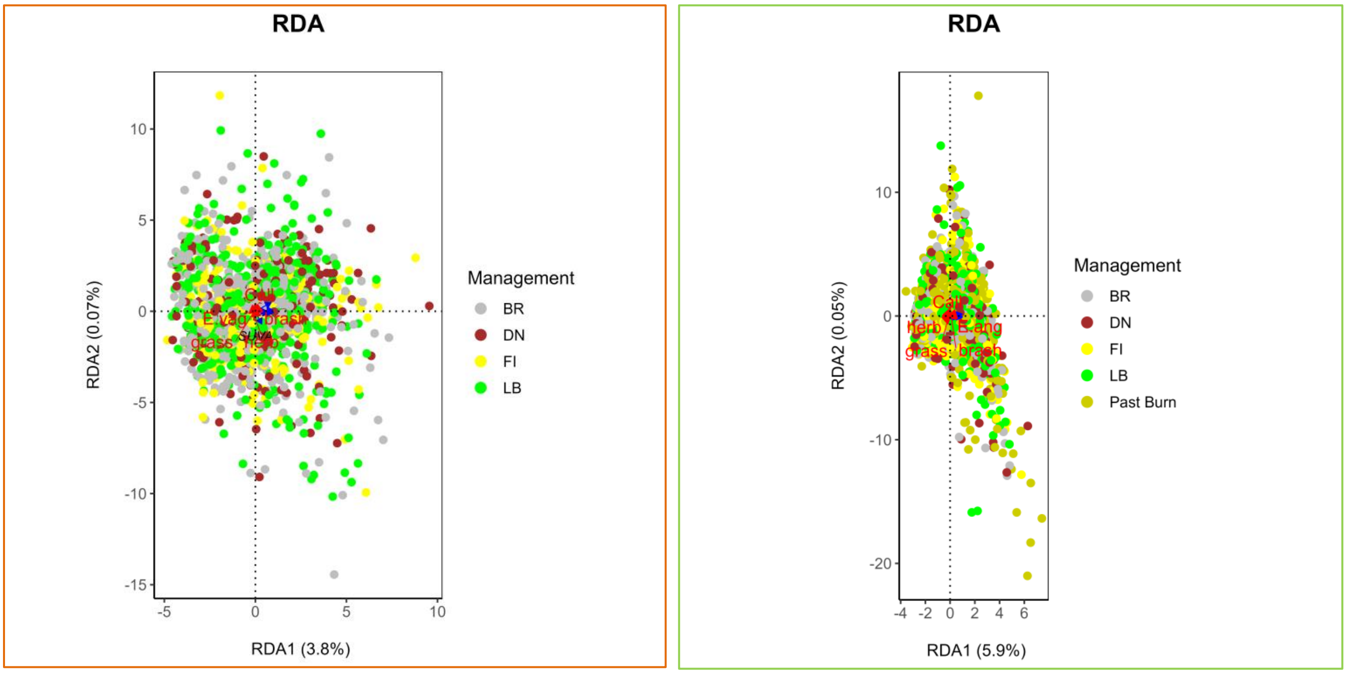


Figure A8.4 Redundancy analysis (RDA) for plots (left) only and plots and slopes (right) combined considering water quality parameters obtained from peat pore water samples as annual averages per sample location (DN[do nothing]), burnt (FI[fire]), past burns (Past Burn) and mown with either left brash (LB) or brash removal (BR)) for all three sites (Nidderdale, Mossdale, Whitendale) during 2016-2021 versus the corresponding annual vegetation cover at each sample location (% cover of heather, sedge, *Sphagnum* moss, other moss, herb, grass, brash and bare ground).

Further stepwise regression analysis was done combined across all years for plots and slopes combined and separately. Whilst the regression models did reveal overall highly significant relationships (i.e. slope was different from zero) for the main vegetation cover types (i.e. heather, sedges, herb, grass, *Sphagnum* moss, other moss, brash and bare ground), overall models explained only a small amount of variation (mostly less than 7%). However, other key factors such as temperature and peat moisture are clearly also a key component, but these were not measured at the sample locations. Water quality parameters showed consistently positive or negative relationships with key vegetation cover across plots and slopes per parameter. Moreover, some vegetation covers showed consistently positive or negative relationships across all parameters; whereas heather, sedge and herb (and for grass 13/15 times) always showed negative slopes, moss, bare and brash always showed positive slopes and *Sphagnum* moss only was included twice (either positive or negative). The overall most frequently (i.e. greater than 4 out of 7 parameters) selected vegetation covers were: (plots & slopes) grass (6), brash (6), herb (5) and heather (4); (plots) grass (5), moss (5), heather (4), herb (4) and brash (4); (slopes) brash (6) herb (5) and grass (4). Therefore, grass, brash and herb were the most dominant covers affecting water quality parameters overall.

Plots and slopes combined showed positive relationships of water quality parameters with:
brash for hazen, UV254, E4/E6, UV465, DOC, SUVA;
moss for hazen, UV254, E4/E6;
grass for E4/E6;

For plot and slopes combined water quality parameters showed negative relationships with:
herb for hazen, UV254, UV465, UV665, DOC;
grass for hazen, UV254, UV465, UV665, DOC;
heather for hazen, UV254, UV465, SUVA;
sedge for UV465.

Plots only showed further additional positive relationships of water quality parameters with:
moss for UV465 SUVA
bare for E4/E6
Sphagnum for SUVA

For plots only water quality parameters additionally showed negative relationships with:
heather for UV665
sedge, ***Sphagnum***, **heather** for DOC

Slopes only explained relationships for E4/E6, DOC and SUVA and additionally showed a positive relationship with **bare** for UV665.

Table A8.1 Summary output for stepwise regression analysis for water quality parameters (Hazen is UV400 *12; E4/E6 is the ratio of UV4465/UV665; SUVA is UV254/DOC) for annual means with all years were included in the analysis versus vegetation cover (Call is *Calluna*[heather], Sedge is (*Eriophorum*[cotton-grass] spp., herb is non shrubs, grass is mainly *Deschampsia flexuosa*, Moss is non-*Sphagnum* moss, brash is litter, bare is exposed peat) in the corresponding years at the peat pore water sample locations. Samples were combined for all three sites (Nidderdale, Mossdale, Whitendale). The significant vegetation types selected for the models are shown together with the overall model constants the R^2 values and p-values.

All years (2016-2021) combined for plots & slopes													
Hazen (Au m-1)		**UV254 (Au m-1)**		**UV465 (Au m-1)**		**UV665 (Au m-1)**		**E4/E6 (ratio)**		**DOC (mg L-1)**		**SUVA (L mg-1 m-1)**	
R Square	**0.054**	R Square	**0.053**	R Square	**0.053**	R Square	**0.024**	R Square	**0.043**	R Square	**0.047**	R Square	**0.012**
P-value	**0.012**	P-value	**0.011**	P-value	**0.016**	P-value	**0.000**	P-value	**0.029**	P-value	**0.000**	P-value	**0.017**
(Constant)	440.109	(Constant)	211.378	(Constant)	21.407	(Constant)	6.543	(Constant)	2.621	(Constant)	38.746	(Constant)	5.605
%herb	**-3.937**	**%herb**	**-1.586**	**%herb**	**-0.190**	**%herb**	**-0.039**	**%brash**	**0.019**	**%herb**	**-0.298**	**%brash**	**0.017**
%brash	**2.899**	**%brash**	**0.637**	**%brash**	**0.072**	**%grass**	**-0.073**	**%Moss**	**0.009**	**%brash**	**0.119**	**%Call**	**-0.005**
%grass	**-5.406**	**%grass**	**-2.560**	**%grass**	**-0.239**			**%grass**	**0.025**	**%grass**	**-0.333**		
%Moss	**0.956**	**%Call**	**-0.293**	**%Call**	**-0.056**								
%Call	**-0.573**	**%Moss**	**0.333**	**%Sedge**	**-0.031**								

All years (2016-2021) combined for plots													
Hazen (Au m-1)		**UV254 (Au m-1)**		**UV465 (Au m-1)**		**UV665 (Au m-1)**		**E4/E6 (ratio)**		**DOC (mg L-1)**		**SUVA (L mg-1 m-1)**	
R Square	**0.039**	R Square	**0.037**	R Square	**0.033**	R Square	**0.013**	R Square	**0.063**	R Square	**0.043**	R Square	**0.028**
P-value	**0.007**	P-value	**0.014**	P-value	**0.008**	P-value	**0.015**	P-value	**0.047**	P-value	**0.023**	P-value	**0.022**
(Constant)	411.479	(Constant)	206.954	(Constant)	16.952	(Constant)	6.814	(Constant)	2.538	(Constant)	48.890	(Constant)	5.882
%Moss	**2.176**	**%Moss**	**0.713**	**%Moss**	**0.083**	**%grass**	**-0.152**	**%brash**	**0.025**	**%herb**	**-0.385**	**%Call**	**-0.015**
%brash	**2.888**	**%brash**	**0.832**	**%brash**	**0.094**	**%herb**	**-0.035**	**%Moss**	**0.008**	**%grass**	**-1.026**	**%Moss**	**0.016**
%grass	**-13.167**	**%grass**	**-5.319**	**%grass**	**-0.499**	**%Call**	**-0.011**	**%bare**	**0.008**	**%Sedge**	**-0.120**	**%Sphagnum**	**0.035**
%herb	**-2.373**	**%herb**	**-1.281**	**%herb**	**-0.093**					**%Sphagnum**	**-0.461**		
		%Call	**-0.339**							**%Call**	**-0.084**		

All years (2016-2021) combined for slopes													
Hazen (Au m-1)		**UV254 (Au m-1)**		**UV465 (Au m-1)**		**UV665 (Au m-1)**		**E4/E6 (ratio)**		**DOC (mg L-1)**		**SUVA (L mg-1 m-1)**	
R Square	**0.066**	R Square	**0.067**	R Square	**0.066**	R Square	**0.034**	R Square	**0.032**	R Square	**0.060**	R Square	**0.008**
P-value	**0.000**	P-value	**0.010**	P-value	**0.000**	P-value	**0.043**	P-value	**0.001**	P-value	**0.007**	P-value	**0.046**
(Constant)	430.446	(Constant)	216.489	(Constant)	17.712	(Constant)	6.464	(Constant)	2.621	(Constant)	38.746	(Constant)	5.605
%herb	**-3.948**	**%herb**	**-1.649**	**%herb**	**-0.164**	**%herb**	**-0.040**	**%brash**	**0.019**	**%herb**	**-0.298**	**%brash**	**0.017**
%brash	**3.249**	**%brash**	**0.506**	**%brash**	**0.125**	**%grass**	**-0.053**	**%Moss**	**0.009**	**%brash**	**0.119**	**%Call**	**-0.005**
		%grass	**-1.881**			**%bare**	**0.019**	**%grass**	**0.025**	**%grass**	**-0.333**		
		%Call	**-0.276**										

Flow

Monthly stream samples allowed comparison of sites and their paired sub-catchments (burnt and mown) in water chemistry, as well as changes over time. The below sections summarise the findings for UV spectra analyses as parameters to assess water quality. There was clear seasonal (summer peaks) and inter-annual variation for the water quality UV spectra parameter measurements in the monthly flow samples (**Figure A8.5** below); UV254 and SUVA were substantially lower in 2013 and E4/E6 ratios were substantially higher in October and November 2020 (unusually high rainfall (see Appendix 1) and flooding in England) compared to all other years, whereas Hazen values displayed a consistent annual pattern throughout the entire monitoring period. On average (mean ± standard deviation), UV254 values, Hazen values and E4/E6 ratios decreased significantly ($p< 0.001$) from Nidderdale (165±109; 426±314; 2.81±0.86, respectively) to Mossdale (144±80; 329±152; 2.65±0.55, respectively) to Whitendale (99±75; 254±196; 2.29±0.87, respectively). Mean SUVA values (**Figure A8.5**) were statistically the same across the three sites (decreasing from Nidderdale: 6.87±3.70 L mg^{-1} m^{-1} to Whitendale: 5.83±2.91 L mg^{-1} m^{-1} to Mossdale: 5.63±2.50 L mg^{-1} m^{-1}).

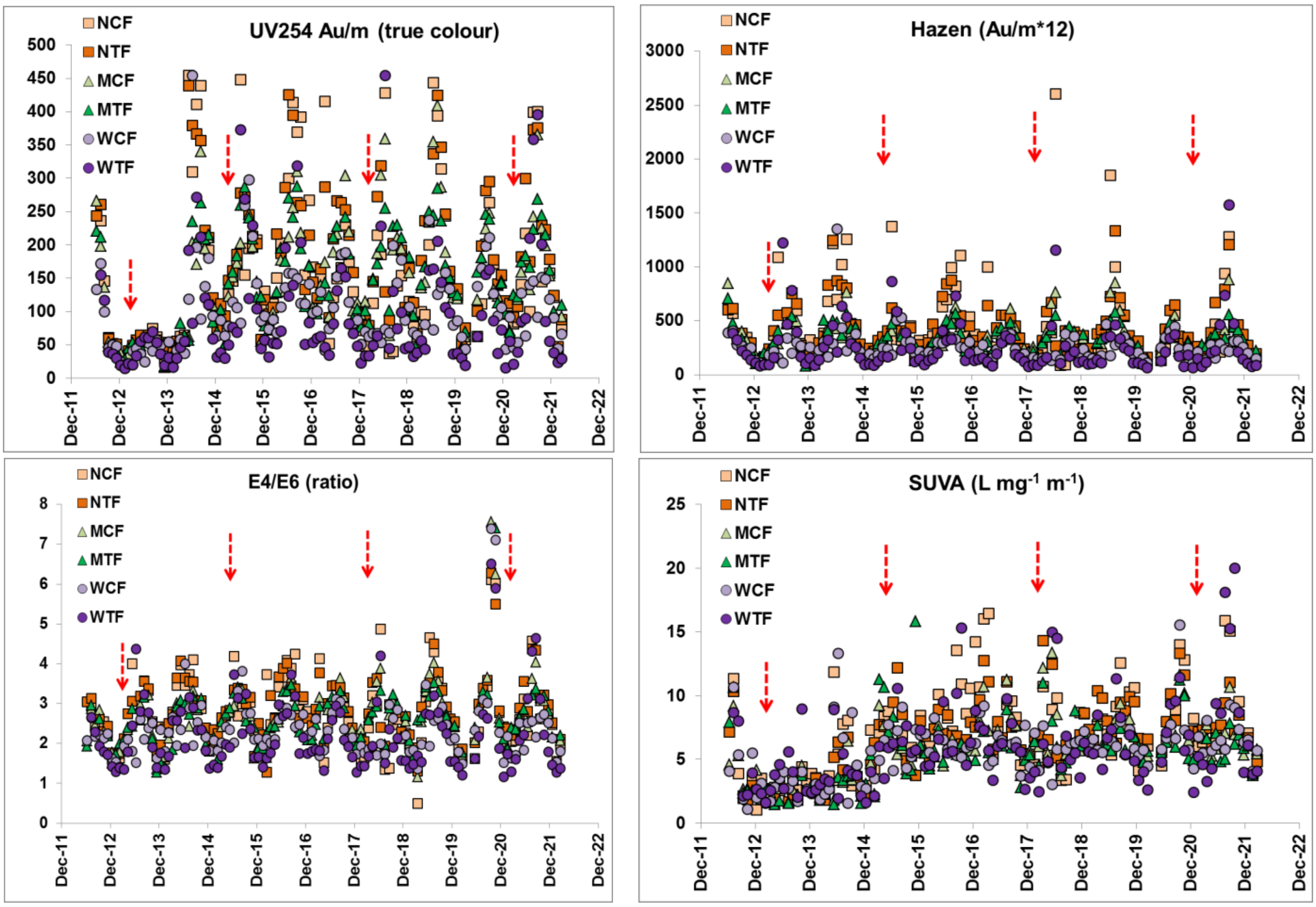


Figure A8.5 Water quality measures from flow weir water samples between July 2012 and March 2022. Absorbance (Au/m) at 254 nm (**top left**), Hazen (**top right**), the absorbance 465nm/665nm (E4/E6) ratio (**bottom left**) and SUVA (L mg-1 m-1) values (**bottom right**) are shown for each of the three sites (N = Nidderdale, M = Mossdale, W = Whitendale) for the stream flow in burnt control (CF) and mown treatment (TF) sub-catchments. The dashed red arrows indicate the onset of different management in March 2013 (and subsequent additional catchment-scale management in 2015, 2018, 2021). Note that the Hazen conversion of absorbance at 400 nm used the average factor (i.e. UV400*12) reported for Yorkshire catchments in Watts et al. (2001). Zero values due to missing data (snow or no flow) and one very high SUVA value, NCF (July-15) = 37.05, was removed.

As shown in the previous report (Heinemeyer et al., 2019b), there were climatic impacts on the water parameters measured in the monthly stream flow samples (in the following the analysis is from Phase 1): the month of measurement had a significant impact on UV254 (F11, 36 = 11.0, p< 0.001), whilst soil temperature had a positive effect on the E4/E6 ratio and Hazen values (coefficient: 0.1 for both; F1, 50 = 300.6, p< 0.001 and F1, 52 = 294.7, p< 0.001, respectively), and total rainfall in the four weeks prior to sampling had a negative impact (coefficient: -0.001 for both; F1, 57 = 24.4, p< 0.001 and F1, 60 = 19.5, p< 0.001, respectively). The below figure (**Figure A8.6**) provides an overall seasonal summary for each of the four main UV spectra related water quality parameters. Whilst there were clear differences between sites, there were no obvious management related differences (i.e. between the two sub-catchments, burnt vs. mown, at each site) for any of the water quality parameters.

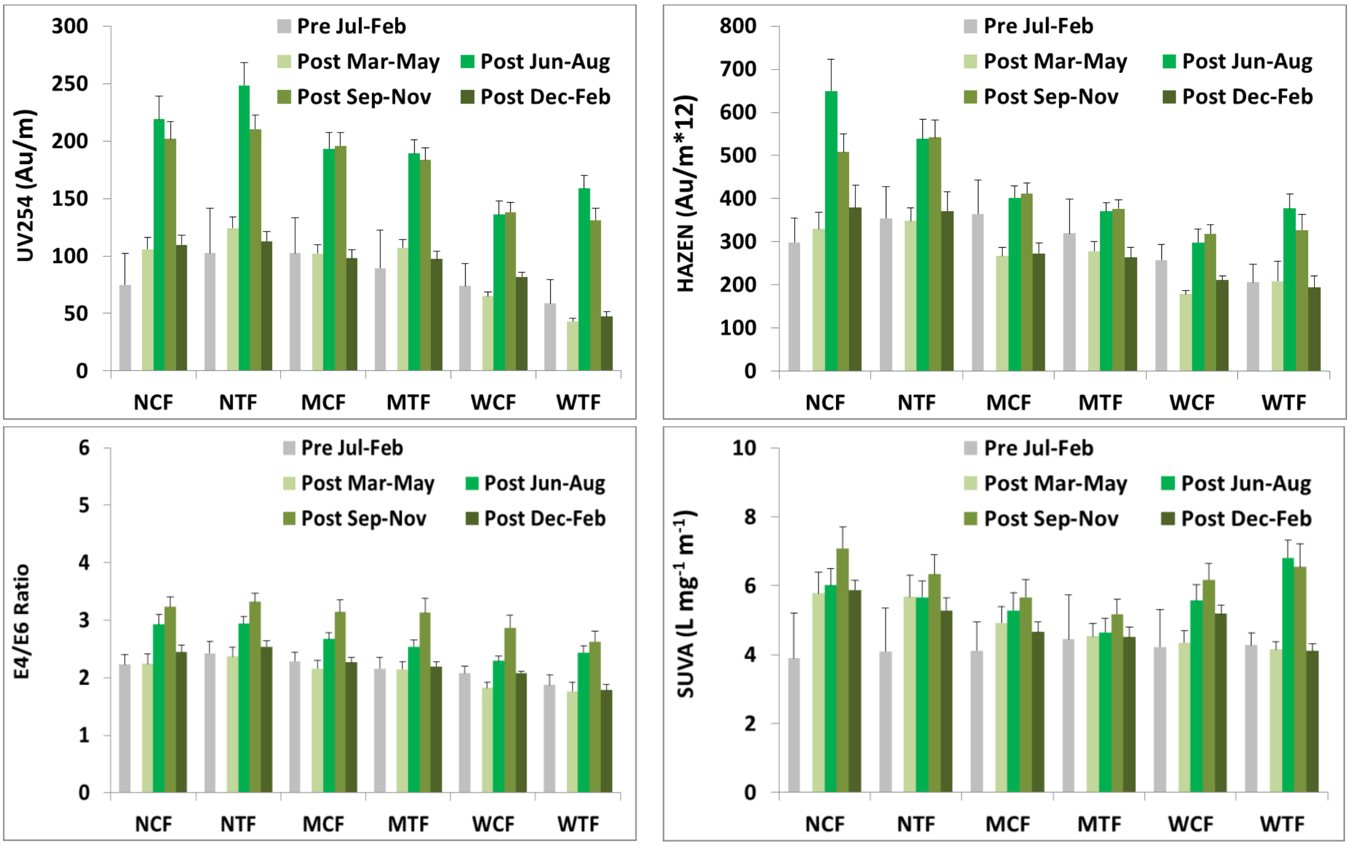


Figure A8.6 Water quality measures (means ± standard error) for monthly flow weir samples per seasonal period (clockwise from top left: UV254 (Au/m), Hazen (Au/m*12), SUVA (L mg^{-1} m^{-1}) and E4/E6 ratio) from the burnt control (C) and mown treatment (T) sub-catchments at each site (N = Nidderdale, M = Mossdale, W = Whitendale) during the pre- (2012/13) and post-management (2013-2021) periods.

The overall pre- versus two post-management periods (Phase 1 & 2) are summarised in box plots in the following figure (**Figure A8.7**).

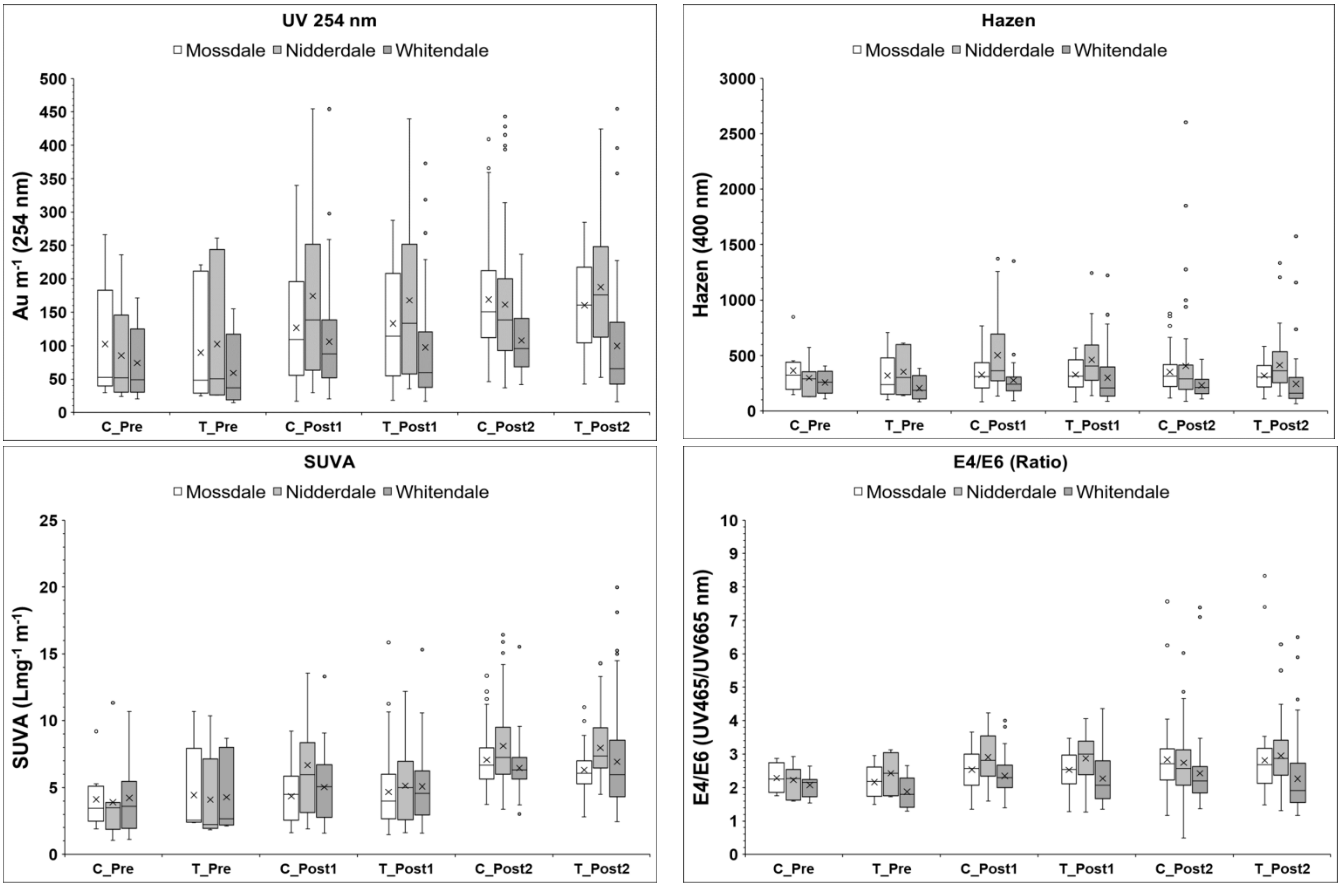


Figure A8.7 Overall water quality measures based on monthly flow weir samples (clockwise from top left: UV254 (Au/m), Hazen (Au/m*12), SUVA (L mg^{-1} m^{-1}) and E4/E6 ratio) from the burnt control (C) and mown treatment (T) sub-catchments at each site (Nidderdale, Mossdale, Whitendale) during the pre- (2012/13) and two post-management (Post1: 2013-2016 & Post2: 2017-2021) periods. The mean is indicated by a marker (x), the median by a line and outliers are shown outside the 1.5 times interquartile range (whiskers) of the lower and upper quartiles (box).

DOC monthly stream flow concentration

The dissolved organic carbon (DOC) data were assessed with a Before vs After Control vs Impact (BACI) design as part of a BACI mixed-effect model with date and site as random effects. Data were log-transformed, with autoregressive correlation and a +0.000001 offset was used to avoid errors with ‘0’ values. The model was: log(DOC.conc. +0.000001) ~ BA * CI, random = list(~1|Date, ~1|Site), correlation = corAR1().

Table A8.2 Summary output for the overall BACI model combining all three sites (Nidderdale, Mossdale and Whitendale) for monthly stream flow concentrations of dissolved organic carbon (DOC) also shown are the back-transformed model estimates.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	2.934	0.153	19.232	<2e-16 ***	2.635 – 3.232
BA	0.074	0.159	0.464	0.644	-0.238 – 0.385
CI	-0.100	0.068	-1.462	0.145	-0.234 – 0.034
BA : CI	**0.106**	**0.071**	**1.492**	**0.137**	**-0.033 – 0.246**

Back-transformed

Term	Estimate	95% Confidence Interval
Intercept	18.80	13.94 – 25.33
BA	1.444	-3.982 – 8.830
CI	-1.789	-3.922 – 0.650
BA : CI	**2.103**	**-0.610 – 5.244**

There was no significant BACI effect (**Table A8.2**), but the about 2.1 mg L^{-1} higher DOC concentration in mown vs. burnt stream flow samples (**Figure A8.8**; top) was overall nearly significant (p=0.137), which was mainly related to much higher DOC in the mown catchment at Mossdale (**Figure A8.8**; bottom). A further BACI analysis separating short-term and long-term post-management period (with date and site as random effects, log-transformed data with autoregressive correlation) also did not detect any overall significant BACI effect.

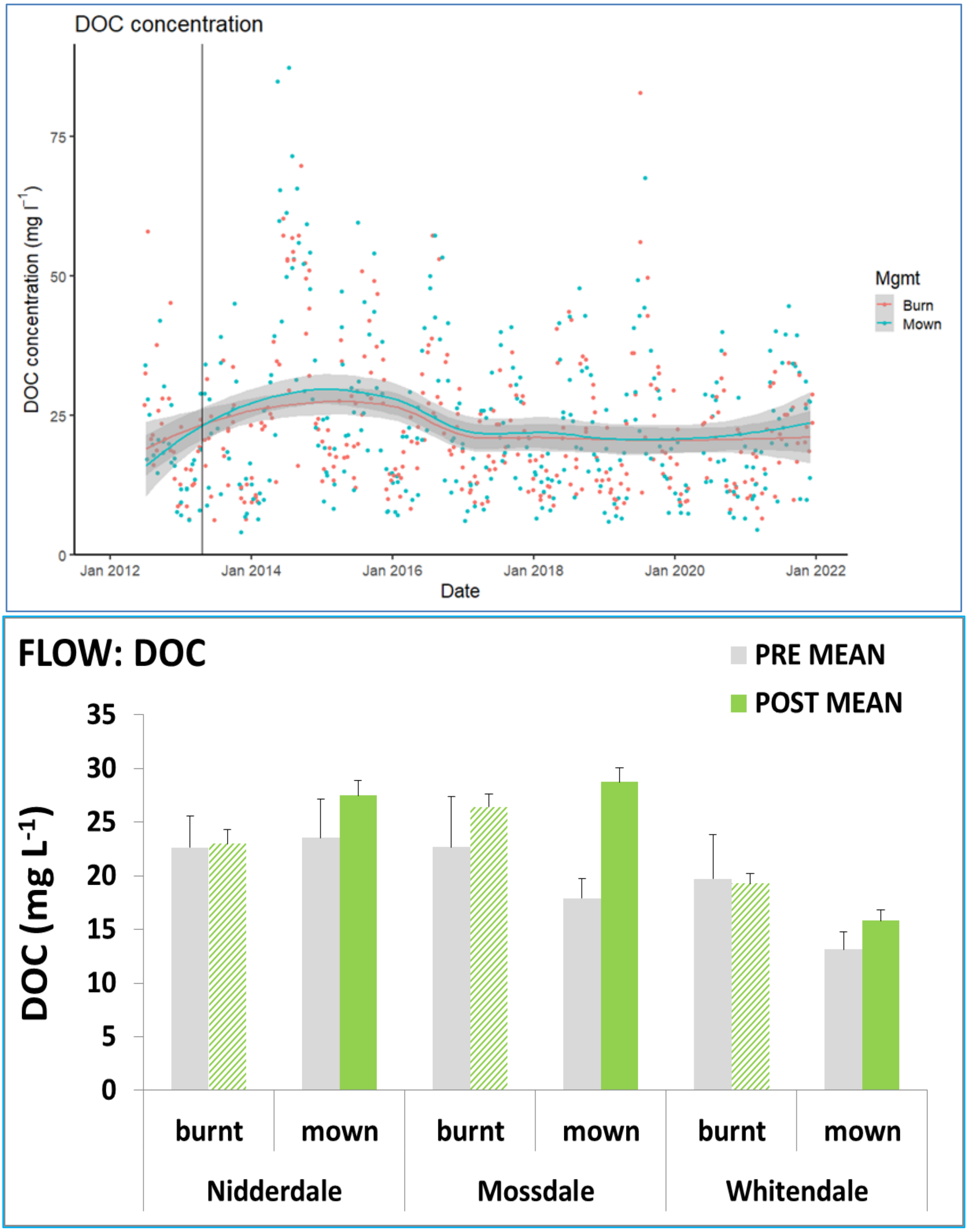


Figure A8.8 Monthly concentrations of stream flow dissolved organic carbon (DOC) in streams of burnt and mown catchments during the pre- (2012/13) and post-management periods (2013-2021). The **top** graph shows the overall data over time with the line separating the pre- (grey bars) vs. post-period (green bars) whilst the **bottom** graph provides the overall means (with SE) for the three sites (Nidderdale, Mossdale, Whitendale) for the pre and post period.

DOC monthly stream flow export

Whilst dissolved organic carbon (DOC) export rates were at first calculated by simply multiplying the concentration with the monthly flow volume (Heinemeyer et al., 2019b), this is known to lead to overestimation of C export as in (non-eroding) peatlands higher flow rates generally have lower concentrations due to dilution effects of rainfall from overland flow, especially under high flow in autumn (Clark et al., 2007). Therefore, the export rates were also estimated by fitting a model to the monthly post-management data (pre-management values were calculated as previously due to limited data to obtain a robust enough model fit). The logarithmic model fit of concentration vs. stream flow resulted in overall very similar equations over time, which were similar (in parameters and goodness of fit [R^2] values) to those reported by Clark et al. (2007). However, for Whitendale the burnt catchment mostly showed the opposite (i.e. positive) relationship, indicating an influence of organo-mineral peat areas (see Clark et al., 2007), which was excluded in the models (**Table A8.3**).

Table A8.3 Summary output of the model fit to the monthly dissolved organic carbon (DOC) concentrations in burnt and mown catchments over the entire post-management period. Not the goodness of fit is equally low to that reported by Clark et al. (2007).

Catchment	(mg/L)	**Nidderdale**	R2	**Mossdale**	R2	**Whitendale**	R2
Control (Burnt)	**DOC**	= -2.057ln(x) + 25.454	0.13	= -2.104ln(x) + 28.674	0.12	= -1.355ln(x) + 20.113	0.1
Treatment (Mown)	**DOC**	= -1.041ln(x) + 29.069	0.04	= -2.001ln(x) + 29.728	0.12	= -2.358ln(x) + 20.517	0.09

The calculated DOC export rates (based on hourly flow rates) were assessed with a Before vs After Control vs Impact (BACI) design as part of a BACI mixed-effect model with date and site as random effects. The model was:

DOC.month.sum ~ BA * CI + (1|Site) + (1|Date).

There was a weakly significant (* $p<0.05$ per period) BACI effect showing a decrease in DOC export (**Table A8.4**) of about 4.0 kg ha^{-1} $month^{-1}$ (0.4 gC m^{-2} $month^{-1}$) within the mown catchments vs. the burnt catchment streams. Another BACI mixed-effect model analysis with date and site as random effects confirmed this overall small but significant BACI effect across both periods for a decrease in DOC export with mown management compared to burn management (**Figure A8.9**).

Table A8.4 Summary output for the overall BACI model combining all three sites (Nidderdale, Mossdale and Whitendale) for monthly stream flow export of dissolved organic carbon (DOC) in streams of burnt (C) and mown I) catchments either for the combined post-management period or the two separate periods (2013-2016 & 2017-2021).

Term	**Estimate**	**Std. Err**	**t value**	**P value signif**	**95% Conf.Int**
Intercept	20.54	5.091	4.035	0.00076 ***	10.74 – 30.352
BA	-2.566	4.387	-0.585	0.560	-11.189 – -6.057
CI	1.563	0.584	0.986	0.324	-1.542 – 4.667
BA : CI	**-4.038**	**0.653**	**-2.444**	**0.00149 ***	**-7.277 – -0.799**

Before vs After (short-term and long-term)

Term	**Estimate**	**Std. Err**	**t value**	**P value signif**	**95% Conf.Int**
Intercept	20.54	5.107	4.023	0.000768 ***	10.74 – 30.35
BA 2013-16	-2.889	4.630	-0.624	0.534 ***	-11.948 – 6.171
BA 2017-21	-2.318	4.542	-0.510	0.611 ***	-11.205 – 6.569
CI	1.563	1.585	0.986	0.324	-1.540 – 4.666
BA 2013-16 : CI	**-3.586**	**1.738**	**-2.063**	**0.0396 ***	**-6.989 – -0.182**
BA 2017-21 : CI	**-4.384**	**1.703**	**-2.574**	**0.0103 ***	**-7.720 – -1.049**

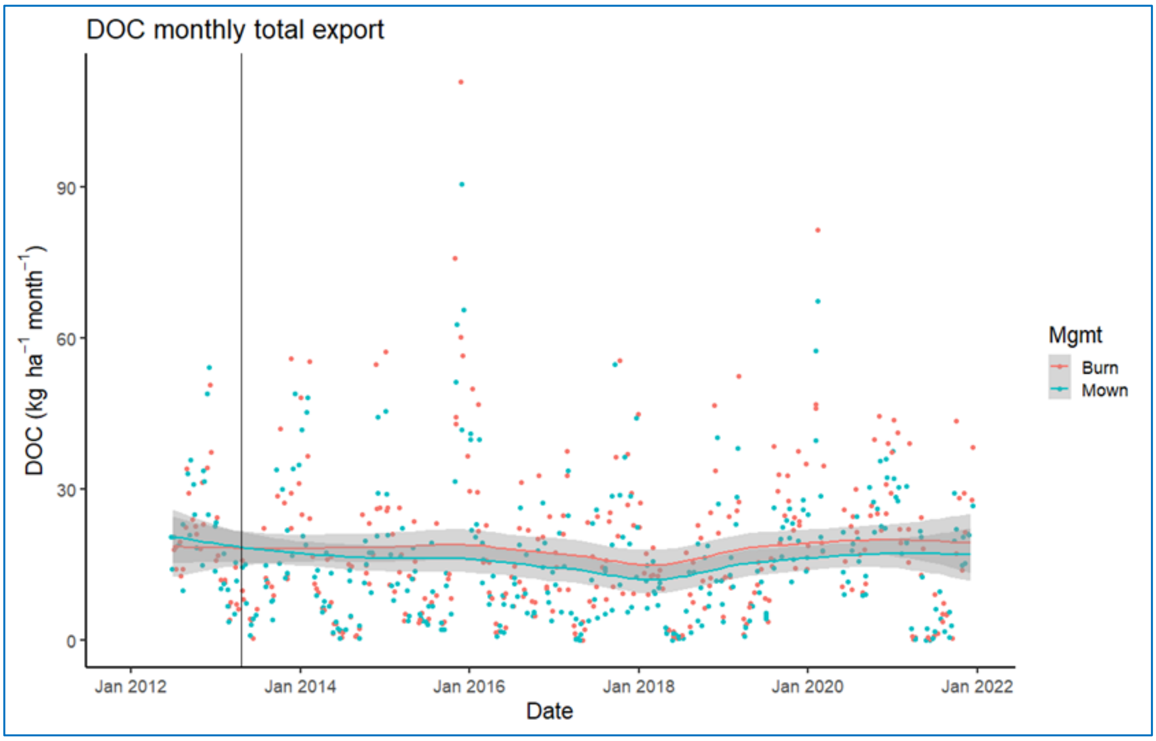


Figure A8.9 Monthly stream flow export of dissolved organic carbon (DOC) in streams of burnt and mown catchments of the three sites (Nidderdale, Mossdale, Whitendale) during the pre- (2012/13) and post-management periods (2013-2021) for the overall export over time with the line separating the pre- (grey bars) vs. post-period (green bars) for the pre and post period.

POC monthly stream flow concentration

The particulate organic carbon (POC) data were assessed with a Before vs After Control vs Impact (BACI) design as part of a BACI mixed-effect model with date and site as random effects. Data were log-transformed, with a +0.000001 offset to avoid errors with '0' values, with autoregressive correlation and the final model was: log(POC.conc. +0.000001) ~ BA * Catchment, random = list(~1|Date, ~1|Site), correlation = corAR1().

Table A8.5 Summary output for the overall BACI model combining all three sites (Nidderdale, Mossdale and Whitendale) for monthly stream flow concentrations of particulate organic carbon (POC) in streams of burnt (C) and mown I) catchments; also shown are the back-transformed model estimates.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	1.057	0.235	4.495	6.95e-06 ***	0.596 – 1.518
BA	**-1.051**	**0.245**	**-4.288**	**1.81e-05 *****	**-1.532 – -0.571**
CI	-0.328	0.178	-1.840	0.0666 .	-0.678 – 0.021
BA : CI	**0.494**	**0.186**	**2.659**	**0.0082 ****	**0.130 – 0.858**

Back-transformed

Term	Estimate	95% Confidence Interval
Intercept	2.878	1.815 – 4.563
BA	-1.872	-2.256 – -1.252
CI	-0.805	-1.417 – 0.061
BA : CI	**1.838**	**0.400 – 3.909**

There was a significant BACI effect (**Table A8.5**), and POC concentration increased significantly with mown management compared to burn management (which declined more from pre to post periods than mown at

Nidderdale and Mossdale) by about 1.8 mg L^{-1}, mostly at Whitendale (**Figure A8.10**). A further BACI analysis separating short-term and long-term post-management period also showed significant BACI effects per period.

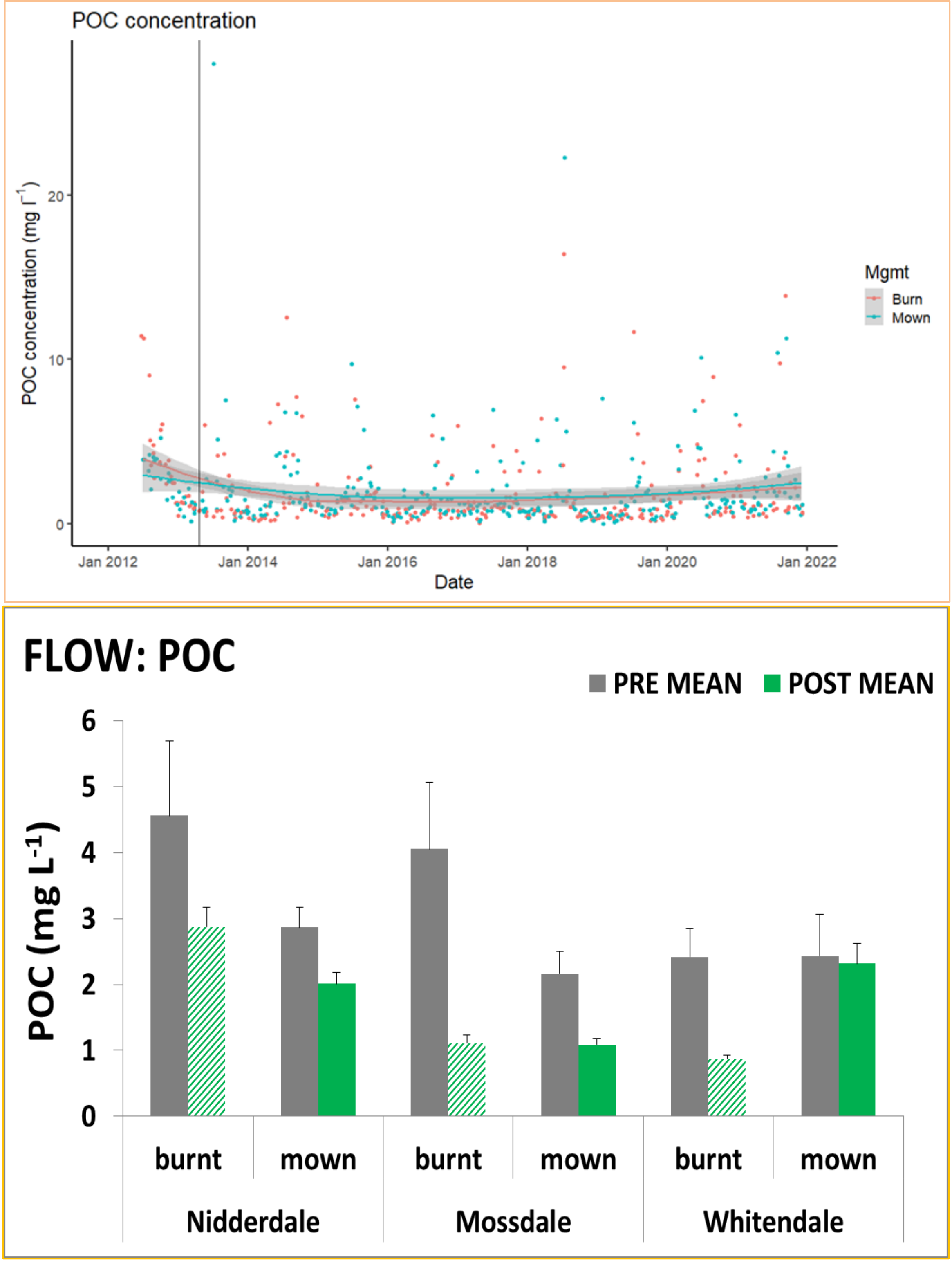


Figure A8.10 Monthly concentrations of stream flow particulate organic carbon (POC) in streams of burnt and mown catchments during the pre- (2012/13) and post-management periods (2013-2021). The **top** graph shows the overall data over time with the line separating the pre- (grey bars) vs. post-period (green bars) whilst the **bottom** graph provides the overall means (with SE) for the three sites (Nidderdale, Mossdale, Whitendale) for the pre and post period.

POC monthly stream flow export

As for DOC, post-management particulate organic carbon (POC) export was also estimated by a model fit to the data, and as for DOC, the Whitendale burnt catchment mostly showed opposite (i.e. positive) relationships to the other sites and catchments, indicating an influence of organo-mineral peat areas (see Clark et al. 2007), which was excluded in the models (**Table A8.6**).

Table A8.6 Summary output of the model fit to the monthly particulate organic carbon (POC) concentrations in burnt and mown catchments over the entire post-management period. Not the goodness of fit is equally low to that reported by Clark et al. (2007).

Catchment	(mg/L)	**Nidderdale**	R2	**Mossdale**	R2	**Whitendale**	R2
Control (Burnt)	**POC**	= -0.629ln(x) + 3.2452	0.28	= -0.147ln(x) + 1.1384	0.07	= -0.13ln(x) + 1.3514	0.1
Treatment (Mown)	**POC**	= -0.118ln(x) + 1.6933	0.11	= -0.091ln(x) + 1.1764	0.03	= -1.608ln(x) + 5.0578	0.28

The calculated POC export rates (based on hourly flow rates) were assessed with a Before vs After Control vs Impact (BACI) design as part of a BACI mixed-effect model with date and site as random effects. The model was:

POC.month.sum ~ BA * Catchment + (1|Site) + (1|Date).

There was no significant BACI effect (**Table A8.7**) between POC export in the mown and burnt catchment streams. Another BACI mixed-effect model analysis with date and site as random effects confirmed this overall lack of any real difference across both periods with mown catchments showing consistently higher POC export already since the pre-management period compared to the burnt catchments (i.e. CI effect in **Table A8.7**; **Figure A8.11**).

Table A8.7 Summary output for the overall BACI model combining all three sites (Nidderdale, Mossdale and Whitendale) for monthly stream flow export of particulate organic carbon (POC) either for the combined post-management period.

Term	**Estimate**	**Std. Err**	**t value**	**P value signif**	**95% Conf.Int**
Intercept	0.922	0.229	4.019	7.24e-05 ***	0.472 – 1.371
BA	-0.110	0.239	-0.462	0.645	-0.579 – 0.358
CI	**0.271**	**0.098**	**2.780**	**0.00574 ****	**0.080 – 0.462**
BA : CI	-0.141	0.102	-1.390	0.166	-0.340 – -0.058

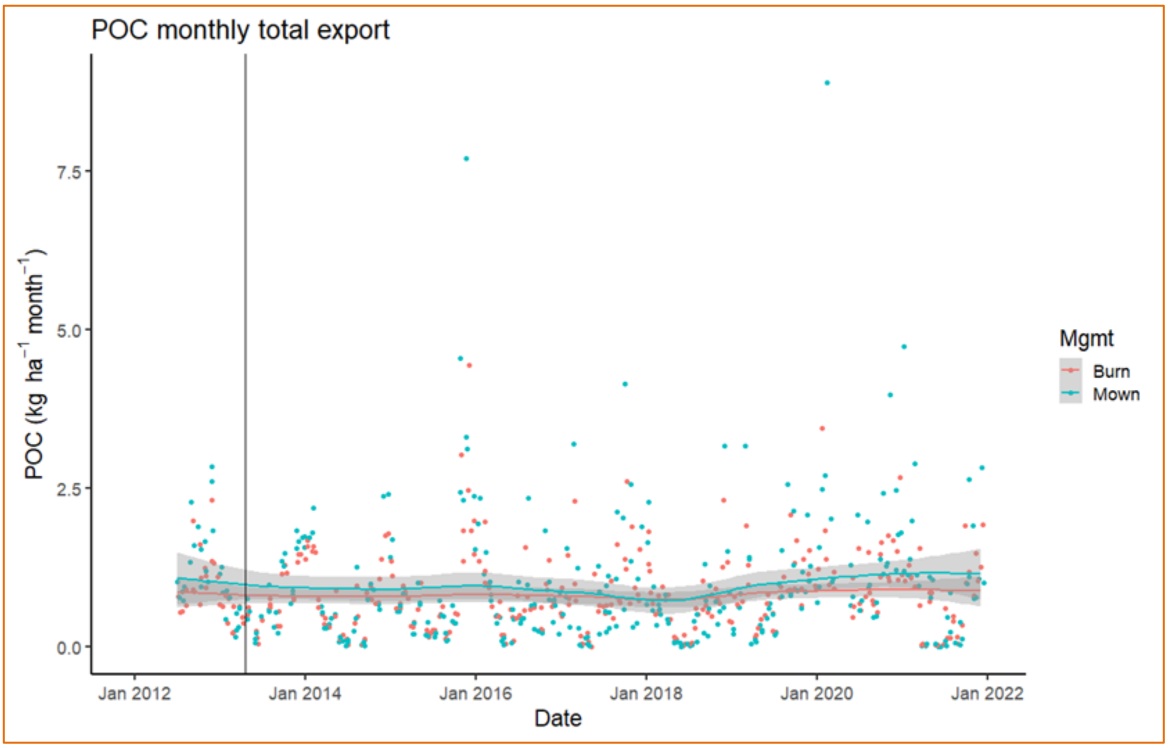


Figure A8.11 Monthly stream flow export of particulate organic carbon (POC) in catchment streams of the three sites (Nidderdale, Mossdale, Whitendale) during the pre- (2012/13) and post-management periods (2013-2021) for the overall export over time with the line separating the pre- (grey bars) vs. post-period (green bars) for the pre and post period.

Elemental export

The concentrations of key elements in the monthly stream samples was analysed by a BACI mixed effect models with site and date as random effects. Zn, Na, K, Fe, Cu and Ca required autoregressive correlation (after checking autocorrelation and partial autocorrelation plots) and log-transformation (after checking model residual plots); their model was: lme(log(response) ~ BA * CI, random = list(~1|Date, ~1|Site), correlation = corAR1()). Mg and Al required autoregressive correlation (after checking autocorrelation and partial autocorrelation plots); their model was: lme(response ~ BA * CI, random = list(~1|Date, ~1|Site), correlation = corAR1()). Pb and P required Gamma distribution with a log link (after checking model residual plots); their model was: glmer(response ~ BA * CI + (1|Site) + (1|Date), family = Gamma(link="log"). Response values that were log-transformed or had a log link had a small offset of +0.000001 added, to avoid errors with '0' values. Only Pb showed a significant BACI effect.

Table A8.8 Summary of the BACI analysis for lead (Pb), the only element with a significant BACI impact, also shown are the back-transformed model parameter estimates.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	-9.956	0.997	-9.990	<2e-16 ***	-11.909 – -8.002
BA	-0.036	0.996	-0.036	0.971	-1.989 – 1.916
CI	-0.331	0.476	-0.694	0.488	-1.264 – 0.603
BA : CI	**-1.074**	**0.509**	**-2.109**	**0.035 ***	**-2.071 – -0.076**

Back-transformed

Term	Estimate	95% Conf.Int
Intercept	0.000047	0.000007 – 0.000335
BA	-0.000002	-0.000041 – 0.000275
CI	-0.000013	-0.000034 – 0.000039
BA : CI	**-0.000031**	**-0.000041 – -0.000003**

Table A8.9 Summary of the elemental concentrations (top part showing the monthly means, the bottom part the corresponding standard errors) in the monthly stream flow samples taken from the burnt and mown catchments during the pre- (2012-13) and post-management (203-2021) period at the three sites (Nidderdale: Nidd; Mossdale: Moss; Whitendale: Whit).

		Na	**Fe**	**Ca**	**K**	**Mg**	**Al**	**Mn**	**Zn**	**P**	**Cu**	**Pb**
	Site	**mg L^{-1}**	**mg L-1**	**mg L-1**	**mg L-1**	**mg L-1**	**mg L-1**	**mg L-1**	**mg L-1**	**mg L-1**	**mg L-1**	**mg L-1**
	Management	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
Pre	Nidd / Burnt	2.506	1.669	0.891	0.815	0.383	0.216	0.085	0.069	0.036	0.019	0.004
	Nidd / Mown	2.620	1.344	0.851	0.730	0.381	0.223	0.047	0.053	0.024	0.013	0.001
	Moss / Burnt	2.539	1.203	1.077	0.623	0.368	0.230	0.025	0.052	0.028	0.015	0.002
	Moss / Mown	2.536	0.763	1.016	0.600	0.359	0.195	0.009	0.045	0.019	0.016	0.013
	Whit / Burnt	3.269	0.739	0.929	0.863	0.674	0.295	0.036	0.048	0.022	0.015	0.012
	Whit / Mown	3.079	0.674	0.684	0.734	0.505	0.190	0.221	0.044	0.019	0.014	0.012
Post	Nidd / Burnt	3.006	3.739	0.775	0.387	0.478	0.187	0.116	0.048	0.025	0.017	0.006
	Nidd / Mown	3.037	2.750	0.654	0.358	0.451	0.224	0.057	0.043	0.028	0.016	0.006
	Moss / Burnt	3.061	1.904	1.102	0.505	0.483	0.207	0.032	0.040	0.022	0.017	0.009
	Moss / Mown	3.370	1.391	1.251	0.386	0.521	0.140	0.013	0.039	0.040	0.016	0.007
	Whit / Burnt	3.950	0.645	0.613	0.558	0.787	0.251	0.036	0.037	0.019	0.016	0.009
	Whit / Mown	3.710	2.702	0.546	0.411	0.640	0.189	0.325	0.044	0.061	0.014	0.004

		Na	Fe	Ca	K	Mg	Al	Mn	Zn	P	Cu	Pb
	Site	mg L-1	mg L-1	mg L-1	mg L-1	mg L-1	mg L-1	mg L-1	mg L-1	mg L-1	mg L-1	mg L-1
	Management	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE
Pre	Nidd / Burnt	0.268	0.431	0.153	0.111	0.034	0.017	0.013	0.012	0.005	0.002	0.002
	Nidd / Mown	0.291	0.307	0.128	0.082	0.036	0.014	0.007	0.006	0.005	0.001	0.001
	Moss / Burnt	0.249	0.237	0.161	0.049	0.034	0.023	0.004	0.005	0.005	0.002	0.002
	Moss / Mown	0.302	0.155	0.146	0.086	0.042	0.017	0.002	0.006	0.002	0.002	0.011
	Whit / Burnt	0.274	0.297	0.241	0.160	0.083	0.021	0.007	0.005	0.004	0.002	0.010
	Whit / Mown	0.259	0.236	0.083	0.103	0.050	0.017	0.047	0.008	0.003	0.001	0.009
Post	Nidd / Burnt	0.086	0.578	0.061	0.043	0.018	0.015	0.006	0.002	0.002	0.002	0.002
	Nidd / Mown	0.085	0.211	0.050	0.044	0.017	0.014	0.002	0.002	0.002	0.002	0.002
	Moss / Burnt	0.103	0.156	0.073	0.167	0.023	0.013	0.004	0.002	0.002	0.002	0.002
	Moss / Mown	0.128	0.139	0.087	0.036	0.024	0.009	0.002	0.003	0.018	0.002	0.002
	Whit / Burnt	0.090	0.033	0.041	0.022	0.030	0.013	0.002	0.002	0.001	0.002	0.002
	Whit / Mown	0.089	0.362	0.038	0.035	0.023	0.020	0.015	0.003	0.022	0.002	0.001

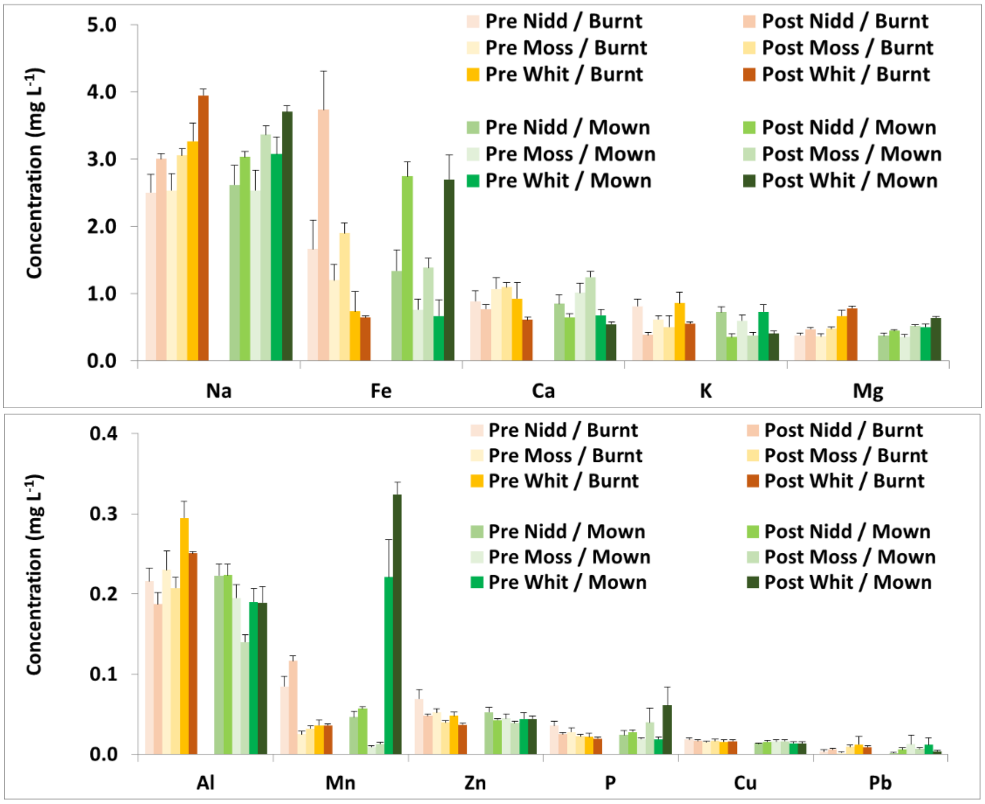


Figure A8.12 Elemental concentration (means +SE) in monthly stream flow samples from the burnt and mown catchments at the three sites (Nidderdale: Nidd; Mossdale: Moss; Whitendale: Whit) during the pre- (2012/13) and post-management (2013-2021) period.

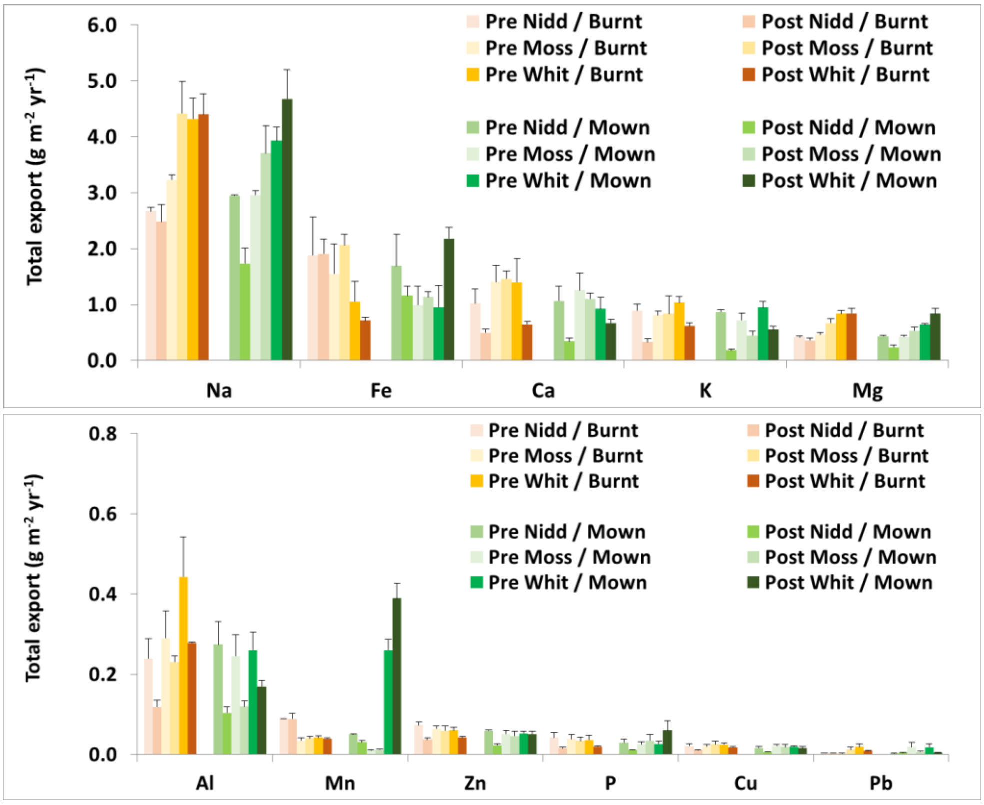


Figure A8.13 Total annual elemental export (as catchment area weighted means +SE) based on monthly stream flow samples from the burnt and mown catchments at the three sites (Nidderdale: Nidd; Mossdale: Moss; Whitendale: Whit) during the pre- (2012/13) and post-management (2013-2021) period.

Table A8.10 Summary of the annual elemental and per catchment area weighted export (top part showing the monthly means, the bottom part the corresponding standard errors) based on the monthly stream flow samples taken from the burnt and mown catchments during the pre- (2012-13) and post-management (203-2021) period at the three sites (Nidderdale: Nidd; Mossdale: Moss; Whitendale: Whit).

		Na	Fe	Ca	K	Mg	Al	Mn	Zn	P	Cu	Pb
	Site	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1
	Management	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
Pre	Nidd / Burnt	2.668	1.883	1.021	0.891	0.415	0.239	0.089	0.073	0.042	0.021	0.003
	Nidd / Mown	2.944	1.693	1.064	0.866	0.437	0.274	0.050	0.059	0.030	0.017	0.002
	Moss / Burnt	3.233	1.546	1.404	0.812	0.467	0.290	0.034	0.064	0.039	0.020	0.002
	Moss / Mown	2.958	0.990	1.259	0.719	0.423	0.246	0.010	0.051	0.025	0.022	0.019
	Whit / Burnt	4.317	1.054	1.398	1.037	0.840	0.443	0.042	0.060	0.036	0.024	0.018
	Whit / Mown	3.929	0.955	0.925	0.946	0.642	0.260	0.260	0.052	0.026	0.019	0.018
Post	Nidd / Burnt	2.481	1.906	0.495	0.333	0.361	0.118	0.088	0.037	0.015	0.010	0.003
	Nidd / Mown	1.734	1.161	0.342	0.180	0.238	0.104	0.031	0.023	0.011	0.006	0.004
	Moss / Burnt	4.421	2.062	1.463	0.837	0.673	0.230	0.040	0.059	0.034	0.025	0.012
	Moss / Mown	3.707	1.135	1.105	0.446	0.536	0.119	0.011	0.046	0.034	0.019	0.006
	Whit / Burnt	4.400	0.713	0.647	0.616	0.845	0.278	0.039	0.042	0.020	0.018	0.009
	Whit / Mown	4.680	2.179	0.673	0.550	0.835	0.170	0.390	0.051	0.060	0.015	0.004

		Na	Fe	Ca	K	Mg	Al	Mn	Zn	P	Cu	Pb
	Site	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1	g m-2 year-1
	Management	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE
Pre	Nidd / Burnt	0.066	0.680	0.265	0.112	0.020	0.049	0.000	0.008	0.012	0.005	0.000
	Nidd / Mown	0.020	0.568	0.267	0.037	0.017	0.058	0.002	0.002	0.008	0.003	0.001
	Moss / Burnt	0.092	0.542	0.296	0.069	0.033	0.069	0.007	0.006	0.011	0.005	0.001
	Moss / Mown	0.085	0.342	0.299	0.125	0.022	0.053	0.002	0.009	0.006	0.003	0.011
	Whit / Burnt	0.380	0.360	0.422	0.103	0.054	0.099	0.004	0.008	0.012	0.003	0.009
	Whit / Mown	0.248	0.385	0.206	0.110	0.019	0.045	0.027	0.005	0.008	0.001	0.008
Post	Nidd / Burnt	0.311	0.267	0.070	0.051	0.044	0.017	0.014	0.004	0.002	0.002	0.001
	Nidd / Mown	0.280	0.165	0.059	0.029	0.037	0.015	0.005	0.003	0.002	0.001	0.002
	Moss / Burnt	0.567	0.201	0.133	0.315	0.072	0.015	0.004	0.012	0.009	0.008	0.006
	Moss / Mown	0.493	0.101	0.099	0.076	0.058	0.014	0.002	0.012	0.015	0.006	0.003
	Whit / Burnt	0.362	0.062	0.046	0.051	0.082	0.019	0.004	0.005	0.002	0.007	0.002
	Whit / Mown	0.516	0.207	0.059	0.067	0.099	0.015	0.038	0.007	0.025	0.005	0.002

Appendix 9 (craneflies)

The project assessed the impacts of both climate and management (and their interaction) on craneflies (Tipulids), which are an important food source for many upland birds (e.g. golden plover). Whilst the climatic impacts and bird modelling (future scenarios) were provided in much detail in the Defra report (Heinemeyer et al., 2019b) the below summary provides a basic summary of the main findings and an update based on the cranefly transect monitoring, together with management impacts on vegetation height (which affects nesting of key upland bird species such as golden plover as modelled previously in Heinemeyer et al., 2019b), which continued into Phase 2.

Plot cranefly traps

Cranefly emergence traps were only monitored during Phase 1 (see Heinemeyer et al., 2019b). However, the findings are of general importance also in relation to interpreting catchment-scale impacts on cranefly populations as assessed over the transects. Therefore, the previous relationship between cranefly (Tipulid) emergence and peat soil moisture is shown in **Figure A9.1** below. Of key importance is the finding of an overall optimum peat soil moisture range of ~85-97% which is very similar to the previously reported values used in modelling impacts on bird populations (Carroll et al., 2015). Below and above this range cranefly emergence significantly reduces as shown in **Figure A9.1** below. Cranefly emergence matters for several upland bird species, such as golden plover, as their chicks rely on this food source for survival (Carroll et al., 2015). Another important aspect for bird populations is nesting success, which for many ground nesting birds is determined by the height of vegetation. Whilst tall vegetation is suitable for nesting of some species like hen harrier, other birds like golden plover require low vegetation heights (see Heinemeyer et al., 2019b). Importantly, vegetation heights differed between managements and across transects over time as shown in the below **Figures A9.2-3**.

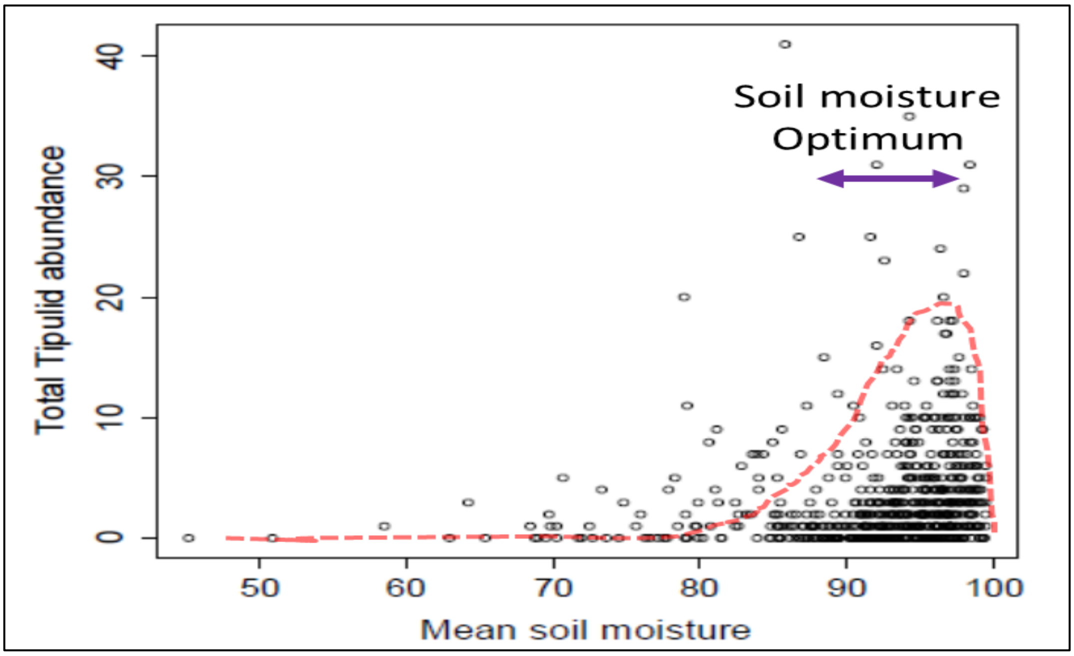


Figure A9.1 Relationship between cranefly (Tipulid) emergence (abundance) in sticky traps (totals per trap; see Heinemeyer et al., 2019b for further information) and soil moisture (%) measured in the top 10 cm of peat at all cranefly traps during Phase 1 for all managements, catchments and sites combined. The red broken line is a manually drawn line for visualisation of the distribution shape with an indication of the optimum soil moisture range.

Plot vegetation heights

Plot vegetation heights were assessed in summer each year. This was done across all monitoring plots per management. However, in 2014, one year after management, heights were estimated based on the heather heights for uncut plots and an estimated management height for burnt and mown plots, which were all interpolated to the measured heights in 2016. Height included all vegetation and was overestimating mean heights as sparsely distributed flower stems from grass and sedges were considered to full height when making measurements (**Figure A9.2**). Therefore, a more robust and meaningful representation of mean height was heather height (**Figure A9.3**), which was measured every year across each monitoring plot. Lowest heights were always recorded on burnt plots versus highest on uncut (old heather) plots.

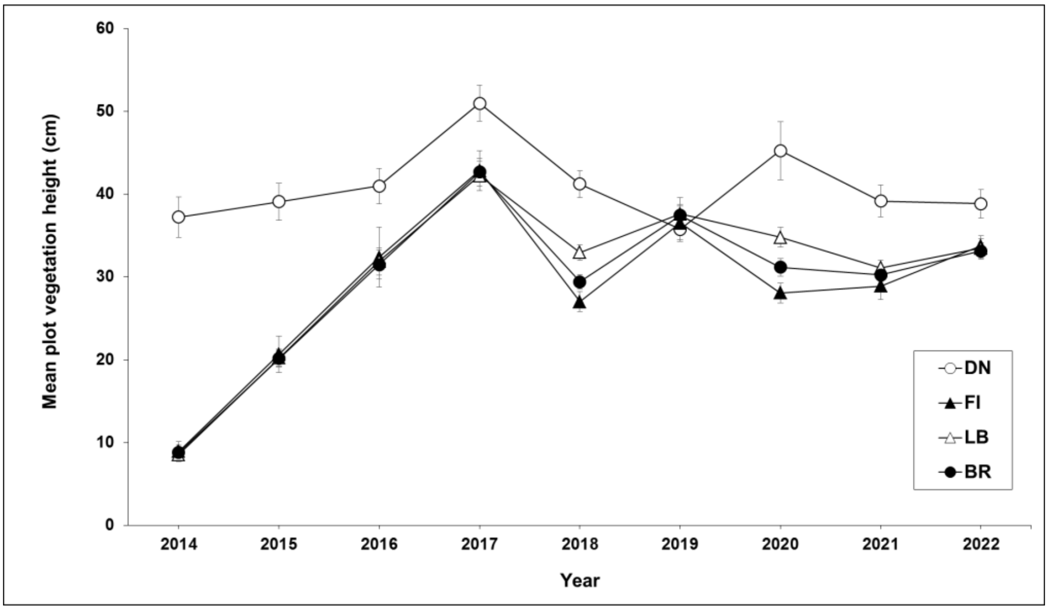


Figure A9.2 Mean vegetation height (± standard error) in summer on the monitoring plots (DN=uncut[do nothing]; FI=burnt[fire]; mown LB=left brash and BR=brash removal) during 2014-2022. Data for 2014 were based on the average management height and 2015 were estimated based on interpolating to data measured in 2016. Heights of any vegetation were measured at 20 points (with up-righted stems for grass/sedge) in each plot with 12 or 24 replicates for uncut and burnt versus the two mown managements, respectively.

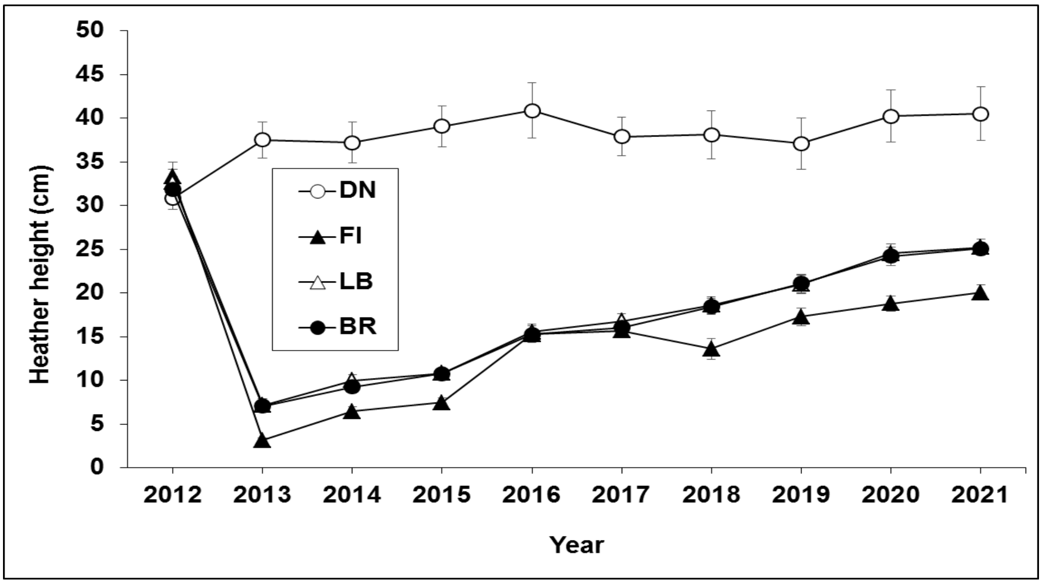


Figure A9.3 Mean heather heights (± standard error) in summer on the monitoring plots (DN=uncut[do nothing]; FI=burnt[fire]; mown LB=left brash and BR=brash removal) during 2012-2022. All heights were measured inside the 5x5 m (1x1 m in 2012) monitoring plots for five plants per plot with 12 or 24 replicates for uncut and burnt versus the two mown managements, respectively.

Cranefly abundance on transects

The recorded mean number of adult craneflies recorded along transects (14 were monitored in each mown and burnt sub-catchment at each site, which included both managed and unmanaged areas of different vegetation across the entire catchment) is shown in **Figure A9.4** below. In the years 2014-2016 significantly higher numbers were recorded on the transects in the mown catchments. However, this difference between managements disappeared in 2017 and there was no further difference observed in any of the subsequent years. Moreover, cranefly numbers per transect increased from about 0.5 to around a maximum of 7 in 2016/17 and subsequently declined to just around 1 per 20 m. These numbers were recorded during April – August and additional observations during other site activities recorded very high numbers in autumn at all three sites, especially in 2019 and 2020, following the very dry summer in 2018. This most likely reflects the previous year's summer larvae suffered under low soil moisture (**Figure A9.1**) and only subsequent larvae generations survived (with eggs laid under higher soil moisture later on in the year).

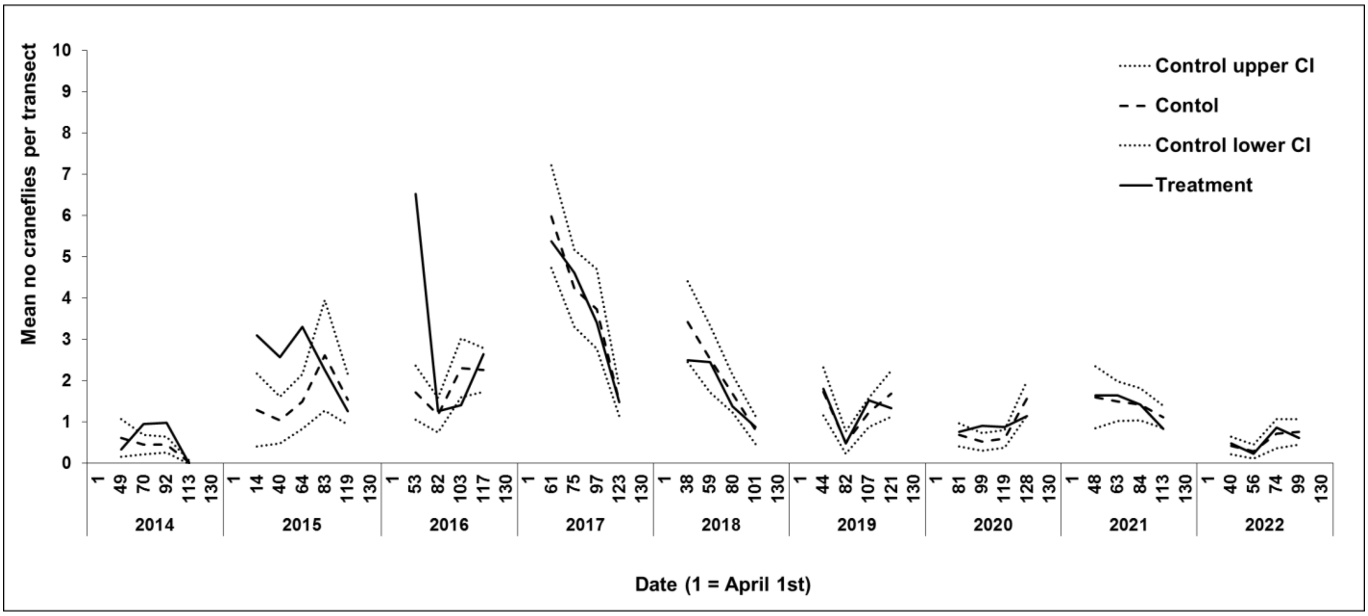


Figure A9.4 Mean cranefly numbers (± 95% confidence interval range for the control [burnt] catchment counts) over time during the 9 years of monitoring across all three sites (Nidderdale, Mossdale, Whitendale). Transects (either 10 m x 2 m wide or 20 m x 1 m wide) were surveyed 4-5 times each year during the bird breeding season (April - August) to count adult craneflies. At each site the control (burnt) and treatment (mown) catchments received catchment-scale management over time and transects (14 per catchment) covered the entire catchment areas, including managed (to and from the 5x5 m monitoring plots) and unmanaged (to and from the slope areas) areas. Note, significant differences are present when the line of mean treatment catchment numbers falls outside the shown confidence interval of the mean for the transects in the burnt catchments.

Transect vegetation heights

Figure A9.5 below provides the mean vegetation heights (including various vegetation types within the burnt and mown catchments) across the cranefly transects over time (note: the decline 2016/17 onwards is partially due to heather beetle damage). Clearly visible is the very tall vegetation in old heather-dominated areas (>40 cm), whereas recently managed areas (or those affected by heather beetle damage) reduce the overall mean vegetation height to less than 20 cm. This overall vegetation height difference between managed and unmanaged areas was similar to that observed at the managed plots (**Figure A9.2-3**).

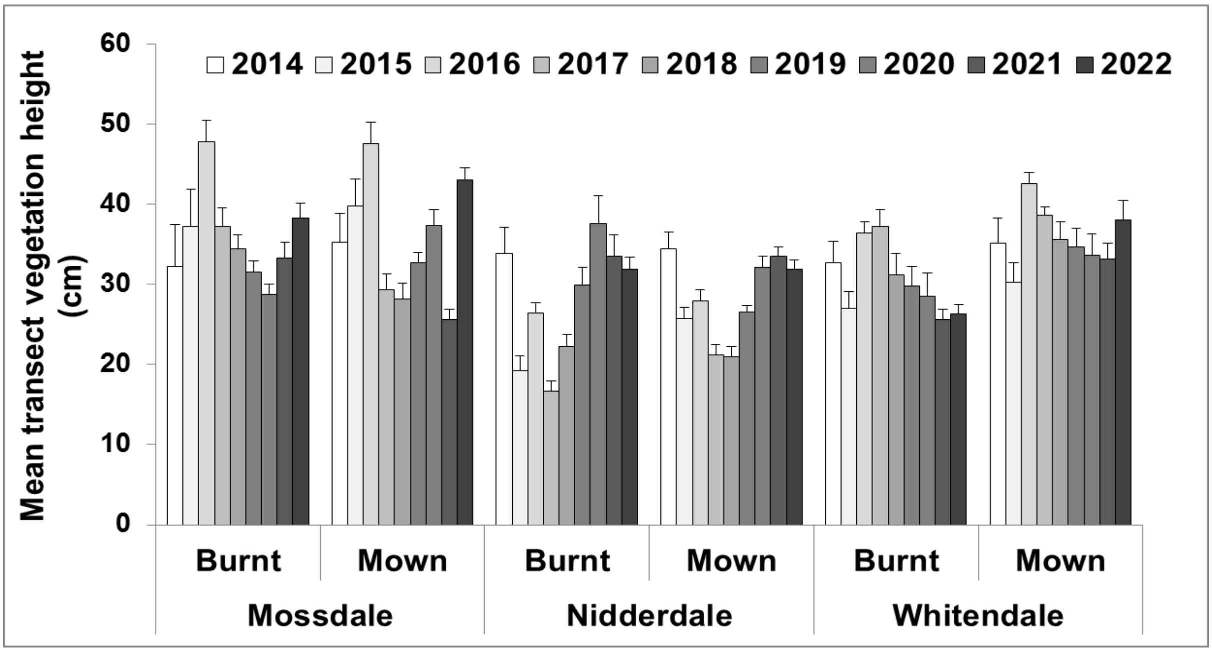


Figure A9.5 Mean vegetation height (± standard error) in summer measured across the cranefly transects in the burnt and mown catchments (note: this included unmanaged areas and different vegetation types) at the three sites (Nidderdale, Mossdale, Whitendale). Data for 2018 and 2019 were not recorded and were estimated based on interpolation between the years either side (but if managed were set to 15 cm as measured in 2017).

Impacts of vegetation height on Golden Plover

Both, cranefly emergence and abundance determines chick survival and thus breeding success of many upland birds, for example, golden plover (see bird modelling section in Heinemeyer et al., 2019b). Moreover, their nesting areas are preferred in low vegetation and as such vegetation height poses a constraint on nesting success (see bird modelling section in Heinemeyer et al., 2019b). Repeating the previous modelling work would not show any different aspects, mainly as there were no further observed differences between mown and burnt areas, neither in vegetation height (**Figures A9.2-3 & A9.5**; the decline in height on burnt plots post 2016/17 was due to heather beetle damage not management) nor in cranefly abundance (**Figure A9.4**; and very low numbers overall) along the transects during 2017-2022. Predicted densities of golden plover (**Figure A9.6**) indicated the benefit from lower vegetation heights after burning compared to mown and especially to uncut areas.

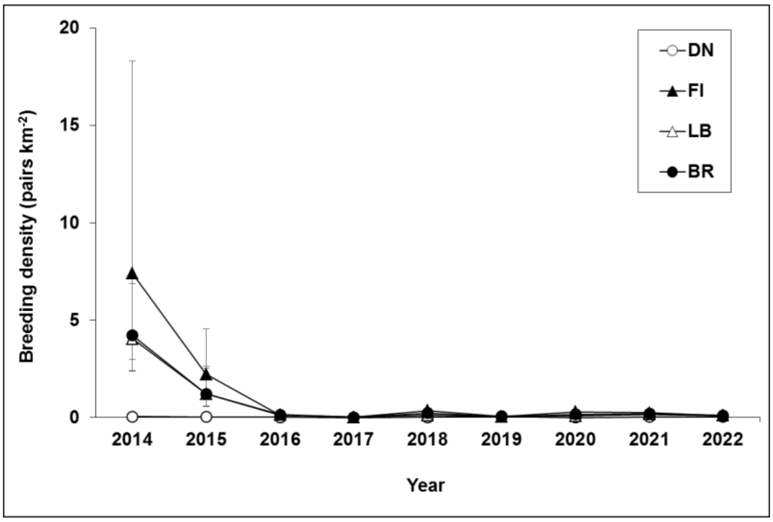


Figure A9.6 Predicted mean (± 95% confidence intervals) densities of breeding pairs of golden plover during 2014-2022 based on plot (DN=uncut[do nothing]; FI=burnt[fire]; mown LB=left brash and BR=brash removal) vegetation heights (including sparse grass and sedge stems). For model information see Heinemeyer et al. (2019b).

However, the predicted number of breeding pairs of golden plover was very low due to the impact of sparse grass and sedge vegetation having a disproportionally influence on vegetation heights due to their flowering stems. Therefore, a more robust measure was to only consider the actual heather heights (**Figure A9.7**). This revealed an even larger difference between managements. Whilst either management increased densities, highest numbers were predicted for burnt plots and over a considerably longer time period.

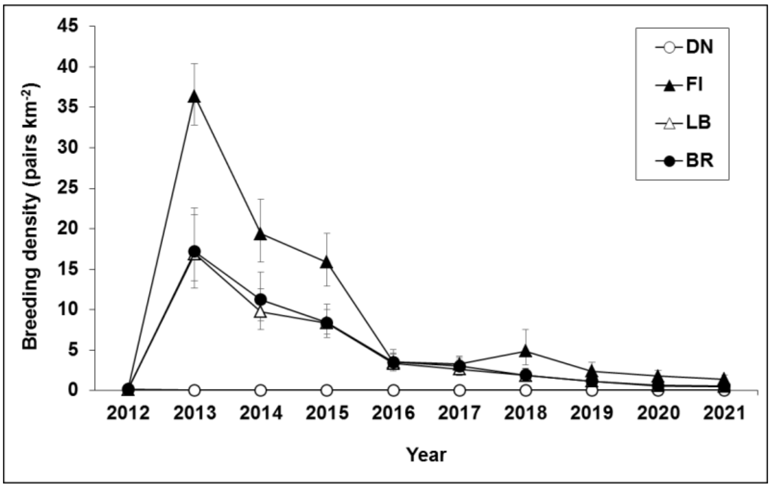


Figure A9.7 Predicted mean (± standard errors) densities of breeding pairs of golden plover during 2012-2022 based on plot (DN=uncut[do nothing]; FI=burnt[fire]; mown LB=left brash and BR=brash removal) heather heights (excluding grasses or sedges). For model information see Heinemeyer et al. (2019b). Note, the increase on burnt FI plots in 2018 reflected the peak of heather beetle damage on burnt plots.

The overall benefit of burning was also visible in the overall transect vegetation height based predictions of golden plover breeding densities (**Figure A9.8**). Whilst the difference was very small, this is for the entire catchment areas, including managed and unmanaged areas of various vegetation types and ages.

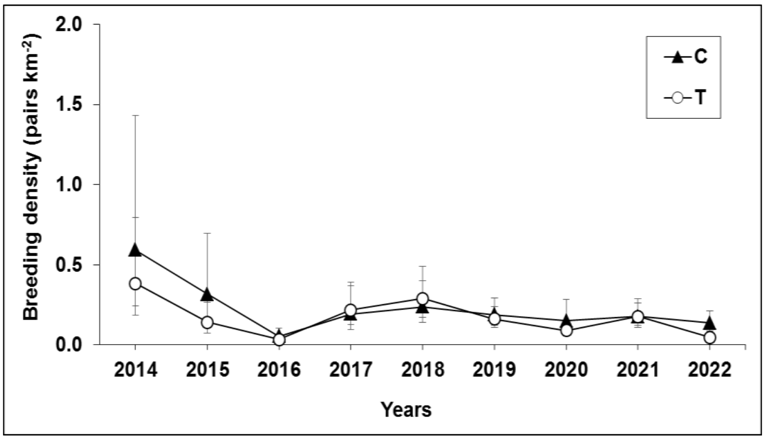


Figure A9.8 Predicted mean densities of breeding pairs of golden plover during 2014-2022 based on plot (DN=uncut[do nothing]; FI=burnt[fire]; mown LB=left brash and BR=brash removal) vegetation heights (including sparse grass and sedge stems). For model information see Heinemeyer et al. (2019b). Mean 2012-2021 (transect vegetation heights).

Overall, these analyses clearly outline some crucial advantages of heather management for ground nesting bird species like golden plover and that burning can deliver a more substantial and longer lasting benefit. However, some complications arise from vegetation structure and composition when scaling up impacts across the landscape scale based on the transects. A more accurate picture could be derived by a remote sensing approach at a catchment-scale using sensors such as LiDAR to scan of the actual vegetation structure and heights, to then be used in landscape-scale model predictions.

Appendix 10 (peat core C accumulation)

The peat core carbon accumulation rates measured at the three sites have been published (Heinemeyer et al., 2018). Furthermore, a clarifying reply was published (Heinemeyer et al, 2019) to a response to this paper (Evans et al., 2019) which clearly addressed all concerns raised. Moreover, in two other publications, Young et al. (2019 & 2021) criticise the original paper, but notably do not question the methods or findings and only highlight already well-known limitations in the interpretation in a wider C budget context. Importantly, their criticism is based on an unvalidated modelling study assuming constant 50 cm deep drainage (which is not the case at any of the sites) and not even including any fire or charcoal representation. Moreover, they also ignore the additional information in the original Heinemeyer et al. paper, which clearly outlined that the measured C accumulation rates (aCAR) do not represent C budgets and that recent C accumulation rates are always higher due to a larger proportion of recent, less decomposed organic matter. However, the main issue is that Young et al. clearly misunderstand the C budget concept in this context, which is not equal to measured C accumulation rates (as outlined in our paper). In a so far unpublished exchange in relation to the Young et al. papers and the Heinemeyer et al. paper it became clear that Young et al. base their critique on this misunderstanding of assuming C accumulation rates were used to infer net carbon budgets, citing Frolking et al. (2014) as evidence to support this assumption. However, Frolking et al. does not provide any support for this assumption, but rather supports the limitations of C accumulation rates (and thus not being equal to a C budget) already outlined in Heinemeyer et al. (2018). Most importantly, however, is the fact that none of the papers question the actual findings of the Heinemeyer et al. (2018) paper, showing the importance of: (1) charcoal to be included in C accumulation rate and C budget assessments, (2) assessing fine scale peat core sections to capture charcoal impacts on bulk density and C content and (3) including charcoal and impacts on soil chemical and physical aspects in peat C models.

The strength of the Heinemeyer et al. study lies in the clarity of the hypothesis, the testing of prescribed vegetation burning related charcoal inputs on aCAR, together with a high level of measurement detail. The approach of Heinemeyer et al. aimed to unravel potential charcoal impacts on organic carbon content (Corg) and bulk density in peat layers across three time periods with different burning frequencies. The different time periods also allowed comparisons with other published studies on C accumulation rates in similar peatland sites across the UK. However, this was not the central aspect of the study; it was done to contextualise the results within the published literature. Young et al. did not model the impact of prescribed burning or indeed burning at all, and they do not show that burning stops peat or carbon accumulation.

Notwithstanding the above critical insights into the peat core C accumulation study, the main findings remain robust and are of key importance to be considered when measuring C accumulation rates and assessing and modelling C budgets. Therefore, the observed peat C accumulation rates, together with other peat physical data (e.g. Corg, bulk density), provide valuable insight and strongly suggest that considerable net C accumulation is occurring overall (but a C budget cannot be assessed by this method). None of the criticisms put forward by Young et al. directly relate to the findings of Heinemeyer et al., nor do they justify their exclusion from evidence-based policy; they merely confirm the potential limitations already highlighted within the Heinemeyer et al. (2018) study as outlined in the below **Table A10.1**.

Table A10.1. Quotes from Heinemeyer et al. (2018) highlighting the awareness and acknowledgement of the issues discussed by Young et al. (2019 & 2021) with added reference numbers to refer to the below list.

“*However, the functional role of charcoal is still little understood (Pingree & DeLuca*[10]*) 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.* [7]*) due to so far unknown interactions.*”

“*In fact, mean C accumulation rates (2015–1950) of 3.2 t CO2 ha*$^{-1}$ *year−1 (87 g C m*$^{-2}$ *year*$^{-1}$*) were very similar to the 3.8 t CO2 ha*$^{-1}$ *year*$^{-1}$ *as* ***reported previously by Evans et al.*** [11] ***for unburnt management*** *based on data presented by Garnett et al.* [4]*).*”

“***C accumulation rates in these studies are generally much higher during the most recent periods*** *(about 50–100 g C m*$^{-2}$ *year*$^{-1}$*),* ***reflecting highly undecomposed peat****, whereas long-term accumulation rates for older layers are about 30 g C m*$^{-2}$ *year*$^{-1}$*.*”

“*However, the* ***conclusions reached here are based on a C-stock inventory which could be different compared with using a C-flux approach****.*”

“*The major disadvantages of the* ***C-flux approach*** *are that it* ***does not capture long-term incorporation of C as charcoal*** *(Clay et al.*[14]*),* ***while 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 C into deeper sections through roots and changes in decomposition rates over time****.*”

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[1] Young, D. M., Baird, A. J. Angela Gallego-Sala, V. & Loisel, J. (2021) A cautionary tale about using the apparent carbon accumulation rate (aCAR) obtained from peat cores. Scientific Reports, 11, 9547.

[3] Heinemeyer, A., Asena, Q., Burn, W. L. & Jones, A. L. (2018) Peatland carbon stocks and burn history: blanket bog peat core evidence highlights charcoal impacts on peat physical properties and long-term carbon storage. GEO: Geography and Environment 5(2), e00063 (2018). https://doi.org/10.1002/geo2.63.

[4] Garnett, M. H., Ineson, P. & Stevenson, A. C. (2000) Effects of burning and grazing on carbon sequestration in a Pennine blanket bog, UK. Holocene, 10, 729-736.

[6] Young, D. M., et al. (2019) Misinterpreting carbon accumulation rates in records from near-surface peat. Sci Rep 9, 17939. https://doi.org/10.1038/s41598-019-53879-8.

[7] Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C. & Crowley, D. (2011) Biochar effects on soil biota – a review, Soil Biology and Biochemistry,43(9), 1812-1836. https://doi.org/10.1016/j.soilbio.2011.04.022.

[9] Davidson, S. J., Van Beest, C., Petrone, R. & Strack, M. (2019) Wildfire overrides hydrological controls on boreal peatland methane emissions. Biogeosciences, 16, 2651–2660.

[10] Flanagan, N. E., Wang, H., Winton, S. & Richardson, C. J. (2020) Low-severity fire as a mechanism of organic matter protection in global peatlands: Thermal alteration slows decomposition. Glob Change Biol. 26(7), 3930-3946.

[11] Pingree, M. R. A. & DeLuca, T. H. (2017) Function of Wildfire-Deposited Pyrogenic Carbon in Terrestrial Ecosystems. Frontiers in Environmental Science, 5(53), 1-7.

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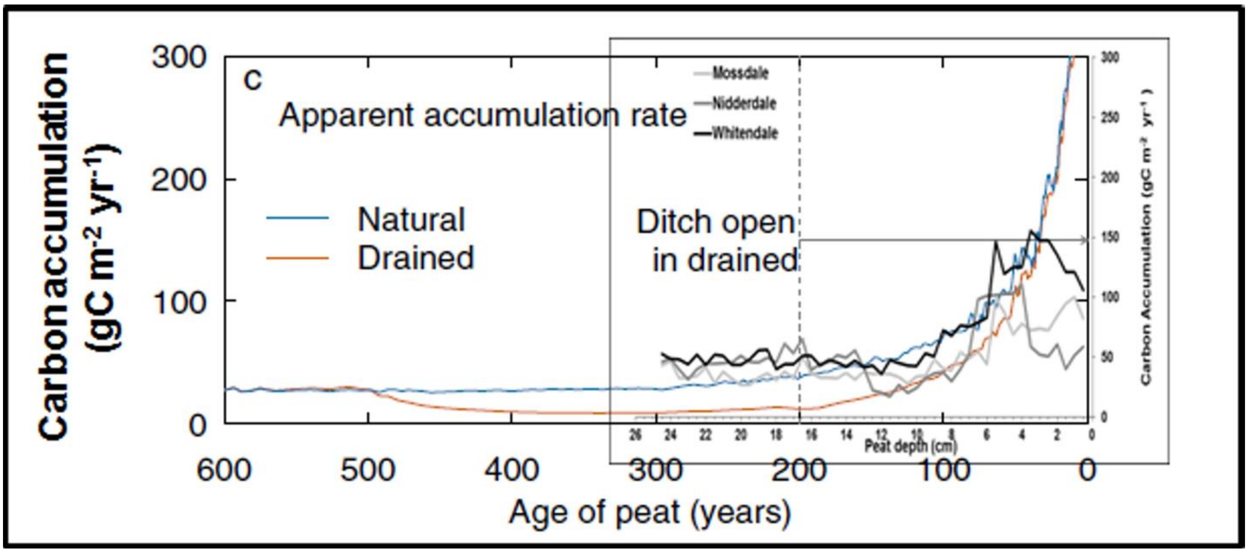
Another important point to consider about Heinemeyer et al. is that when one ignores the noise and high aCAR values in very young peat layers, aCAR is about 20 g C m^{-2} yr^{-1} where there is no or very low charcoal evidence (c.f. Figure 7e[3]). This increases to about 45 g C m^{-2} yr^{-1} as a lower limit under high charcoal counts. Crucially, this difference can be explained by measured charcoal inputs (which was estimated to be about 5% of standing biomass of ~558 g C m^{-2} as estimated in Heinemeyer et al., 2019b; although it is only about 2% if assuming a Corg of 60%), additional yet unknown litter layer char (Worrall et al., 2013) and an unknown amount from charred stalks (~15% of total biomass after combustion; Matt Davies, Ohio State University, unpublished data); which possibly explains some of the aCAR noise above this lower limit under high charcoal counts.

Moreover, deep drainage impacts on C losses (i.e. decreasing Corg) are not apparent at any of the sites, which, for the Heinemeyer et al. sites, is highlighted by the high, and with depth increasing, Corg data throughout the peat core record (e.g. Heinemeyer et al., 2019b), apart from a decrease at the peat base/mineral layer. Important is also that the observed aCAR values are within the range of the in Young et al. reported rates for unburnt sites (see the below **Figure A10.1**). In fact, observed aCAR values in Heinemeyer et al. within the deeper layers are actually higher than those reported by Young et al., which could relate to the input of recalcitrant C via charcoal overall increasing long-term peat C accumulation (as predicted by Clay & Worrall (2011) and Worrall et al., (2013)). However, the aCAR data show that there is a slight drop in C accumulation rates at around 9-12 cm depth (1900-1870) at the two sites with drainage (Nidderdale and Mossdale) implemented in the 1970s (this assumes a 5-10 cm drop in water tables that affected the peat ~60-100 years earlier in relation to peat depth/age). Crucially, the drop displayed agrees with reduced aCAR as predicted by the model of Young et al. (cf. Fig 2[6]). This highlights the value of detailed %Corg assessments to detect potential management (drainage) induced peat C loss and the generic value of the Young et al. model scenarios. The below **Figure A10.1** shows apparent carbon (C) accumulation rates (aCAR) from Heinemeyer et al.[3] overlaid (based on peat depth/age estimates for the three sites, Nidderdale, Mossdale and Whitendale) onto simulated rates for natural and drained peatlands shown in Young et al.'s[6] Figure 2c.



Surprisingly, so far it has not been possible to establish who the editors for the two Young et al. papers were, nor was it possible to publish detailed comments to their two papers as part of an open and constructive scientific debate; considering the unfounded and misleading accusations made this is highly unfortunate. Finally, we certainly agree with the final statement in the abstract by Young et al. (2021) "we propose that data from peat cores are used with existing or new C balance models to produce reliable estimates of how peatland C function has changed over time.". We further suggest that any C balance modelling work should not omit crucial fire-mediated C cycle processes, such as the effect of charcoal C inputs on long-term C storage via recalcitrance (+ effect), Corg (+ effect), bulk density (+ effect), decomposition (- effect) and methane emissions (- effect) within UK peatlands[3], [9], [10]. Only then can models provide relevant evidence for comparisons to study cores taken from sites with (prescribed) fire history in relation to C accumulation rates and hypothetical C balance impacts.

Appendix 11 (peat rod surface growth)

The peat surface change rods (hammered into the bedrock) installed during 4th - 7th August 2014 were used in the short-term to detect peat shrinkage/expansion rates in relation to water table changes and impacts on bulk density and thus potentially soil carbon accumulation estimates (Morton & Heinemeyer, 2019). The same rods were used in the medium-term to detect peat growth (accumulation or loss determined by subtraction of measured rod length above the peat surface). There were two sets of peat rods, one across the three sites (Nidderdale, Mossdale and Whitendale) at all 5x5 m monitoring plots (burnt = FI[fire]; combined *Sphagnum* pellet treatments for mown with left brash = LB or with brash removal = BR; uncut = DN[do nothing]), the other across the two Mossdale catchments covering the main mature vegetation types (heather, cotton-grass and *Sphagnum* moss) and recently managed heather-dominated areas within the catchments (burnt vs. mown) for a range of slope conditions. Detecting small changes in peat growth (about 1 mm per year) not only requires time but also similar moisture conditions to address the aforementioned moisture impacts on bulk density and thus peat surface changes. However, water tables could only be recorded for the monitoring plots at the three sites (the additional plots at the Mossdale site did not have permanent dipwells installed). Whilst it was attempted to obtain near identical moisture conditions, this was not possible as the year 2022 was an extreme drought year. Therefore measurements taken during 15th – 18th March 2022 were used to calculate peat growth rates. These dates showed similar water table depths but were on average 4.5±0.7 cm higher than in 2014. The growth rates are therefore only indications as clearly more time is needed to obtain robust growth rates addressing potential measurement errors and moisture impacts. The below **Table A11.1** summarises the median peat growth across the three sites and managements. Differences (comparing the median versus zero in a one sample T test and a Wilcoxon Signed Rank test) were only significant or marginally significant, respectively, for Nidderdale FI and BR.

Table A11.1 Median peat growth (mm per year) for the three sites and as an overall median for each management.

Peat growth (mm/yr)	**Nidderdale**			**Mossdale**			**Whitendale**			**ALL Sites**		
	Median		SE	Median		SE	Median		SE	Median		SE
Uncut	0.37	±	0.33	0.37	±	0.21	0.13	±	0.72	0.31	±	0.09
Burnt	0.69	±	0.20	-1.19	±	1.00	0.37	±	0.16	0.31	±	0.09
Mown	0.06	±	0.16	0.19	±	0.20	0.31	±	0.26	0.25	±	0.03

The below **Table A11.2** summarises the median peat growth across the various vegetation and managements within the Mossdale catchments. Differences (comparing the median versus zero in a one sample T test and a Wilcoxon Signed Rank test) were significant for both tests for overall peat growth (***) and for cotton-grass (*) (*Eriophorum*), *Sphagnum* moss (***) and heather-dominated (*Calluna vulgaris*) mown areas (*).

Table A11.2 Median peat growth (mm per year) for the Mossdale site within heather-dominated areas across the two catchments (burnt vs mown) and as an overall median for each management.

Peat growth (mm/yr) Mossdale			
Category	Median		SE
Burnt	0.37	±	0.41
Mown	0.63	±	0.22
Calluna	1.50	±	0.57
Eriophorum	0.69	±	0.22
Sphagnum	1.88	±	0.41
All	0.60	±	0.1

The Mossdale catchments included mostly low slope areas but also some steeper slopes. As runoff is affected by slope, water table depth generally decreases with increasing slope, which further relates to peat depth (due to carbon accumulation generally reducing with declining water tables. The below **Figure A11.1** summarises the water table and peat depth versus slope at the monitoring location. Whilst the water tables do indicate a weak reduction initially, with a steeper decline only for slopes greater than 10 degrees, these water tables do not represent a mean annual water table but only a single measurement in 2014. However, averaging the six measurements taken during 2014-2015 was not significantly different. The general slope effect on peat accumulation is much clearer, indicating deep peat confined to slopes of less than 5 degrees with a steep decline initially and a subsequent levelling off at slopes of greater than 10 degrees. Therefore, peat accumulation rates are to be much smaller on plots of shallow peat on greater slopes, and as such much more difficult to detect compared to deep peats on low slopes.

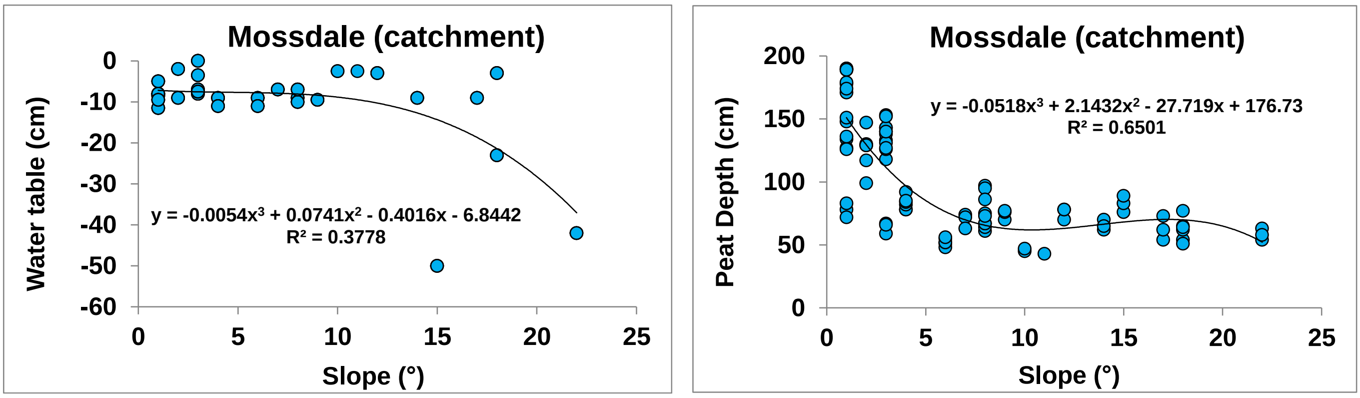


Figure A11.1 Water table depth (left) and peat depth (right) versus slope across the peat rod plots at Mossdale (covering all vegetation and managements). Provided are also the best fit regression equations and their R^2. Both comparisons showed highly significant (***) correlations.

The water table depths and slopes within the Mossdale catchments differed between the vegetation and managements as shown in **Figure A11.2**. Whilst cotton-grass showed the lowest water tables, only mature *Calluna* plots showed significantly lower water tables than all other plots. However, it is again important to note that these are only single measurements of water table depth in 2014; although using the six measurements during 2014-2015 did only result in lowest mean water tables on mown plots. Whilst mown areas did not provide the same slope range (i.e. lowest mean slope) compared to steeper burnt areas for plots in 2014 (first management was done in 2013), mature heather areas included steeper slope areas than the other two vegetation types and management areas with *Sphagnum* moss areas showing the lowest mean slope. However, slopes on mature *Calluna* areas were only significantly (*) higher compared to mown areas.

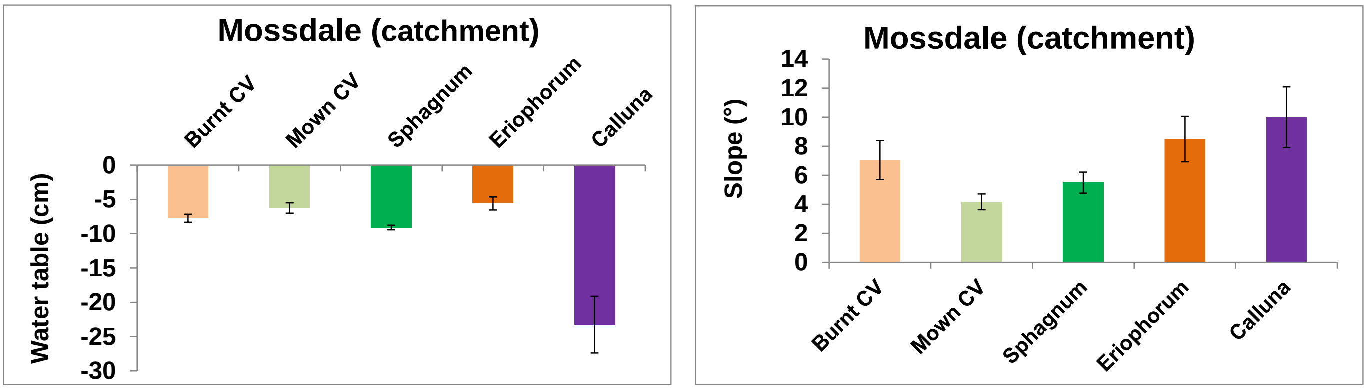


Figure A11.2 Mean ±SE water table depth (left) and slope (right) versus the peat rod plots at Mossdale within heather-dominated areas of burnt (Burnt CV) and mown (Mown CV), *Sphagnum* moss, *Eriophorum* (cotton-grass) and *Calluna* (heather).

Appendix 12 (soil respiration)

The previous soil respiration (SR) assessment also included laboratory incubations. However, here only the continued field measurements are considered.

Different statistical models were compared, the best was a generalised mixed-model with a Gamma distribution and log link. This was necessary because of the left limit and right skew. The log link cannot handle '0' values, so an adjusted response variable was used y = SR + 0.00000001. A BACI fixed effect structure, with soil temperature and chamber temperature covariates, was used, with site and date random effects:
Flux ~ Management * Period + Tsoil + Tcham + (1|Site/Block/Plot) + (1|Date)

For management, uncut (DN[do nothing]) was used as the control level. Other managements were compared with DN in the model. For period, the post-management period was divided into 2013-16 and 2017-21, to look at immediate and longer-term effects. FI was then used as the control level of management and omitted DN. This was done to compare the alternative mown managements, mown with leaving brash (LB) or brash removal (BR), against the traditionally applied burn management. The following section summarises the results of the main findings for the SR analysis (see also below **Tables A12.1-3**):

- Soil respiration in FI plots was higher than in DN, LB, or BR plots BEFORE management.
- Soil respiration was higher during the 2017-21 period than the pre-management 2012-13 period for DN plots.
- Soil respiration was **positively influenced by soil temperature** and chamber temperature.
- Soil respiration was **negatively affected by FI management** across **2013-16 and 2017-21**, when compared with DN management.
- Soil respiration was **negatively affected by BR management during 2013-16**, when compared with DN management. This was not apparent in 2017-21.
- The mown **LB management led to greater soil respiration than FI management**, across the post-management periods (i.e. relating to long-term carbon losses from litter decomposition). There was no significant difference in effects of FI and BR managements (indicating that removal of decomposable matter was mainly responsible). However, the overall reduction (i.e. estimate in the following **Table A12.1**) was larger for the FI management (which was near significant for 2017-2021 shown in **Table A12.2**), suggesting an additional suppression of decomposition processes by charcoal.

Table A12.1 Output of the generalised mixed-model with Gamma distribution and log link. DN Uncut[do nothing] as control versus FI = burnt[fire] and mown: LB = brash left vs. BR = brash removal and across the two post-management periods (2013-2016 & 2017-2021) vs. the before period.

Term	Estimate	Std. Err	t value	P value significance	95% Conf. Int
Intercept	**-1.0102**	**0.1838**	**-5.495**	**3.91e-08 *****	**-1.3705 – -0.6500**
FI	**0.2833**	**0.1130**	**2.508**	**0.0122 ***	**0.0619 – 0.5048**
LB	-0.0808	0.0979	-0.826	0.409	-0.2726 – 0.1110
BR	0.0362	0.0978	0.371	0.711	-0.1554 – 0.2278
2013-16	0.1996	0.1795	1.056	0.291	-0.1622 – 0.5415
2017-21	**0.3829**	**0.1771**	**2.162**	**0.0306 ***	**0.0358 – 0.7301**
Tsoil	**0.0450**	**0.0083**	**5.398**	**6.75e-08 *****	**0.0287 – 0.0613**
Tcham	**0.0425**	**0.0063**	**6.715**	**1.89e-11 *****	**0.0301 – 0.0549**
FI : 2013-16	**-0.2819**	**0.1035**	**-2.723**	**0.00647 ****	**-0.4848 – -0.0790**
LB : 2013-16	0.0523	0.0897	0.583	0.560	-0.1235 – 0.2280
BR : 2013-16	**-0.2013**	**0.0898**	**-2.243**	**0.0249 ***	**-0.3773 – -0.0254**
FI : 2017-21	**-0.2500**	**0.1020**	**-2.450**	**0.0143 ***	**-0.4500 – -0.0500**
LB : 2017-21	0.0371	0.0884	0.420	0.675	-0.1362 – 0.2104
BR : 2017-21	-0.1122	0.0885	-1.268	0.205	-0.2856 – 0.0612

Table A12.2 EM means – **SR values** at **mean soil temp, 10.93° C, and mean chamber temp, 14.73° C**, for each management (FI = burnt[fire]; Mown: LB = brash left vs BR = brash removal; DN = uncut[do nothing]) across different periods (before vs. post-management of 2013-2016 & 2017-2021).

	DN	**FI**	**LB**	**BR**
Before	1.11 ± 0.196	1.48 ± 0.261	1.03 ± 0.171	1.15 ± 0.192
2013-16	1.35 ± 0.129	1.35 ± 0.129	1.31 ± 0.116	1.14 ± 0.101
2017-21	1.63 ± 0.148	1.69 ± 0.154	1.56 ± 0.130	1.51 ± 0.126

Table A12.3 Output of the generalised mixed-model with Gamma distribution and log link. FI as control versus mown: LB = brash left & BR = brash removal and across the two post-management periods (2013-2016 & 2017-2021) vs. the before period.

Term	**Estimate**	**Std. Err**	**t value**	**P value significance**	**95% Conf. Int**
Intercept	-0.7629	0.1770	-4.310	1.63e-05 ***	-1.1097 – -0.4160
LB	**-0.3901**	**0.1063**	**-3.669**	**0.000243 *****	**-0.5984 – -0.1817**
BR	**-0.2742**	**0.1062**	**-2.583**	**0.00980 ****	**-0.4823 – -0.0661**
2013-16	-0.1359	0.1742	-0.780	0.435	-0.4774 – 0.2055
2017-21	0.0866	0.1713	0.506	0.613	-0.2491 – 0.4223
Tsoil	**0.0528**	**0.0089**	**5.923**	**3.16e-09 *****	**0.0353 – 0.0703**
Tcham	**0.0425**	**0.0064**	**6.679**	**2.40e-11 *****	**0.0300 – 0.0550**
LB : 2013-16	**0.3497**	**0.0901**	**3.883**	**0.000103 *****	**0.1732 – 0.5263**
BR : 2013-16	0.0943	0.0901	1.048	0.295	-0.0822 – 0.2709
LB : 2017-21	**0.3060**	**0.0888**	**3.447**	**0.000568 *****	**0.1320 – 0.4800**
BR : 2017-21	*0.1531*	*0.0888*	*-1.725*	*0.0850 .*	*-0.0209 – 0.3270*

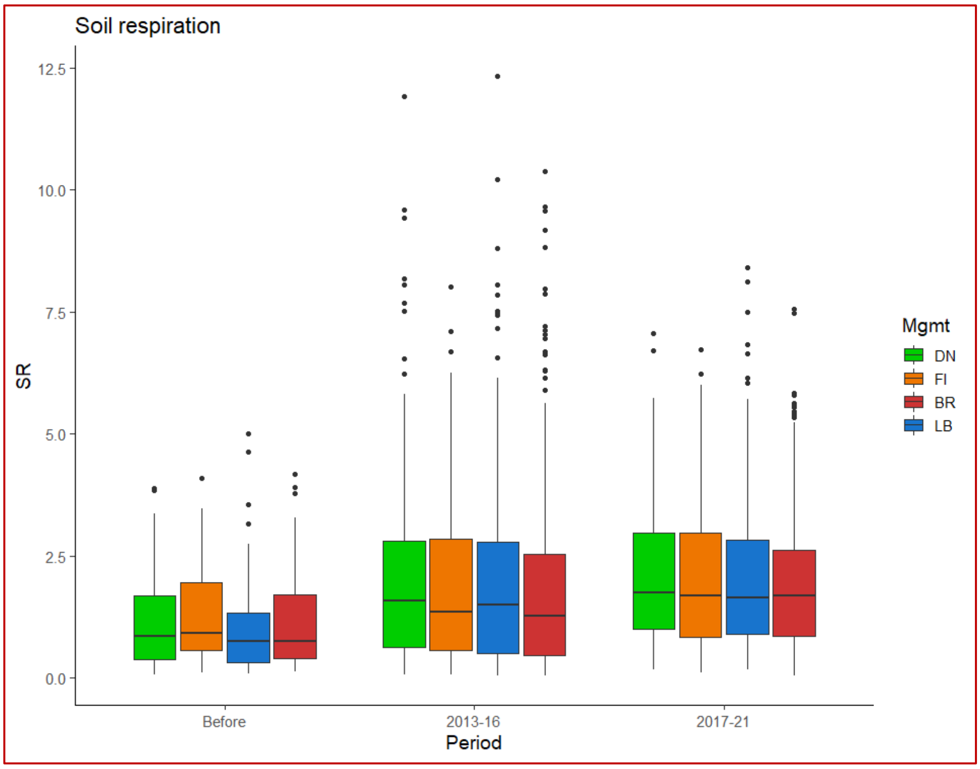


Figure A12.1 Soil respiration (SR) for the different managements (FI = burnt[fire]; Mown: LB = brash left vs BR = brash removal; DN = uncut[do nothing]) and across different periods (before vs. post-management of 2013-2016 & 2017-2021).

There was no significant interaction of management with temperature in the models (confirming the previous soil temperature (Tsoil) analysis [and see also following **Appendix 13**], showing only some insulation effect from mown managements (LB vs BR) and a minimal FI impact).

Change in SR (delta) from pre- to post-management

- The difference (delta) between post-management and pre-management SR was then used as a response variable.
- The difference was calculated using annual mean SR for each plot, and subtracting the pre-management SR annual means from post-management SR.
- The statistical model used was a mixed-effect model, using management as the fixed effect and soil temperature and chamber temperature as covariate fixed effects, site and year as random effects. Only the post-management data was used for the analyses, as the pre-management SR values were used to find DELTA. A gaussian distribution was suitable and the analysis fitted the data well.
    - DELTA ~ Mgmt + Tsoil + Tcham + (1|Site/Block) + (1|Year).
- It used the 2013-16 and 2017-21 structure of management period to look at whether management effects remained after 5+ years.
    - DELTA ~ Mgmt * Period + Tsoil + Tcham + (1|Site/Block) + (1|Year).

Summary of results

- The mixed-effect models showed that **SR was lower following FI and BR management than following DN no management**.
- Post-hoc Tukey test found that the effect on **SR of LB management was significantly greater** than the effect of DN and BR management. The means of SR delta for DN management overlapped with the means of FI and BR management.

Table A12.4 Output of mixed-effect model and EM means for the managements (FI = burnt[fire]; Mown: LB = brash left vs BR = brash removal) compared to DN = uncut[do nothing].

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	-1.097	0.3415	-3.212	0.00172 **	-1.761 – -0.434
FI	**-0.193**	**0.0884**	**-2.186**	**0.0292 ***	**-0.366 – -0.020**
LB	0.056	0.0755	0.762	0.446	-0.090 – 0.205
BR	**-0.150**	**0.0755**	**-1.988**	**0.0472 ***	**-0.298 – -0.003**
Tsoil	0.028	0.0297	0.956	0.339	-0.030 – 0.089
Tcham	**0.111**	**0.0163**	**6.826**	**2.25e-11 *****	**0.078 – 0.143**

EM means

Mgmt	DELTA	Tukey's CLD
DN	0.894 ± 0.159	AB
FI	0.701 ± 0.159	A
LB	**0.952 ± 0.152**	**B**
BR	0.744 ± 0.152	A

- Analysis using the split in post-management period showed that **the impact of FI can be split into two phases**.
    - During **2013-16 there was a strong negative effect of FI management** on SR. During **2017-21, there was a significant increase in SR delta for FI management**.
- The impact of **BR management was significantly negative compared with DN during 2013-16, but not during 2017-21**.
- Post-hoc tests showed that the FI management significantly lowered SR delta during 2013-16, whereas DN and LB managements had significant positive effects during 2013-16.

Table A12.5 Output of mixed-effect model and EM means for the managements (FI = burnt[fire]; Mown: LB = brash left vs BR = brash removal) compared to DN = uncut[do nothing].

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	-1.054	0.3714	-2.838	0.00573 **	-1.769 – -0.350
FI	**-0.402**	**0.1310**	**-3.071**	**0.00222 ****	**-0.658 – -0.147**
LB	0.003	0.1131	-0.027	0.979	-0.224 – 0.217
BR	**-0.238**	**0.1131**	**-2.109**	**0.0354 ***	**-0.459 – -0.018**
2017 : 21	-0.129	0.2457	-0.523	0.611	-0.604 – 0.347
Tsoil	0.031	0.0299	1.050	0.294	-0.025 – 0.093
Tchamber	**0.111**	**0.0163**	**6.795**	**2.72e-11 *****	**0.077 – 0.142**
FI : 2017-21	**0.379**	**0.1754**	**2.160**	**0.0312 ***	**0.038 – 0.722**
LB : 2017-21	0.109	0.1517	0.717	0.474	-0.187 – 0.405
BR : 2017-21	0.159	0.1517	1.047	0.296	-0.137 – 0.455

EM means

Mgmt	Period	DELTA	Tukey's CLD
DN	2013-16	0.966 ± 0.212	B
FI	2013-16	0.563 ± 0.212	A
LB	2013-16	0.963 ± 0.202	B
BR	2013-16	0.727 ± 0.202	AB
DN	2017-21	0.837 ± 0.196	AB
FI	2017-21	0.814 ± 0.197	AB
LB	2017-21	0.943 ± 0.187	AB
BR	2017-21	0.758 ± 0.187	AB

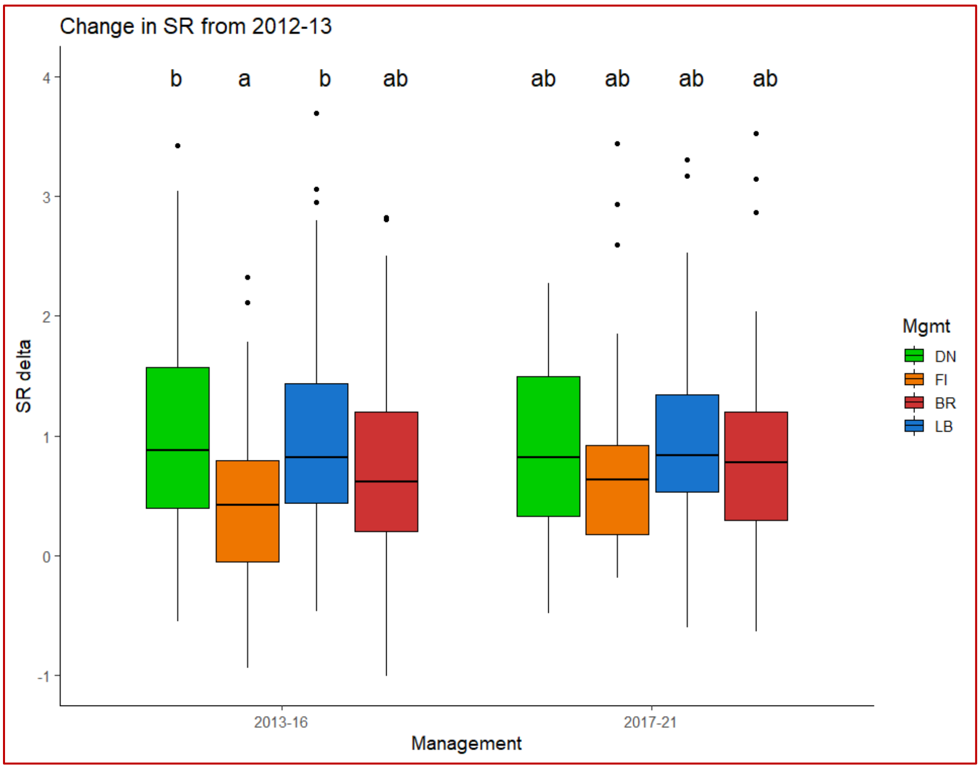


Figure A12.2 Difference in soil respiration (SR delta; before vs. after) for the different managements (FI = burnt[fire]; Mown: LB = brash left vs BR = brash removal; DN = uncut[do nothing]) for the two post-periods (2013-2016 & 2017-2021). Significant post-hoc difference are indicated by different letters.

Soil respiration of root and decomposition

Soil respiration (SR) was also measured at uncut versus cut areas (i.e. repeatedly cutting roots to allow separating soil decomposition from root respiration fluxes – subtracting cut fluxes from uncut fluxes). Overall microbial SR was slightly higher than root SR (mostly during 2013-2015). However, soil respiration of root and decomposition flux percentages, using only the post-management data (as pre-management fluxes suffered from increased root decomposition after cutting), did not reveal any overall differences between managements.

Table A12.6 Summary of the root (%root) and microbial (&Micr) components of the soil respiration flux per year and management (DN = uncut[do nothing]; FI = burnt[fire]; Mown: LB = brash left vs BR = brash removal). Note: the 2013 fluxes show an artificially high decomposition flux from the initial cutting of roots.

	DN		**FI**		**LB**		**BR**	
	%Root	%Micr	%Root	%Micr	%Root	%Micr	%Root	%Micr
2013	25.13 ± 3.38	74.87 ± 3.38	21.19 ± 2.88	78.81 ± 2.88	25.15 ± 2.43	74.85 ± 2.43	27.36 ± 2.53	72.63 ± 2.53
2014	21.46 ± 3.12	78.54 ± 3.12	35.65 ± 3.36	64.35 ± 3.36	31.04 ± 2.69	68.96 ± 2.43	31.78 ± 2.64	68.22 ± 2.64
2015	52.73 ± 3.61	47.27 ± 3.61	42.93 ± 4.16	57.07 ± 4.16	44.70 ± 2.66	55.30 ± 2.66	41.48 ± 2.74	58.52 ± 2.74
2016	57.63 ± 4.06	42.37 ± 4.06	55.01 ± 4.62	44.99 ± 4.62	52.71 ± 3.38	47.29 ± 3.38	53.66 ± 3.27	46.34 ± 3.27
2017	38.87 ± 4.01	61.13 ± 4.01	41.51 ± 3.66	58.49 ± 3.66	42.84 ± 2.52	57.16 ± 2.52	37.91 ± 2.90	62.09 ± 2.90
2018	46.94 ± 2.97	53.06 ± 2.97	50.47 ± 2.95	49.54 ± 2.95	47.81 ± 2.14	52.19 ± 2.14	46.51 ± 2.14	53.49 ± 2.14
2019	52.94 ± 4.27	47.06 ± 4.27	50.87 ± 4.93	49.13 ± 4.93	56.07 ± 2.92	43.93 ± 2.92	57.31 ± 3.02	42.69 ± 3.02
2020	53.54 ± 3.55	46.46 ± 3.55	52.54 ± 3.27	47.46 ± 3.27	54.58 ± 2.16	45.42 ± 2.16	54.45 ± 2.30	45.55 ± 2.30
2021	50.78 ± 2.81	49.22 ± 2.81	48.20 ± 3.08	51.80 ± 3.08	48.94 ± 1.87	51.06 ± 1.87	49.24 ± 1.85	50.76 ± 1.85

Table A12.6 Summary of the root (%root) and microbial (&Micr) components of the soil respiration flux per season and period (2013-2016 & 2017-2021) and management (DN = uncut[do nothing]; FI = burnt[fire]; Mown: LB = brash left vs BR = brash removal).

		DN		**FI**		**LB**		**BR**	
		%Root	%Micr	%Root	%Micr	%Root	%Micr	%Root	%Micr
2013 - 2016	Spring	39.51 ± 4.13	60.49 ± 4.13	41.79 ± 4.42	58.21 ± 4.42	38.76 ± 3.23	61.24 ± 3.23	36.80 ± 3.27	63.20 ± 3.27
	Summer	35.96 ± 3.20	64.04 ± 3.20	36.66 ± 3.00	63.34 ± 3.00	36.01 ± 2.28	63.99 ± 2.28	38.48 ± 2.25	61.52 ± 2.25
	Autumn	35.13 ± 3.78	64.87 ± 3.78	35.68 ± 3.76	64.32 ± 3.76	36.90 ± 2.55	63.10 ± 2.55	35.41 ± 2.51	64.59 ± 2.51
	Winter	72.85 ± 4.43	27.15 ± 4.43	42.71 ± 10.9	57.29 ± 10.9	48.75 ± 7.77	51.25 ± 7.77	49.96 ± 7.76	50.04 ± 7.76
2017 - 2021	Spring	46.59 ± 3.51	53.41 ± 3.51	45.45 ± 3.63	54.55 ± 3.63	46.02 ± 2.53	53.98 ± 2.53	47.10 ± 2.37	52.90 ± 2.37
	Summer	49.05 ± 2.41	50.95 ± 2.41	51.28 ± 2.16	48.72 ± 2.16	48.97 ± 1.46	51.03 ± 1.46	48.52 ± 1.69	51.48 ±1.69
	Autumn	47.66 ± 2.99	52.34 ± 2.99	48.17 ± 3.28	51.83 ± 3.28	53.71 ± 2.01	46.29 ± 2.01	48.94 ± 2.21	51.06 ± 2.21
	Winter	52.81 ± 4.91	47.19 ± 4.91	49.02 ± 4.18	50.98 ± 4.18	48.69 ± 3.28	51.31 ± 3.28	51.19 ± 3.17	48.81 ± 3.17

Appendix 13 (soil temperatures)

Soil temperatures (Tsoil) were monitored in two different ways. Firstly, Tsoil was monitored using internal sensors (both Tinytag; for methods see Heinemeyer et al., 2019b). All main managements were assessed comparing:
DN = uncut[do nothing]; FI = burnt[fire]; Mown: LB = brash left vs. BR = brash removal.

Internal soil temperatures (Tsoil) under radiation shields at soil surface 2012-15

Effect sizes of hourly recordings

The effect sizes of management treatments showed **little effect of DN management on surface soil temperature compared to FI management**. Across all the sites overall the effect was negligible, at individual sites there were small or very small effects amongst negligible results. This agrees with the output of the GLS modelling (below), which did not show any significant BACI interactions for DN management.

The effect sizes of the **mown managements, BR and LB, were larger, suggesting that mown management is more impactful on surface soil temperature**. This is also in agreement with the output from GLS statistical analysis (below). The **negligible effect sizes of DN and BR on mean surface soil temperature with data from all sites is likely influenced by the mixed responses across different sites**, whereas responses to LB were more uniform across sites. Taking the direction of effect size into consideration, **LB management near-ubiquitously lowered surface soil temperature** (brash insulation). For hourly recordings, the only metrics that increased with LB management were the minima at Mossdale and Whitendale; both were negligible positive effect sizes. The lowering of hourly maxima with LB management, and negligible or very small effect on hourly minima, gives surface soil temperatures lower max-min ranges. The direction of effect size of BR and DN managements varied across sites. These managements decreased all hourly temperature metrics at Mossdale, and almost all metrics at Whitendale (barring a very small increasing effect on hourly minima with BR management). However, at Nidderdale, mean and maximum temperatures increased with DN and BR managements. **The inconsistency of effect size across sites suggests that site characteristics are an important factor for these managements** (for BR this is likely linked to the swale cutting at Nidderdale, leaving coarser and easily removable brash compared to the other two sites with a double chop resulting in a fine and quite dense/compacted brash layer, difficult to remove by raking), whereas LB management was more consistent across sites.

Table A13.1 Effect sizes for hourly soil temperature recordings comparing DN, BR and LB versus FI.

Site	Metric	DN effect size	BR effect size	LB effect size
All sites	Mean	+ 0.040 (negligible)	- 0.086 (negligible)	- 0.336 (small)
	Max	+ 0.031 (negligible)	- 0.252 (small)	- 0.368 (small)
	Min	- 0.085 (negligible)	+ 0.139 (very small)	- 0.030 (negligible)
	Range	+ 0.092 (negligible)	- 0.332 (small)	- 0.357 (small)
Nidderdale	Mean	+ 0.051 (negligible)	+ 0.144 (very small)	- 0.211 (small)
	Max	+ 0.185 (very small)	+ 0.032 (negligible)	- 0.219 (small)
	Min	- 0.084 (negligible)	+ 0.460 (small)	- 0.117 (very small)
	Range	+ 0.238 (small)	- 0.275 (small)	- 0.124 (very small)
Mossdale	Mean	- 0.036 (negligible)	- 0.088 (negligible)	- 0.242 (small)
	Max	- 0.222 (small)	- 0.258 (small)	- 0.387 (small)
	Min	- 0.208 (small)	- 0.143 (very small)	+ 0.035 (negligible)
	Range	- 0.067 (negligible)	- 0.164 (very small)	- 0.444 (small)
Whitendale	Mean	- 0.108 (very small)	- 0.207 (small)	- 0.399 (small)
	Max	- 0.121 (very small)	- 0.424 (small)	- 0.251 (small)
	Min	- 0.121 (very small)	+ 0.142 (very small)	+ 0.0065 (negligible)
	range	- 0.041 (negligible)	- 0.474 (small)	- 0.257 (small)

Effect sizes of daily temperature summary data (daily means of average, maxima, minima and range)

The effect sizes of daily means, minima, maxima and ranges were larger than those observed for hourly data. There was a lower resolution for this data and the daily values incorporate the full variability of a day's diurnal cycle. This could allow for greater differences between managements than when using hourly values.

The **effect sizes of LB tend to be larger than other treatments, and the effect sizes of DN the smallest**, similarly to when using hourly recordings. **DN management, when considering all sites together, had a negligible effect on the surface mean and minimum temperatures and a small effect on maximum temperatures**. These low effect sizes could be due to varied effect size directions across sites. There were signs of potentially large effects of **DN management at individual sites**. There were **medium warming effect sizes recorded on the daily maxima and minima at Nidderdale**, and a **very large cooling effect on the minima at Mossdale**.

With the data from all sites combined, **BR management had a slightly stronger effect on mean surface soil temperature than DN**, although still very small, likely due to varied effect size directions across sites. **Large effect sizes of BR management on temperature minima at Mossdale and Nidderdale** suggests a strong potential of brash management to affect the retaining of heat during cold periods (insulation). However, these effect sizes operated in opposite directions, warming at Nidderdale and cooling at Mossdale.

We again see a **consistent lowering of mean and maxima surface soil temperatures with LB management** (insulation), alongside increases in minima at some sites, leading to **smaller daily ranges in temperature**. LB management increased daily minima at Nidderdale and Mossdale, not Whitendale where LB management increased daily minima with a very small effect.

Table A13.2 Effect sizes for daily soil temperature summary data comparing DN, BR and LB versus FI.

Site	Metric	DN effect size	BR effect size	LB effect size
All sites	Mean	- 0.033 (negligible)	- 0.108 (very small)	- 0.513 (medium)
	Max	- 0.058 (negligible)	- 0.190 (very small)	- 0.572 (medium)
	Min	- 0.346 (small)	- 0.037 (negligible)	+ 0.369 (small)
	Range	+ 0.063 (negligible)	- 0.167 (very small)	- 0.649 (medium)
Nidderdale	Mean	+ 0.122 (very small)	+ 0.454 (small)	- 0.492 (small)
	Max	+ 0.527 (medium)	+ 0.310 (small)	- 0.626 (medium)
	Min	+ 0.627 (medium)	+ 1.141 (large)	+ 0.615 (medium)
	Range	+ 0.399 (small)	- 0.207 (small)	- 0.744 (medium)
Mossdale	Mean	- 0.077 (negligible)	- 0.209 (small)	- 0.466 (small)
	Max	- 0.248 (small)	- 0.111 (very small)	- 0.944 (large)
	Min	- 1.274 (very large)	- 0.928 (large)	+ 0.700 (medium)
	Range	+ 0.264 (small)	+ 0.115 (very small)	- 1.120 (large)
Whitendale	Mean	- 0.231 (small)	- 0.477 (small)	- 0.756 (medium)
	Max	- 0.141 (very small)	- 0.520 (medium)	- 0.217 (small)
	Min	- 0.059 (negligible)	- 0.409 (small)	- 0.170 (very small)
	range	- 0.112 (very small)	- 0.335 (small)	- 0.186 (very small)

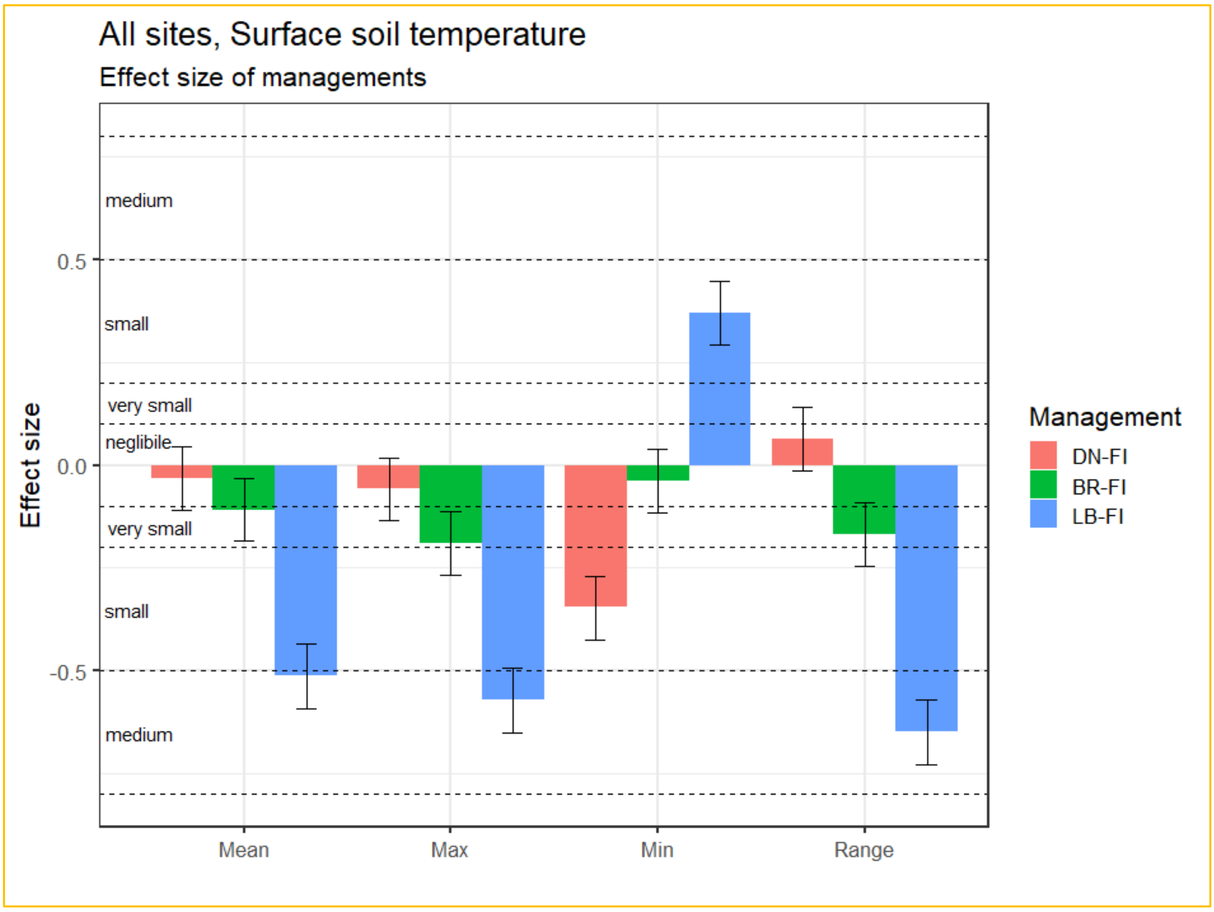


Figure A13.1 Daily effect sizes of management treatments on surface temperature, comparing DN, BR and LB versus FI, compared across all sites (see **Table A13.2**).

Temperature at 0.5 cm and 5 cm depth, external loggers, Nov 2014 – June 2015

The effect sizes on temperature across depth were calculated from data post-management. Therefore, it was not possible to calculate BACI effect sizes, only Control-Impact (C-I) effect sizes. This is an important caveat, as the differences between plots before management are not taken into account. However, the previous surface temperature analysis did not reveal any large overall differences between pre-management temperatures (see below BACI, which only found an about 0.7°C higher pre-management difference in temperatures on FI vs LB and BR but not vs DN), showed clear similarities to the 0.5 cm temperatures (see Heinemeyer et al., 2019b) and the overall magnitude of the effect sizes on temperature across soil depths were low. **Most effect sizes were negligible**. The **largest effect sizes were recorded at Mossdale at 5 cm, with warming effects of DN and LB management at this depth**. This somewhat echoes the output of the linear mixed-effect analyses, which found a significant warming effect of DN at 5 cm at Mossdale, but no other significant impacts of management on soil temperature at these depths.

The effect sizes for temperature across soil depth showed good consistency of DN management. **At 0.5 cm below the surface, the temperature was lower in DN managed plots than in FI plots across all sites**, possibly due to surface soil being more exposed to solar radiation. Conversely, **the temperature was higher in DN compared to FI plots at 5 cm depth**, likely due to increased insulation from a large canopy activity in the DN plots.

The effect sizes of **LB management showed a similar pattern, with a cooling effect at 0.5 cm and a warming effect at 5 cm**. Whitendale was the exception to this, with cooler temperatures also recorded at 5 cm in the LB plots.

Table A13.3 Effect sizes from **hourly recordings** below surface temperature. These are not BACI, as data is from 2014 – 2015.

Site	**DN – FI**		**M(LB) – FI**	
	0.5 cm	5 cm	0.5 cm	5 cm
All sites	- 0.060 (neg.)	0.176 (v. small)	- 0.077 (neg.)	0.059 (neg.)
Nidderdale	- 0.120 (v. small)	0.120 (v. small)	- 0.056 (neg.)	0.0017 (neg.)
Mossdale	- 0.032 (neg.)	0.470 (small)	- 0.090 (neg.)	0.327 (small)
Whitendale	- 0.021 (neg.)	0.016 (neg.)	- 0.088 (neg.)	- 0.108 (v. small)

Table A13.4 Effect sizes from **daily means** below surface temperature. These are not BACI, as data is from 2014 – 2015.

Site	**DN – FI**		**M(LB) – FI**	
	0.5 cm	5 cm	0.5 cm	5 cm
All sites	- 0.067 (neg.)	0.182 (v. small)	- 0.087 (neg.)	0.061 (neg.)
Nidderdale	- 0.139 (v. small)	0.126 (v. small)	- 0.063 (neg.)	0.0020 (neg.)
Mossdale	- 0.034 (neg.)	0.479 (small)	- 0.098 (neg.)	0.335 (small)
Whitendale	- 0.024 (neg.)	0.015 (neg.)	- 0.102 (v. small)	- 0.115 (v. small)

All sites (combined) as an example for SURFACE temperature (internal sensor under radiation shield) analysis for monthly averages (LMER - Linear Mixed-Effects Models with GLS - Generalized least squares modelling)

During the season when managements were conducted (Spring 2013), only certain plots had data. These sections of the data were removed (as well as data from room temperature records before site visits), so that comparisons across managements were even, and would not be skewed by dates for which only some plots were recorded. Finally, the last two months from the data were trimmed, so there were two complete years of 'After' data. This led to the following datasets:

- **Nidderdale**
  22/03/2012 – 03/03/2013 … 16/04/2013 – 15/04/2015
- **Mossdale**
  17/03/2012 – 27/02/2013 … 16/04/2013 – 15/04/2015
- **Whitendale**
  30/03/2012 – 19/02/2013 … 18/04/2013 – 17/04/2015

Initially a BACI analysis was conducted using mixed-effect models of monthly statistics, the **monthly means** of surface soil average, maxima, and minima temperature. The models included month nested in year as a random effect, plot was also a random effect and was nested in site for the analysis of all sites together.

There were no significant differences in the impact of managements on monthly average soil temperatures. However, LB lowered temperature maxima and BR lowered temperature minima. The results across all sites were reflected in Mossdale and Whitendale, which showed the same effects of management (no effect on average soil temperature, lower maxima with LB, lower minima with BR). For unknown reasons, at Nidderdale, none of the management treatments had a significant interaction with BA (Before/After).

Then **daily means** of surface soil average, maxima, and minima temperature were used, which also included daily temperature ranges. Random effects in the model were month nested in year and plot nested in site [y ~ BA * CI + (1|Year/Month) + (1|Site/Plot)]. ANOVA on the random effects showed that month, plot, and site were highly significant, as expected. **Therefore, controlling for these important random effects means that the mixed-effects models are preferable to the t-tests shown later**.

To summarise the results from analysing data from all sites together,

- BA (before/after) was a significant factor for all four response variables, soil temperatures were generally higher in 2013-2015 than in 2012-2013.
- There were no significant interactions for DN between Before/After.
- All **significant BACI interactions were for mown treatments**.

Significant BA * CI interactions

- Daily average soil temperature
  - Mown LB was the only management treatment with significant interaction with BA.
    - LB management lowered soil temperature compared to FI.
- Daily maxima
  - Mown BR and mown LB both had significant interactions with BA.
    - BR management elevated daily maxima soil temperatures.
    - LB management decreased daily maxima soil temperatures.
- Daily minima
  - Mown BR was the only management treatment with significant interaction with BA.
    - BR management led to lower minima soil temperatures.
- Daily temperature range
  - Mown BR and mown LB both had significant interactions with BA.
    - BR management led to increased daily ranges in soil temperatures.
    - LB management led to decreased daily ranges in soil temperatures.

The results from individual sites were as follows

- Daily average soil temperature
  - Lower temperatures with LB management at Mossdale and Whitendale, no significant BACI interactions at Nidderdale.
- Daily maxima
  - Higher maxima with BR management at Nidderdale.
  - Lower maxima with LB management at all sites.
- Daily minima
  - Lower minima with BR management at all sites.
- Daily temperature ranges
  - Larger ranges with BR management at Mossdale and Nidderdale.
  - Smaller ranges with LB management at all sites.

Subsequently, incorporating an autoregressive correlation term was explored, as was also done by Brown et al. (2014) for the EMBER project. Correlograms and partial correlograms of the data revealed auto correlation of the data through time. A first order continuous autoregressive correlation structure (corCAR1) was used; corCAR1 is for continuous data and is better able to handle unevenly spaced data, so is more suited to this dataset where there is a gap during the management implementation. ANOVA comparisons of first order correlations with other orders of correlation showed that corCAR1 fitted the data best, according to model fitting criterion such as AIC and log-likelihood. The mixed-effect models with autoregressive correlation yielded similar output to mixed effects models without the autoregressive term.

The following is a summary of the significant BACI interactions for all sites together.

- Daily average soil temperature
    - Mown LB was the only management treatment with significant interaction with BA.
        - **Daily average temperatures were lower with LB management** (***).
- Daily maxima
    - Mown LB was the only management treatment with significant interaction with BA.
        - **Daily maxima were lower with LB management** (***).
- Daily minima
    - Mown BR was the only management treatment with significant interaction with BA.
        - **Daily minima were lower with BR management** (*).
- Daily temperature range
    - Mown BR and mown LB both had significant interactions with BA.
        - **Daily temperature ranges were higher with BR management** (***).
        - **Daily temperature ranges were lower with LB management** (***).

Table A13.5 All sites least-square means of **daily** surface soil temperatures averages, maxima, minima, and ranges, as given by post-hoc tests.

	Average	Max	Min	Range
FI:Before	6.90 ± 0.27 °C	10.3 ± 0.37 °C	4.43 ± 0.22 °C	6.07 ± 0.23 °C
DN:Before	7.05 ± 0.27 °C	10.4 ± 0.37 °C	4.65 ± 0.22 °C	6.00 ± 0.22 °C
BR:Before	6.92 ± 0.27 °C	10.2 ± 0.37 °C	4.48 ± 0.22 °C	5.89 ± 0.22 °C
LB:Before	6.94 ± 0.27 °C	10.3 ± 0.37 °C	4.49 ± 0.22 °C	5.99 ± 0.22 °C
FI:After	8.03 ± 0.19 °C	12.1 ± 0.26°C	5.06 ± 0.15 °C	7.10 ± 0.16 °C
DN:After	8.17 ± 0.19 °C	12.4 ± 0.26 °C	5.29 ± 0.15 °C	7.12 ± 0.16 °C
BR:After	8.04 ± 0.19 °C	12.3 ± 0.26 °C	4.89 ± 0.15 °C	7.42 ± 0.16 °C
LB:After	7.88 ± 0.19 °C	11.3 ± 0.26 °C	5.19 ± 0.15 °C	6.22 ± 0.16 °C

Table A13.6 All sites least-square means of **monthly** averages, monthly maxima, and monthly minima, as given by post-hoc tests.

	Average	Max	Min
FI:Before	7.54 ± 1.33 °C	17.5 ± 2.28 °C	0.76 ± 0.86 °C
DN:Before	6.95 ± 1.33°C	17.2 ± 2.28 °C	1.01 ± 0.86 °C
BR:Before	6.84 ± 1.32 °C	16.6 ± 2.27 °C	0.68 ± 0.85 °C
LB:Before	6.87 ± 1.32 °C	17.0 ± 2.27 °C	0.69 ± 0.85 °C
FI:After	7.85 ± 1.32 °C	17.9 ± 2.27 °C	1.72 ± 0.85 °C
DN:After	7.58 ± 1.32 °C	18.0 ± 2.27 °C	1.78 ± 0.85 °C
BR:After	7.86 ± 1.32 °C	18.3 ± 2.27 °C	1.29 ± 0.85 °C
LB:After	7.71 ± 1.32 °C	16.9 ± 2.27 °C	1.71 ± 0.85 °C

The results from individual sites were as follows

- Daily average soil temperature
    - No BA * CI effect on average soil temperature at individual sites.
- Daily maxima
    - Higher maxima with BR management at Nidderdale (*).
    - Lower maxima with LB management at Mossdale (***) and Whitendale (***).
- Daily minima
    - No BA * CI effect on average soil temperature at individual sites. At Whitendale, BR * BA was close to being significant (p=0.075), with a cooling effect on minima.
- Daily temperature ranges
    - Larger ranges with BR management at Mossdale (*) and Nidderdale (***)
    - Smaller ranges with LB management at Mossdale (***) and Whitendale (***).

T-tests

T-tests are often used as an alternative to way to analyse BACI data (but are statistically less rigorous/robust), effectively by studying the differences between control and impact and compare these differences between the 'Before' and 'After' periods. This was used to compare FI and DN management treatments. As mentioned earlier, the t-tests are not as descriptive as mixed-effects models for this data, as they do not take random effects such as site or plot, or autoregressive terms, into account.

BACI t-tests of all plots together **revealed a significant effect of management treatment on soil temperature daily minima and consequently daily temperature ranges**, **but not on temperature average of maxima:**

- Daily minima were on average 0.309 °C cooler in FI plots than DN plots, before management
- After management, FI plot minima were on average 0.0938 °C cooler than DN plots
- The change in minima is small, approximately 0.2 °C, but it was significant in the T-test.
- Looking at the plot, there looks to be a seasonal effect. Differences between FI and DN are more constrained during winter months, and there is more variation in summer months (which makes sense as it reflects greater radiation/energy input to be affected by vegetation removal).
- Daily temperature ranges were 0.00147 °C larger in FI plots before management
- After management, daily ranges were 0.258 °C larger in DN plots
- Again, a small change, but it was significant in the test.

All sites, <u>average</u> soil temp

Full LMER model using BACI structure

- **LB and BR managements both had warming effects on soil temperature, relative to FI**, according to the BACI analysis
    - BR:A p=0.002132 **
    - LB:A p=0.020581 *

Least-square means pairwise contrasts of management:time

- There were statistically **significant differences between the soil temperatures in treatment plots before management began**. Mown treatment plots were significantly cooler than FI plots prior to management implementation. DN plots were also cooler, but not significantly so (0.59 °C cooler, p=0.1344). There was no significant difference between BR, LB, or DN plots before management.
    - FI:B – BR:B ** (p=0.0076). **BR:B** was 0.70 °C **cooler** than **FI:B**
    - BI:B – LB:B * (p=0.0126). **LB:B** was 0.67 °C **cooler** than **FI:B**

- The following were the significantly different pairwise comparisons (with p-values for significance). The differences between managements is given in least-square means.
    - DN:B - DN:A * (p=0.0181). **DN:A** was 0.63 °C **warmer** than **DN:B**
    - DN:B - FI:A *** (p=0.0001). **FI:A** was 0.90 °C **warmer** than **DN:B**
    - DN:B - BR:A *** (p<0.0001). **BR:A** was 0.91 °C **warmer** than **DN:B**
    - DN:B - LB:A *** (p=0.0003). **LB:A** was 0.77 °C **warmer** than **DN:B**
    - BR:B - BR:A *** (p<0.0001). **BR:A** was 1.02 °C **warmer** than **BR:B**
    - BR:B - FI:A *** (p<0.0001). **FI:A** was 1.00 °C **warmer** than **BR:B**
    - BR:B - DN:A *** (p<0.0001). **DN:A** was 0.74 °C **warmer** than **BR:B**
    - BR:B - LB:A *** (p<0.0001). **LB:A** was 0.87 °C **warmer** than **BR:B**
    - LB:B - LB:A *** (p<0.0001). **LB:A** was 0.84 °C **warmer** than **LB:B**
    - LB:B - FI:A *** (p<0.0001). **FI:A** was 0.98 °C **warmer** than **LB:B**
    - LB:B - DN:A *** (p=0.0001). **DN:A** was 0.71 °C **warmer** than **LB:B**
    - LB:B - BR:A *** (p<0.0001). **BR:A** was 0.84 °C **warmer** than **LB:B**

- **FI was the only management for which After temperature did not increase from the before temperature**. However, the caveat is that the FI ‘before’ temperature was significantly higher than other treatment plots. The significant pairwise contrasts all involve DN, BR, and LB ‘before’, so these plots may have been in cooler areas prior to management. It’s difficult to say with perfect clarity that the managements caused the temperature rises. However, overall changes were less than 1°C.

All sites, <u>maximum</u> temperature

Full LMER model using BACI structure

- Output of full LMER model shows significant BA:CI interactions
    - BR:A p=0.00381 **
        - **Monthly maxima of soil temperature increased with BR management relative to FI management**

Least-square means pairwise contrasts of management:time

- There were no statistically significant pairwise contrasts between ‘before’ maxima. The closest to significance was the contrast between FI:B – BR:B (FI:B 0.91 °C warmer p=0.1465).

- The following were the significantly different pairwise comparisons (with p values for significance). The differences between managements is given in least-square means.
    - BR:B - BR:A *** (p<0.0001). The **BR:A** maxima were 1.64 °C **warmer** than **BR:B**
    - BR:B - FI:A *** (p=0.0001). The **FI:A** maxima were 1.32 °C **warmer** than **BR:B**
    - BR:B - DN:A *** (p<0.0001). The **DN:A** maxima were 1.41 °C **warmer** than **BR:B**
    - LB:B - FI:A * (p=0.0287). The **FI:A** maxima were 0.91 °C **warmer** than **LB:B**
    - LB:B - DN:A * (p=0.0105). The **DN:A** maxima were 1.00 °C **warmer** than **LB:B**
    - LB:B - BR:A *** (p<0.0001). The **BR:A** maxima were 1.23 °C **warmer** than **LB:B**
    - FI:A - LB:A ** (p=0.0010). The **LB:A** maxima were 1.02 °C **cooler** than **FI:A**
    - DN:A - LB:A *** (p=0.0002). The **LB:A** maxima were 1.10 °C **cooler** than **DN:A**
    - BR:A - LB:A *** (p<0.0001). The **LB:A** maxima were 1.34 °C **cooler** than **BR:A**

- **BR was the only management that led to soil temperature monthly maxima increasing from ‘before’ levels to ‘after’ levels**. The soils in BR plots could be more exposed to radiation.

- **LB monthly maxima were significantly lower than all the other managements**, possibly due to the protective effects of the brash from radiation.

All sites, minimum temperature

Full LMER model using BACI structure

- Output of full LMER model did not show any significant BA:CI interactions.

Least-square means pairwise contrasts of management:time

- However, there were statistically significant pairwise contrasts

- The ‘before’ minima of the treatment plots were not statistically different. The p-values of the ‘before’ comparisons ranged between 0.59-1.00.

- The following were the significantly different pairwise comparisons (with p-values for significance). The differences between managements is given in least-square means.
    - FI:B - FI:A *** (p<0.0001). The **FI:A** minima were 0.96 °C **warmer** than **FI:B**
    - FI:B - DN:A *** (p<0.0001). The **DN:A** minima were 1.03 °C **warmer** than **FI:B**
    - FI:B - BR:A * (p=0.0307). The **BR:A** minima were 0.53 °C **warmer** than **FI:B**
    - FI:B - LB:A *** (p<0.0001). The **LB:A** minima were 0.96 °C **warmer** than **FI:B**
    - DN:B - DN:A *** (p=0.0004). The **DN:A** minima were 0.77 °C **warmer** than **DN:B**
    - DN:B - FI:A *** (p=0.0020). The **FI:A** minima were 0.71 °C **warmer** than **DN:B**
    - DN:B - LB:A *** (p=0.0004). The **LB:A** minima were 0.71 °C **warmer** than **DN:B**
    - BR:B - BR:A *** (p<0.0001). The **BR:A** minima were 0.61 °C **warmer** than **BR:B**
    - BR:B - FI:A *** (p<0.0001). The **FI:A** minima were 1.04 °C **warmer** than **BR:B**
    - BR:B - DN:A *** (p<0.0001). The **DN:A** minima were 1.11 °C **warmer** than **BR:B**
    - BR:B - LB:A *** (p<0.0001). The **LB:A** minima were 1.04 °C **warmer** than **BR:B**
    - LB:B - LB:A *** (p<0.0001). The **LB:A** minima were 1.03 °C **warmer** than **LB:B**
    - LB:B - FI:A *** (p<0.0001). The **FI:A** minima were 1.03 °C **warmer** than **LB:B**
    - LB:B - DN:A *** (p<0.0001). The **DN:A** minima were 1.10 °C **warmer** than **LB:B**
    - LB:B - BR:A *** (p=0.0001). The **BR:A** minima were 0.60 °C **warmer** than **LB:B**
    - FI:A - BR:A * (p=0.0169). The **BR:A** minima were 0.43 °C **cooler** than **FI:A**
    - DN:A - BR:A ** (p=0.0029). The **BR:A** minima were 0.50 °C **cooler** than **DN:A**
    - BR:A - LB:A ** (p=0.0012). The **LB:A** minima were 0.43 °C **warmer** than **BR:A**

- All managements had warmer minima after management than before, this is likely not a treatment effect, but due to warmer years in 2013-2015.

The **lowest minima were associated with the BR management**, these plots had lower monthly minima than all other management types in the ‘after’ period. Could be due to exposed soil lacking the insulation of vegetation or brash.

Appendix 14 (net ecosystem exchange and ecosystem respiration)

The chamber-based CO_2 fluxes of net ecosystem exchange (NEE) in ambient light and dark (Reco) conditions as measured in the field over vegetated ground allowed a basic comparison of before and after management and between management types: DN = uncut[do nothing]; FI = burnt[fire]; Mown: LB = brash left vs. BR = brash removal. In addition, light response curves (based on light and temperature responses of NEE and Reco responses to temperature) were fitted to allow model predictions of NEE over time, which enabled calculation of the CO_2 C-balance. However, context to these data are presented in **Appendix 16**.

At all sites (combined)

Light conditions

- Mixed effect model used for analyses.
  - Data was normal, so a linear mixed effect model was used.
    - Formula: Flux ~ Mgmt * Period + PAR + Tcham + Tair_day + (1|Site/Plot)
  - Different random effect structures were tested. Those with too many random effects were overfitted, leading to singularity issues and potential type I errors.

Summary of results

- Significant BACI interactions for all impact managements across both post-management periods
  - **FI, BR, and LB managements led to increases in NEE fluxes** (**more respiration**/less C uptake) than DN management across the full post-management period. Increases in 2013-16 were greater than in 2017-21, suggesting a strong initial impact followed by a slight degradation of impact through time (likely regrowing of vegetation in a sigmoidal way toward maturity).

Table A14.1 Summary output from full BACI analysis for NEE of FI = burnt[fire] and Mown: LB = brash left vs. BR = brash removal vs. DN = uncut[do nothing].

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	-1.362	0.4735	-2.877	0.00421 **	-2.278 – -0.448
FI	-0.493	0.6495	-0.759	0.448	-1.759 – 0.772
LB	-0.205	0.5624	-0.364	0.716	-1.302 – 0.891
BR	-0.0805	0.5624	-0.143	0.886	-1.177 – 1.015
2013-16	-1.062	0.4741	-2.239	0.0252 *	-1.988 – -0.133
2017-21	-2.040	0.4773	-4.274	2.00e-05 ***	-2.973 – -1.106
PAR	-0.0019	0.00020	-9.436	<2e-16 ***	-0.0023 – -0.0015
Tcham	0.0299	0.01737	1.722	0.0851 .	-0.0038 – 0.0642
Tair	0.0166	0.02174	0.761	0.447	-0.0271 – 0.0584
FI : 2013-16	3.544	0.6684	5.302	1.26e-07 ***	2.238 – 4.853
LB : 2013-16	2.582	0.5790	4.460	8.61e-06 ***	1.450 – 3.715
BR : 2013-16	2.582	0.5792	4.458	8.66e-06 ***	1.449 – 3.715
FI : 2017-21	2.532	0.6709	3.775	0.000164 ***	1.221 – 3.845
LB : 2017-21	1.879	0.5811	3.233	0.00124 **	0.743 – 3.017
BR : 2017-21	1.529	0.5811	2.631	0.00857 **	0.393 – 2.667

- **Comparing FI with M managements, there were no significant BACI interactions**, although BACI interactions *were close to statistical significance*. Both mown managements with 2013-16, and BR management with 2017-21 were close to statistical significance. These suggest a possibility that NEE fluxes were higher with FI management than with M managements (more respiration/less uptake).
- NEE fluxes were lower with higher levels of PAR (less respiration/more uptake).
- Post-hoc contrasts showed that NEE fluxes significantly increased with FI, LB, and BR managements during 2013-16 vs. pre-management levels. NEE fluxes for all managements then lowered during 2017-21.

Table A14.2 Summary for NEE BACI analysis for Mown: LB = brash left vs. BR = brash removal vs. FI = burnt[fire].

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	-2.030	0.4498	-4.514	9.42e-06 ***	-2.898 – -1.165
LB	0.279	0.5300	0.526	0.599	-0.755 – 1.313
BR	0.406	0.5302	0.766	0.444	-0.628 – 1.441
2013-16	2.450	0.4457	5.495	4.43e-08 ***	1.579 – 3.323
2017-21	0.456	0.4485	1.017	0.3092	-0.421 – 1.334
PAR	-0.00176	0.00021	-8.424	<2e-16 ***	-0.0022 – -0.0013
Tcham	0.0381	0.0181	2.102	0.0357 *	0.0028 – 0.0737
Tair	0.0151	0.0227	0.667	0.505	-0.0299 – 0.0589
LB : 2013-16	-0.967	0.5441	-1.778	0.0756 .	-2.032 – 0.097
BR : 2013-16	-0.974	0.5445	-1.789	0.0737 .	-2.041 – 0.090
LB : 2017-21	-0.644	0.5457	-1.181	0.238	-1.711 – 0.424
BR : 2017-21	-0.998	0.5458	-1.829	0.0675 .	-2.066 – 0.070

Table A14.3 Estimated marginal means for NEE from full BACI model.

	DN	FI	LB	BR
Before	-1.76 ± 0.467	-2.52 ± 0.466	-1.96 ± 0.336	-1.84 ± 0.336
2013-16	-2.82 ± 0.260	**0.23 ± 0.260**	-0.44 ± 0.191	-0.32 ± 0.191
2017-21	-3.80 ± 0.263	**-1.76 ± 0.264**	-2.12 ± 0.193	-2.35 ± 0.193

Table A14.4 Significant post-hoc contrasts for NEE fluxes. A positive estimate equals a higher net C uptake.

Contrast	Estimate	P value
DN 2012 – DN 2017-21	2.040 ± 0.477	0.0012 **
DN 2013-16 – DN 2017-21	0.978 ± 0.278	0.0220 *
FI 2012 – FI 2013-16	-2.482 ± 0.474	<0.0001 ***
FI 2013-16 – FI 2017-21	1.990 ± 0.278	<0.0001 ***
LB 2012 – LB 2013-16	-1.520 ± 0.337	0.0004 ***
LB 2013-16 – LB 2017-21	1.682 ± 0.196	<0.0001 ***
BR 2012 – BR 2013-16	-1.520 ± 0.338	0.0004 ***
BR 2013-16 – BR 2017-21	2.031 ± 0.196	<0.0001 ***
DN 2013-16 – FI 2013-16	-3.051 ± 0.352	<0.0001 ***
DN 2013-16 – LB 2013-16	-2.378 ± 0.305	<0.0001 ***
DN 2013-16 – BR 2013-16	-2.502 ± 0.305	<0.0001 ***
DN 2017-21 – FI 2017-21	-2.039 ± 0.357	<0.0001 ***
DN 2017-21 – LB 2017-21	-1.674 ± 0.309	<0.0001 ***
DN 2017-21 – BR 2017-21	-1.448 ± 0.309	0.0004 ***

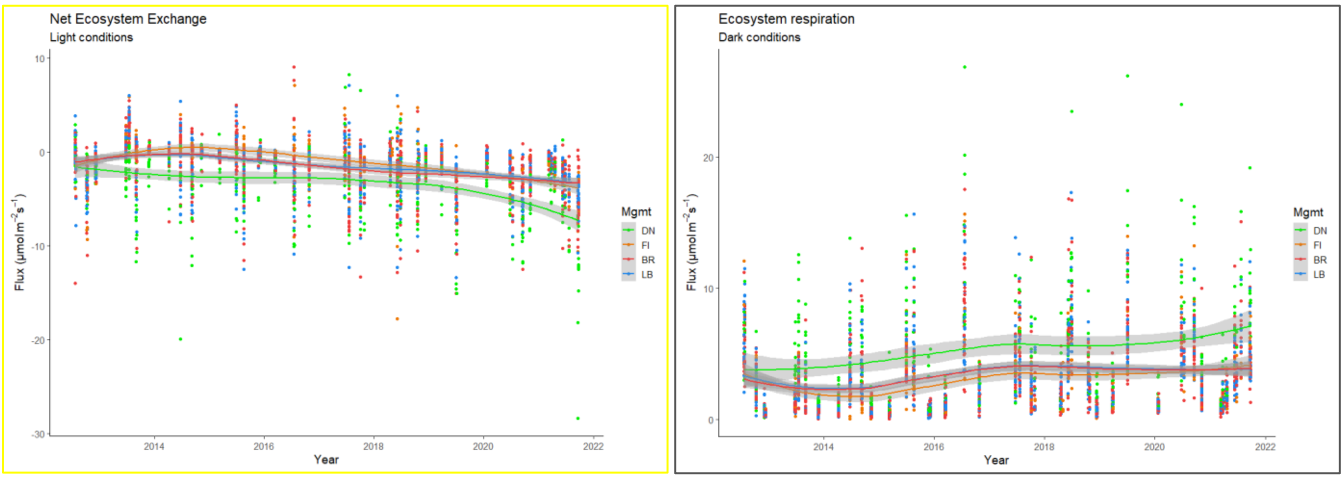


Figure A14.1 NEE flux in the light (**left**) vs. dark (**right**). Note the effect of the wet year 2017 (at Nidderdale & Mossdale) followed by the overall dry year 2018 had on both NEE and Reco (more similar fluxes).

Dark conditions

- Mixed effect model used for analyses.
    - Formula: Flux ~ Mgmt * Period + Tcham + Tair_day + Tsoil + (1|Site/Plot)
  - Different random effect structures were tested. Those with too many random effects were overfitted, leading to singularity issues and potential type I errors.

Summary of results

- Significant BACI interactions for all impact managements across both post-management periods.
  - **FI, BR, and LB managements led to lower dark/night-time Reco fluxes** (less respiration) than DN management across the full post-management period.
- Comparing FI with M managements, **there were no significant BACI interactions**, although the BR : 2013-16 interaction was close to significance (lowest Reco for FI). Therefore, there is no evidence of difference in Reco fluxes during dark conditions for FI and M managements, although there is a possibility there could be an initial difference between FI and BR following management.
- Dark NEE (Reco) fluxes were higher with higher temperatures (air, soil, and chamber temperatures) (more respiration).
- Post-hoc contrasts showed that Reco fluxes significantly lowered with FI, LB, and BR managements during 2013-16 compared with pre-management levels (less respiration). Reco fluxes for all managements then increased during 2017-21.

Table A14.5 Summary for Reco BACI analysis for Mown: LB = brash left vs. BR = brash removal vs. FI = burnt[fire].

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	-0.105	0.4651	-0.225	0.823	-0.994 – 0.786
FI	0.306	0.6171	0.495	0.621	-0.895 – 1.505
LB	0.201	0.5342	0.377	0.706	-0.837 – 1.240
BR	-0.0413	0.5342	-0.077	0.938	-1.080 – 0.998
2013-16	0.0956	0.3954	0.242	0.809	-0.678 – 0.869
2017-21	1.522	0.3967	3.837	0.000128 ***	0.746 – 2.298
Tcham	0.0628	0.01008	6.226	5.69e-10 ***	0.0428 – 0.0823
Tair	0.222	0.01757	12.656	<2e-16 ***	0.188 – 0.257
Tsoil	0.0989	0.01863	5.307	1.22e-07 ***	0.062 – 0.135
FI : 2013-16	-2.812	0.5571	-5.048	4.83e-07 ***	-3.902 – -1.722
LB : 2013-16	-2.212	0.4822	-4.587	4.75e-06 ***	-3.155 – -1.269
BR : 2013-16	-1.980	0.4822	-4.107	4.15e-05 ***	-2.924 – -1.037
FI : 2017-21	-2.553	0.5593	-4.565	5.26e-05 ***	-3.647 – -1.459
LB : 2017-21	-2.053	0.4841	-4.241	2.32e-05 ***	-3.000 – -1.106
BR : 2017-21	-1.938	0.4841	-4.003	6.45e-05 ***	-2.885 – -0.991

Table A14.6 Summary for Reco BACI analysis for Mown: LB = brash left vs. BR = brash removal vs. FI = burnt[fire].

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	0.404	0.4048	0.999	0.319	-0.378 – 1.187
LB	-0.103	0.4843	-0.213	0.831	-1.045 – 0.839
BR	-0.343	0.4844	-0.709	0.479	-1.285 – 0.599
2013-16	-2.582	0.3648	-7.079	2.05e-12 ***	-3.296 – -1.869
2017-21	-0.928	0.3658	-2.536	0.0113 *	-1.643 – -0.212
Tcham	0.0418	0.01012	4.130	3.79e-05 ***	0.0219 – 0.0614
Tair	0.203	0.01771	11.437	<2e-16 ***	0.168 – 0.238
Tsoil	0.123	0.01898	6.469	1.25e-10 ***	0.085 – 0.160
LB : 2013-16	0.619	0.4454	1.391	0.165	-0.252 – -1.490
BR : 2013-16	0.847	0.4454	1.902	0.0573 .	-0.024 – -1.718
LB : 2017-21	0.510	0.4471	1.140	0.255	-0.365 – -1.384
BR : 2017-21	0.623	0.4472	1.394	0.164	-0.252 – -1.498

Table A14.7 Estimated marginal means for Reco from full BACI model.

	DN	FI	LB	BR
Before	4.34 ± 0.458	4.64 ± 0.457	4.54 ± 0.338	4.29 ± 0.338
2013-16	4.43 ± 0.324	**1.93 ± 0.324**	2.42 ± 0.249	2.41 ± 0.249
2017-21	5.86 ± 0.326	**3.61 ± 0.326**	4.01 ± 0.250	3.88 ± 0.250

Table A14.8 Significant post-hoc contrasts for Reco fluxes. A positive estimate equals a lower net C loss.

Contrast	Estimate	P value
DN 2012 – DN 2017-21	-1.522 ± 0.397	0.0071 **
DN 2013-16 – DN 2017-21	-1.427 ± 0.230	<0.0001 ***
FI 2012 – FI 2013-16	2.717 ± 0.395	<0.0001 ***
FI 2013-16 – FI 2017-21	-1.686 ± 0.230	<0.0001 ***
LB 2012 – LB 2013-16	2.116 ± 0.281	<0.0001 ***
LB 2013-16 – LB 2017-21	-1.586 ± 0.164	<0.0001 ***
BR 2012 – BR 2013-16	1.885 ± 0.281	<0.0001 ***
BR 2013-16 – BR 2017-21	-1.469 ± 0.164	<0.0001 ***
DN 2013-16 – FI 2013-16	2.506 ± 0.417	<0.0001 ***
DN 2013-16 – LB 2013-16	2.010 ± 0.361	<0.0001 ***
DN 2013-16 – BR 2013-16	2.022 ± 0.361	<0.0001 ***
DN 2017-21 – FI 2017-21	2.248 ± 0.420	<0.0001 ***
DN 2017-21 – LB 2017-21	1.852 ± 0.364	<0.0001 ***
DN 2017-21 – BR 2017-21	1.979 ± 0.364	<0.0001 ***

At the individual sites

BACI comparison for FI vs. M (LB & BR) did not show any evidence of difference between FI and M managements at Nidderdale or Mossdale for either NEE or Reco. However, at Whitendale there was a significant difference, but this reflected the heavy heather beetle attach on FI plots in 2015, unrelated to management; both NEE and Reco were significantly reduced on FI versus LB and BR plots. However, there were no significant post-hoc contrasts between FI and LB or BR.

Table A14.8 Estimated marginal means for NEE from full BACI model at Whitendale.

	DN	FI	LB	BR
Before	-1.21 ± 1.325	-3.07 ± 1.325	-1.43 ± 1.233	-1.17 ± 1.233
2013-16	-2.22 ± 0.678	**0.17 ± 0.679**	-0.80 ± 0.625	-0.99 ± 0.625
2017-21	-3.73 ± 0.684	**-1.29 ± 0.683**	-2.58 ± 0.629	-2.69 ± 0.629

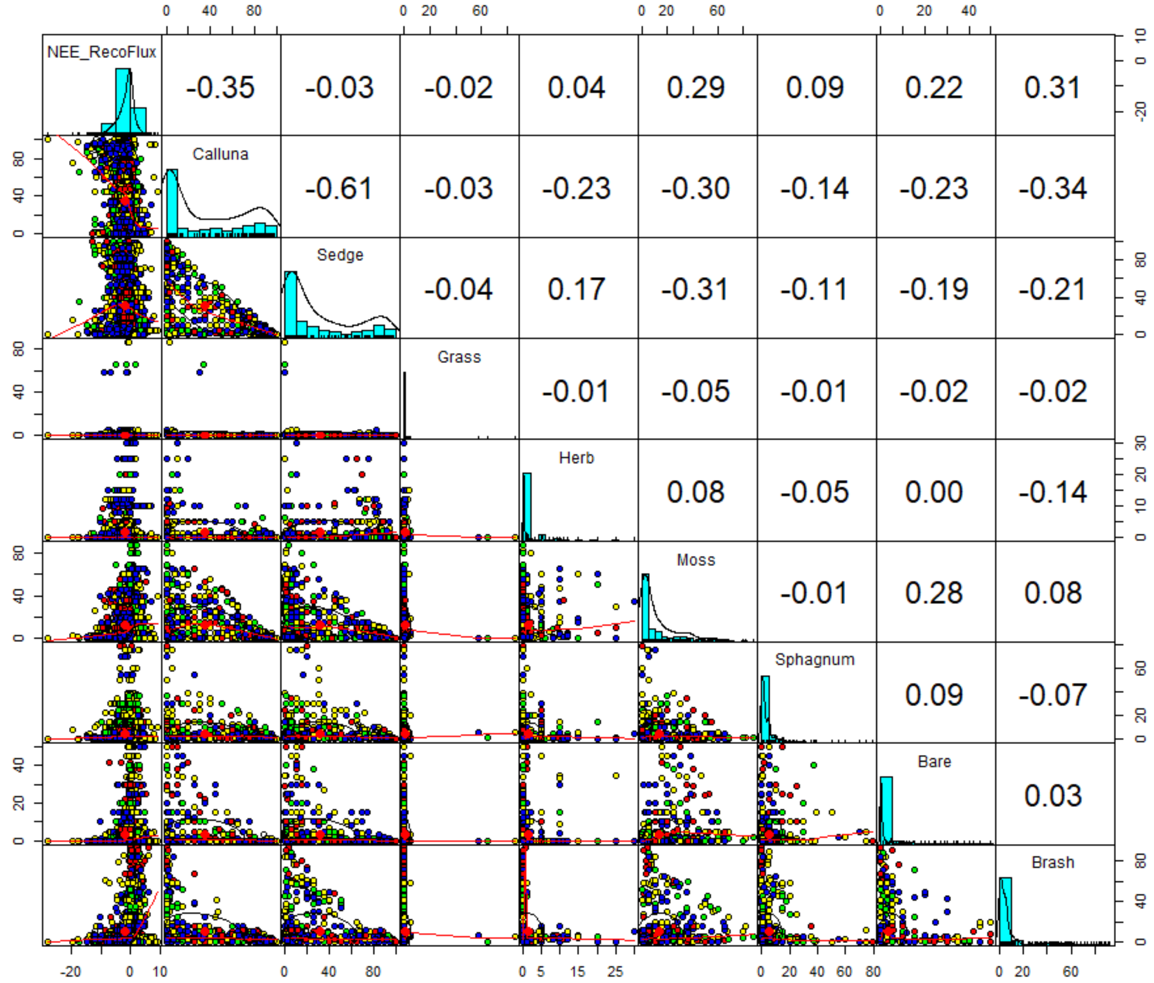
Table A14.9 Estimated marginal means for Reco from full BACI model at Whitendale.

	DN	FI	LB	BR
Before	4.01 ± 0.963	3.82 ± 0.963	4.00 ± 0.864	4.00 ± 0.864
2013-16	4.37 ± 0.574	**2.40 ± 0.574**	2.11 ± 0.485	2.28 ± 0.485
2017-21	5.44 ± 0.577	**3.51 ± 0.578**	4.23 ± 0.488	3.58 ± 0.488

Relationship between NEE flux and vegetation

Light conditions

The following **Figure A14.2** shows **correlations of NEE flux (in the light) with vegetation data**. There was a **reasonable correlation with *Calluna*, moss, bare and brash ground**. **The correlation with *Sphagnum* is low**, and there is **very low correlation with sedge, grass, and herb**.



A linear mixed-effect model was used to identify impacts of vegetative composition on NEE flux in light conditions. *Incorporating all vegetation types led to an over-fitted model*. Vegetation types were removed from the model according to significance in the model and correlation with NEE flux as shown in the above **Figure A14.2**. The final model was,

NEE flux ~ **Calluna + Moss + Bare + Brash** + (1|Site/Plot) + (1|Date)

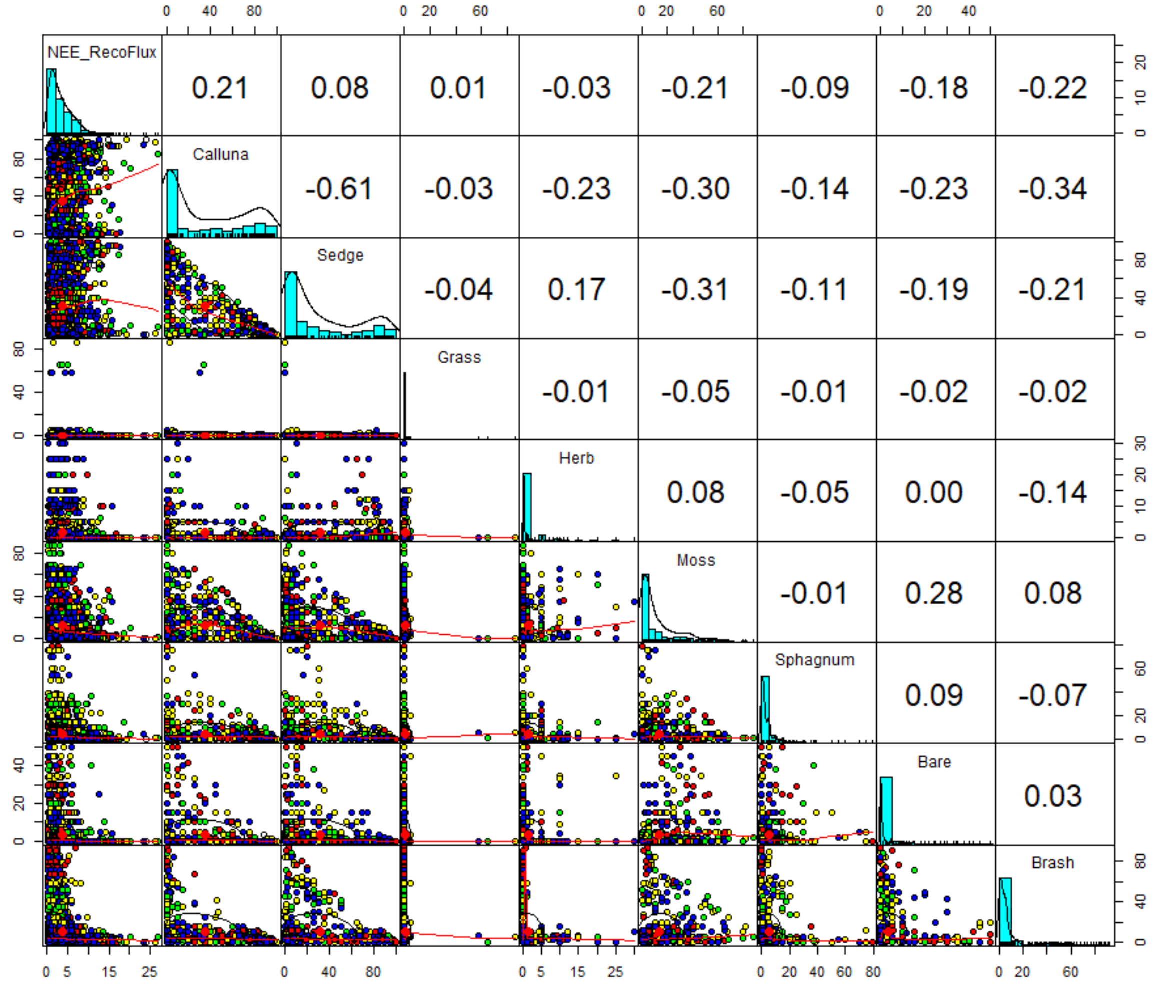
- In light, **plots with higher proportion of *Calluna* had lower flux levels** (more C uptake), whereas plots with **higher proportions of moss, brash, and bare ground had higher flux levels** (more respiration).

Table A14.10 Statistical analysis summary of output for correlation of NEE vs. vegetation types.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	-1.510	0.2175	-6.944	0.00346 **	-1.977 – -1.033
Calluna	-0.0254	0.00194	-13.117	<2e-16 ***	-0.0294 – -0.0214
Moss	0.0298	0.00331	9.008	<2e-16 ***	0.0233 – 0.0364
Bare	0.0260	0.00662	3.922	9.14e-05 ***	0.0129 – 0.0390
Brash	0.0327	0.00402	8.120	8.56e-16 ***	0.0248 – 0.0406

Dark conditions

The following **Figure A14.3** shows **correlations of Reco (NEE flux in the dark) with vegetation data**. There was a **reasonable correlation with *Calluna*, moss, bare and brash ground**. The **correlation with sedges and *Sphagnum* is low**, and there is **very low correlation with grass and herb**.



A linear mixed-effect model was again used to identify impacts of vegetative composition on NEE (Reco) flux in dark conditions. Vegetation types were again removed from the model according to significance in the model and correlation with NEE flux as shown in the above **Figure A14.3**. The formula for the linear mixed effect model (using the significant correlations from was,

Reco flux ~ Calluna + Moss + Sphagnum + Bare + Brash + (1|Site/Plot) + (1|Date)

- In dark conditions, **plots with higher proportion of *Calluna* had higher flux levels** (more respiration), whereas plots with **higher proportions of moss, *Sphagnum*, brash, and bare ground had lower flux levels** (less respiration).

Table A14.11 Statistical analysis summary of output for correlations of Reco vs. vegetation types.

Term	**Estimate**	**Std. Err**	**t value**	**P value signif**	**95% Conf.Int**
Intercept	4.257	0.2074	20.526	3.78e-09 ***	3.858 – 4.657
Calluna	0.00733	0.00268	2.737	0.00639 **	0.0021 – -0.0126
Moss	-0.0227	0.00398	-5.712	1.41e-08 ***	-0.0306 – -0.0150
Sphagnum	-0.0330	0.00539	-6.124	1.22e-09 ***	-0.0433 – -0.0220
Bare	-0.0326	0.00855	-3.812	0.000143 ***	-0.0500 – -0.0160
Brash	-0.0300	0.00374	-8.023	1.87e-15 ***	-0.0372 – -0.0226

Appendix 15 (CO_2-C balance)

The CO_2 NEE fluxes were used as previously (Heinemeyer et al., 2019b) to obtain parameters for the NEE in the light (Pmax) and Reco in the dark response curves vs. air temperature (Tair) during the measurement period.

Table A15.1 Annual regression equations (with R^2) over time at Nidderdale (Nidd), Mossdale (Moss) and Whitendale (Whit) for uncut, burnt and mown managements for dark respiration (Reco; exponential) and maximum NEE uptake (Pmax; linear) vs. air temperature (Tair).

UNCUT	**Reco**	**NIDD** EQN	R2	**MOSS** EQN	R2	**WHIT** EQN	R2
	2012	= 0.4805e0.0923x	0.99	= 0.7586e0.1205x	0.97	= 0.1411e0.1948x	0.99
	2013	= 0.6004e0.0762x	0.98	= 0.4707e0.0972x	0.80	= 0.3821e0.1064x	0.82
	2014	= 0.5425e0.0871x	0.72	= 0.2852e0.1518x	0.75	= 0.5499e0.0956x	0.97
	2015	= 1.014e0.0634x	0.40	= 0.8588e0.0826x	0.91	= 0.4683e0.1006x	0.93
	2016	= 1.1631e0.0793x	0.67	= 0.976e0.102x	0.95	= 0.5805e0.0825x	0.85
	2017	= 0.8108e0.092x	0.53	= 1.9187e0.0785x	0.77	= 0.5691e0.0978x	0.68
	2018	= 1.2326e0.074x	0.57	= 1.5969e0.0669x	0.65	= 0.8623e0.0815x	0.95
	2019	= 0.9485e0.0913x	0.79	= 1.3189e0.0891x	0.95	= 0.9177e0.0919x	0.99
	2020	= 1.2567e0.0702x	0.77	= 1.0279e0.0919x	0.98	= 0.9751e0.1057x	0.86
	2021	= 1.3877e0.0556x	0.50	= 0.8706e0.0924x	0.67	= 0.6626e0.0941x	0.91
	Pmax	**NIDD** EQN	R2	**MOSS** EQN	R2	**WHIT** EQN	R2
	2012	= -0.3542x - 4.4436	0.96	= -0.6115x - 6.2393	0.93	= -0.3677x - 1.6399	0.98
	2013	= -0.3937x - 5.2585	0.77	= -0.5686x - 5.7886	0.44	= -0.3819x - 3.7656	0.38
	2014	= -0.6653x - 1.4868	0.28	= -1.9143x + 12.447	0.99	= -1.2427x + 6.9802	0.97
	2015	= -0.5806x - 3.3194	0.34	= -0.5994x - 6.2608	0.35	= -1.0145x + 2.3834	0.87
	2016	= -1.4885x + 2.3935	0.67	= -1.261x - 4.3346	0.63	= -1.0049x + 1.0829	0.93
	2017	= -1.2297x + 0.2692	0.44	= -0.8385x - 9.025	0.11	= -0.7x - 4.7862	0.30
	2018	= -0.9018x - 2.9774	0.51	= -1.1704x - 1.5554	0.67	= -0.6093x - 4.3346	0.74
	2019	= -1.8206x + 7.6357	0.77	= -1.913x + 2.7537	0.99	= -2.0109x + 7.5792	0.98
	2020	= -0.7553x - 5.9831	0.62	= -1.1701x - 1.7799	0.92	= -1.738x + 3.6788	0.60
	2021	= -0.7559x - 4.845	0.18	= -0.9713x - 4.7466	0.30	= -1.2608x - 1.0294	0.63

BURNT	**Reco**	**NIDD** EQN	R2	**MOSS** EQN	R2	**WHIT** EQN	R2
	2012	= 0.4501e0.0903x	0.99	= 0.5271e0.1619x	0.99	= 0.4633e0.1481x	0.94
	2013	= 0.1406e0.1142x	0.95	= 0.3614e0.058x	0.98	= 0.6322e0.0305x	0.58
	2014	= 0.1447e0.1292x	0.94	= 0.4113e0.0661x	0.62	= 0.1846e0.097x	0.84
	2015	= 0.2758e0.097x	0.70	= 0.3789e0.0693x	0.76	= 0.2834e0.1255x	0.92
	2016	= 0.4471e0.0968x	0.87	= 0.4909e0.106x	0.76	= 0.3767e0.1192x	0.83
	2017	= 0.5912e0.0882x	0.71	= 0.6357e0.09x	0.64	= 0.6726e0.0898x	0.62
	2018	= 0.3905e0.0954x	0.83	= 0.7022e0.0825x	0.91	= 0.6256e0.0829x	0.75
	2019	= 0.3777e0.1349x	0.89	= 0.6619e0.1084x	0.99	= 0.6418e0.0848x	0.71
	2020	= 0.8489e0.0832x	0.76	= 1.1067e0.0708x	0.91	= 0.941e0.0721x	0.77
	2021	= 0.6759e0.0715x	0.72	= 0.8985e0.0886x	0.89	= 0.951e0.0604x	0.74
	Pmax	**NIDD** EQN	R2	**MOSS** EQN	R2	**WHIT** EQN	R2
	2012	= -0.3843x - 3.0176	0.50	= -0.562x - 4.3454	0.99	= -1.3733x - 0.5333	0.96
	2013	= -0.0182x - 0.3048	0.35	= -0.0212x - 0.1443	0.53	= -0.0255x - 0.4048	0.71
	2014	= -0.1631x + 0.1894	0.64	= -0.1078x - 0.5309	0.39	= -0.0998x + 0.4715	0.72
	2015	= -0.3468x - 1.1972	0.34	= -0.2386x - 0.3858	0.63	= -0.4829x + 0.5904	0.86
	2016	= -0.4465x - 0.6511	0.58	= -0.5391x - 2.8508	0.30	= -1.351x + 5.535	0.97
	2017	= -0.4818x - 2.557	0.38	= -0.2748x - 8.2407	0.10	= -1.3884x + 8.7615	0.80
	2018	= -0.6185x - 0.9403	0.94	= -0.5767x - 1.7989	0.66	= -0.2986x - 0.5261	0.70
	2019	= -1.6888x + 6.5006	0.85	= -0.9x + 0.2565	0.98	= -0.703x + 1.3459	0.94
	2020	= -0.7582x - 4.5142	0.46	= -0.9218x - 0.2381	0.83	= -0.593x - 4.804	0.65
	2021	= -0.7905x + 1.8481	0.72	= -1.0701x + 0.6371	0.81	= -0.991x - 0.0141	0.90

MOWN	**Reco**	**NIDD** EQN	R2	**MOSS** EQN	R2	**WHIT** EQN	R2
	2012	= 0.5195e0.0962x	0.96	= 0.9578e0.1109x	0.93	= 0.2566e0.1423x	0.99
	2013	= 0.1282e0.1017x	0.96	= 0.2805e0.0835x	0.94	= 0.4751e0.0693x	0.99
	2014	= 0.1959e0.1161x	0.93	= 0.2662e0.1389x	0.98	= 0.192e0.119x	0.97
	2015	= 0.3222e0.087x	0.52	= 0.3359e0.1042x	0.91	= 0.1872e0.1416x	0.79
	2016	= 0.376e0.1136x	0.72	= 0.5217e0.1056x	0.82	= 0.3195e0.1048x	0.86
	2017	= 1.7047e0.0524x	0.65	= 0.309e0.171x	0.99	= 0.3903e0.0975x	0.74
	2018	= 0.8905e0.0848x	0.87	= 0.76e0.0946x	0.60	= 0.6027e0.0762x	0.83
	2019	= 0.3932e0.1445x	0.93	= 0.8097e0.1002x	0.88	= 0.5543e0.0822x	0.98
	2020	= 0.64e0.0845x	0.87	= 1.0268e0.0669x	0.83	= 0.5794e0.0894x	0.85
	2021	= 0.8612e0.0597x	0.89	= 0.733e0.0798x	0.56	= 0.6134e0.0784x	0.79
	Pmax	**NIDD** EQN	R2	**MOSS** EQN	R2	**WHIT** EQN	R2
	2012	= -0.2523x - 4.5993	0.44	= -0.7544x - 6.0024	0.95	= -0.7556x - 0.5303	0.96
	2013	= -0.0345x - 0.2228	0.56	= -0.0507x - 0.9905	0.04	= -0.0708x - 0.7223	0.13
	2014	= -0.1557x - 0.0648	0.40	= -0.9078x + 6.6141	0.99	= -0.4187x + 3.2536	0.87
	2015	= -0.3288x + 0.3811	0.41	= -0.9459x + 4.521	0.96	= -0.6176x + 4.1111	0.94
	2016	= -0.9159x + 3.2069	0.66	= -0.7777x + 0.2843	0.76	= -0.7888x + 3.6681	0.79
	2017	= -0.8053x - 1.7687	0.72	= -1.5099x + 7.299	0.54	= -0.676x - 0.6226	0.55
	2018	= -1.1119x + 0.7474	0.61	= -1.0275x - 1.3089	0.47	= -0.4173x - 1.7605	0.52
	2019	= -2.1811x + 14.473	0.95	= -1.4176x + 3.1886	0.98	= -1.2825x + 7.1294	0.95
	2020	= -0.711x + 2.7781	0.74	= -0.95x + 0.5011	0.60	= -1.4039x + 8.0295	0.99
	2021	= -0.6434x + 2.1633	0.59	= -0.9045x + 1.9935	0.45	= -0.7832x + 0.9809	0.70

Moreover, the CO_2 NEE fluxes were also used as previously (Heinemeyer et al., 2019b) to obtain parameters for the linear regressions of the seasonal flux responses to photosynthetic active radiation (PARslope) vs. the corresponding monthly totals of PAR measured at the weather stations at each site. For the initial year this was done for the seasonal measurements over only the initial pre-management year (2012/13). Subsequently, the uncut (no management) plots were fitted over two years to allow a more stable regression fit (covering a wider PAR range), which was also done for the managed plots (burnt and mown) once plants had established again (from 2014/15 onwards).

Table A15.2 Regression (linear) equations (with R^2) over time (annual at first and bi-annual over time reflecting pre-management phase and recovery after initial management) at Nidderdale (Nidd), Mossdale (Moss) and Whitendale (Whit) for uncut, burnt and mown managements for the slope of the seasonal light response curves (PAR SLOPE) vs. the corresponding monthly total photosynthetic active radiation (PAR) sums.

PAR SLOPE	NIDD		MOSS		WHIT	
UNCUT	EQN	R2	EQN	R2	EQN	R2
2012	= 1.4065x	0.8	= 0.6649x	0.52	= 0.6307x	0.18
2012-2013	= 1.2058x	0.32	= 0.7683x	0.8	= 0.7421x	0.8
2013-2014	= 1.3239x	0.36	= 0.7857x	0.82	= 0.9261x	0.49
2014-2015	= 1.228x	0.32	= 0.6785x	0.57	= 0.9345x	0.31
2015-2016	= 1.131x	0.76	= 0.7447x	0.14	= 1.0487x	0.21
2016-2017	= 1.1468x	0.75	= 0.8253x	0.12	= 1.0667x	0.24
2017-2018	= 0.997x	0.87	= 0.7597x	0.9	= 1.1239x	0.82
2018-2019	= 0.99x	0.86	= 0.7804x	0.83	= 1.1501x	0.87
2019-2020	= 1.0199x	0.94	= 1.1587x	0.86	= 1.0474x	0.94
2020-2021	= 1.2182x	0.86	= 1.192x	0.64	= 0.923x	0.6

PAR SLOPE	NIDD		MOSS		WHIT	
BURN	EQN	R2	EQN	R2	EQN	R2
2012	= 1.3651x	0.87	= 0.41x	0.10	= 1.2822x	0.84
2013	= 0.3764x	0.51	= 0.3237x	0.58	= 0.4019x	0.66
2014	= 0.5176x	0.61	= 0.5371x	0.97	= 0.4926x	0.74
2014-2015	= 0.7458x	0.64	= 0.905x	0.61	= 0.6205x	0.58
2015-2016	= 1.0106x	0.78	= 0.9532x	0.53	= 0.5377x	0.27
2016-2017	= 0.9183x	0.62	= 0.7622x	0.41	= 0.7832x	0.04
2017-2018	= 0.9146x	0.62	= 0.994x	0.90	= 0.8408x	0.76
2018-2019	= 1.0783x	0.66	= 1.0748x	0.92	= 1.0279x	0.83
2019-2020	= 1.143x	0.88	= 1.3071x	0.94	= 1.0985x	0.82
2020-2021	= 1.3282x	0.86	= 1.3624x	0.78	= 0.9254x	0.93

PAR SLOPE	NIDD		MOSS		WHIT	
MOWN	EQN	R2	EQN	R2	EQN	R2
2012	= 0.9183x	0.4	= 0.7	0.83	= 1.0353x	0.74
2013	= 0.4949x	0.94	= 0.4511x	0.94	= 0.4318x	0.83
2014	= 0.7378x	0.59	= 0.4068x	0.84	= 0.643x	0.87
2014-2015	= 0.9877x	0.55	= 0.8786x	0.38	= 0.5903x	0.65
2015-2016	= 1.133x	0.7	= 1.0134x	0.34	= 0.7057x	0.59
2016-2017	= 0.8659x	0.65	= 0.8226x	0.63	= 0.8899x	0.89
2017-2018	= 0.9621x	0.8	= 0.9221x	0.86	= 1.0026x	0.94
2018-2019	= 1.0669x	0.94	= 0.9539x	0.83	= 1.1464x	0.92
2019-2020	= 1.1656x	0.86	= 1.3142x	0.87	= 1.2075x	0.89
2020-2021	= 1.2221x	0.90	= 1.1766x	0.70	= 1.0052x	0.91

Based on these equations (**Table A15.1-2**) the hourly NEE flux (net uptake or release) of CO_2 was calculated using the hourly weather station data for each site. The sum of these net fluxes over time allowed estimating the total annual net C-uptake. The following **Figure A15.1** summarises the monthly and annual totals for each site for the uncut (ageing heather) plots. However, as the light response curves were derived by combining the four replicates per management per seasonal measurement, no replication-based error bar calculation is provided. The same calculations were done for the burnt and mown managements. However, all three sites were affected by heather beetle causing defoliation of heather (mostly on burnt plots and first at Whitendale, then at Mossdale yet least at Nidderdale) and thus a switch from C sink to C source over time during 2017-2021. The resulting C sink/source changes over time are shown in **Figure A15.2** across all sites combined and in **Figure A15.3** for the individual sites.

Notably, overall the burnt plots became a net CO_2-C sink already three years post-management, whereas mown plots required a longer time (**Figure A15.2**).

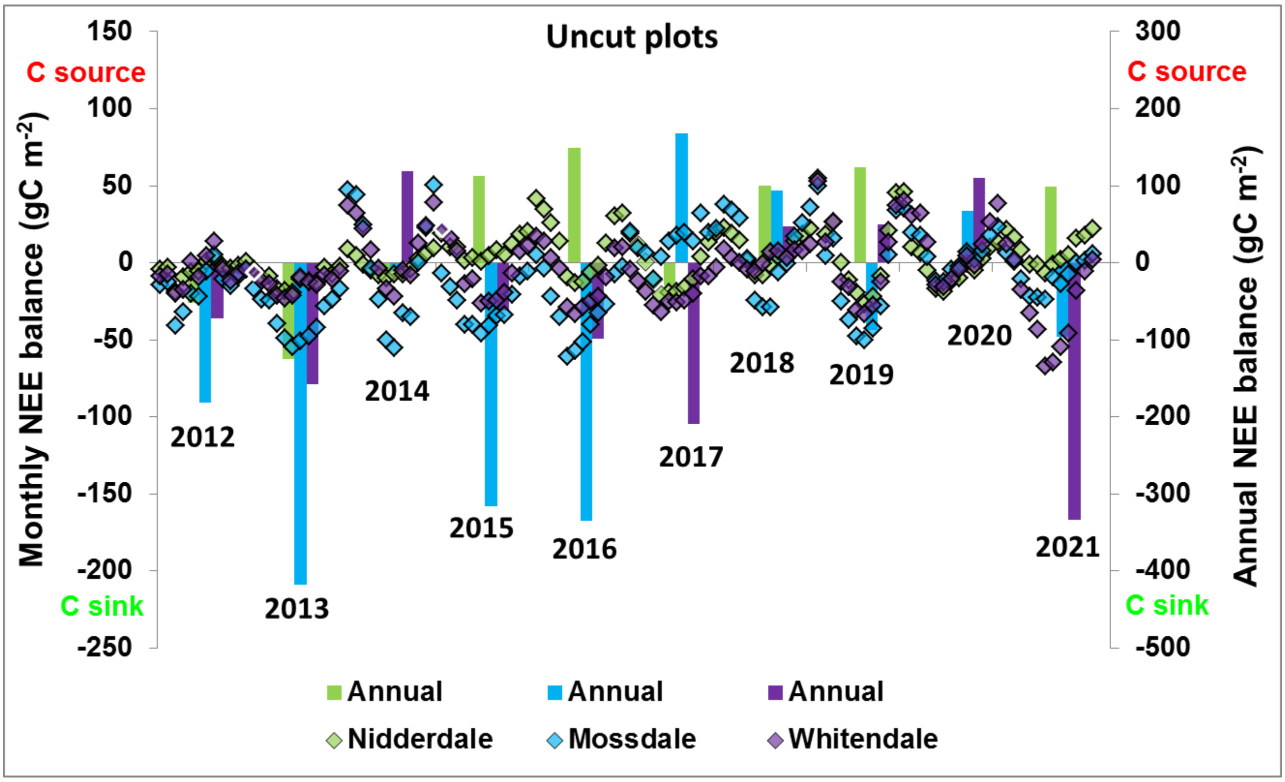


Figure A15.1 Monthly (diamonds) and annual (bars) total C balance for the uncut management at Nidderdale (green), Mossdale (blue) and Whitendale (purple) from 2012-2021. Positive numbers indicate a C source.

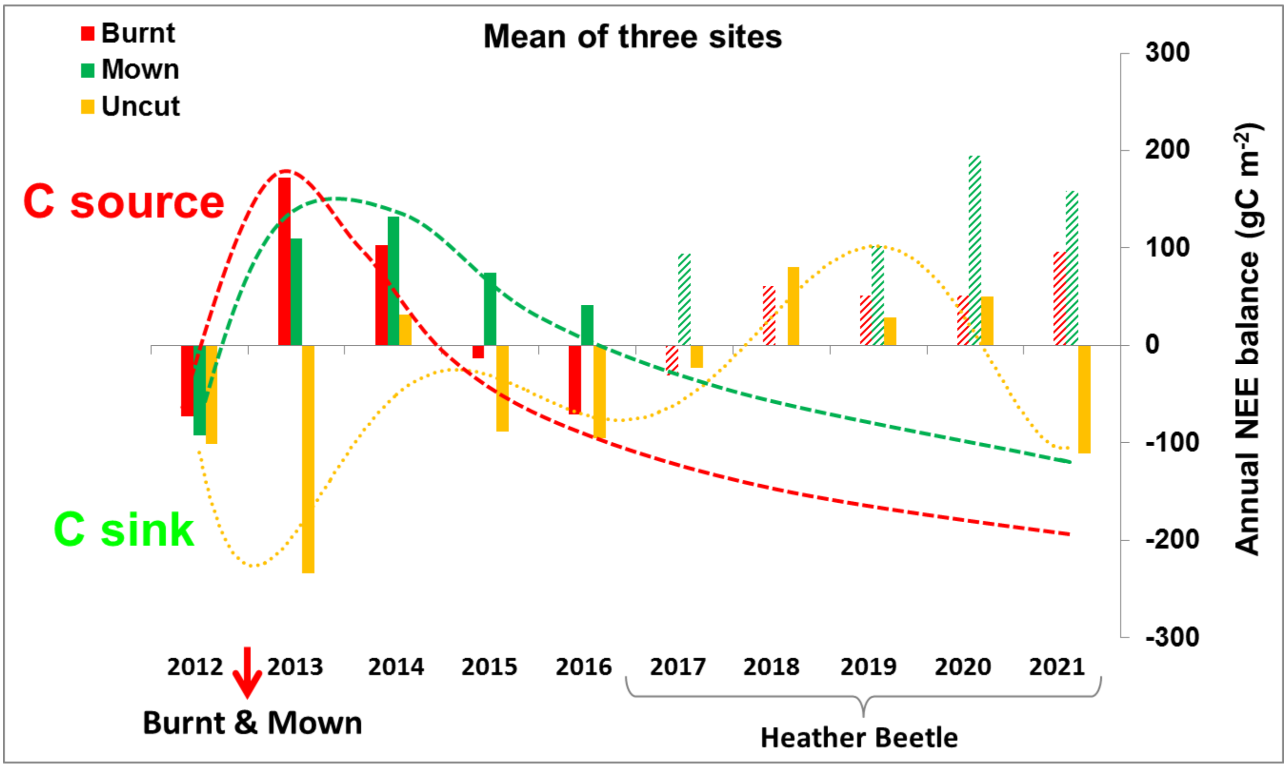


Figure A15.2 Annual total C balance for the burnt (red), mown (green; with leaving brash) and uncut (yellow) management combined across the Nidderdale, Mossdale and Whitendale sites from 2012-2021. Shaded areas indicate heather beetle damage (2017-2021) which greatly reduced net C uptake (i.e. defoliated heather). The yellow (uncut) line is a polynomial fit, whereas the red and green lines are manually fitted to the period of no heather beetle damage (i.e. showing strong recovery from 2014-2016). Positive numbers indicate a C source.

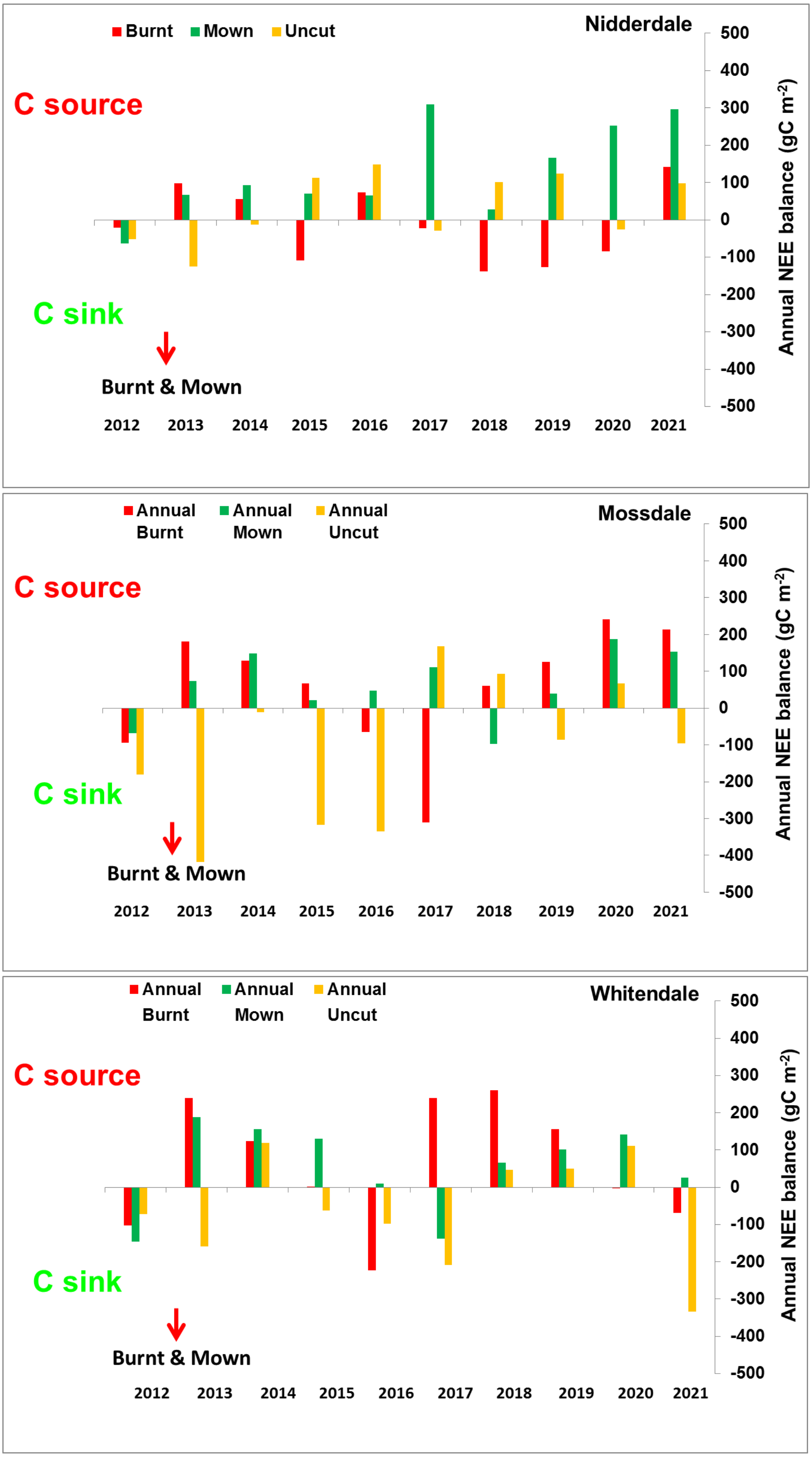


Figure A15.3 Annual total C balance for the Nidderdale, Mossdale and Whitendale sites from 2012-2021 for the burnt (red), mown (green; with leaving brash) and uncut (yellow) management (arrow indicates management start). Periods of quick, initial post-management recovery was halted on burnt plots around 2016/17 due to heather beetle damage (at Nidderdale also mown plots around 2020/21). Positive numbers indicate a C source.

The annual C-flux totals were then progressively averaged over time (**Figure A15.4**), which included progressively adding the estimated C emissions from the initial combustion (Heinemeyer et al., 2019b) and subtracting a C sink via the formation of charcoal (Heinemeyer et al., 2018). Interestingly, whilst the burnt management indicated a rapid recovery (up to the heather beetle damage during 2017-2021; see **Figure A15.5**), the mown management showed a fairly consistent continuation of a large C source likely relating to long-term brash decomposition on mown plots (which had some additional but limited heather beetle damage mainly during 2020-2021).

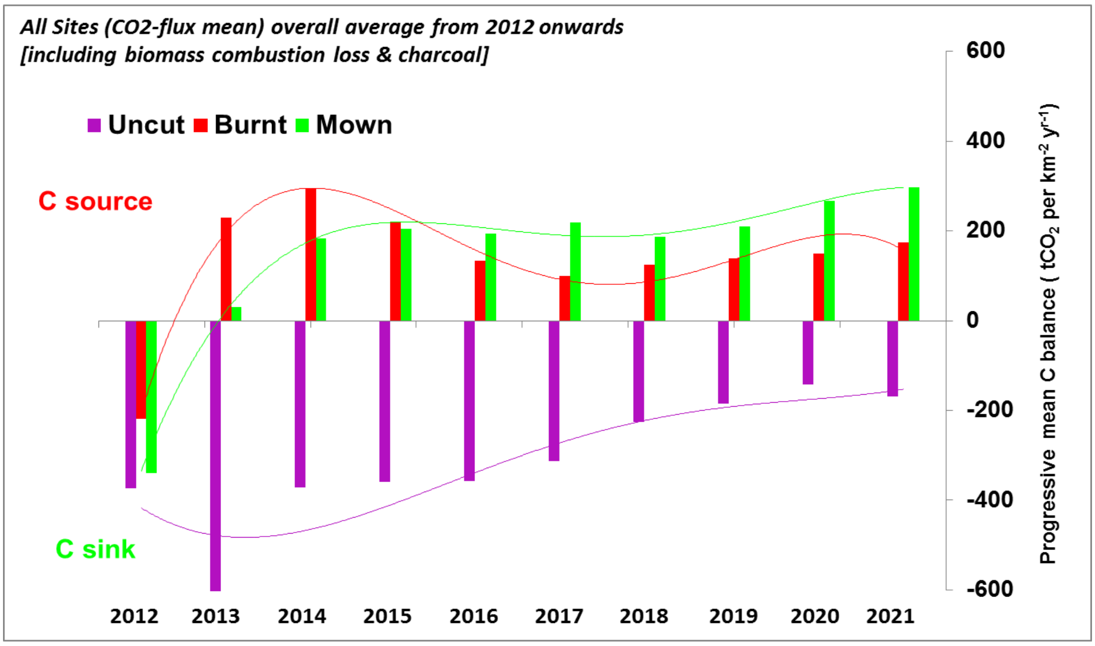


Figure A15.4 Annual totals of progressive mean CO_2 C-flux balance for the uncut (purple), burnt (red) and mown (green; with leaving brash) management combined across the Nidderdale, Mossdale and Whitendale sites from 2012-2021. Lines represent polynomial fitting (4th order). Burnt fluxes include cumulative emissions from the estimated combustion and charcoal sequestration (Heinemeyer et al., 2019b) – both were allocated annually as equal parts over a 22-year management rotation as indicated by charcoal records (Heinemeyer et al., 2018).

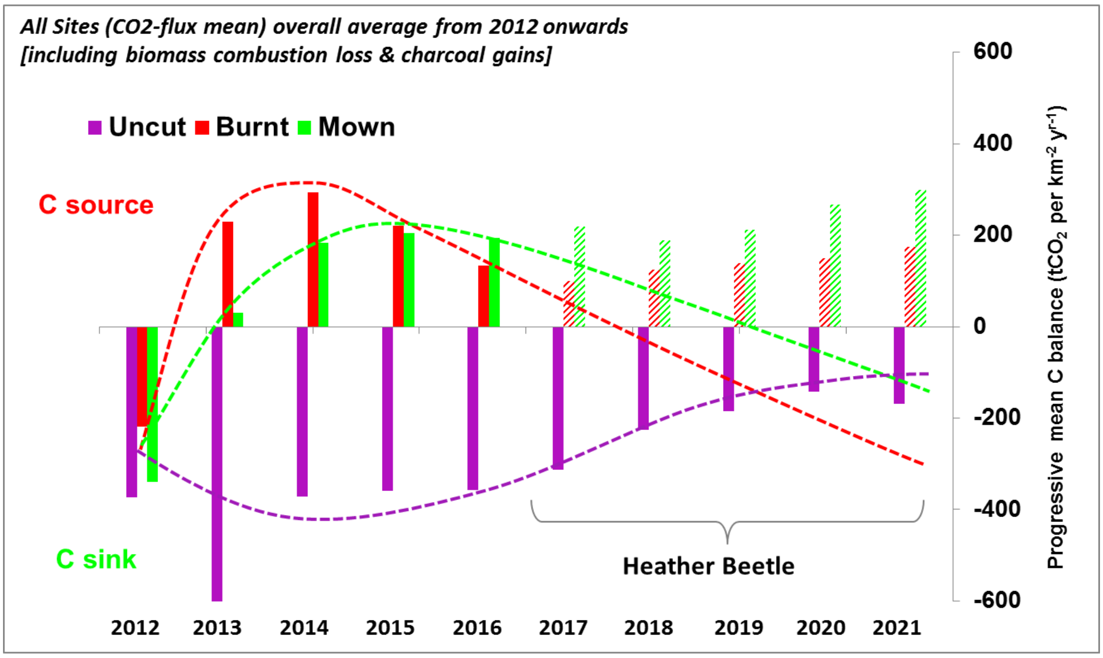


Figure A15.5 Annual totals of progressive mean CO_2 C-flux balance (including estimated combustion emissions and charcoal gains as in Fig. A15.4) for the uncut (purple), burnt (red) and mown (green; with leaving brash) management combined across the Nidderdale, Mossdale and Whitendale sites from 2012-2021. Lines represent the best estimate fit excluding the period of heather beetle damage (2017-2021; dashed bars), which mainly reduced net C uptake (i.e. defoliated heather) in burnt plots and less on mown plots.

The following graph (**Figure A15.6**) compares the measured versus the estimated C balance, where years with obvious heather beetle impact on fluxes (see **Figure A15.3** and **Figure A15.5** above) were replaced based on interpolation with those fluxes from unaffected sites/plots. The charcoal data are maximum estimates based on Clay & Worrall (2011) and Worrall et al. (2013) indicating an about 75% biomass combustion loss and a potential of up to ~30% char production (depending on temperatures and other conditions). However, whilst their field experimental data of charcoal production indicate less than 5% charcoal production, the latter did not include litter (at the soil surface) layer conversion into charcoal (i.e. it was done in the field with tray collection of char produced only from the canopy) and the former scraped char layers of the ground after one month of the fire (resulting in likely underestimation as charcoal falls within cracks and gets washed into the peat). However, both studies included long-term modelling scenarios clearly outlining the potential benefit for C storage by fire conversion of biomass into charcoal, with lower decomposition rates than litter.

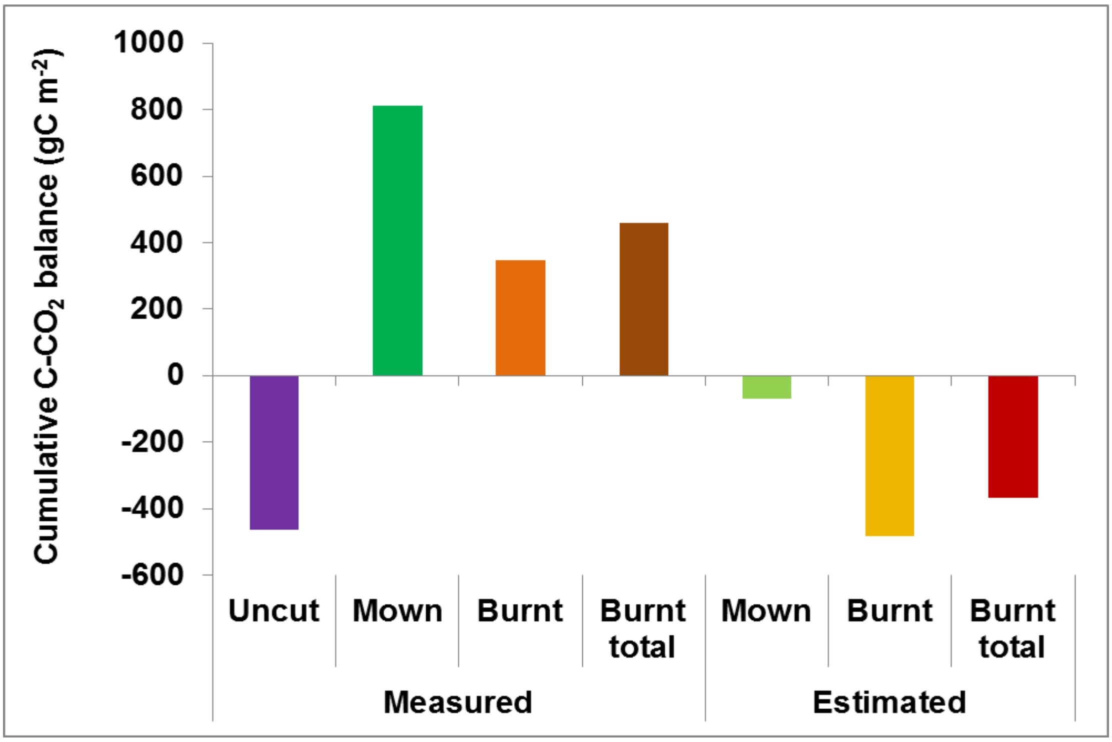


Figure A15.6 Cumulative C-CO$_2$ balance based on measured fluxes for the uncut, mown (with brash left) and burnt plots versus the estimated values when excluding heather beetle affected periods for mown and burnt plots. Burnt totals include the estimated annual C losses from combustion and estimated maximum C gains from charcoal as allocated over an average 22-year management cycle (to be comparable to annual brash decomposition included in fluxes measured on mown plots).

Finally, it is important to note that although the NEE (light) fluxes were marginally lower in the burnt vs. mown plots (**Table A14.1**), this does not take into account the increased C uptake in relation to higher nutrient content from ash fertilisation (i.e. increased Mn, Fe and P levels) in burnt plots (**Figure A4.1**) allowing a faster light response (**Table A15.2**). Together with lower NEE in the dark (Reco) respiration (**Table A14.6**) and soil respiration (**Figure A12.2**) in burnt plots this resulted in an overall greater net C uptake over time using the climate data. Important is also that overall net respiration periods are much longer than net photosynthesis over the year (due to light and temperature effects interacting). Therefore, a simple NEE model based on overall annual light responses is likely inadequate for UK blanket bogs due to the large seasonal changes in light and thus light responses of the C uptake. This could also explain the somehow unexpected greatest NEE (C uptake) reported for only one year after burning in a heather burning study by Clay et al. (2015), which seems impossible (as the fire would have consumed and severely damaged any photosynthetic biomass, which should result in a high net C loss, and not C gain) as well as the subsequent positive NEE (C loss). It seems very likely that an overall annual light response curve masks periods of seasonal net uptake (especially considering changing N-levels and enzymatic activity).

Appendix 16 (methane emissions)

The field analysers monitored methane fluxes, at first over vegetation free plots, then over vegetated NEE flux locations (i.e. measured at the same time as NEE fluxes). For more information see the previous description (Heinemeyer et al., 2019b). Due to the large fluctuations in methane fluxes over time, the median provides a much more ecologically meaningful average than the mean.

METHANE ANNUAL MEDIANS, POST-MARCH 2015 (VEGETATED PLOTS)

Full BACI analysis with vegetation (either including *Calluna* or sedge)

A BACI analysis of the post- March 2015 data (i.e. measured over plots with vegetation, not just soil) was conducted, using **annual median** values for all continuous responses for all plots. Generalised linear mixed modelling (GLMM) was used, with a Gamma distribution and log link due to a few extremely high outliers. There were five values below 0, the lowest was -0.45 (i.e. representing methane oxidation). Therefore, an adjustment of +0.451 was applied to all measurements to make the data suitable for the Gamma log link distribution. Initially all vegetation and environmental variables were incorporated into the statistical model, however this led to convergence problems. After investigation, this was primarily caused by the vegetation data, particularly the sedge (i.e. mainly cotton-grass, *Eriophorum* spp.) and *Calluna* data which showed a strongly inverse correlation (plots tended to be on a spectrum of sedge-dominant to *Calluna*-dominant). Therefore, the two statistical approaches below show the results for when either ***Calluna*** was included in the model, or for when **sedge** was included, separately. The Nelder Mead optimiser was also used, which can help model convergence and therefore improve the model's fit. *The covariates for bare, herb, and grass were removed in both approaches, as they were non-significant and showed little correlation with methane fluxes* (and cover was generally very low).

Overall, there was a **significant negative *Calluna* but a positive sedge effect on methane emissions**. Moreover, **methane emissions decreased significantly from uncut (DN) to mown with brash (LB), without brash (BR) to bunt (FI)**.

mod: MethaneFlux + 0.451 ~ Mgmt + WTD + Tcham + **Sedge** + Brash + (1 | Site/Plot) + (1 | Year)
mod1: MethaneFlux + 0.451 ~ Mgmt + Tcham + WTD + **Calluna** + Moss + Sphagnum + Brash + (1 | Site/Plot) + (1 | Year); npar AIC BIC logLik deviance Chisq Df Pr(>Chisq)

```
mod    12 4005.6 4056.2 -1990.8   3981.6
mod1   14 3997.1 4056.2 -1984.6   3969.1 12.453  2   0.001976 **
```

With *Calluna*, *Sphagnum* moss and other moss (excluding sedge)
Model: MethaneFlux+0.451 ~ Management + Tcham + WTD + Calluna + Moss + Sphagnum + Brash + (1|Site/Plot) + (1|Year).

Table A16.1 Output of mixed-effect model comparing burnt (FI), mown without (LB) or with brash removal (BR) to uncut and listing the significant model terms.

Term	**Estimate**	**Std. Err**	**t value**	**P value signif**	**95% Conf.Int**
Intercept	4.290	0.6059	7.081	1.43e-12 ***	3.103 – 5.478
FI	-1.472	0.3657	-4.024	5.71e-05 ***	-2.189 – -0.755
LB	-1.175	0.3381	-3.474	0.000513 ***	-1.837 – -0.512
BR	-0.878	0.3227	-2.721	0.00652 **	-1.510 – -0.245
Tcham	**0.0291**	**0.0142**	**2.053**	**0.0401 ***	0.0013 – 0.0569
WTD	**0.0150**	**0.0073**	**2.046**	**0.0408 ***	0.0006 – 0.0294
Calluna	**-0.0146**	**0.0026**	**-5.675**	**1.39e-08 *****	-0.0196 – -0.0095
Moss	-0.0090	0.0047	-1.898	0.0577 .	-0.0183 – 0.0003
Sphagnum	-0.0107	0.0060	-1.768	0.0771 .	-0.0225 – 0.0012
Brash	**-0.0290**	**0.0070**	**-4.150**	**3.33e-05 *****	-0.0427 – -0.0153

Table A16.2 Estimated marginal mean response from the full BACI model (back-transformed at mean values of chamber temperature, water table depth, *Calluna*, Moss, *Sphagnum*, and Brash cover). Note the highest emissions on uncut (DN) plots, then mown with brash removal (BR), then mown with brash left (LB), indicating a sign. brash effect (likely oxidising bacteria in that layer similar to reports for *Sphagnum* moss layers), and lowest emissions on burnt (FI) plots. Significance levels are shown in the post-hoc table section.

DN	FI	LB	BR
38.59 ± 19.70	**8.86 ± 4.46**	**11.92 ± 5.63**	**16.04 ± 7.54**

Significant post-hoc contrasts

Contrast	Estimate	P value
DN – FI	1.472 ± 0.366	0.0003 ***
DN – LB	1.175 ± 0.338	0.0029 **
DN – BR	0.878 ± 0.323	0.0330 *

With Sedge and brash (excluding heather)
Model: MethaneFlux+0.451 ~ Management + Tcham + WTD + Sedge + Brash + (1|Site/Plot) + (1|Year).

Table A16.3 Output of mixed-effect model comparing burnt (FI), mown without (LB) or with brash removal (BR) to uncut and listing the significant model terms.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	2.926	0.5744	5.095	3.49e-07 ***	1.801 – 4.052
FI	-1.263	0.3779	-3.343	0.000829 ***	-2.004 – -0.523
LB	-0.917	0.3449	-2.658	0.00785 **	-1.593 – -0.241
BR	-0.655	0.3307	-1.982	0.0475 *	-1.303 – -0.007
Tcham	**0.0287**	**0.0144**	**2.002**	**0.0452 ***	**0.0006 – 0.0569**
WTD	0.0137	0.0074	1.860	0.0629 .	-0.0007 – 0.0282
Sedge	**0.0103**	**0.0024**	**4.306**	**1.67e-05 *****	**0.0056 – 0.0150**
Brash	-0.0173	0.0069	-2.491	0.0127	-0.0309 – -0.0037

Table A16.4 Estimated marginal mean response from the full BACI model (back-transformed at mean values of chamber temperature, water table depth, Sedge and Brash cover). Note the highest emissions on uncut (DN) plots, then mown with brash removal (BR), then mown with brash left (LB), indicating a sign. brash effect (likely oxidising bacteria in that layer similar to reports for *Sphagnum* moss layers), and lowest emissions on burnt (FI) plots. Significance levels are shown in the post-hoc table section.

DN	FI	LB	BR
31.88 ± 16.68	**9.01 ± 4.68**	**12.74 ± 6.19**	16.55 ± 8.00

Significant post-hoc contrasts

Contrast	Estimate	P value
DN – FI	1.263 ± 0.378	0.0046 **
DN – LB	0.917 ± 0.345	0.0393 *
DN – BR	0.655 ± 0.331	0.1947

Overall, **chamber temperature (Tcham) and (albeit less so) water table depth (wtd) showed a significant positive relationship with methane emissions**, whilst brash cover showed a significant negative impact (but only on heather-dominated plots). The sedge versus brash cover effect clearly supports the anticipated impacts of **sedge aerenchyma (increasing methane flux) versus brash layer (reducing methane emissions by enhanced microbial oxidation)**.

Investigation of interactive terms (i.e. pH & water table depth)

Methane emissions were clearly linked to vegetation and key environmental parameters, especially temperature and water table depths. Of interest are the periods of high methane emissions (**Figure A16.1**) and their possible causes. Especially noteworthy are the similarities in methane emissions and the pH in monthly stream flow samples (allowing a link to the overall catchment behaviour over time – plot-level pH showed similar patterns but were sampled less frequently). Stream pH values (**Figure A16.2**) indicated a threshold of above ~4.0 for which two periods of peak pH overlapped with the peak periods in methane emissions during 2015-2017 and 2020. Moreover, there were obvious links to higher and lower methane emissions and stream flow pH with similar directions in peat wetness (as indicated by water table depth fluctuations), especially considering the wet periods of 2015-2017 and 2019/20 and the two very dry summers in the years 2018 and 2021 (**Figure A16.3**).

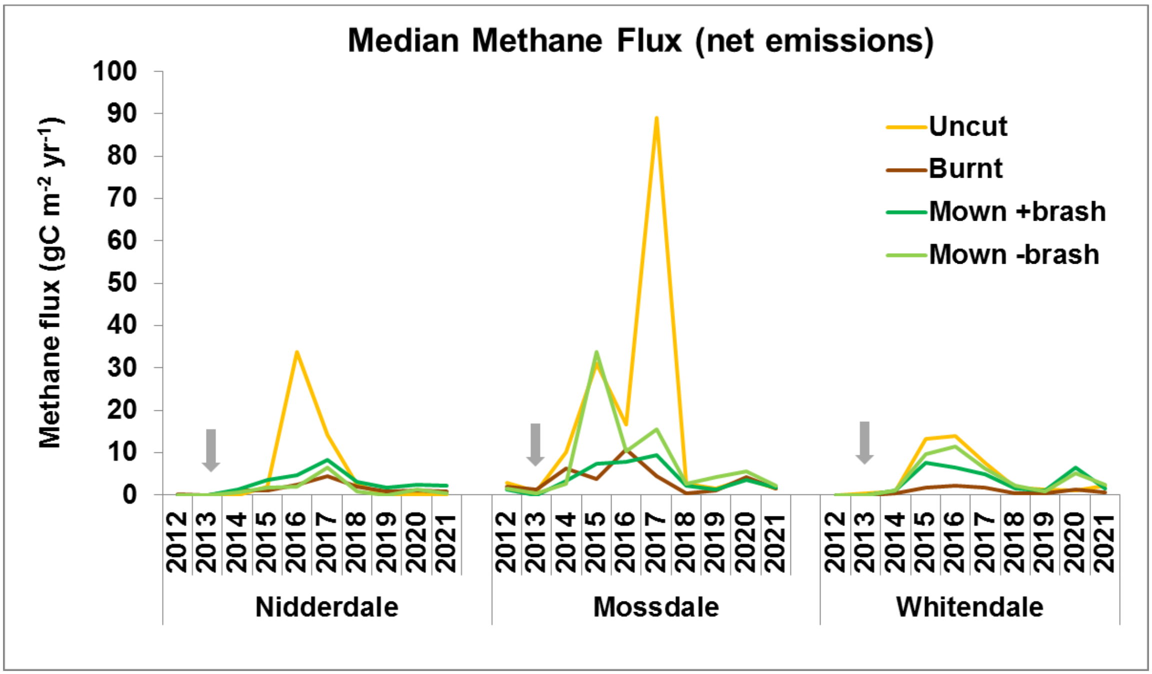


Figure A16.1 Median methane emissions at the three sites, Nidderdale, Mossdale and Whitendale during 2012-2021. The grey arrows indicate the onset of management.

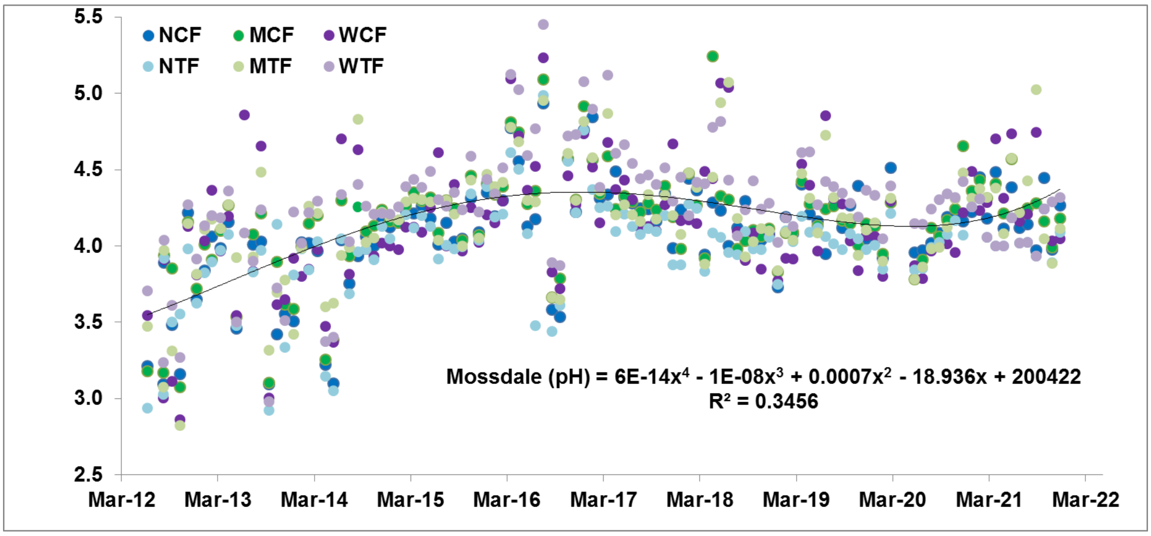
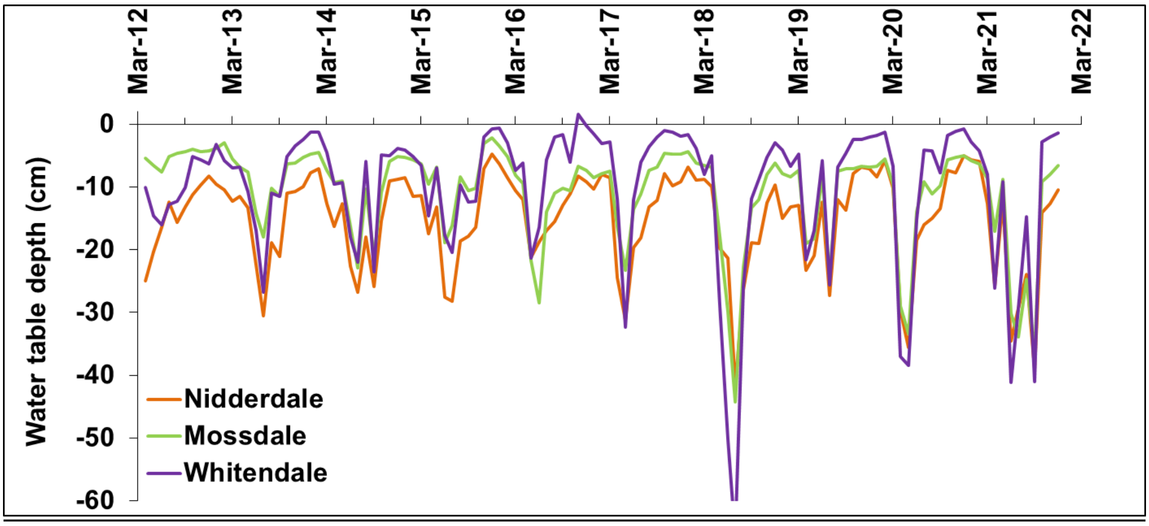


Figure A16.2 Monthly pH in stream (flow) samples at the two catchments (control burnt = C; treatment mown = T) Nidderdale, Mossdale and Whitendale sites during 2012-2021. Management started around March 2013. The curve shows a sample polynomial regression as a guide for pH peaks and troughs over time.



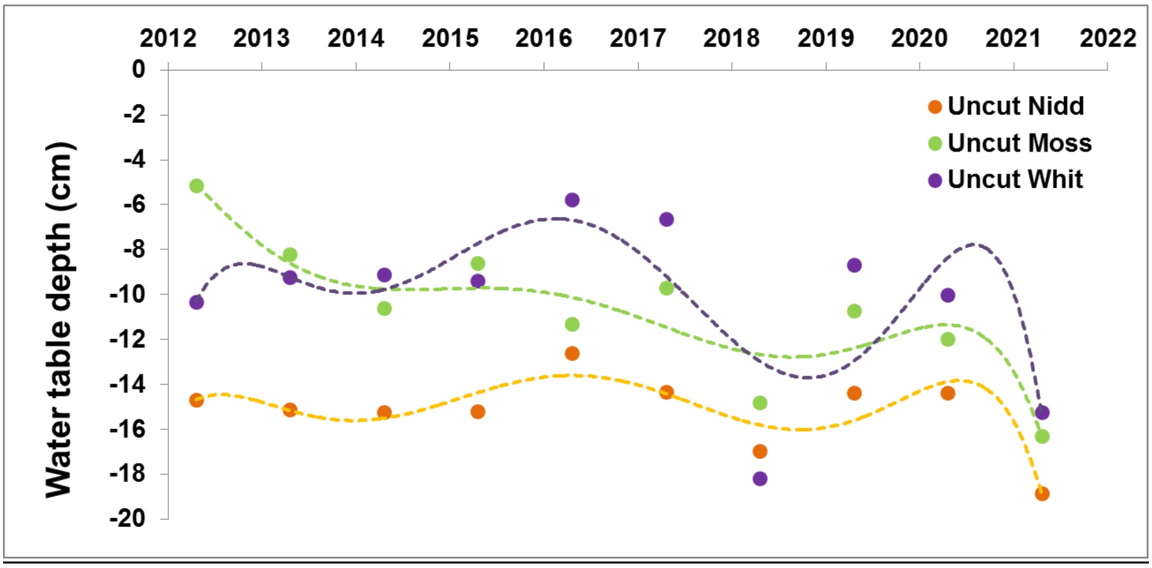


Figure A16.3 Mean monthly water table depth (WTD) in the uncut (DN) plots at the three sites, Nidderdale, Mossdale and Whitendale during 2012-2021. Note especially the wet periods of 2015-2017 and 2019/20 and the two very dry summers in the years 2018 and 2021.

For the statistical analysis, first data from 2015 onwards were used (i.e. fluxes measured over vegetated plots), which included the vegetation cover data. The annual median values, for each plot, for all continuous variables were used (flux, Tsoil, Tcham, **flow pH**, WTD, and all vegetation proportions). Note flow pH was observed to seem to relate positively (i.e. highest methane and high pH during 2015-2017) over the years to methane emissions (based on monthly flow samples). Abdalla et al. (2016) also suggest a positive relationship for mean annual water table depth (WTD) of around 0-10 cm and a potential higher emission under higher pH. However, most likely is a link to declining SO_4 deposition (along the lines of Boothroyd et al., 2021) – lowered SO_4 levels during the very wet and warm 2016-2017 when levels of SO_4 declined further (being reduced at depth); electrons on SO_4 are used to produce CO_2 instead of methane (reduced methanogensis) but over time this pool is used up under long periods of anoxic conditions. Therefore, methane production could have increased as available SO_4 was a limiting factor (and SO_4 pool is known to become limited in summer during higher microbial activity (Nedwell & Watson, 1995)). Moreover, the suppressive SO_4 effect decreases with higher temperatures (Gauci et al., 2005). Drought induces SO_4 production (oxidation of S) and thus lowers the pH (Clark et al., 2005) - as observed in 2018 - coincidentally this drought induced acidification also decreases solubility and export of DOC (normally increased under higher temperatures but if drought, then this is decreased due to WTD effect being greater than the temperature effect). Note: see the graphs **Figure A16.2-3** above on pH vs. WTD (in relation to wet and dry 'drought' periods); however, methane fluxes during 2012-2014 excluded vegetation (i.e. only over soil) and a such were lower even though water tables were relatively high in 2012 (especially on Mossdale).

A mixed-effect model was used, with Gamma distribution and a log link. The response data (methane flux) was adjusted by +0.451 to allow computation with the Gamma distribution (non-positive data is not possible). The scale function was used for all the continuous explanatory variables (environmental variables, and vegetation variables). The scale function centres each continuous explanatory variable around 0, the mean is transformed to 0 and values are represented as standard deviations from the mean. This standardises the data, which is useful when many different scales or units are used and can improve the fit of the model.

All two-way interactions between vegetation and environmental variables were incorporated (i.e. Calluna*Tcham, Calluna*Tsoil, Calluna*WTD, Calluna*pH; the same for each vegetation group), two-way interactions between environmental variables (i.e. Tsoil, Tcham, pH, and WTD), and interactions between management and environmental variables. Two-way interactions between management and vegetation were not included, *as the vegetation was typically heavily driven by management – which might confound the interaction term in the model* (i.e. DN tends to be *Calluna* dominant, LB tends to be sedge dominant). This led to a large model, which was simplified by removing least-significant terms, checking model assumptions and indices of model fit such as AIC and deviance throughout. The random effects used were site and year, plot was initially included, but then omitted, as it led to an over-fitted model with convergence problems.

The final statistical model, following simplification was:

MethaneFlux + 0.451 ~Mgmt + scale(Calluna)*scale(WTD) + scale(Calluna)*scale(flow.pH) + scale(Sedge)*scale(WTD) + cale(Sedge)*scale(flow.pH) + scale(Sphagnum) + scale(Moss)*scale(Tsoil) + scale(Moss)*scale(WTD) + scale(Brash) + Mgmt*scale(WTD) + Mgmt*scale(flow.pH) + Mgmt*scale(Tsoil) + (1|Site) + (1|Year)

Table A16.5 Output of mixed-effect model comparing burnt (FI), mown without (LB) or with brash removal (BR) to uncut (DN) for all years post 2015 (vegetated plots) and listing the significant model terms.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	4.641	0.503	9.220	< 2e-16 ***	
FI	-2.431	0.202	-12.038	< 2e-16 ***	
LB	-2.005	0.201	-9.983	< 2e-16 ***	
BR	-1.758	0.176	-9.964	< 2e-16 ***	
sc(Calluna)	-1.379	0.241	-5.732	9.94e-09 ***	
sc(Sedge)	-0.705	0.226	-3.122	0.00180 **	
sc(Sphagnum)	-0.404	0.088	-4.580	4.65e-06 ***	
sc(Moss)	-0.436	0.129	-3.374	0.000740 ***	
sc(Brash)	-0.398	0.067	-5.939	2.87e-09 ***	
sc(Tsoil)	-0.038	0.147	-0.255	0.799	
sc(WTD)	**0.315**	**0.158**	**1.991**	**0.0464 ***	
sc(pH)	**0.423**	**0.136**	**3.120**	**0.00181 ****	
sc(Calluna) : sc(WTD)	**0.711**	**0.208**	**3.425**	**0.000616 *****	
sc(Calluna) : sc(pH)	**-0.302**	**0.095**	**-3.185**	**0.00145 ****	
sc(Sedge) : sc(WTD)	**0.583**	**0.202**	**2.888**	**0.00388 ****	
sc(Sedge) : sc(pH)	**-0.241**	**0.096**	**-2.514**	**0.0120 ***	
sc(Moss) : sc(Tsoil)	0.130	0.053	2.432	0.0150 *	
sc(Moss) : sc(WTD)	**0.421**	**0.127**	**3.309**	**0.000938 *****	
FI : sc(Tsoil)	-0.221	0.203	-1.086	0.278	
LB : sc(Tsoil)	0.216	0.187	1.156	0.258	
BR : sc(Tsoil)	**0.389**	**0.175**	**2.221**	**0.0263 ***	
FI : sc(WTD)	**-0.501**	**0.190**	**-2.643**	**0.00821 ****	
LB : sc(WTD)	0.004	0.199	0.019	0.984	
BR : sc(WTD)	-0.071	0.193	-0.366	0.714	
FI : sc(pH)	**-0.724**	**0.263**	**-2.757**	**0.00584 ****	
LB : sc(pH)	**-0.564**	**0.183**	**-3.082**	**0.00206 ****	
BR : sc(pH)	-0.299	0.166	-1.806	0.0709 .	

Independent Mgmt effects are at continuous = 0, all continuous variables are scaled – so effectively Mgmt effect is at mean values of other variables.

Interactions:

- The **significant effect of pH indicates that methane flux increased in DN plots with higher pH**. The interactions of managements with pH indicate the following,
    - there was no significant difference between BR and DN for the methane flux pH response
    - The **response of methane flux to pH in FI and LB plots was significantly less than in DN plots**.
- **Methane flux increased with higher WTD** (more saturated ground in DN plots.
    - the increase in methane fluxes with wetter ground on FI plots was statistically less than DN.
- With **higher soil temps**, the methane flux from **BR** plots increases (less brash layer on BR to allow methane oxidation), no effect for other managements
- **Calluna & Sedge** – higher flux with **wetter** and **more acidic** conditions
- **Moss** – higher flux with wetter warmer conditions

High methane with vegetation (during methane peak years 2014-17)

Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod']

Family: Gamma (log)

Formula: Formula: MethaneFlux + 0.001 ~ scale(Calluna) * scale(WTD) + scale(Sphagnum) * scale(WTD)
+ scale(WTD) * scale(Tcham) + scale(Brash) + (1 | Site)
Control: glmerControl (optimizer = "Nelder_Mead") Family: Gamma (log)
Data: subset(Methane_annualmedian_2014_17, Flux >=0)

Control: glmerControl(optimizer = "Nelder_Mead")

Table A16.6 Output of mixed-effect model comparing the high methane flux period (2014-2017) for overall vegetation cover and listing the significant model terms.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	**4.186**	**0.358**	**11.705**	**< 2e-16 *****	**3.485 – 4.887**
sc(Calluna)	**0.175**	**0.110**	**1.592**	**0.111**	**-0.040 – 0.390**
sc(Sphagnum)	**-0.216**	**0.084**	**-2.562**	**0.0104 ***	**-0.381 – -0.051**
sc(Brash)	**-0.382**	**0.084**	**-4.577**	**4.73e-06 *****	**-0.546 – -0.219**
sc(WTD)	**0.465**	**0.128**	**3.629**	**0.000285 *****	**0.214 – 0.716**
sc(Tcham)	**0.705**	**0.131**	**5.371**	**7.85e-08 *****	**0.448 – 0.962**
sc(Calluna) : sc(WTD)	**0.236**	**0.104**	**2.280**	**0.0226 ***	**0.033 – 0.439**
sc(Sphag.) : sc(WTD)	**-0.256**	**0.122**	**-2.094**	**0.0363 ***	**-0.496 – -0.016**
sc(WTD) : sc(Tcham)	**0.354**	**0.145**	**2.436**	**0.0148 ***	**0.069 – 0.639**

- ➔ **Significantly higher fluxes with wetter ground (higher WTD) and higher chamber temperatures** (also with Tsoil, not shown here: Est: 0.311 SE: 0.120 t val: 2.582; P val: 0.00981**; CI: 0.075 – 0.546)
- ➔ The interaction of WTD and Tcham was additive, so **wet and warm soils lead to high methane fluxes**
- ➔ Significant interaction for *Calluna* and WTD indicates that **wet ground with high Calluna abundance has high methane flux** (possibly relating to high C input from large heather root biomass)
- ➔ **Lower fluxes with higher cover of *Sphagnum* and Brash** (oxidation layer effect). The interaction of *Sphagnum* and WTD suggests that ***Sphagnum* could help to lower methane fluxes in wet conditions**, compared with other vegetation groups.

No significant pH effect. For a model with only the independent variables, **methane fluxes are higher with lower sedge, brash, *Sphagnum* cover and with higher soil temperatures**.

INDIVIDUAL SITES (considering separate management)

Nidderdale

Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod']

Family: Gamma (log)

Formula: MethaneFlux + 0.351 ~ scale(Calluna) * scale(WTD) + scale(Sedge) * scale(WTD) + scale(Sphagnum) * scale(WTD) + scale(Moss) * scale(WTD) + scale(Brash) + Mgmt * scale(WTD) + (1 | Year)

Control: glmerControl(optimizer = "Nelder_Mead")

Table A16.7 Output of mixed-effect model for Nidderdale comparing burnt (FI), mown without (LB) or with brash removal (BR) to uncut and listing the significant model terms.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	3.101	0.160	19.386	< 2e-16 ***	3.103 – 5.478
FI	-1.052	0.145	-7.242	4.43e-13 ***	-2.189 – -0.755
LB	-0.788	0.143	-5.517	3.45e-08 ***	-1.837 – -0.512
BR	-0.906	0.135	-6.725	1.76e-11 ***	-1.510 – -0.245
sc(Calluna)	-1.053	0.128	-8.202	2.37e-16 ***	
sc(Sedge)	-0.347	0.121	-2.870	0.00410 **	
sc(Sphagnum)	-0.320	0.093	-3.440	0.000581 ***	
sc(Moss)	-0.702	0.115	-6.108	1.01e-09 ***	
sc(Brash)	-0.386	0.082	-4.692	2.71e-06 ***	
sc(WTD)	**0.580**	**0.114**	**5.111**	**3.21e-07 *****	0.0013 – 0.0569
sc(Calluna) : sc(WTD)	**1.595**	**0.118**	**13.470**	**< 2e-16 *****	
sc(Sedge) : sc(WTD)	**1.097**	**0.113**	**9.706**	**< 2e-16 ****	
sc(Sphag) : sc(WTD)	0.277	0.129	2.154	0.0312 *	-0.0183 – 0.0003
sc(Moss) : sc(WTD)	**0.719**	**0.104**	**6.918**	**4.59e-12 *****	
FI : sc(WTD)	**-0.410**	**0.142**	**-2.876**	**0.00403 ****	
LB : sc(WTD)	0.122	0.146	0.838	0.402	
BR : sc(WTD)	**-0.547**	**0.135**	**-4.063**	**4.84e-05 *****	

- ➔ **Emissions were lower with all vegetation type cover but especially for *Calluna* and moss.**
- ➔ **Wetter conditions increased emissions** (on DN plots), especially together with **Calluna, sedge and other moss** but less so with **Sphagnum moss**
- ➔ Emissions on **wetter BR and on FI plots increased less than DN plots.**
- ➔ No pH effect.

Mossdale

Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod']

Family: Gamma (log)

Formula: MethaneFlux + 0.001 ~ +scale(Sedge) * scale(flow.pH) + scale(Sedge) * scale(Tsoil) + scale(Brash) * scale(WTD) + Mgmt * scale(flow.pH) + Mgmt * scale(WTD) + (1 | Year)

Control: glmerControl(optimizer = "Nelder_Mead")

Table A16.8 Output of mixed-effect model for Mossdale comparing burnt (FI), mown without (LB) or with brash removal (BR) to uncut and listing the significant model terms.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	6.302	0.502	12.582	< 2e-16 ***	3.103 – 5.478
FI	-3.604	0.374	-9.633	< 2e-16 ***	-2.189 – -0.755
LB	-3.676	0.354	-10.377	< 2e-16 ***	-1.837 – -0.512
BR	-2.812	0.329	-8.556	< 2e-16 ***	-1.510 – -0.245
sc(Sedge)	**0.626**	**0.123**	**5.111**	**3.20e-07 *** **	
sc(Brash)	0.003	0.106	0.031	0.975	
sc(Tsoil)	0.388	0.161	2.411	0.0159 *	
sc(WTD)	**1.459**	**0.344**	**4.238**	**2.25e-05 *** **	
sc(flow pH)	**0.979**	**0.370**	**2.649**	**0.00807 *** **	
sc(Sedge) : sc(Tsoil)	**-0.401**	**0.114**	**-3.513**	**0.000443 ** **	
sc(Sedge) : sc(pH)	**0.253**	**0.108**	**2.347**	**0.0189 * **	-0.0183 – 0.0003
sc(Brash) : sc(WTD)	**0.427**	**0.154**	**2.777**	**0.00549 *** **	
FI : sc(WTD)	-0.537	0.391	-1.374	0.170	
LB : sc(WTD)	**-1.031**	**0.369**	**-2.792**	**0.00525 ** **	
BR : sc(WTD)	**-1.228**	**0.349**	**-3.521**	**0.000430 *** **	
FI : sc(pH)	**-1.042**	**0.436**	**-2.392**	**0.0167 ** **	
LB : sc(pH)	**-1.477**	**0.324**	**-4.555**	**5.24e-06 *** **	
BR : sc(pH)	**-1.422**	**0.299**	**-4.748**	**2.05e-06 *** **	

- Overall strong **positive sedge and wtd impacts on methane** (on DN)

- **Sedge impact reduced under warmer Tsoil and increased under higher wtd** (correlating with less surface methane oxidation) and lower pH (oxidation at depth via SO_4)

- **Brash layer increased methane emissions under wetter conditions** (maybe due to more substrate)

- **Increased emissions under higher wtd on LB and BR plots were less than on DN plots**

- **Strong pH effect** (at the wettest site) **increasing emissions on DN** but less so on all alternative managed plots; the estimate of the interactions of management with pH have a greater magnitude than the effect of pH on DN (1.042, 1.477, 1.422, compared with 0.979), so methane flux slightly decrease with rising pH for the three alternative managements, whereas it increases with pH for DN managements.

Whitendale

Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) ['glmerMod']

Family: Gamma (log)

Formula: MethaneFlux + 0.451 ~ scale(Calluna) + scale(Sphagnum) + scale(Brash) + scale(Tsoil) * scale(flow.pH) + Mgmt * scale(flow.pH) + (1 | Plot) + (1 | Year)

Control: glmerControl(optimizer = "Nelder_Mead")

Table A16.9 Output of mixed-effect model for Whitendale comparing burnt (FI), mown without (LB) or with brash removal (BR) to uncut and listing the significant model terms.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	2.512	0.510	4.924	8.47e-07 ***	3.103 – 5.478
FI	-0.752	0.487	-1.544	0.123	-2.189 – -0.755
LB	-0.258	0.427	-0.603	0.547	-1.837 – -0.512
BR	-0.082	0.412	-0.198	0.843	-1.510 – -0.245
sc(Calluna)	**-0.321**	**0.119**	**-2.693**	**0.00708 ****	
sc(Sphagnum)	**-0.210**	**0.078**	**-2.697**	**0.00701 ****	
sc(Brash)	**-0.238**	**0.078**	**-3.048**	**0.00231 ****	
sc(Tsoil)	-0.157	0.151	-1.040	0.298	
sc(flow pH)	0.472	0.259	1.827	0.0672 .	
sc(Tsoil) : sc(pH)	**-0.397**	**0.183**	**-2.168**	**0.302 ***	
FI : sc(pH)	-0.682	0.379	-1.802	0.0715 .	
LB : sc(pH)	**-0.492**	**0.178**	**-2.768**	**0.00564 ****	
BR : sc(pH)	-0.024	0.175	-0.138	0.891	

➔ ***Calluna*, *Sphagnum* and brash cover all reduce methane emissions on DN plots**

➔ **Higher pH increased emissions on DN plots** (marginally significant)

➔ **Higher Tsoil reduces the positive pH effect on methane emissions on DN plots**

➔ **The positive pH effect on methane emissions was less on LB** (compared to DN plots)

➔ **The positive pH effect on methane emissions was (**marginally significant) **less on FI** (compared to DN)

INDIVIDUAL SITES (without considering management)

The above analysis was redone but separating each into ***a vegetation:environmental interaction analysis*** *irrespective of management and* ***a management:environmental interaction analysis****. Because the vegetation groups were often intrinsically linked with management. the other analyses for individual sites could have been over-fitted, which could lead to some less robust output.*

Nidderdale

Formula: MethFlux + 0.351 ~ scale(Calluna) * scale(WTD) + scale(Sedge) * scale(WTD) + scale(Moss) * scale(WTD) + scale(Sphagnum) * scale(WTD) + scale(Tsoil) + (1 | Year)

Table A16.7a Output of mixed-effect model for Nidderdale comparing vegetation:environmental analysis for methane emissions (all managements combined) and listing the significant model terms.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	2.421	0.322	7.509	5.97e-14 ***	1.789 – 3.053
sc(Calluna)	-0.323	0.302	-1.071	0.284	-0.914 – 0.268
sc(Sedge)	0.171	0.269	0.638	0.524	-0.355 – 0.698
sc(Moss)	-0.365	0.211	-1.728	0.0839 .	-0.779 – 0.049
sc(Sphagnum)	-0.127	0.141	-0.901	0.368	-0.404 – 0.150
sc(WTD)	**0.378**	**0.127**	**2.969**	**0.00299 ****	**0.129 – 0.628**
sc(Tsoil)	**-0.374**	**0.125**	**-3.002**	**0.00268 ****	**-0.618 – -0.130**
sc(Calluna) : sc(WTD)	**1.908**	**0.330**	**5.781**	**7.43e-09 *****	**1.261 – 2.555**
sc(Sedge) : sc(WTD)	**1.465**	**0.302**	**4.849**	**1.24e-06 *****	**0.873 – 2.058**
sc(Moss) : sc(WTD)	**0.882**	**0.227**	**3.879**	**0.000105 *****	**0.436 – 1.328**
sc(Sphag.) : sc(WTD)	**0.481**	**0.184**	**2.609**	**0.00907 ****	**0.120 – 0.842**

- Methane fluxes highest with wet ground (high WTD), additive interaction for *Calluna*, Sedge, Moss, and *Sphagnum* with WTD – high abundances of these vegetation groups in wet ground was associated with higher methane fluxes.
- High soil temperatures had a negative effect on methane fluxes, conversely to Mossdale.

Formula: MethFlux + 0.351 ~ Mgmt * scale(WTD) + scale(Tsoil) + (1 | Year)

Table A16.7b Output of mixed-effect model for Nidderdale comparing management:environmental analysis for methane emissions (all managements combined) and listing the significant model terms.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	2.655	0.352	7.544	4.55e-14 ***	1.965 – 3.347
FI	**-0.788**	**0.324**	**-2.431**	**0.0150 ***	**-1.424 – -0.153**
LB	0.249	0.282	0.880	0.379	-0.305 – 0.802
BR	-0.521	0.281	-1.854	0.0638 .	-1.071 – 0.030
sc(WTD)	**0.978**	**0.241**	**4.056**	**4.98e-05 *****	**0.506 – 1.451**
sc(Tsoil)	**-0.428**	**0.142**	**-3.024**	**0.00250 ****	**-0.706 – -0.151**
FI : sc(WTD)	**-0.997**	**0.322**	**-3.092**	**0.00199 ****	**-1.629 – -0.365**
LB : sc(WTD)	**-0.788**	**0.261**	**-3.019**	**0.00253 ****	**-1.299 – -0.276**
BR : sc(WTD)	**-0.923**	**0.301**	**-3.063**	**0.00219 ****	**-1.514 – -0.333**

- Wet ground in DN plots led to high methane flux.
- The negative management interaction with WTD indicates that a different relationship for methane flux with WTD for the other managements. The change in methane flux across the WTD gradient is significantly lower for these three managements compared to DN.
- Soil temperature had a negative effect on methane flux, and there was no management interaction for soil temperature – all management responded similarly across the soil temperature gradient
- Methane fluxes from FI plots were generally lower than from DN plots. Methane fluxes from LB and BR plots were significantly lower than from DN plots only under wetter soils.

Mossdale

Formula: MethFlux + 0.001 ~ scale(Calluna) + scale(Sedge) + scale(Moss) + scale(WTD) * scale(Tsoil) + (1 | Year)

Table A16.8a Output of mixed-effect model for Mossdale comparing vegetation:environmental analysis for methane emissions (all managements combined) and listing the significant model terms.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	4.219	0.371	11.362	<2e-16 ***	3.491 – 4.946
sc(Calluna)	**1.614**	**0.279**	**5.792**	**6.96e-09 *****	**1.068 – 2.160**
sc(Sedge)	**1.156**	**0.278**	**4.163**	**3.14e-05 *****	**0.612 – 1.700**
sc(Moss)	**0.939**	**0.224**	**4.193**	**2.75e-05 *****	**0.500 – 1.378**
sc(WTD)	0.320	0.224	1.425	0.154	-0.120 – 0.759
sc(Tsoil)	**0.445**	**0.223**	**1.999**	**0.0456 ***	**0.009 – 0.881**
sc(WTD) : sc(Tsoil)	**0.406**	**0.187**	**2.174**	**0.0297 ***	**0.040 – 0.773**

- Methane fluxes were increased with *Calluna*, sedge, and moss abundances
- Warmer soil temperatures were associated with higher methane fluxes. The additive WTD : Tsoil interaction shows that methane fluxes were higher still in warm, wet soils.
- WTD as an independent factor was non-significant, it only increased fluxes when soils were relatively warm.

Formula: MethFlux + 0.001 ~ Mgmt * scale(WTD) + Mgmt * scale(flow.pH) + Mgmt * scale(Tsoil) + (1 | Year)

Table A16.8b Output of mixed-effect model for Mossdale comparing management:environmental analysis for methane emissions (all managements combined) and listing the significant model terms.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	5.699	0.455	12.519	<2e-16 ***	4.806 – 6.591
FI	**-2.620**	**0.385**	**-6.804**	**1.02e-11 *****	**-3.374 – -1.865**
LB	**-2.566**	**0.315**	**-8.136**	**4.08e-16 *****	**-3.184 – -1.948**
BR	**-2.061**	**0.338**	**-6.097**	**1.08e-09 *****	**-2.724 – -1.399**
sc(WTD)	**1.158**	**0.425**	**2.725**	**0.00644 ****	**0.325 – 1.990**
sc(flow.pH)	**0.899**	**0.393**	**2.291**	**0.0220 ***	**0.130 – 1.669**
sc(Tsoil)	**0.683**	**0.285**	**2.400**	**0.0164 ***	**0.125 – 1.241**
FI : sc(WTD)	-0.847	0.494	-1.715	0.0864 .	-1.814 – 0.121
LB : sc(WTD)	**-1.133**	**0.459**	**-2.468**	**0.0136 ***	**-2.033 – -0.233**
BR : sc(WTD)	**-0.983**	**0.473**	**-2.078**	**0.0377 ***	**-1.910 – -0.056**
FI : sc(pH)	-0.637	0.444	-1.432	0.152	-1.508 – 0.234
LB : sc(pH)	**-1.011**	**0.325**	**-3.112**	**0.00186 ****	**-1.648 – -0.374**
BR : sc(pH)	**-1.113**	**0.314**	**-3.540**	**0.00040 *****	**-1.729 – -0.497**
FI : sc(Tsoil)	**-0.920**	**0.406**	**-2.265**	**0.0235 ***	**-1.717 – -0.124**
LB : sc(Tsoil)	**-0.758**	**0.372**	**-2.037**	**0.0416 ***	**-1.487 – -0.029**
BR : sc(Tsoil)	-0.148	0.379	-0.390	0.697	-0.891 – 0.596

- Methane fluxes were overall lower in FI, LB, BR plots
- In DN plots, fluxes increased with wetter ground, higher pH, and warmer soils, independently
- The increase in methane flux with progressively wetter ground was significantly lower for LB and BR managed plots than for DN plots. The difference between FI and DN was close to significance.
- The increase in methane flux with higher flow pH was significantly lower for LB and BR managed plots than for DN plots.
- The increase in methane flux with warmer soil temperatures was significantly lower for FI and LB managed plots than for DN plots.

Whitendale

Formula: MethaneFlux + 0.451 ~ scale(Calluna) + scale(Sedge) + scale(WTD) * scale(flow.pH) + (1 | Year)

Table A16.9a Output of mixed-effect model for Whitendale comparing vegetation:environmental analysis for methane emissions (all managements combined) and listing the significant model terms.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	2.493	0.362	6.892	5.5e-12 ***	1.784 – 3.201
sc(Calluna)	**-0.214**	**0.106**	**-2.015**	**0.0439 ***	**-0.421 – -0.006**
sc(Sedge)	**0.223**	**0.107**	**2.081**	**0.0374 ***	**0.013 – 0.433**
sc(WTD)	**0.236**	**0.119**	**1.974**	**0.0484 ***	**0.002 – 0.470**
sc(flow.pH)	0.180	0.148	1.214	0.225	-0.111 – 0.471
sc(WTD) : sc(pH)	**0.256**	**0.086**	**2.997**	**0.00273 ****	**0.089 – 0.424**

- Methane fluxes increased with sedge abundance, and decreased with *Calluna* abundance.
- Methane fluxes were higher from wet ground.
- The additive interaction for WTD and pH indicate that methane fluxes were higher still when wet ground had a higher pH.

Formula: MethaneFlux + 0.451 ~ scale(WTD) + Mgmt * scale(flow.pH) + Mgmt * scale(Tcham) + (1 | Year)

Table A16.9b Output of mixed-effect model for Whitendale comparing management:environmental analysis for methane emissions (all managements combined) and listing the significant model terms.

Term	Estimate	Std. Err	t value	P value signif	95% Conf.Int
Intercept	2.629	0.457	5.756	8.61e-09 ***	1.734 – 3.525
FI	-0.167	0.300	-0.557	0.577	-0.756 – 0.421
LB	0.116	0.211	0.548	0.584	-0.298 – 0.530
BR	0.268	0.211	1.270	0.204	-0.145 – 0.681
sc(WTD)	0.052	0.130	0.397	0.691	-0.203 – 0.306
sc(flow.pH)	0.046	0.289	0.159	0.874	-0.520 – 0.611
sc(Tcham)	0.322	0.277	1.164	0.245	-0.220 – 0.864
FI : sc(pH)	-0.633	0.401	-1.579	0.114	-1.418 – 0.153
LB : sc(pH)	**-0.574**	**0.235**	**-2.445**	**0.0145 ***	**-1.033 – -0.114**
BR : sc(pH)	-0.157	0.230	-0.683	0.495	-0.607 – 0.293
FI : sc(Tcham)	**0.973**	**0.398**	**2.447**	**0.0144 ***	**0.194 – 1.753**
LB : sc(Tcham)	-0.314	0.226	-1.394	0.163	-0.757 – 0.128
BR : sc(Tcham)	-0.220	0.229	-0.960	0.337	-0.668 – 0.229

- The only significant terms were a negative interaction for LB:pH and a positive interaction for FI:Tcham.
- With higher flow pH, methane fluxes were lower from LB managed plots than from DN managed plots
- With warmer chamber temperatures, methane fluxes were higher from FI managed plots than from DN managed plots.

Comparing methane flux from soil plots versus vegetated plots

A mixed effect model shows a **statistically significant difference between the two measurements (vegetated vs soil only/cut vegetation)**. Flow pH, chamber temperature, soil temperature, and WTD were included as co-variates, with plot nested in site as a random factor. **Only DN plots were analysed (comparing pre March 2015 'soil only' with post March 2015 'vegetated')**, *so the vegetation was consistent and unaffected by management (but the graph clearly shows the same applies to the other treatments post-management – see next section)*.

Notwithstanding climatic differences and other changes (e.g. pH), the output shows that measurements over **vegetation increased methane flux** recordings **by 345.47 ± 148.16 compared to over soil**. This was confirmed by post-hoc contrast test (p=0.0210).

Table A16.10 Output of mixed-effect model for all sites combined for uncut (DN) plots (which had a comparison of vegetated vs. soil only/cut vegetation) and listing the significant model terms.

Term	**Estimate**	**Std. Err**	**t value**	**P value signif**	**95% Conf.Int**
Intercept	917.75	769.893	1.192	0.235	-611.48 – 2381.14
Vegetation	**345.47**	**148.158**	**2.332**	**0.0202 ***	51.18 – 630.94
Flow pH	-231.54	184.126	-1.257	0.209	-582.33 – 139.72
Tcham	11.21	13.260	0.845	0.399	-15.01 – 36.83
Tsoil	-8.21	23.809	-0.345	0.731	-54.00 – 39.13
WTD	7.41	6.164	1.201	0.231	-4.44 – 19.75

A similar mixed effect model analysis, but with all managements included (the full dataset comparing pre March 2015 'soil only' with post March 2015 'vegetated'), also showed that measuring fluxes over vegetation rather than soil increased flux recordings. The output shows that measurements over **vegetation increased methane flux** recordings **by 80.76 ± 26.93 compared to over soil**. This was confirmed by a post-hoc contrast test (p=0.0028).

Table A16.11 Output of mixed-effect model for all sites combined for all plots (which had a comparison of vegetated vs. soil only/cut vegetation) and listing the significant model terms.

Term	**Estimate**	**Std. Err**	**t value**	**P value signif**	**95% Conf.Int**
Intercept	168.06	142.094	1.183	0.239	-109.36 – 439.35
Vegetation	**80.76**	**26.932**	**2.999**	**0.00273 ****	27.61 – 133.13
Flow pH	-42.55	33.150	-1.284	0.199	-106.42 – 23.66
Tcham	2.45	2.402	1.020	0.308	-2.26 – 7.15
Tsoil	0.74	4.313	0.171	0.864	-7.63 – 9.28
WTD	1.91	1.101	1.731	0.0835 .	-0.21 – 4.12

Methane emissions in the Light vs DARK (2021; measured in March, April, June, July and September)

Methane fluxes were higher in the light (~82% when in the dark) across all three sites (Repeated Measures ANOVA ***) during June/July and September (but not in March or April and only when excluding the DN plots).

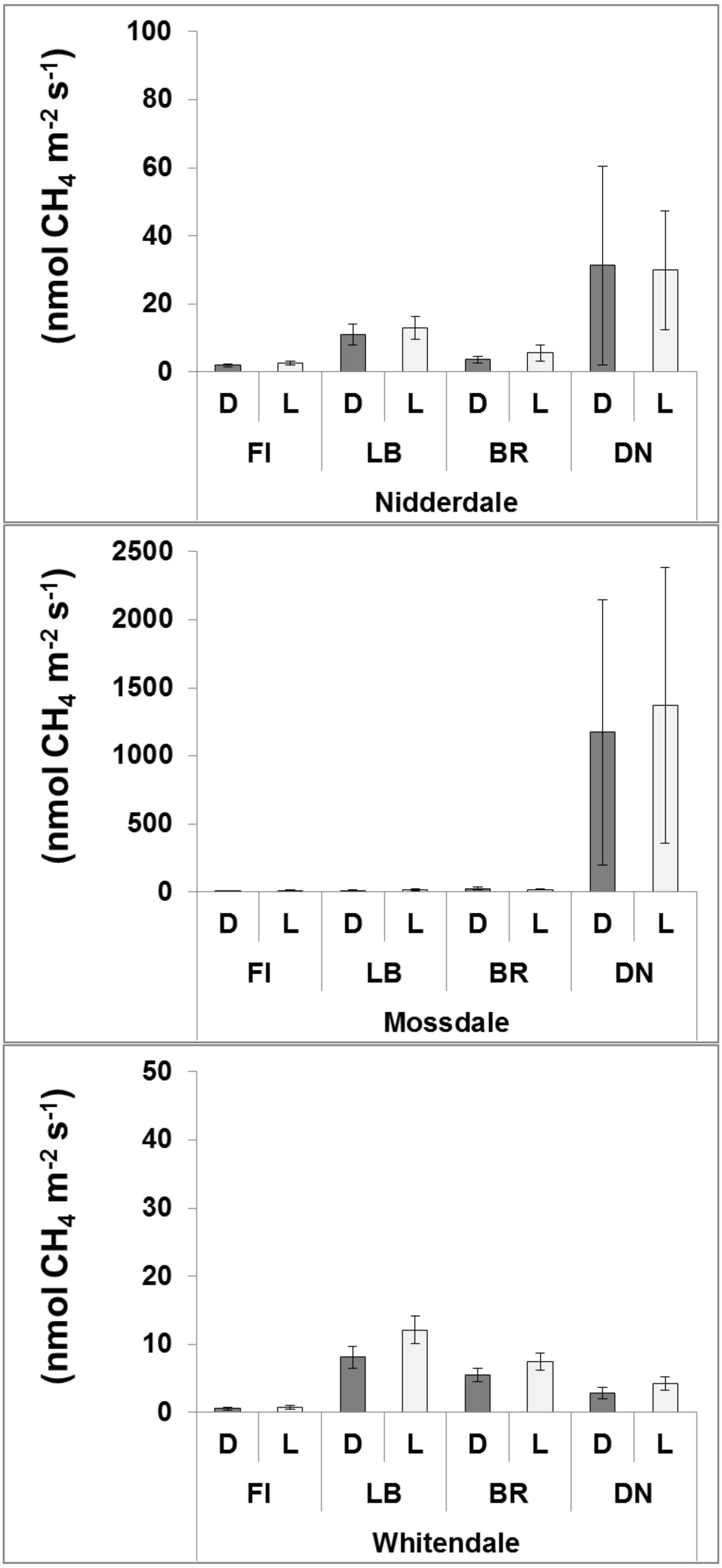


Figure A16.4 Mean methane emissions for the three sites (Nidderdale, Mossdale, Whitendale) durin 2021 (measuring fluxes in the light [L] and subsequently in the dark [D]) and the individual managements (FI=burnt[fire]; LB=mown with brash; BR=mown with brash removal; DN=uncut[do nothing]).

A correlation analysis shown in **Table A16.12** below revealed that overall there was a significant negative effect by (arcsine transformed) *Calluna* and positive effect by sedge and brash cover (when excluding DN plots) on methane emissions in 2021.

Correlations

	Methane	ArcsineCall	**ArcsineSedge**	ArcsineMoss	ArcsineSph	ArcsineBrash
Pearson Correlation	1	**-.257****	**.243****	0.005	-0.028	**.145****
Sig. (2-tailed)		**0.000**	**0.000**	0.911	0.541	**0.001**
N	480	480	480	480	480	480

A subsequent correlation analysis of the difference (of Light – Dark) methane fluxes shown in **Table A16.13** below revealed that overall there was a significant negative effect by (arcsine transformed) *Calluna* and positive effect by sedge cover (when excluding DN plots) on methane emissions in July and September 2021.

Correlations

		DIFF1	DIFF2	DIFF3	DIFF4	ArcsinCall	ArcsinSedge
DIFF1 (March)	**Pearson Correlation**	1	0.010	0.135	0.248	-0.194	0.244
	Sig. (2-tailed)		0.941	0.303	0.056	0.138	0.060
	N	60	60	60	60	60	60
DIFF2 (April)	Pearson Correlation	0.010	1	0.033	0.112	-0.152	0.187
	Sig. (2-tailed)	0.941		0.802	0.394	0.245	0.153
	N	60	60	60	60	60	60
DIFF3 (June./July)	**Pearson Correlation**	0.135	0.033	1	0.241	**-.429****	**.447****
	Sig. (2-tailed)	0.303	0.802		0.064	**0.001**	**0.000**
	N	60	60	60	60	60	60
DIFF4 (September)	**Pearson Correlation**	0.248	0.112	0.241	1	**-.498****	**.508****
	Sig. (2-tailed)	0.056	0.394	0.064		**0.000**	**0.000**
	N	60	60	60	60	60	60

A more in-depth analysis with a longer data set is needed to evaluate a possible generic light/dark response of methane emissions. So far only one year (2021) was available.

Appendix 17 (carbon balance)

The following **Figure A17.1** shows the cumulative NEE C-balance over the 10 year study period (2012-2021). Statistical tests were only performed on the actual NEE (and Reco) fluxes as NEE fluxes of the four replicates per management were combined for the light and temperature response modelling as outlined in **Appendix 15**.

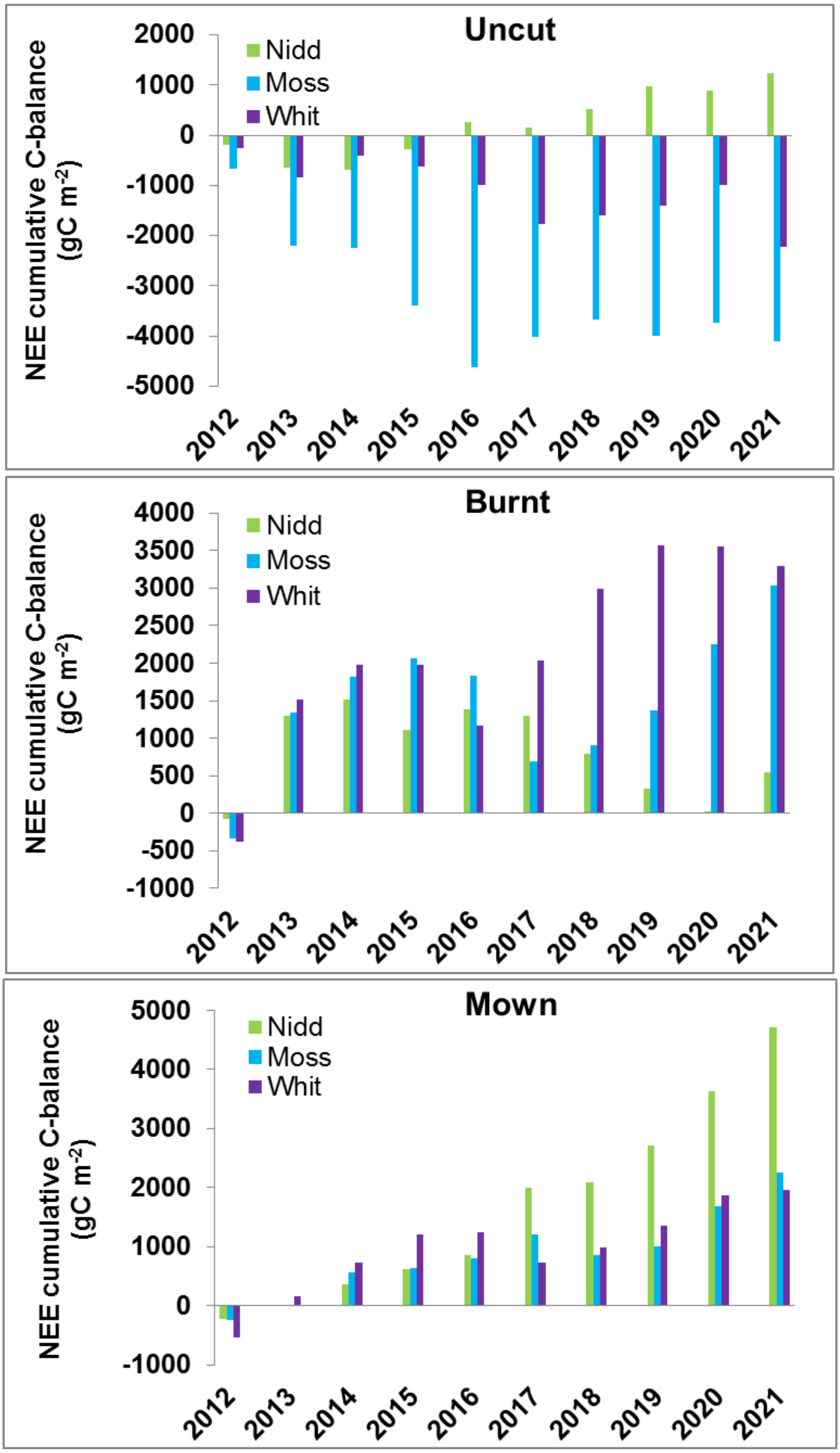


Figure A17.1 Cumulative NEE C-balance (negative = C sink). Note the impact of heather beetle outbreaks from 2016/17 onwards (especially at Mossdale and Whitendale on burnt plots and at Nidderdale on mown plots).

Whilst the NEE C-balance only included the chamber CO_2 fluxes, the additional inclusion of C fluxes as methane and in stream flow as dissolved and particulate organic carbon (DOC & POC) allowed estimating Net Ecosystem Carbon Balance (NECB). However, NEE and NECB balance were only considered further (e.g. in relation to water table depths; wtd) for uncut plots as so far calculations for either management would not reflect a complete management cycle, thus representing a meaningless comparison.

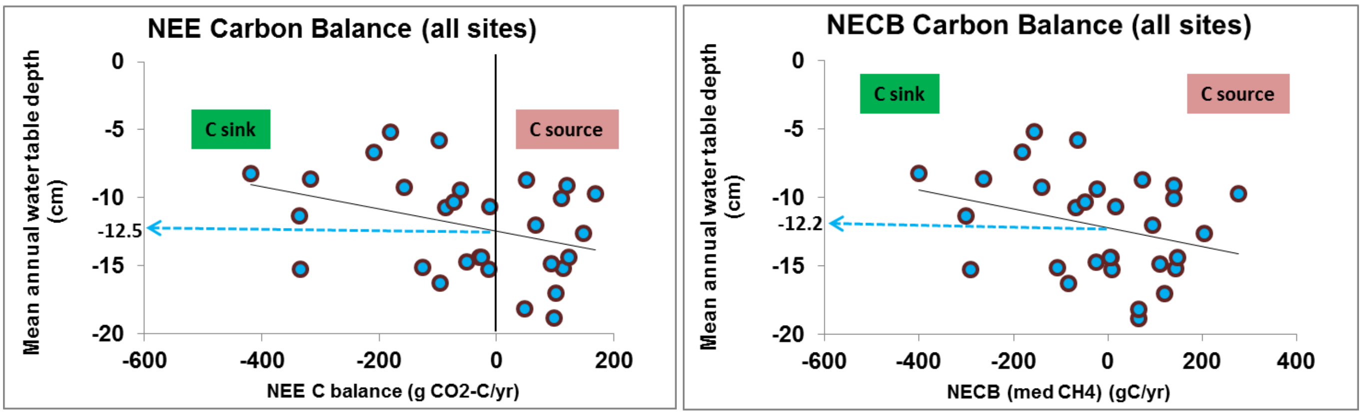


Figure A17.2 Mean annual water table depth (wtd) versus (left) NEE C-balance and (right) NECB C-balance. Indicated (arrows) are the wtd thresholds of C sink vs. C source based on linear regressions.

Whilst the above NEE and NECB estimates were clearly related to annual water table depths (**Figure A17.2**), the wtd threshold between C sink vs. C source was around 12.5-12.2 cm, respectively, which is strikingly similar to estimates reported by Evans et al. 2021. However, it is clear that both C balances are affected by the previous year's hydrology, especially considering early season fluxes but also annually following drought years. Moreover, the overall variance in water table depth (a higher value indicating a generally larger proportion of lower water table depths supporting more C loss from decomposition) is likely also of importance determining the C sink/source threshold. Therefore, NEE and NECB estimates were also compared to biennial water table depth and the variance (**Figure A17.3**). This showed a similar albeit slightly lower water table depths threshold for NEE and NECB of around 12.1-11.9 cm, respectively, and a clear positive relationship with water table depths variance (i.e. larger variance = more positive C balance [shifting from C sink but C source].

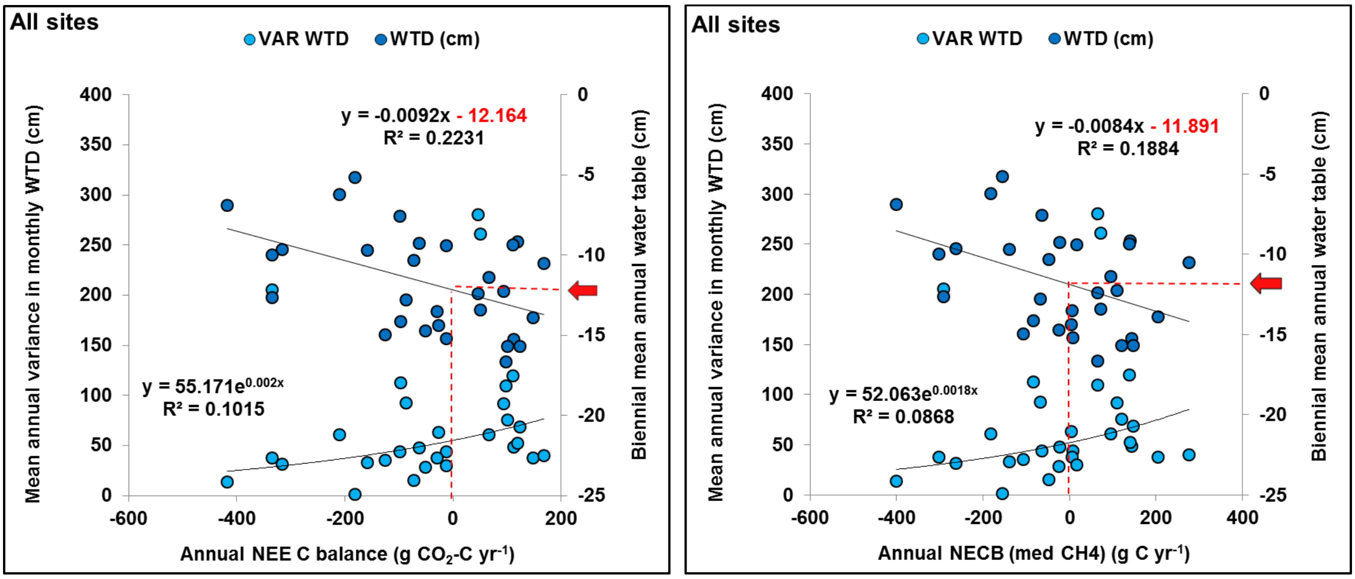


Figure A17.3 Mean biennial water table depth (wtd) and mean annual variance in wtd versus (left) NEE C-balance and (right) NECB C-balance (based on median methane emissions). Indicated (arrows) are the wtd thresholds of C sink vs. C source based on linear regressions together with exponential regressions for wtd variance.

Whilst water tables are of key importance in explaining a peatland's C balance, other factors are also important. For example, both temperature and light regulate aspects of C input (photosynthesis) and outputs (decomposition). However, both parameters do not show a strong overall relationship with C balance as shown for NEE (**Figure A17.4**), with the response to light measured as photosynthetic active radiation (PAR) being especially weak. A possible explanation might be that these UK blanket bog sites might be associated with a climatic range of relatively little response to changes in PAR. However, this does not mean that a shift outside this 'envelope' is not of potential crucial relevance, especially when this can mean crossing thresholds of sustainable peatland growth (Gallego-Sala et al., 2012); notably, temperature and light correlate and affect the water balance of peatlands by driving evapotranspiration and thus water loss to the atmosphere. Interestingly, the below PAR range (**Figure A17.4**) overlaps with the upper range of those data shown in Gallego-Sala et al. (2018), indicating that the three sites are at the potential upper (climatic/latitudinal) global maximum of the C balance for bogs in relation to annual PAR sums of around 7,000 mol m^{-2} (*cf*. blue bog line in Fig. 2a in Gallego-Sala et al., 2018).

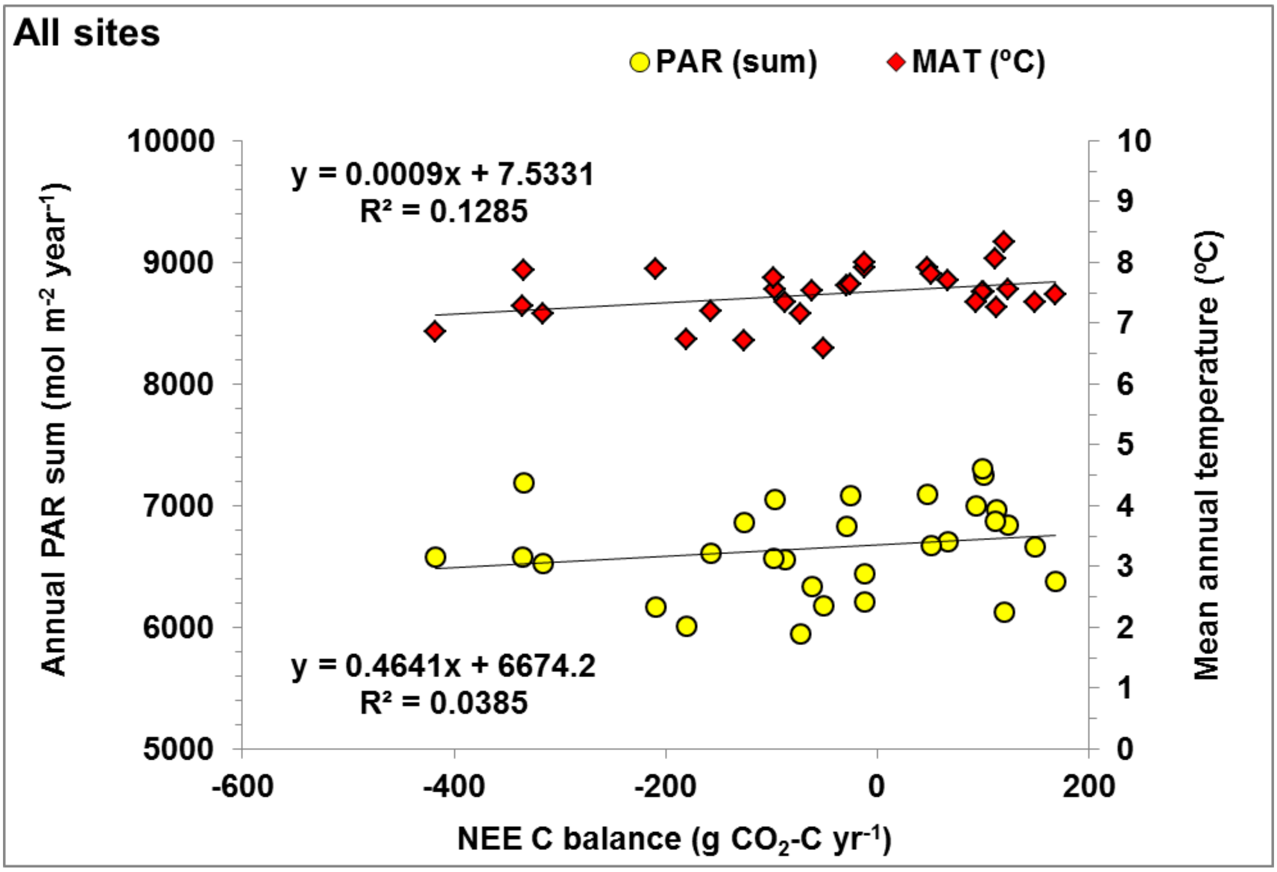


Figure A17.4 Mean annual photosynthetic active radiation (PAR) sums and mean annual temperatures at the sites versus the corresponding NEE carbon balance. The linear repression lines and their equations are also provided.

Based on the available project data (but excluding periods of heather beetle impacts damaging and reducing heather cover and thus net C uptake, notably at burnt plots on Mossdale [**Figure A3.2**] and Whitendale [**Figure A3.3**] and less so on mown plots at Nidderdale [**Figure A3.1**]) a simple hypothetical long-term scenario up to 25 years is proposed (**Figure A17.5**), where unmanaged, ageing heather close to 50 years, becomes a near neutral C sink and burnt and mown plots reach an optimum C uptake, which is lower for mown plots due to continued brash decomposition, after which both managements show a slow decline in the C balance due to ageing heather. Notably, these scenarios do not consider impacts on other ecosystem services. For example, for mowing there are concerns on negative impacts on water quality (from brash decomposition) and biodiversity (via reduced micro-topography), whilst an unmanaged landscape results in reduced habitat diversity (patchwork of vegetation age structure) likely reducing plant and animal diversity and leading to increased wildfire risk (**Figure A17.6**). However, research on large-scale impacts on water quality and biodiversity is largely missing (Harper et al., 2018; Heinemeyer et al., 2019b).

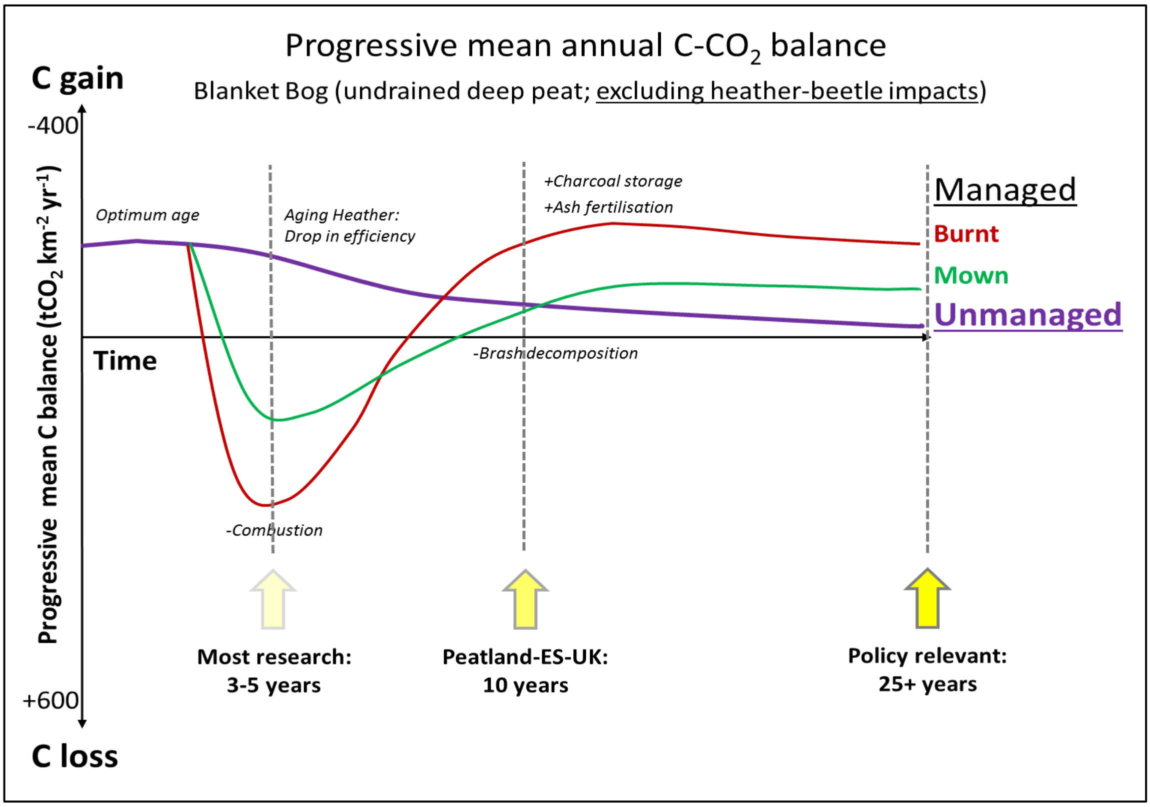


Figure A17.5 Hypothetical scenarios of the progressive mean CO$_2$-C balance over time for unmanaged (likely drop in C uptake efficiency), burnt (including combustion loss vs. estimated maximum C gains from charcoal & ash fertilisation) and mown (brash decomposition losses) heather. Whilst most research is ~3-5 years long, the Peatland-ES-UK study so far achieved 10 years. However, to obtain ecologically and policy relevant outcomes at least 25 years are needed (Heinemeyer et al., 2019b).

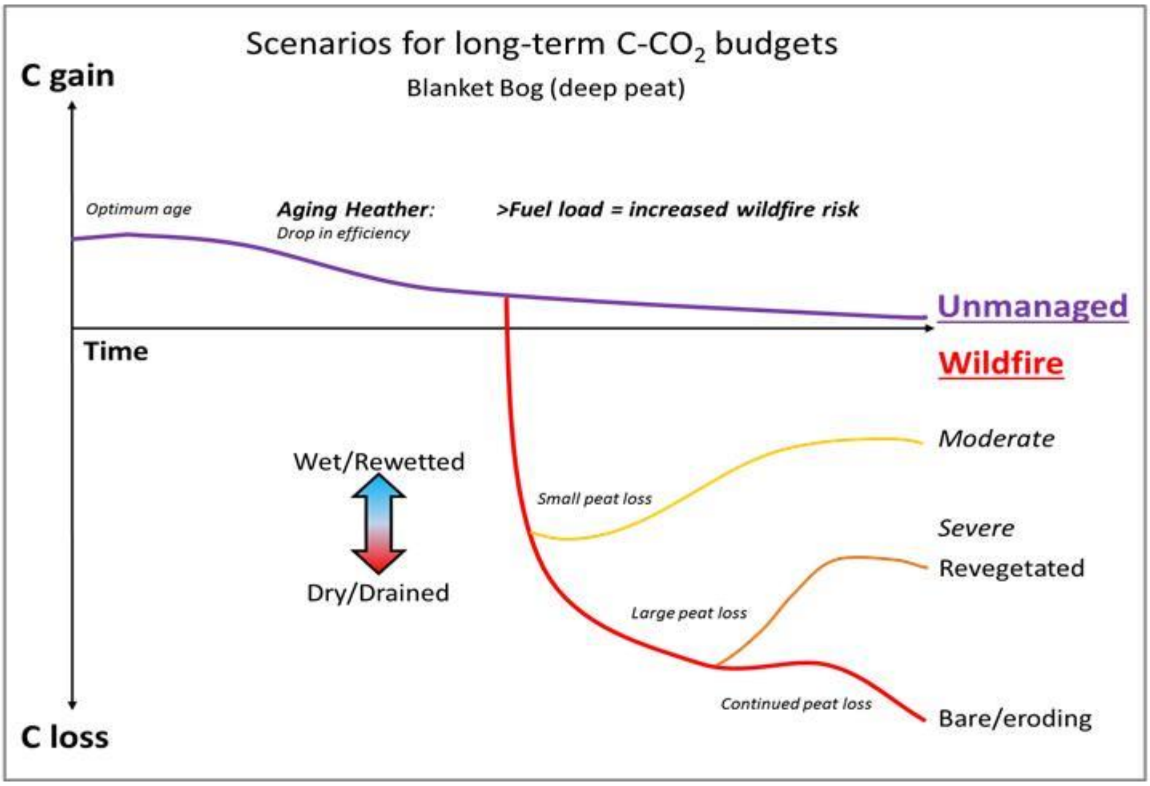


Figure A17.6 Hypothetical scenarios of C budgets (including combustion and erosion of peat) over time for either unmanaged, ageing heather (likely drop in efficiency) and wildfire as a consequence of increased fuel load (dense heather) with either moderate or severe fires leading to small or large peat losses, respectively, and (if remaining bare) to continued peat erosion.

Moreover, the potential consequences of no management (sometimes anticipated as a consequence of applying the "precautionary principle" demanding cessation of burning and possibly all management), could be devastating in the long-term, especially when consuming peat carbon (**Figure A17.6**) as fire risk is a growing issue in the UK heather moorlands (Barbar-Lomax et al., 2022). In fact, the precautionary principle should not be used as a basis for decision-making as outlined and discussed by Peterson (2007). However, the precautionary principle is rarely (if ever) applied when considering other even more understudied/unproven peatland management options as, for example, for mowing/cutting of heather or no management. Notably, no management will result in a large increase in heather biomass and thus evapotranspiration, drying out peat by lowering the water table on unmanaged heather-dominated plots (**Figure A5.2**) and thus making it more likely for any fires to then also burn peat, causing likely huge C loss and long-lasting damage (**Figure A17.6**). This effect would be even larger if trees were to establish on the peat, causing further drying and increased peat decomposition (Friggens et al., 2020). Moreover, any fire impacts depend on the site conditions. Overall, wet sites are likely to be more resilient to fire as are rewetted sites, whereas dry and drained sites are particularly vulnerable. However, it is important to note that even intact wet or rewetted peatlands can dry out during prolonged warm and dry periods, with water tables dropping and peat surface drying out due to transpiration losses. Even *Sphagnum* moss layers can dry out and ignite. Surprisingly little is known about overall fire vulnerability/resilience in relation to site condition and management, especially restoration practices aimed at increasing water tables and surface wetness.

The overall C balance also included the monthly measurements of stream flow losses as dissolved and particulate organic carbon (DOC and POC, respectively). Whilst previously (Heinemeyer et al., 2019b) the DOC and POC concentrations were simply multiplied by the monthly flow volumes at the flow weirs, this artificially inflates the total export rates as most flow samples were collected under lower flow rates and DOC and POC concentrations are generally diluted under higher flow rates. Therefore, a simple logarithmic fit to the DOC and POC versus flow volumes was performed to obtain an overall dilution correction (i.e. modelling export concentrations based on the overall measurement relationships per site and catchment). Although the overall model fit was not very good (**Table A17.1**), this has been reported previously (Clark et al., 2007). Moreover, any predicted values below the observed minimum concentration in each catchment (during 2012-2021) were replaced by the minimum concentration. Annual totals (**Table A17.2**) were, however, very similar to the previous export totals (DOC and POC 6% and 20% or 2.2 and 0.7 gC m^{-2} lower).

Table A17.1 Model equations for concentrations (mg/L) of DOC and POC versus stream flow rates (m^{3} h^{-1}).

Catchment	(mg/L)	**Nidderdale**	R2	**Mossdale**	R2	**Whitendale**	R2
Control (Burnt)	**DOC**	$= -2.057\ln(x) + 25.454$	0.13	$= -2.104\ln(x) + 28.674$	0.12	$= -1.355\ln(x) + 20.113$	0.1
Treatment (Mown)	**DOC**	$= -1.041\ln(x) + 29.069$	0.04	$= -2.001\ln(x) + 29.728$	0.12	$= -2.358\ln(x) + 20.517$	0.09
Control (Burnt)	**POC**	$= -0.629\ln(x) + 3.2452$	0.28	$= -0.147\ln(x) + 1.1384$	0.07	$= -0.13\ln(x) + 1.3514$	0.1
Treatment (Mown)	**POC**	$= -0.118\ln(x) + 1.6933$	0.11	$= -0.091\ln(x) + 1.1764$	0.03	$= -1.608\ln(x) + 5.0578$	0.28

Table A17.2 Annual export (gC m^{-2}) of DOC and POC at the sites and catchments (burnt vs. mown) and overall.

Site	Nidderdale				Mossdale				Whitendale				Average all sites			
Catchment	**Burnt**	**Mown**	**Burnt**	**Mown**	**Burnt**	**Mown**	**Burnt**	**Mown**	**Burnt**	**Mown**	**Burnt**	**Mown**	**Burnt**	**Mown**	**Burnt**	**Mown**
Year	POC (gC m-2)		DOC (gC m-2)		POC (gC m-2)		DOC (gC m-2)		POC (gC m-2)		DOC (gC m-2)		POC (gC m-2)		DOC (gC m-2)	
2012	1.2	1.7	23.3	34.0	0.8	1.2	29.6	30.9	1.5	1.6	23.0	18.1	1.2	1.5	25.3	27.7
2013	0.8	0.9	14.2	17.5	0.7	0.8	24.5	20.8	0.8	0.9	13.0	11.2	0.8	0.8	17.2	16.5
2014	0.9	0.9	16.8	18.6	0.8	0.8	26.8	22.1	0.9	1.0	14.5	12.4	0.9	0.9	19.4	17.7
2015	0.8	1.1	20.0	22.2	1.0	1.1	38.0	30.9	1.4	1.9	20.1	15.4	1.1	1.4	26.1	22.8
2016	0.9	0.7	15.9	14.5	0.7	0.8	27.1	22.2	1.1	1.4	17.5	14.3	0.9	1.0	20.2	17.0
2017	0.7	0.3	9.8	5.7	0.8	1.0	29.2	28.1	1.5	2.0	22.7	17.8	1.0	1.1	20.6	17.2
2018	0.8	0.3	10.8	6.4	0.7	0.7	23.0	19.5	1.0	1.1	15.0	12.4	0.8	0.7	16.3	12.8
2019	0.9	0.9	17.9	17.7	0.8	0.8	28.9	20.4	1.2	1.5	18.7	15.2	1.0	1.1	21.8	17.8
2020	1.0	1.2	20.6	23.5	1.0	1.1	37.3	29.7	1.6	2.7	23.1	19.3	1.2	1.7	27.0	24.2
2021	0.7	0.8	14.4	16.9	0.7	0.7	26.9	19.5	1.3	2.0	19.1	16.1	0.9	1.2	20.1	17.5

Adding all C fluxes (including NEE, methane, DOC, POC) together allowed calculation of the annual net ecosystem carbon balance (NECB) budgets. This was done for the main managements (burnt, mown, uncut) as shown in **Table A17.3** and for the three sites as an average of the annual proportion of managed (burnt and mown) areas, increasing over time across the catchments with new management areas in 2013, 2015, 2018 and 2021, and unmanaged (uncut) areas as shown in **Table A17.4**. However, the included combustion losses and charcoal gains of carbon are uncertain estimates. Especially for charcoal and charred remains (e.g. sticks) there are no specific data available and char production as well as C content of it is very variable and cannot be repeated easily in an experimental setup whilst sampling all components in the field is challenging or near impossible. Therefore, these estimates of C gains are maximum estimates and the actual amount of char and C contained within it is likely much less. Furthermore, whilst these gains have been included in the C balance, even charcoal will decompose, albeit much slower than litter (see Worrall et al., 2013).

Table A17.3 Annual C fluxes and the corresponding net ecosystem carbon balance (NECB), the latter also either excluding uncertain fluvial (DOC & POC) losses or including an annual net loss (over a 22 year management cycle) of 12.69 gC m^{-2} (consisting of estimated combustion loss and estimated maximum charcoal C gains). Negative numbers indicate a net C uptake.

Management	Year	NEE	CH_4	DOC	POC	NECB	Excl. Fluvial	With combustion
Burnt (FI)	2012	-72.4	0.7	25.3	1.2	-45.3	-71.7	-32.6
	2013	172.2	0.4	17.3	0.7	190.7	172.7	203.4
	2014	102.8	2.5	19.7	1.0	126.0	105.3	138.7
	2015	-13.4	2.2	27.6	1.1	17.6	-11.1	30.3
	2016	-71.3	5.1	21.0	0.9	-44.3	-66.2	-31.6
	2017	-30.7	3.6	20.3	1.2	-5.6	-27.0	7.1
	2018	61.1	0.9	16.7	0.9	79.6	62.0	92.3
	2019	51.4	0.8	23.0	0.8	76.0	52.2	88.7
	2020	51.0	2.2	28.6	1.3	83.2	53.2	95.8
	2021	95.6	0.8	20.6	0.9	117.9	96.4	130.6
	10-year mean	**34.6**	**1.9**	**22.0**	**1.0**	**59.6**	**36.6**	**72.3**
	SE	25.3	0.5	1.3	0.1	24.5	25.1	25.8
	Median	**51.2**	**1.5**	**20.8**	**0.9**	**77.8**	**52.7**	**90.5**
Mown (LB)	2012	-92.8	0.4	21.8	1.0	-69.6	-92.4	
	2013	109.7	0.0	16.4	0.9	127.0	109.7	
	2014	132.3	1.9	17.4	0.8	152.4	134.2	
	2015	74.2	6.1	21.3	1.3	102.9	80.3	
	2016	41.1	6.3	16.1	1.0	64.5	47.4	
	2017	93.9	7.5	17.5	1.0	119.9	101.5	
	2018	-0.6	2.3	12.4	0.7	14.8	1.7	
	2019	101.9	1.4	16.6	1.2	121.1	103.2	
	2020	194.2	4.2	22.5	1.5	222.4	198.4	
	2021	158.2	2.2	17.0	1.2	178.6	160.4	
	10-year mean	**81.2**	**3.2**	**17.9**	**1.1**	**103.4**	**84.5**	
	SE	26.1	0.8	1.0	0.1	26.4	26.2	
	Median	**97.9**	**2.3**	**17.2**	**1.0**	**120.5**	**102.4**	
Uncut (DN)	2012	-101.6	1.0	23.5	1.1	-76.0	-100.6	
	2013	-233.9	0.4	16.9	0.8	-215.9	-233.5	
	2014	31.4	3.6	18.5	0.9	54.5	35.1	
	2015	-88.5	15.5	24.4	1.2	-47.4	-73.0	
	2016	-94.9	21.5	18.6	0.9	-53.9	-73.4	
	2017	-23.5	37.0	18.9	1.1	33.4	13.5	
	2018	80.4	2.3	14.5	0.8	98.0	82.7	
	2019	28.9	1.0	19.8	1.0	50.8	29.9	
	2020	50.6	1.7	25.6	1.4	79.2	52.2	
	2021	-110.6	1.0	18.8	1.1	-89.7	-109.6	
	10-year mean	**-46.2**	**8.5**	**20.0**	**1.0**	**-16.7**	**-37.7**	
	SE	30.6	3.9	1.1	0.1	30.8	30.7	
	Median	**-56.0**	**2.0**	**18.9**	**1.0**	**-7.0**	**-29.8**	

Table A17.4 Annual C flux components and the corresponding net ecosystem carbon balance (NECB) for each site as a sum of the proportional areas which were either unmanaged (uncut) or managed (burnt and mown) areas, the latter increasing over time across the catchments with new management areas in 2013, 2015, 2018 and 2021. Note, these calculations do not include combustion losses or charcoal gains. Negative numbers indicate a net C uptake.

Site	Year	NEE	CH4	DOC	POC	NECB
Nidderdale	2012	-49.8	0.0	24.9	1.0	-23.8
	2013	-83.9	0.0	15.8	0.8	-67.2
	2014	4.6	0.3	17.7	0.9	23.5
	2015	60.1	2.1	21.1	1.0	84.3
	2016	117.0	21.7	15.2	0.8	154.7
	2017	40.0	11.1	7.7	0.5	59.3
	2018	7.5	2.5	8.6	0.6	19.3
	2019	61.1	0.8	17.8	0.9	80.7
	2020	40.4	1.2	22.1	1.1	64.7
	2021	194.8	1.2	15.6	0.8	212.4
	10-year mean	**39.2**	**4.1**	**16.7**	**0.8**	**60.8**
	SE	25.0	2.2	1.7	0.1	25.7
	Median	**40.2**	**1.2**	**16.8**	**0.9**	**62.0**
Mossdale	2012	-161.0	2.9	26.7	0.6	-130.7
	2013	-309.2	0.7	22.6	0.7	-285.1
	2014	18.1	9.0	24.4	0.8	52.4
	2015	-172.1	20.9	34.5	1.1	-115.7
	2016	-204.6	13.7	24.6	0.8	-165.5
	2017	60.9	56.3	28.6	0.9	146.7
	2018	26.7	1.8	21.3	0.7	50.5
	2019	14.6	1.3	24.7	0.8	41.3
	2020	155.2	3.9	33.5	1.0	193.6
	2021	127.6	1.5	23.2	0.7	153.1
	10-year mean	**-44.4**	**11.2**	**26.4**	**0.8**	**-5.9**
	SE	49.3	5.4	1.4	0.0	50.4
	Median	**16.4**	**3.4**	**24.6**	**0.8**	**45.9**
Whitendale	2012	-82.6	0.0	18.9	1.6	-62.1
	2013	-83.7	0.3	12.1	0.9	-70.5
	2014	123.2	0.7	13.4	1.0	138.4
	2015	-10.8	9.8	17.7	1.6	18.4
	2016	-101.4	10.1	15.9	1.2	-74.1
	2017	-105.2	6.0	20.3	1.8	-77.2
	2018	140.0	1.0	13.7	1.1	155.9
	2019	112.7	0.9	16.9	1.4	131.8
	2020	77.4	3.3	21.2	2.2	104.1
	2021	-84.2	1.5	17.6	1.6	-63.4
	10-year mean	**-1.5**	**3.4**	**16.8**	**1.4**	**20.1**
	SE	32.6	1.2	0.9	0.1	32.0
	Median	**-46.7**	**1.3**	**17.3**	**1.5**	**-21.9**

Appendix 18 (greenhouse gas emissions)

The components of the C balance together with the N_2O emissions were used to derive greenhouse gas (GHG) emissions (tCO_2eq per km^{-2} yr^{-1}). The method is described in Heinemeyer et al. (2019b) and considers a multiplier for the warming potential of the CO_2eq over 100 years of x25 for methane and x298 for N_2O.

Table A18.1 Annual GHG components (NEE, CH_4 and N_2O) to derive overall net GHGs for the burnt, mown and uncut managements, which for burning also considered the annual net CO_2eq loss (over a 22 year management cycle) of 12.69 gC m^{-2} (consisting of estimated combustion loss and maximum charcoal gains) of 46.53 tCO_2eq per km^{-2} yr^{-1}. Methane emissions are based on median fluxes and the 10-year means of net GHGs are either based on the 10-year mean or the median methane emissions (the latter a more robust long-term measure due to the intermittent high peak in methane emissions in 2015-2017). Negative numbers indicate a net GHG benefit (cooling).

All Sites	**Year**	**NEE CO2**	**CH4 g in CO2 eq**	**N2O g in CO2 eq**	**net GHGs (10-year means)**	**Including Combustion**	**net GHGs +Combustion (median of methane)**
Burnt (FI)	2012	-265.6	23.7	10.4	**-231.5**	**-184.9**	
	2013	631.5	14.9	10.4	**656.8**	**703.4**	
	2014	376.9	84.8	10.4	**472.1**	**518.6**	
	2015	-49.0	74.5	10.4	**36.0**	**82.5**	
	2016	-261.4	169.9	10.4	**-81.1**	**-34.6**	
	2017	-112.5	121.4	10.4	**19.3**	**65.8**	
	2018	224.2	29.9	10.4	**264.5**	**311.0**	
	2019	188.6	25.7	10.4	**224.7**	**271.3**	
	2020	187.0	73.3	10.4	**270.7**	**317.2**	
	2021	350.7	26.3	10.4	**387.4**	**434.0**	
	10-year mean	**127.0**	**64.4**	**10.4**	201.9	**248.4**	**229.4**
	SE	92.9	16.1	0.0	85.1	85.1	94.0
	Median	**187.8**	**51.6**	**10.4**	**244.6**	**291.1**	
Mown (LB)	2012	-340.2	14.1	10.4	**-315.7**		
	2013	402.4	0.0	10.4	**412.8**		
	2014	485.1	63.0	10.4	**558.6**		
	2015	272.0	204.7	10.4	**487.1**		
	2016	150.6	210.3	10.4	**371.3**		
	2017	344.3	251.6	10.4	**606.4**		
	2018	-2.1	76.0	10.4	**84.3**		
	2019	373.6	45.4	10.4	**429.4**		
	2020	712.0	140.5	10.4	**862.9**		
	2021	580.0	74.8	10.4	**665.2**		
	10-year mean	**297.8**	**108.0**	**10.4**	**416.2**		**388.4**
	SE	95.7	27.9	0.0	103.9		**86.2**
	Median	**359.0**	**75.4**	**10.4**	**458.3**		
Uncut (DN)	2012	-372.5	32.7	10.4	**-329.4**		
	2013	-857.7	12.2	10.4	**-835.0**		
	2014	115.3	120.4	10.4	**246.1**		
	2015	-324.5	515.2	10.4	**201.1**		
	2016	-347.9	715.4	10.4	**377.9**		
	2017	-86.2	1233.1	10.4	**1157.3**		
	2018	294.9	75.7	10.4	**381.0**		
	2019	106.1	33.2	10.4	**149.8**		
	2020	185.4	56.2	10.4	**252.0**		
	2021	-405.6	34.1	10.4	**-361.0**		
	10-year mean	**-169.3**	**282.8**	**10.4**	**124.0**		**-103.8**
	SE	112.2	130.2	0.0	169.9		**127.0**
	Median	**-205.3**	**66.0**	**10.4**	**223.6**		

Table A18.2 Annual net GHG (including median methane fluxes) for each site for their three managements (uncut, burnt, mown), which for burnt also consider estimates of combustion losses and maximum charcoal gains. Grey numbers indicate the pre-management period (2012/13), which consisted of tall heather on all managements (thus net C uptake and negative net GHG). Negative numbers indicate a net GHG benefit (cooling).

Site	Year	net GHGs UNCUT	net GHGs BURNT	net GHGs BURNT +Combustion	net GHGs Mown
Nidderdale	2012	**-178.8**	*-66.6*	*-20.1*	*-223.5*
	2013	**-449.6**	**367.6**	**414.1**	**257.0**
	2014	**-35.9**	**248.2**	**294.7**	**396.4**
	2015	**492.2**	**-351.1**	**-304.6**	**386.4**
	2016	**1681.7**	**363.1**	**409.7**	**405.9**
	2017	**374.8**	**79.5**	**126.0**	**1423.5**
	2018	**460.2**	**-425.5**	**-379.0**	**220.7**
	2019	**468.7**	**-425.8**	**-379.3**	**674.0**
	2020	**-79.0**	**-258.9**	**-212.4**	**1021.5**
	2021	**376.9**	**555.6**	**602.1**	**1165.7**
	10-year mean	**311.1**	**8.6**	**55.1**	**572.8**
	SE	184.3	115.5	115.5	157.7
	Median	**375.8**	**6.4**	**53.0**	**401.1**
Mossdale	2012	**-554.9**	*-331.8*	*-285.3*	*-242.1*
	2013	**-1498.2**	**716.4**	**763.0**	**280.9**
	2014	**302.4**	**694.3**	**740.8**	**660.6**
	2015	**-115.6**	**387.9**	**434.4**	**337.9**
	2016	**-664.4**	**131.4**	**177.9**	**442.8**
	2017	**3598.9**	**-973.6**	**-927.1**	**726.6**
	2018	**441.9**	**245.8**	**292.3**	**-270.5**
	2019	**-256.9**	**506.0**	**552.6**	**196.0**
	2020	**383.5**	**1031.5**	**1078.0**	**818.5**
	2021	**-296.4**	**843.8**	**890.3**	**629.0**
	10-year mean	**134.0**	**325.2**	**371.7**	**358.0**
	SE	426.4	190.2	190.2	120.5
	Median	**-186.3**	**447.0**	**493.5**	**390.4**
Whitendale	2012	**-254.3**	*-367.1*	*-320.6*	*-523.7*
	2013	**-557.4**	**886.5**	**933.0**	**700.4**
	2014	**471.8**	**473.8**	**520.4**	**618.8**
	2015	**226.8**	**71.1**	**117.6**	**737.1**
	2016	**116.3**	**-737.8**	**-691.2**	**265.3**
	2017	**-501.6**	**952.1**	**998.6**	**-330.9**
	2018	**241.1**	**973.1**	**1019.7**	**302.6**
	2019	**237.6**	**594.0**	**640.5**	**418.2**
	2020	**451.7**	**39.5**	**86.0**	**748.7**
	2021	**-1163.6**	**-237.1**	**-190.5**	**201.0**
	10-year mean	**-73.2**	**264.8**	**311.3**	**313.8**
	SE	167.8	190.2	190.2	139.6
	Median	**171.5**	**272.4**	**319.0**	**360.4**

Table A18.3 Annual GHG components (NEE, CH_4 and N_2O) to derive overall net GHGs for each site for the uncut management. Methane emissions are based on median fluxes and the net GHGs are either based on the 10-year mean or the median methane emissions (the latter a more robust long-term measure due to the intermittent high peak in methane emissions in 2015-2017). Negative numbers indicate a net GHG benefit (cooling).

Uncut						
Site	**Year**	**NEE CO2**	**CH4 g in CO2 eq**	**N2O g in CO2 eq**	**net GHGs UNCUT**	**net GHGs UNCUT (with median CH4)**
Nidderdale	2012	-189.2	0.0	10.4	**-178.8**	
	2013	-460.0	0.0	10.4	**-449.6**	
	2014	-47.2	0.9	10.4	**-35.9**	
	2015	413.5	68.3	10.4	**492.2**	
	2016	544.5	1126.8	10.4	**1681.7**	
	2017	-106.5	470.9	10.4	**374.8**	
	2018	368.9	80.8	10.4	**460.2**	
	2019	452.7	5.6	10.4	**468.7**	
	2020	-94.8	5.4	10.4	**-79.0**	
	2021	361.4	5.0	10.4	**376.9**	
	10-year mean	**124.3**	**176.4**	**10.4**	**311.1**	**140.3**
	SE	108.2	115.1	0.0	184.3	
	Median	**157.1**	**5.5**	**10.4**	**375.8**	
Mossdale	2012	-663.5	98.1	10.4	**-554.9**	
	2013	-1533.6	25.0	10.4	**-1498.2**	
	2014	-43.6	335.7	10.4	**302.4**	
	2015	-1160.7	1034.7	10.4	**-115.6**	
	2016	-1228.9	554.0	10.4	**-664.4**	
	2017	615.7	2972.8	10.4	**3598.9**	
	2018	343.1	88.4	10.4	**441.9**	
	2019	-318.0	50.7	10.4	**-256.9**	
	2020	245.4	127.6	10.4	**383.5**	
	2021	-353.8	47.0	10.4	**-296.4**	
	10-year mean	**-409.8**	**533.4**	**10.4**	**134.0**	**-286.5**
	SE	229.9	289.1	0.0	426.4	
	Median	**-335.9**	**112.9**	**10.4**	**-186.3**	
Whitendale	2012	-264.8	0.0	10.4	**-254.3**	
	2013	-579.4	11.6	10.4	**-557.4**	
	2014	436.8	24.6	10.4	**471.8**	
	2015	-226.2	442.6	10.4	**226.8**	
	2016	-359.4	465.3	10.4	**116.3**	
	2017	-767.7	255.6	10.4	**-501.6**	
	2018	172.6	58.1	10.4	**241.1**	
	2019	183.8	43.3	10.4	**237.6**	
	2020	405.5	35.7	10.4	**451.7**	
	2021	-1224.4	50.3	10.4	**-1163.6**	
	10-year mean	**-222.3**	**138.7**	**10.4**	**-73.2**	**-165.1**
	SE	169.9	57.3	0.0	167.8	
	Median	**-245.5**	**46.8**	**10.4**	**171.5**	

The following figures summarise the main aspects of the above GHG data (**Figure A18.1**) and compare the site values versus estimates from the IUCN UK Peatland Code (**Figure A18.2**) based on Smyth et al. (2015). Note that the site values are most similar to their ‘Near Natural’ category. However, there are basically no other adequate data (long-term and considering all major C fluxes) for heather-dominated blanket bogs, and the value of this study becomes very clear when considering the knowledge gaps highlighted for such ecosystems in the recent Defra report by Evans et al. (2022) on aligning the Peatland Code with the UK peatland emissions inventory.

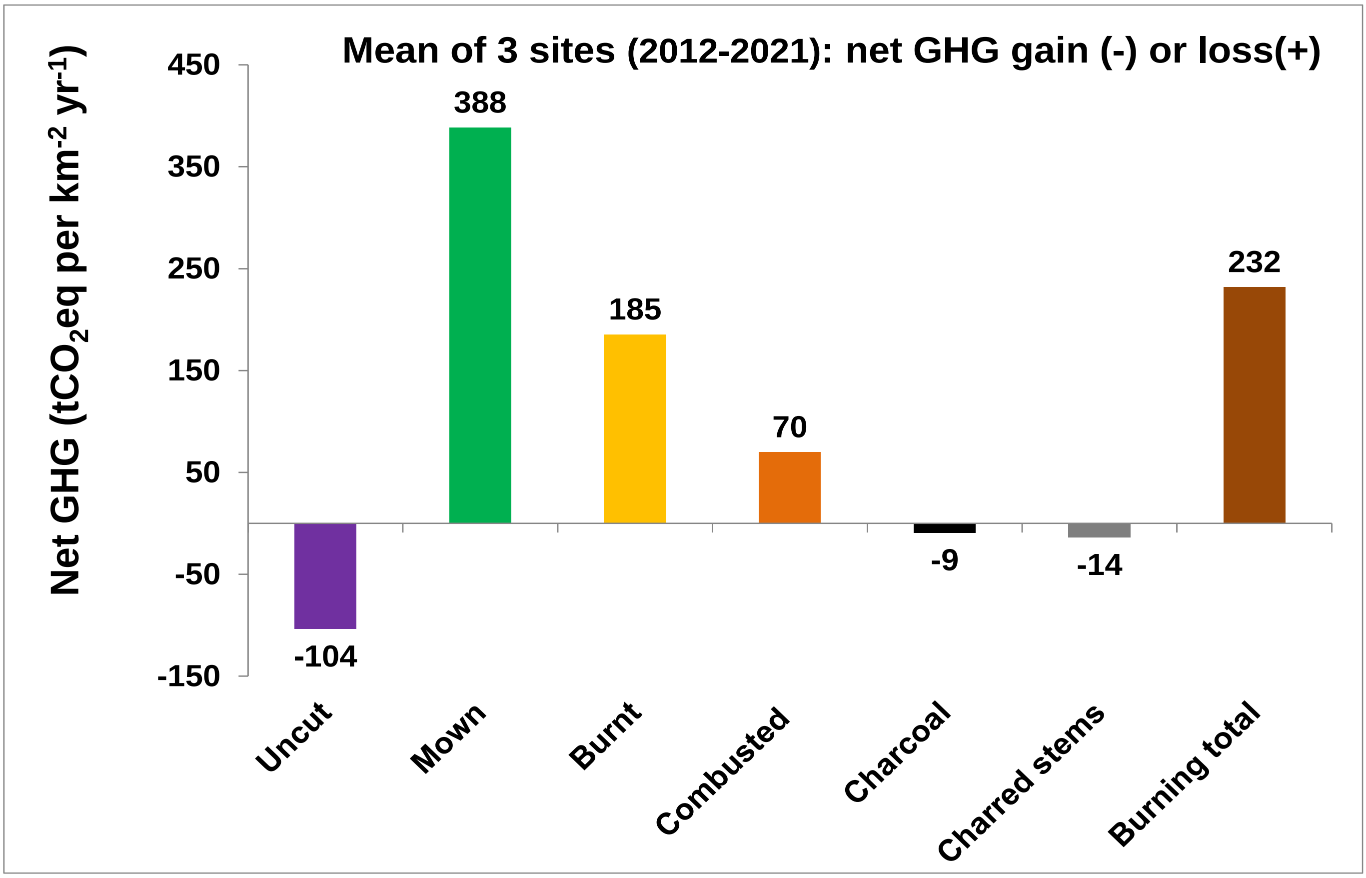


Figure A18.1 Mean net GHG emissions of the three sites (during 2012-2021) for the main management comparisons of uncut, mown and burnt; for data refer to the last column in **Table A18.1** (small differences are due to rounding). For the burnt management the estimated combustion losses and maximum charcoal gains as well as the charred stems (based on adjusting estimates provided by Clay & Worrall (2011) and Worrall et al. (2013) and unpublished data for heather areas kindly provided by Matt Davies) are included in the burning total. Negative numbers indicate a net GHG benefit (cooling).

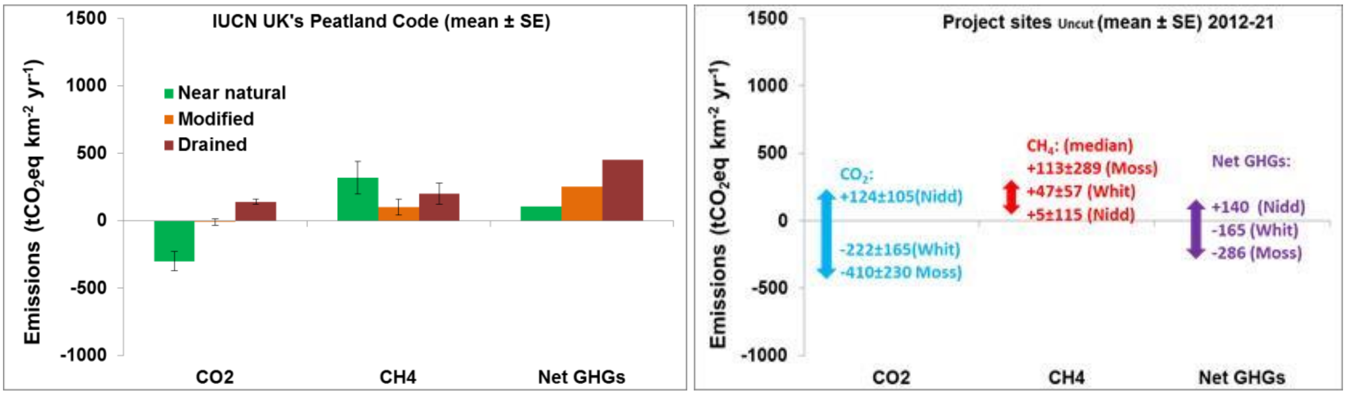


Figure A18.2 Comparison of the IUCN UK (left) estimated mean C-fluxes (converted to tCO_2eq km^{-2} yr^{-1}) and net greenhouse gas emissions (net GHGs) calculated over a 100-year period as in the IPCC Fourth Assessment Report (2007) including CO_2-equivalents of CH_4 (GWP100 of 25) and N_2O (GWP100 of 298) emissions for the three blanket bog categories (i.e. ‘near natural’, ‘modified’ and ‘drained’) to the ranges (CO_2 shown as blue arrows, CH_4 shown as red arrows and purple arrows for net GHGs also including N_2O) of the three project sites (bottom) Nidderdale (Nidd), Mossdale (Moss) and Whitendale (Whit). The ranges (mean values are also shown in the highlighted cells in **Table A18.3**) are based on the sites’ mean values (± standard error (SE) of the 10 annual balance during 2012-2021) for the uncut plot-level management and are assumed to represent ‘modified’ blanket bog. Note: as the three shown IUCN UK’s Peatland Code categories assume no POC export (cf. data in Table 1 in Smyth et al. 2015) measured POC export for the three project sites was also excluded. Negative numbers indicate a net GHG benefit (cooling).

Important to note is here that overall, the grouse moors (uncut) are similar to the 'near natural' bog emissions as per IUCN UK Peatland Programme data (**Figure A18.2**) - the overall average of the three sites shows a net C uptake, fairly low methane and an overall net GHG benefit. The wetter (Moss) the better for CO_2 uptake (threshold of C sink to C source is around 12 cm mean annual water table depth) but the more methane is emitted. If using median methane emissions this still results in 'good' (cooling) net GHG emissions across all three sites. However, if mean methane emissions were used (as shown in **Table A18.3**), the wetter sites (Moss & Whit) would be large net GHG contributors. Moreover, this is based on using a 100 year warming potential, not a more important 20 year impact (considering the fast rate of climate change and increasing methane emissions globally). However, emission factors for the three sites compared well to the near natural to modified status.

Table A18.4 Comparison of the IUCN UK's Peatland Code emission values ($tCO_2eq\ ha^{-1}\ yr^{-1}$) by component, and the corresponding net emission factors, to the project sites (Nidderdale, Mossdale and Whitendale) ranging from least to most modified blanket bog. The same CO_2 equivalent calculations were applied as in in Smyth et al. (2015; *cf*. Table 1); therefore, no POC data were included for the study (Defra) sites. **Values from Evans et al. (2022).

Peatland Code Category	**Statistics**	**CH_4**	**CO_2**	**N_2O**	**DOC**	**POC**	**Emission Factor**
Pristine*	-	-	-	-	-	-	**Unknown**
Near Natural (NN)	Mean (±StE)	3.2(1.2)	-3.0(0.7)	0.0(0.0)	0.88	0	**1.08**
	Median	1.5	-2.3	0.0			
NN**	Mean	3.21	-2.87	0	0.69	0	**1.03**
Modified	Mean (±StE)	1.0(0.6)	-0.1(2.3)	0.5(0.3)	1.14	0	**2.54**
	Median	0.2	0.1	0.5			
Modified**	Mean	1.54	0.03	0.06	0.69	0.21	**2.53**
Drained	Mean (±StE)	2.0(0.8)	1.4(1.8)	0.0(0.0)	1.14	0	**4.54**
	Median	1.0	-0.9	0.0			
Actively Eroding	Mean (±StE)	0.8(0.4)	2.6(2.0)	0.0(0.0)	1.14	19.3	**23.84**
	Median	0.1	0.4	0.0			

Study (Defra) sites	**Descriptive Statistic**	**CH4**	**CO2**	**N2O**	**DOC**	**POC**	**Emission Factor**
Mossdale ('least modified')	Mean (±StE)	**3.7 ± 1.8**	**-1.6 ± 1.8**	**0.12**	**0.9 ± 0.0**	**0.00**	3.10
	Median	**1.1**	**0.6**		**0.8**		**2.67**
Whitendale ('modified')	Mean (±StE)	**1.1 ± 0.4**	**-0.1 ± 1.2**	**0.12**	**0.6 ± 0.0**	**0.00**	1.74
	Median	**0.4**	**-1.7**		**0.6**		**-0.59**
Nidderdale ('most modified')	Mean (±StE)	**1.4 ± 0.7**	**1.4 ± 0.9**	**0.12**	**0.6 ± 0.1**	**0.00**	3.47
	Median	**0.4**	**1.5**		**0.6**		**2.54**

How mowing versus burning compares over time (and also versus uncut) requires more time (i.e. completion of the management cycle and full regrowth of vegetation), but all indications are that mowing will likely be a big issue as it continues to lose a lot of carbon from brash decomposition and also emits a lot of methane from wetter and more sedge dominated vegetation (even compared to burning with high initial biomass combustion losses). Moreover, heather beetle damage caused major C losses and reduced C uptake and mainly on burnt plots. To compare uncut to burning or mowing, monitoring over a full management cycle is pivotal to come to firm conclusions – one cannot compare this until this has been done (as it would always show a reduction in C uptake due to disturbance and initial emissions).

Appendix 19 (stream nitrogen export)

The project added a new stream flow monitoring aspect in the Phase 2. Whilst previously only DOC and POC were monitored, nitrogen (N) export of the main components was added in 2018 (i.e. after four years into post-management period). As such no comparison to pre-management values could be made and potential before management change differences could explain some or all of the observed post-management differences. Therefore, interpretation of the following needs to be done with this caveat in mind.

Sample filtering

Particulate matter was separated from approximately 50-200 ml (depending on seasonal variation in concentration) of flow water samples by filtering under vacuum through a pre-ashed (combusted in a muffle furnace for 2 hours at 550°C) and weighed 0.7 µm glass-fibre filter (Whatman glass microfiber filters, Grade GF/F, 25 mm diameter, Sigma-Aldrich, Dorset, UK). Filters were dried after filtration in an oven at 60°C for two days, put in a desiccator and re-weighed to determine the amount of particulate matter. Filtrate was transferred into 15 ml centrifuge tubes before storing at -20°C, ready for subsequent TbN and Nitrate/Ammonium analysis.

Particulate nitrogen (and carbon)

Particulate nitrogen (and carbon) were analysed using a Flash EA 1112 NC analyser (Thermo Scientific, UK). Dried filter papers with the filtered particulate matter, and also blank filter papers were folded into tin foil capsules for analysis. A certified Birch Leaf Standard (Elemental Microanalysis, UK) was used to calibrate the instrument and also used throughout the run to check for any instrument drift.

Total Bound Nitrogen

Total bound Nitrogen (TbN) concentrations of the sample filtrate were determined using a Total Carbon Analyser (VarioTOC cube, Elementar Analysensysteme GmbH, Hanau, Germany) fitted with an ECD TbN module. Prior to analysis, samples were defrosted, mixed (lab vortex) and diluted by a factor of 2 with ultrapure water, to ensure concentrations were within the range of standards (as DOC was measured simultaneously with TbN). Samples were acidified with 0.1 ml 10%HCL to remove inorganic carbon. An eight-point calibration (0.5, 1, 2, 5, 10, 20, 50 and 100 ppm) of sodium carbonate (Na_2CO_3), potassium hydrogen phthalate (KHP), ammonium chloride (NH_4Cl) and sodium nitrate (NO_3) solution was used, with 20 ppm regularly analysed throughout a run to account for any drift. A 2.5 mg/l Total Nitrogen Standard (Sigma Aldrich, Germany) was used as a quality check. All samples were analysed in triplicate (but fewer values were used for averaging if a measurement failed, removing any obvious outliers). Sample vials were acid washed in 10% HCL after each run.

Nitrate N (NO3-N) and ammonium N (NH4-N)

Nitrate N (NO_3-N) and ammonium N (NH_4-N) were determined colorimetrically using a SEAL Analytical Autoanalyser 3 (AA3) with an XY-2 Autosampler. A range of standards from 0-2 mg/L were prepared using a 1.00 mg/L ammonium standard solution and 0.50 mg/L nitrate standard solution (Sigma-Aldrich, Germany).

Calculation of N fractions

Total N (TN) was measured as: TbN + PON + DIN (NH_4 and NO_3 were measured as part of TbN) + DON, with: **TbN** = Total bound Nitrogen, the sum of all organic nitrogen (e.g. urea, nicotinic acid) and inorganic nitrogen (nitrate and ammonia), **PON** = Particulate organic nitrogen determined by filtration (0.7um gf/f) and determining %N with a C/N analyser (combustion), **DIN** = including nitrate (NO_3) and ammonia (NH_4) determined by an auto-analyser module (AA3) module linked to the VarioTOC, and **DON** = TbN – DIN.

Overall, there is one similar study covering peatland catchments to some degree (i.e. including large areas of non-deep peat soils), Chapman et al. (2001), which allowed a comparison to the data obtained in this study covering blanket bog peatlands site. Overall, the obtained total N and the contributions of its components were very similar to those obtained by Chapman et al. (2001), the below figures show the comparisons for the relationship of DON vs. DOC (**Figure A18.1**), the concentrations of total N and its components in monthly flow samples (**Table A19.1**) and their catchment area weighted monthly export rates (**Table A19.2**).

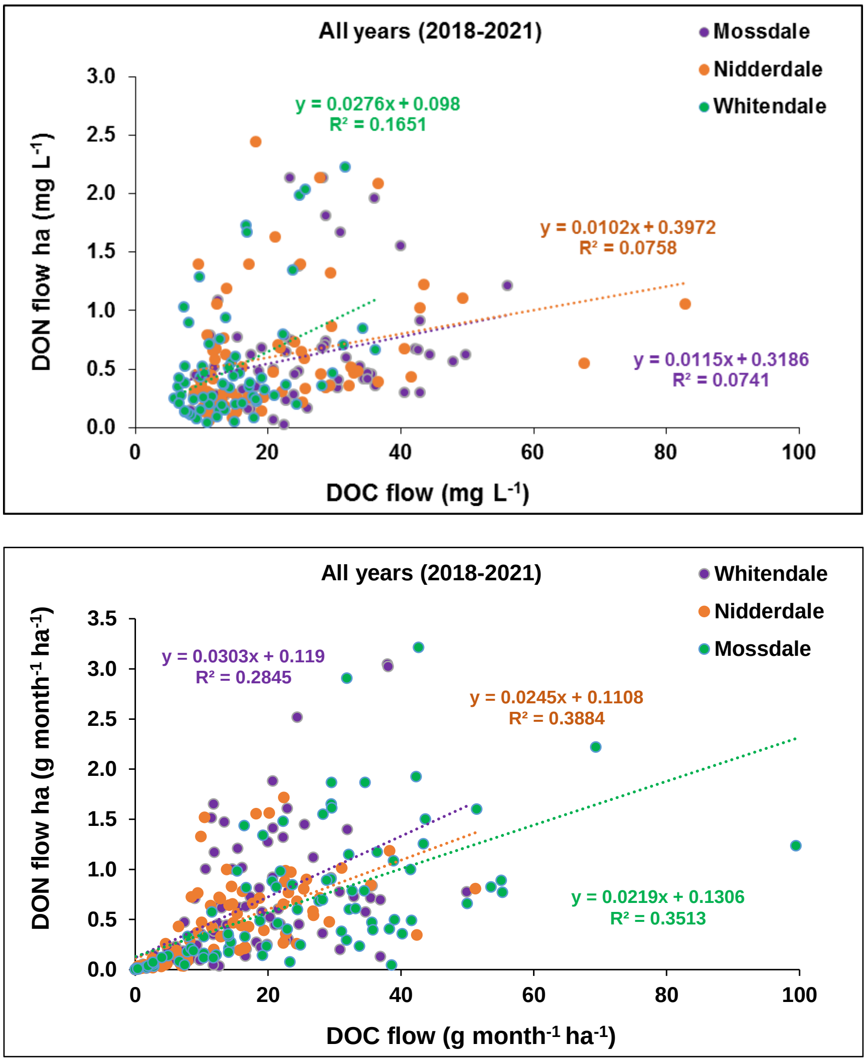


Figure A18.1 Mean dissolved organic N (DON) vs. dissolved organic C (DOC) as (top) concentration (mg/L) or flow (bottom) weighted (per catchment area) export rates (g per month and hectare) across all years (2018-2021) and sites (Nidderdale, Mossdale, Whitendale). The best fit linear repressions are also provided. For a comparison, the mean values for the linear regressions of flow weighted export in Chapman et al. (2001) were: 0.026*DOC +0.023.

The following figures summarise the averages for the in monthly stream flow samples measured percentage of N (%), total N (TN) and its component data (dissolved organic N [DON], particulate N [PON], total bound Nitrogen (TbN) the sum of all organic nitrogen and inorganic nitrogen (DIN), nitrate [NO3], ammonium [NH4]) collected monthly during 2018-2021. Whilst the below **Figure A18.2** summarises the concentrations, the following **Figure A18.3** summarises the catchment-scale weighted monthly export. A repeated measures ANOVA did not reveal any significant differences between management (i.e. catchments), but year was a significant factor for concentrations of Total N, TbN, NO_3, DIN, DON and for all N parameters for export rates. For export rates only Total N (p= 0.095) and DON (p= 0.074) showed a near significant time x catchment interaction.

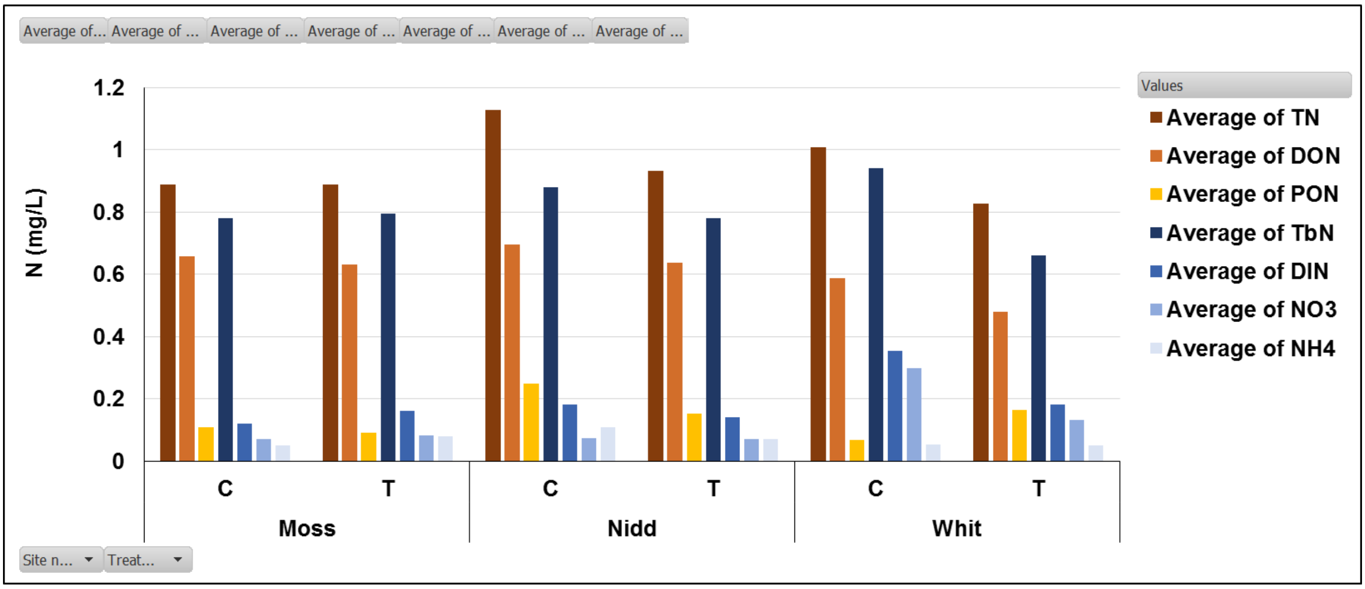


Figure A18.2 Mean concentration (mg/L) in monthly stream flow samples across all years (2018-2021) and sites (Mossdale [Moss], Nidderdale [Nidd], Whitendale [Whit]). Shown are total N (TN) and its component data (dissolved organic N [DON], particulate N [PON], total bound Nitrogen (TbN) the sum of all organic nitrogen and inorganic nitrogen (DIN), nitrate [NO_3], ammonium [NH_4]).

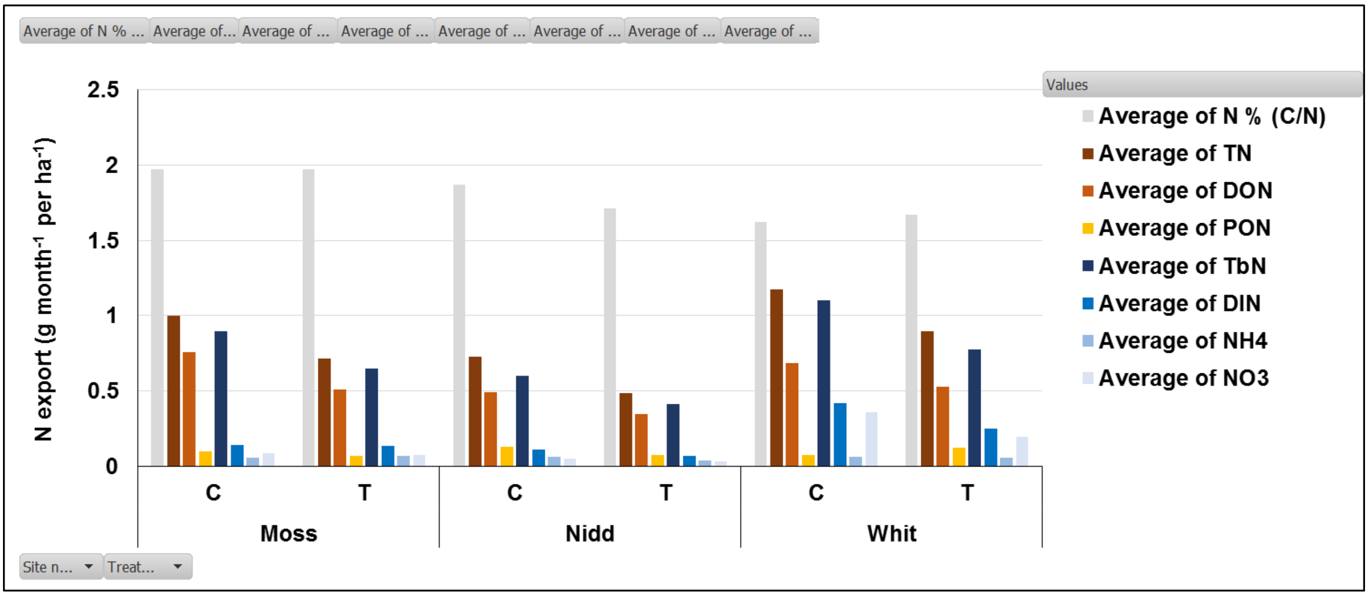


Figure A18.3 Mean flow weighted (per catchment area) export rates (g per month and hectare) across all years (2018-2021) and sites (Mossdale [Moss], Nidderdale [Nidd], Whitendale [Whit]). Shown are total N (TN) and its component data (dissolved organic N [DON], particulate N [PON], total bound Nitrogen (TbN) the sum of all organic nitrogen and inorganic nitrogen (DIN), nitrate [NO_3], ammonium [NH_4]).

The below box plots (**Figure A18.4**) relate to the Chapman et al. (2001; *cf*. Fig. 2) providing concentrations together with the corresponding export rates for the key N components (total N, DON, NO_3 and NH_4).

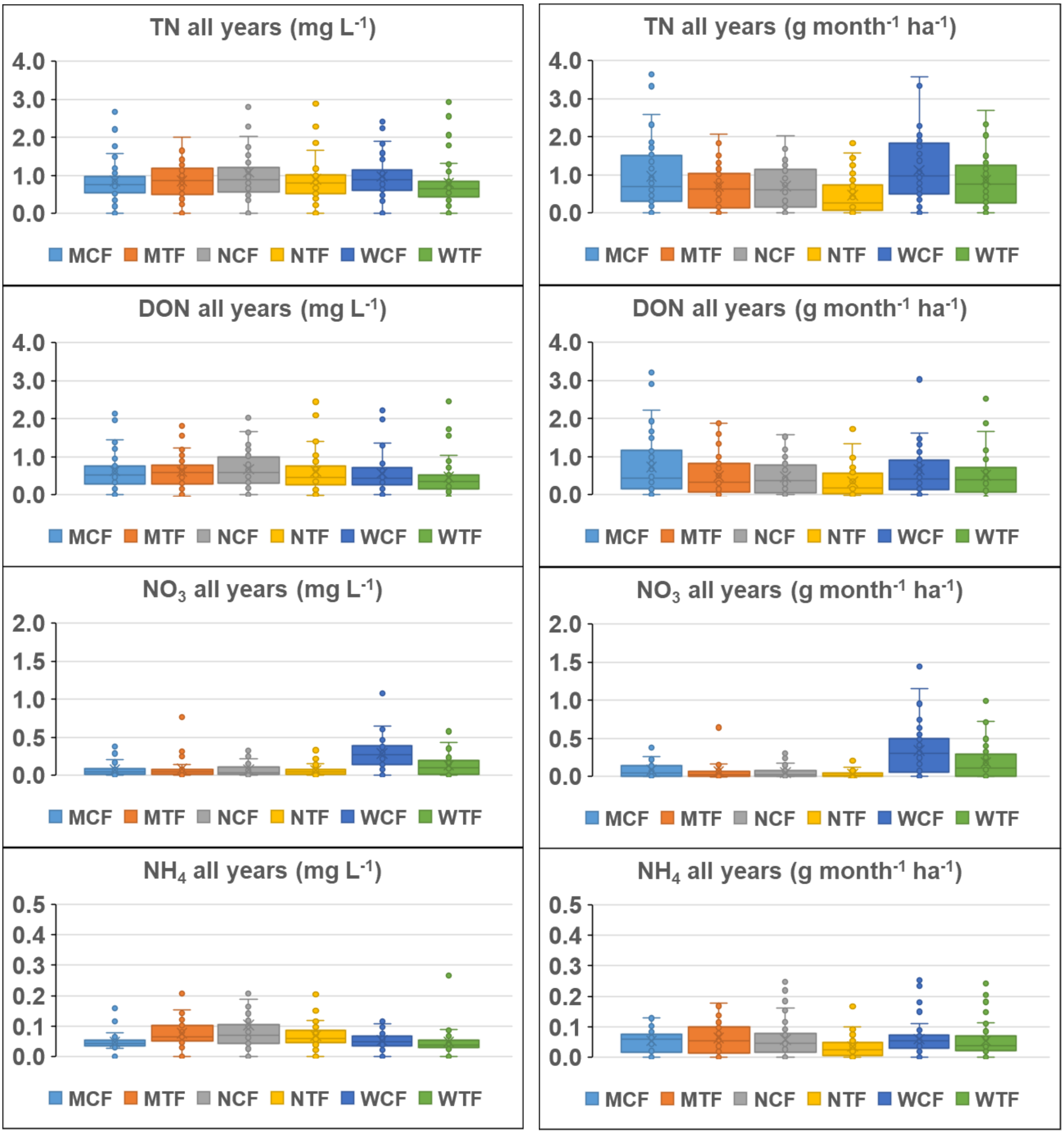


Figure A18.4 Box plots for (left) average concentrations (mg/L) and (right) flow-weighted average monthly export rates (g/month/ha) for total N (TN), dissolved organic N (DON), nitrate (NO_3) and ammonia (NH_4). The mean is indicated by a marker (x), the median by a line and outliers are shown outside the 1.5 times interquartile range (whiskers) of the lower and upper quartiles (box).

The below **Table A19.1** summarises the overall (2018-2021) and individual annual N concentrations (and their descriptive statistics), across the entire year or separately for winter and summer periods, measured at the three sites (combined for Nidderdale, Mossdale and Whitendale) for the main N parameters compared to those reported in Chapman et al. (2001). The comparison shows overall very good agreement between the Chapman et al. data and data for the three sites in this study. However, the Chapman et al study represents only one year and considerably larger catchments with a very high proportion of non (deep) peat and mineral soils.

Table A19.1 Comparison of N concentrations (mg/L) in Chapman *et al.* (2001; *cf*. Table 3) for all peaty sites (note: all sites included considerable non-peat areas and some sites with very little deep peat or peaty podzol or gley areas) for total N (TN) and its component data (particulate N [PN], nitrate [NO_3], ammonia [NH_4] and dissolved organic N [DON]) collected monthly during April 1997-1998 to the Peatland-ES-UK sites (Nidderdale, Mossdale, Whitendale) during 2018-2021. The percentages of N components are also provided (vs. total N).

mg/l	**Chapman et al. (2001; *cf*. Table 3)**				
All sites	**TN**	**PN**	**NO3**	**NH4**	**DON**
Annual					
Mean	0.570	0.035	0.394	0.029	0.183
Std dev	0.520	0.050	0.500	0.017	0.130
Median	0.410	0.024	0.191	0.025	0.159
Range Min	0.058	0.000	<0.01	<0.01	0.000
Range Max	3.350	0.430	3.050	0.110	0.873
No of Samples	313	214	289	209	303
% TN		5	50	5	40
Winter	TN	PN	NO3	NH4	DON
Mean	0.648	0.030	0.469	0.029	0.167
Std dev	0.580	0.030	0.560	0.017	0.120
Median	0.457	0.023	0.269	0.025	0.146
Range Min	0.080	0.000	<0.01	<0.01	0.000
Range Max	3.210	0.210	2.950	0.110	0.681
No of Samples	155	95	152	120	149
% TN		3	58	5	34
Summer	TN	PN	NO3	NH4	DON
Mean	0.508	0.040	0.312	0.029	0.199
Std dev	0.440	0.060	0.410	0.017	0.140
Median	0.349	0.024	0.138	0.025	0.171
Range Min	0.058	0.000	<0.01	<0.01	0.012
Range Max	3.350	0.430	3.050	0.087	0.873
No of Samples	158	119	137	89	154
% TN		6	42	4	48

mg/l	**PeatlandESUK 2018**				
All sites	**TN**	**PN**	**NO3**	**NH4**	**DON**
Annual 2018					
Mean	0.792	0.185	0.207	0.081	0.324
Std dev	0.628	0.364	0.169	0.136	0.211
Median	0.651	0.086	0.165	0.061	0.284
Range Min	0.235	0.012	0.006	0.025	0.000
Range Max	5.013	2.519	1.073	1.192	1.224
No of Samples	72	72	72	72	72
% TN		23	26	10	41
Winter	TN	PN	NO3	NH4	DON
Mean	0.558	0.068	0.241	0.057	0.192
Std dev	0.168	0.042	0.128	0.021	0.102
Median	0.557	0.060	0.235	0.052	0.178
Range Min	0.235	0.012	0.024	0.025	0.000
Range Max	0.964	0.164	0.502	0.119	0.368
No of Samples	36	36	36	36	36
%TN		12	43	10	34
Summer	TN	PN	NO3	NH4	DON
Mean	1.025	0.302	0.173	0.106	0.444
Std dev	0.812	0.489	0.198	0.189	0.216
Median	0.823	0.139	0.099	0.069	0.434
Range Min	0.272	0.028	0.006	0.033	0.043
Range Max	5.013	2.519	1.073	1.192	1.151
No of Samples	36	36	36	36	36
%TN		29	17	10	43

mg/l	**PeatlandESUK 2019**				
All sites	**TN**	**PN**	**NO3**	**NH4**	**DON**
Annual 2019					
Mean	0.743	0.115	0.092	0.067	0.469
Std dev	0.358	0.117	0.141	0.036	0.250
Median	0.622	0.085	0.030	0.060	0.421
Range Min	0.211	0.012	0.000	0.022	0.068
Range Max	2.013	0.810	0.650	0.205	1.210
No of Samples	72	72	72	72	72
% TN		15	12	9	63
Winter	TN	PN	NO3	NH4	DON
Mean	0.665	0.082	0.139	0.066	0.378
Std dev	0.321	0.062	0.173	0.038	0.204
Median	0.592	0.072	0.064	0.059	0.336
Range Min	0.211	0.012	0.000	0.022	0.068
Range Max	1.529	0.366	0.650	0.164	0.933
No of Samples	36	36	36	36	36
%TN		12	21	10	57
Summer	TN	PN	NO3	NH4	DON
Mean	0.822	0.148	0.046	0.068	0.560
Std dev	0.380	0.148	0.076	0.036	0.261
Median	0.770	0.103	0.015	0.061	0.522
Range Min	0.305	0.020	0.000	0.028	0.198
Range Max	2.013	0.810	0.317	0.205	1.210
No of Samples	36	36	36	36	36
%TN		18	6	8	68

mg/l	**Chapman et al. (2001; *cf*. Table 3)**				
All sites	**TN**	**PN**	**NO3**	**NH4**	**DON**
Annual					
Mean	0.570	0.035	0.394	0.029	0.183
Std dev	0.520	0.050	0.500	0.017	0.130
Median	0.410	0.024	0.191	0.025	0.159
Range Min	0.058	0.000	<0.01	<0.01	0.000
Range Max	3.350	0.430	3.050	0.110	0.873
No of Samples	313	214	289	209	303
% TN		5	50	5	40
Winter	TN	PN	NO3	NH4	DON
Mean	0.648	0.030	0.469	0.029	0.167
Std dev	0.580	0.030	0.560	0.017	0.120
Median	0.457	0.023	0.269	0.025	0.146
Range Min	0.080	0.000	<0.01	<0.01	0.000
Range Max	3.210	0.210	2.950	0.110	0.681
No of Samples	155	95	152	120	149
% TN		3	58	5	34
Summer	TN	PN	NO3	NH4	DON
Mean	0.508	0.040	0.312	0.029	0.199
Std dev	0.440	0.060	0.410	0.017	0.140
Median	0.349	0.024	0.138	0.025	0.171
Range Min	0.058	0.000	<0.01	<0.01	0.012
Range Max	3.350	0.430	3.050	0.087	0.873
No of Samples	158	119	137	89	154
% TN		6	42	4	48

mg/l	**PeatlandESUK 2020**				
All sites	**TN**	**PN**	**NO3**	**NH4**	**DON**
Annual 2020					
Mean	1.285	0.134	0.099	0.063	0.988
Std dev	0.715	0.175	0.150	0.048	0.685
Median	1.050	0.080	0.042	0.045	0.782
Range Min	0.186	0.019	0.000	0.024	-0.210
Range Max	2.886	1.267	0.767	0.266	2.445
No of Samples	60	60	60	60	60
% TN		10	8	5	77
Winter	TN	PN	NO3	NH4	DON
Mean	0.807	0.094	0.105	0.058	0.550
Std dev	0.410	0.070	0.114	0.031	0.378
Median	0.806	0.073	0.061	0.042	0.586
Range Min	0.186	0.019	0.006	0.024	-0.056
Range Max	1.861	0.276	0.423	0.141	1.397
No of Samples	30	30	30	30	30
%TN		12	13	7	68
Summer	TN	PN	NO3	NH4	DON
Mean	1.762	0.174	0.094	0.068	1.426
Std dev	0.633	0.233	0.181	0.060	0.644
Median	1.794	0.102	0.014	0.046	1.472
Range Min	0.642	0.030	0.000	0.027	-0.210
Range Max	2.886	1.267	0.767	0.266	2.445
No of Samples	30	30	30	30	30
%TN		10	5	4	81

mg/l	**PeatlandESUK 2021**				
All sites	**TN**	**PN**	**NO3**	**NH4**	**DON**
Annual 2021					
Mean	1.013	0.124	0.085	0.064	0.740
Std dev	0.473	0.109	0.090	0.039	0.401
Median	0.937	0.086	0.055	0.051	0.682
Range Min	0.362	0.015	0.000	0.024	0.177
Range Max	2.919	0.586	0.427	0.222	2.451
No of Samples	72	72	72	72	72
% TN		12	8	6	73
Winter	TN	PN	NO3	NH4	DON
Mean	0.811	0.085	0.047	0.064	0.539
Std dev	0.229	0.056	0.060	0.039	0.193
Median	0.805	0.069	0.021	0.051	0.480
Range Min	0.362	0.015	0.000	0.024	0.177
Range Max	1.234	0.249	0.204	0.174	0.943
No of Samples	36	36	36	36	36
%TN		11	6	8	66
Summer	TN	PN	NO3	NH4	DON
Mean	1.214	0.162	0.123	0.064	0.942
Std dev	0.564	0.135	0.099	0.040	0.453
Median	1.023	0.135	0.087	0.051	0.848
Range Min	0.473	0.022	0.005	0.031	0.266
Range Max	2.919	0.586	0.427	0.222	2.451
No of Samples	36	36	36	36	36
%TN		13	10	5	78

The below **Table A19.2** summarises for the individual annual 2018-2021 (flow-weighted) N export rates (and their descriptive statistics), across the entire year or separately for winter and summer periods, measured at the three sites (Nidderdale, Mossdale and Whitendale) for the main N parameters compared to those reported in Chapman et al. (2001) for the most peat dominated site (Highlands). The comparison shows overall very good agreement between the Chapman et al. data and data for the three sites in this study. However, the Chapman et al study site (Highlands) represents only one year and a catchment with only 54% (deep) peat and 13% peaty podzol soils.

Table A19.2 Comparison of Chapman *et al*. (2001; *cf*. Table 4) for the most peaty site ('Highland') for total N (TN) and its component data (particulate N [PN], nitrate [NO_3], ammonia [NH_4] and dissolved organic N [DON]) collected monthly during April 1997-1998 to the Peatland-ES-UK sites (Nidderdale, Mossdale, Whitendale) during 2018-2021. Units are the same and flow weighted (i.e. gN per month and hectare catchment size). The percentage values are also provided (vs. total N) and the winter/summer ratio (as in the brackets for the Chapman table).

Chapman et al. (2001; *cf*. Table 4)

flow weighted	TN	PN	NO3	NH4	DON
Highland	*Soil type 54% Peat, 13% Peaty podzols*				
Annual	0.293	0.019 (8)	0.089 (28)	0.016 (7)	0.169 (57)
Winter	0.287	0.014 (5)	0.091 (37)	0.015 (7)	0.167 (51)
Summer	0.309	0.033 (9)	0.085 (22)	0.017 (6)	0.174 (63)
Ratio		0.42	1.07	0.88	0.96

PeatlandESUK (2018)

g month-1 ha-1	TN	PN	%	NO3	%	NH4	%	DON	%
Nidderdale									
Annual 18	0.196	0.031	16	0.066	33	0.022	11	0.078	40
Winter18	0.304	0.042	14	0.115	38	0.032	11	0.115	38
Summer 18	0.089	0.020	23	0.017	19	0.012	13	0.040	45
Ratio		2.1		6.9		2.8		2.8	
Mosdale									
Annual 18	0.464	0.076	16	0.136	29	0.053	11	0.198	43
Winter18	0.579	0.086	15	0.213	37	0.071	12	0.210	36
Summer 18	0.348	0.066	19	0.060	17	0.036	10	0.186	53
Ratio		1.3		3.5		2.0		1.1	
Whitendale									
Annual 18	0.646	0.074	12	0.295	46	0.047	7	0.230	36
Winter18	0.836	0.080	10	0.418	50	0.063	7	0.274	33
Summer 18	0.456	0.068	15	0.171	38	0.031	7	0.186	41
Ratio		1.2		2.4		2.0		1.5	

PeatlandESUK (2019)

g month-1 ha-1	TN	PN	%	NO3	%	NH4	%	DON	%
Nidd									
Annual 19	0.540	0.120	22	0.024	4	0.051	9	0.345	64
Winter19	0.461	0.079	17	0.031	7	0.056	12	0.296	64
Summer19	0.619	0.161	26	0.016	3	0.046	8	0.395	64
Ratio		0.5		1.9		1.2		0.8	
Moss									
Annual 19	0.622	0.073	12	0.022	4	0.058	9	0.469	75
Winter19	0.602	0.073	12	0.035	6	0.062	10	0.433	72
Summer19	0.641	0.074	12	0.009	1	0.053	8	0.505	79
Ratio		1.0		3.9		1.2		0.9	
Whit									
Annual 19	0.808	0.076	9	0.243	30	0.066	8	0.423	52
Winter19	0.919	0.049	5	0.356	39	0.069	8	0.444	48
Summer19	0.698	0.104	15	0.129	18	0.064	9	0.401	58
Ratio		0.5		2.8		1.1		1.1	

Chapman et al. (2001; *cf*. Table 4)

flow weighted	TN	PN	NO3	NH4	DON
Highland	*Soil type 54% Peat, 13% Peaty podzols*				
Annual	0.293	0.019 (8)	0.089 (28)	0.016 (7)	0.169 (57)
Winter	0.287	0.014 (5)	0.091 (37)	0.015 (7)	0.167 (51)
Summer	0.309	0.033 (9)	0.085 (22)	0.017 (6)	0.174 (63)
Ratio		0.42	1.07	0.88	0.96

PeatlandESUK (2020)

g month-1 ha-1	TN	PN		NO3		NH4		DON	
Nidd									
Annual20	1.215	0.172	14	0.029	2	0.075	6	0.939	77
Winter20	1.140	0.157	14	0.055	5	0.098	9	0.829	73
Summer20	1.289	0.186	14	0.003	0	0.052	4	1.048	81
Ratio		0.8		20.3		1.9		0.8	
Moss									
Annual 20	1.694	0.122	7	0.104	6	0.086	5	1.383	82
Winter20	1.394	0.148	11	0.084	6	0.096	7	1.066	76
Summer20	1.995	0.096	5	0.124	6	0.075	4	1.700	85
Ratio		1.5		0.7		1.3		0.6	
Whit									
Annual 20	1.774	0.132	7	0.344	19	0.085	5	1.213	68
Winter20	1.581	0.122	8	0.501	32	0.101	6	0.856	54
Summer20	1.967	0.141	7	0.188	10	0.068	3	1.570	80
Ratio		0.9		2.7		1.5		0.5	

PeatlandESUK (2021)

g month-1 ha-1	TN	PN		NO3		NH4		DON	
Nidd									
Annual21	0.569	0.082	14	0.040	7	0.053	9	0.394	69
Winter21	0.762	0.117	15	0.074	10	0.081	11	0.489	64
Summer21	0.376	0.047	12	0.006	2	0.024	6	0.299	80
Ratio		2.5		13.1		3.4		1.6	
Moss									
Annual 21	0.782	0.070	9	0.049	6	0.050	6	0.613	78
Winter21	0.977	0.102	10	0.082	8	0.073	8	0.720	74
Summer21	0.587	0.038	6	0.015	3	0.027	5	0.506	86
Ratio		2.7		5.3		2.7		1.4	
Whit									
Annual 21	1.027	0.109	11	0.227	22	0.044	4	0.648	63
Winter21	1.197	0.108	9	0.391	33	0.058	5	0.639	53
Summer21	0.856	0.109	13	0.062	7	0.029	3	0.656	77
Ratio		1.0		6.3		2.0		1.0	

Appendix 20 (management effect matrix)

In summary, notwithstanding the discussed limitations of the so far medium-term study capturing intermediate effects and the lack of an overall unmanaged catchment-scale control, the findings across the various sections of the report can be summarised in a management effect matrix (**Table A20.1** on the following pages) highlighting observed or likely ecological impacts and ecosystem services benefits. Importantly, this matrix was conceived by Natural England for the Defra report (Heinemeyer et al., 2019b) and has only been updated with the latest findings.

Table A20.1 (following pages) Management effect matrix showing direction of actual change (+ increasing, - reducing, (+) or (-) minor, (NC) no change) and biodiversity/ecosystem services (ES) effect (green +ve, red -ve, with the strength of tone indicating the effect degree as interpreted by the project team – as in the previous Defra report) in response to management mainly comparing burning to mowing (also considering the individual plot-level managements: mown with (LB) or without (BR) brash) or either management to uncut plots in relation to plot and catchment scale measurements presented in this project. Note: the interpretation needs to consider the so far limited post-management monitoring period of 9 years only, longer term impacts are likely to be different as vegetation reaches maturity (see Hancock et al., 2018) and the entire catchment management changes (see Harper et al., 2018). Sph. refers to *Sphagnum* spp., Eri. to *Eriophorum* spp., Call. to *Calluna vulgaris*, 'Bare/brash/burnt' refers to the combined cover of bare, brash or burnt ground.

Variable	Burning	Mowing	Notes
Vegetation composition (cover & abundance)	*Calluna* -	*Calluna* -	Both managements reduced cover. Faster initial growth on mown (sprouting) than on burnt (germination) but similar cover and height after 4 years. Highest increase in cover on driest site, especially on burnt plots, but greatest increase in height on wettest site. However, sites suffered from heather beetle set backs, especially on burnt plots at the wetter sites and mown plots on the driest site.
	Cotton-grass (*Eriophorum*) spp. +-	Cotton-grass (*Eriophorum*) spp. +	Greater *Eriophorum vaginatum* cover increase after mowing. Potentially beneficial regarding function but methane flux and over-dominance can be an issue especially on grazed sites (increase in *Sphagnum* cover of more importance but trajectory still uncertain).
	Sphagnum (+)	*Sphagnum* (+)	Slight increase overall, possibly more on mown (especially *Sphagnum capillifolium*) than burnt plots but different starting points, mown declining at first, and mown as well as uncut highly variable over time. Overall greatest cover on the wettest site.
	Other bryophytes NC	Other bryophytes NC	Decline at first then slow recovery to pre-management levels. Most increase (and indication of drying) on uncut plots.
	Bare/brash/burnt (+)	Bare/brash/burnt (+)	Greater bare/burnt after burning and greater brash on mown plots but then declining and similar cover on managed plots by 4th year. Similar brash cover on burnt and uncut after 10 years with mown slightly higher.
Vegetation Species Richness	+	NC	Species richness only significantly increased after burning (and was lower pre-management compared to other management plots).
Vegetation Diversity	(++)	(+)	Diversity increased significantly more on burnt than mown but both increased compared to uncut. Higher *Sph.* diversity on drier site.
***Sphagnum* addition**	NC(+-)	NC	Added as Beadamoss pellets in year 2 but no overall sign of success, only one site showed some higher cover on treated burnt vs. untreated burnt plots for one of the three species (i.e. *Sphagnum capilifolium*). Planting of plugs to be considered better.
***Calluna* height**	-	-	Decreased after management, initially mostly on burnt (greater regeneration from stems on mown vs. seed on burn) but by year 4 & 9 no difference (both ~15 cm & ~21 cm, well below uncut ~35 cm) but slightly (significantly) reduced on burnt plots by heather beetle.
***Calluna* biomass**	L:W +, LAI - NC	L:W +, LAI - NC	Though 'leafy to woody ratio' (L:W) higher 3 years after burn and mown vs. uncut and pre-teatment, Leaf Area Index (LAI), and hence quantity of leaves, much greater pre-treatment, so likely similar direction of long-term recovery to pre-management levels. Heather beetle damage caused variable regrowth (affecting it more on burnt plots), otherwise likely similar biomass on burnt and mown plots.
***Calluna* nutrition**	N+, K+, Mn+, Zn+, P+ Mg (+)	N+, Mn+, Zn+, P+	Nutrition value increased on both mown and burnt (often for more and longer) vs. uncut in terms of N, P, Mn (Mg on burnt) & K but not other elements, apart from less Al, with benefits to light response and C-uptake of photosynthesis (N, Mn, Mg) and likely also regarding grouse for P, K and possibly Mn. Also some Mn benefit by burning to *Eriophorum* shoots and especially in flower heads.

Variable	Burning	Mowing	Notes
Microtopography	NC	-	Mowing reduced microtopographic variability by removing some of the hummock/tussock tops, even visible after 10 years - also remaining visible (but not measured as part of the project) across catchments as bare patches where machinery cut into peat.
Peat pipes	NC	NC	No difference in peat pipe numbers (based on manual GPR surveys) between managements or compared to uncut plots. Small average diameter of mostly <10 cm and frequency similar to previously reported blanket bog values (0.05 pipes per metre survey length).
Peat depth accumulation	NC (+)	NC (+)	No real difference in plot-level peat accumulation (GPR survey 2016) but a small (~0.25 mm/year) median increase over 8 years with peat rods (yet highly variable). Additional plots within the wettest catchment indicated slightly higher increase on mown areas reflecting brash layer effects, whereas burnt plots only increased C-content via charcoal (without height increase). However, highest increase was measured on *Sphagnum* (1.88 mm/year), old *Calluna* (1.50 mm/year) and *Eriophorum* (0.69 mm/year) dominated areas.
Peat carbon accumulation	(+)	n.a.	Peat cores with dated time periods from historic burn areas revealed higher C accumulation during periods of more frequent burns (for some periods since ~1700 AD; i.e., not a C budget) with higher bulk density and organic C content linked to charcoal abundance.
Peat physical properties	(-)	(+)	Bulk density or peat depth did not change due to mowing, but bulk density was higher (with peat moisture impacts) under burning reflecting charocal inputs. Soil temperature averages were unaffected by management, but brash cover and uncut plots showed smaller temperature ranges (brash insulation with reduced maxima) and burnt plots showed only slightly increased maximum temperatures.
Peat chemical properties	NC	NC	Peat pore water pH increased over time by one unit, which seemed to be related to a general recovery from acidification, but also partly related to a soil temperature increase of about 1^{o}C over 5 yrs. However, pH did not change significantly due to management although burnt plots showed the strongest increase over time. Peat chemistry (in the surface 5 cm) indicated surface charcoal accumulation in burnt compared to mown plots and mown plots showed increased surface lignin concentrations (when leaving brash).
Peat pore water quality	NC	NC	Peat pore water DOC, UV absorption spectra did not differ between managements or cf. uncut plots but between sites. However, vegetation type did explain some of the observed variability in Phase 1 with > SUVA under more sedge and *Sphagnum* cover and < SUVA under more *Calluna* cover. A more complex relationship with vegetation became evident over time with heather, sedge and herb reducing UV colour aspects vs. increases under moss, bare and brash. Overall pH increased by 1 unit with a peak during 2016-2018 (partly in relation to soil temperature) but without any management impact (only slightly and not significantly higher in burnt plots).
Flow water quality	(-)	(-)	As for pore water, streams showed an increase over time in pH and in conductivity unrelated to management. Stream water showed not sinificantly higher N concentrations and total N export for burnt (which could be beneficial for counteracting elevated atmospheric N deposition) but higher DOC and POC concentrations in mown streams and slightly higher DOC export in burnt streams. UV absorption spectra only showed seasonal and interannual differences related to air temperature and rainfall. However, stream P concentrations increased significantly in mown catchments.
Water table & soil moisture	+	+	Water table depth and surface soil moisture and soil moisture under comparable water tables was initially lower on burnt than on mown plots after management (during the first five years burnt ~2 cm lower than mown plots) but with considerable site differences and seasonal fluctuations. WTD became ~2 cm higher on burnt plots over the last 5 years but mown had lower ranges. Uncut became the driest over time.
Stream flow	+	-	Stream flow was reduced at two sites by ~15% after mowing (higher flow loss on burnt), which increased with an increase in catchment management area to about 20% but only in catchments with historic drainage. These two sites indicated higher runoff from burnt than from mown catchments under equally high (near saturation) water table and rainfall conditions. Only the driest site had a significantly higher peak flow with shorter lag in the burnt vs. mown catchment and a non-significantly lower duration. However, runoff/retention from near saturated catchments became similar over time. Overall, impacts on flooding downstream remain uncertain.

Variable	Burning	Mowing	Notes
Cranefly emergence	-	(+)	Indicated lower spring emergence on very dry areas (and lower soil moisture vs. water table depth relationships on burnt plots) increased cranefly emergence on wetter (mown) areas in the dry years but indicated possible reductions in wetter years, particularly on already wet sites. Emergence traps indicated an optimum soil moisture range of between 80%-97%.
Cranefly abundance	(-)	(+)	Overall greater summer abundance in mown than burnt catchment transects in dry periods but with the opposite impact in wetter years and also negative impacts by mowing on emergence in plots on the wettest site (risk of becoming too wet).
Bird populations (i.e. three cranefly dependant upland spp.)	+	+	Models predicted a decline in populations for all three bird species (golden plover, dunlin and red grouse) under predicted warmer and drier future (2050-2080) summer scenarios, with greater reductions under burn than mown management (particularly when leaving brash). However, modelling did not consider the possibility that on very wet sites mowing could result in water logging causing death of cranefly larvae and thus reduced bird numbers. Golden plover predictions including vegetation height, which was lower overall on managed plots (and lowest and thus most beneficial for breeding densities on burnt plots when considering heather regrowth) vs. uncut catchment areas, showed initial post-management benefits of either management. Unmanaged, tall vegetation areas showed serious negative consequences on densities.
Soil respiration (CO_2)	-	(+)	Reduced soil respiration and temperature sensitivity (Q_{10}) on burnt (and mown with brash removal) compared to mown (with brash left) plots, particularly the top 5 cm peat layer (which respired a very high proportion (~60%) of the top 20 cm).
Net ecosystem exchange (CO_2)	(+)	(-)	Initially (2013) higher net C losses after management on burnt vs. mown plots, but 4 yrs after management no difference with both mamagements overall loosing C compared to net gains by uncut plots with highest 5 yr mean C gains on the wettest and a small loss on the driest site. Overall quicker recovery on burnt than mown plots (linked to higher nutrient content and lower respiration, but variable due to heather beetle impact). Uncut declining overall in net C uptake, related to lower nutrient and higher respiration, thus both managements likely beneficial long-term.
Net methane emissions (CH_4)	(-)	(+)	Higher median emissions on mown than burnt plots (although uncut plots showed highest peak fluxes). Very high site and interannual variability in net flux and particularly in mean vs. median estimates; peak in methane emissions (2015-2017), which was linked to warmer, wetter and less acidic soil conditions. Overall highest flux on the wettest, least modified site with an overall significantly positive relationships with water table, soil temperature and sedge cover (negative with lower pH, higher heather cover and brash layer - likely increasing oxidative layer). Therefore, net emissions likely to be lower on burnt (cf. mown) plots due to lower water tables and less *Eriophorum vaginatum* cover (plant-mediated methane flux was about 60%). Methane flux ~20% lower in the dark vs. light.
Net Ecosystem Carbon Balance (NECB)	(+) less as faster C uptake recovery	(+) higher when incl. brash decomposition	Overall uncut was a small net C sink, especially on the wetter sites, but this depended on including fluvial C losses and either using the median or mean of C fluxes (particularly methane flux was highest in years 4-5 post-management when both managements showed about 8 times larger C losses than uncut mainly due to very low net ecosystem exchange C uptake). However, burnt areas showed ~32% less C loss than mown areas even when including emissions from burnt heather, and C loss for mown (brash decomposition) also likely to still increase. Overall, uncut (old heather) showed a declining C sink strength over time with a mean annual water table threshold defining C-sink/-source threshold of around 12 cm.
Net Greenhouse Gas Emissions (net GHGs) in CO_2 equivalents)	+ lower methane	+ higher methane	Uncut plots had lowest net GHGs (small sink) being a net GHGs sink on the wetter sites vs. a source on the driest site but the ranges for net GHG component fluxes (CO_2 and CH_4) aligning with the IUCN UK 'near intact' status. Both managements had positive net GHGs (source) with the greatest on mown plots (and on the wettest sites), being nearly twice that of burnt plots (lowest on the driest site). Site and interannual variability was very high and overall high changes in net GHGs depending on using the mean or median for net methane emissions. But as for NECB, net GHGs were greatest on mown plots, even when including the emissions from biomass burning (red) and mown plots do not yet include the complete brash C losses (decomposition).
Air quality (pollution)	+	(+)	Larger amount of air pollution (e.g. SO_2; NO_x; particulate matter) from burning than mowing equal areas, mainly due to burning heather (i.e. biomass), with mowing resulting in overall much lower emissions and pollution from vehicle use (i.e. diesel).

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This project was designed in response to a Natural England and Defra request for a research project to address evidence needs. The aims, methods, sites, design, etc. were approved and funded for the first 5 years by Defra. A Project Advisory Group was established with representatives from a wide variety of interested parties including water companies, conservation groups, upland management and shooting organisations. This group as a whole was consulted and updated throughout the project and helped to act as an external source of advice and input.

After the first five-year phase of the project, Defra funding was not continued. The Project Advisory Group recognised the value of the work overall, the value of what had already been carried out and the importance of continuing into the medium and long term, according to Defra's and Natural England's original intention and tender specification. The organisations represented on the Project Advisory Group as a whole worked collaboratively to provide funds with which to continue the research. Funding for the second five years of the project therefore came from organisations with a range of backgrounds and beliefs, united by a common recognition that the only way to a positive and productive plan for moorland management in future is to answer the questions that had been identified, in a way that gives reliable answers, over a timescale that is appropriate.

The project itself remains the same and was not influenced in any way by this change in funding stream. In recent years some voices in the scientific community (e.g. Brown & Holden, 2020) have used this as an excuse to call into question the validity and credibility of the research and of those who carry it out. To do so ignores the important facts laid out above that the project, its analysis or interpretation continued exactly as planned at the onset by ourselves, Defra and NE and the findings retain that value and credibility, which has also been recognised by further funding from the NERC.

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