Effects of burning and grazing on carbon sequestration in a Pennine blanket bog, UK

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Abstract: Terrestrial ecosystems contain large amounts of carbon (C) and have the potential to significantly increase atmospheric carbon dioxide (CO_2) concentrations. Peatlands are particularly important for C storage, although little is known about the effects of anthropogenic activities on C balance in these ecosystems. Sheep-grazing and rotational burning are widely practised on blanket peat moorlands in the United Kingdom. The effects of these activities on C sequestration in peat has been investigated with a long-term randomized block experiment with treatments: (a) grazed + unburnt; (b) grazed + burnt every ten years; (c) ungrazed + unburnt. C accumulation under these treatments was compared by identifying a chronologically synchronous horizon within the peat common to all treatment plots. This fixed point was defined by the 'take-off' in concentration of spheroidal carbonaceous particles and was supported by the record of charcoal fragments. There was no significant difference in recent C accumulation rates between lightly grazed and ungrazed plots. In contrast, after 30 years there was significantly less C stored in the blanket peat in plots which had been burned every ten years. The results indicate that light sheep-grazing at this site did not affect rates of C accumulation in blanket peat, but decadal burning of moorland reduced C sequestration.

Key words: Carbon storage, charcoal, moorland management, peat accumulation, spheroidal carbonaceous particles, SCP.

Introduction

Terrestrial ecosystems contain three times more carbon (C) than the atmosphere (Schimel, 1995) and play an important role in regulating the atmospheric concentration of greenhouse gases (Melillo *et al.*, 1996), particularly carbon dioxide (CO_2). There is concern that anthropogenic disturbance of these ecosystems is depleting terrestrial C stores and causing a net transfer of C to the atmosphere (Houghton, 1995), thereby augmenting industrial sources of CO_2 and perhaps contributing to climate change (Kattenberg *et al.*, 1996). For example, deforestation of tropical rainforests is estimated to be transferring *c.* 1.6 Gt C annually to the atmosphere (Schimel, 1995).

Little is known about the effects of anthropogenic activities on peatland C balance despite the large amounts of C known to be stored in these ecosystems: northern peatlands contain one fifth (Gorham, 1991) of the global terrestrial C store and approximately the same amount of C as the atmosphere (Clymo, 1996). In Great Britain, nearly half of all soil C is contained within Scottish blanket peats (Milne and Brown, 1997).

While peatlands have been exploited for fuel, grazing, horticulture and afforestation by human societies, there have been few attempts to investigate the effect of these activities on peatland C balance, although drainage and mining for fuel and horticultural use is believed to have greatly depleted peatland C stores (Immirzi *et al.*, 1992).

In the current study, a randomized block experiment set up by Dr R.J. Elliot in 1954 at Hard Hill, Moor House National Nature Reserve (NNR), was used to determine whether sheep grazing and burning of moorland every ten years influenced C accumulation in peats.

Materials and methods

Site description

Moor House NNR is located in the northern Pennine hills of England (Figure 1). The experiment on Hard Hill was originally established to investigate the effects of grazing and rotational

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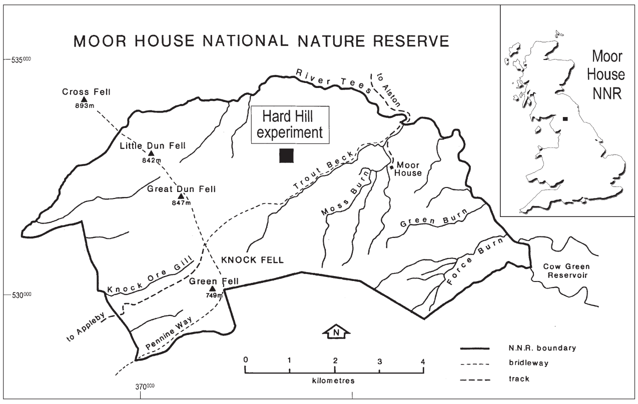

Figure 1 Location of Hard Hill experimental plots within Moor House National Nature Reserve and Great Britain.

Table 1 Site characteristics of the Hard Hill experimental plots (climate data from Heal and Smith, 1978)

	Hard Hill plots
Grid references:	
Block A	NY 743330
Block B	NY 740330
Block C	NY 736330
Block D	NY 738331
Altitude (m)	600–630
Mean annual temperature (°C)	5.1
Mean annual rainfall (mm)	1900
Original vegetation	Calluneto-Eriophoretum
Soil type	Blanket bog (1–2 m thick)

burning on blanket bog vegetation. The experimental design is factorial and consists of three different burning treatments (burnt every ten years, burnt every 20 years, not burnt) × two grazing treatments (grazed and ungrazed); thus, there are six different treatment plots in each experimental block (grazed and ungrazed versions of each burning treatment). Each of the six treatment plots is replicated in a random pattern in four blocks which are all located on a uniform and generally uneroded gentle slope to the southeast of the summit of Hard Hill.

The entire study area was burned prior to the construction of the experimental blocks in 1954. The method of burning used is similar to traditional moorland burning (Hobbs and Gimingham, 1987). Characteristics of the site and location of the experimental blocks are shown in Table 1.

In the present study, two burning treatments have been sampled to investigate the effects of rotational burning: the ten-year rotation and the unburnt plots. Both plots were grazed. Additionally, to investigate the effects of grazing, samples were also collected from ungrazed plots which also had not been burnt; thus a total of three treatments in each experimental block were sampled (ten-year burn and grazed, unburnt and grazed, unburnt and ungrazed). All four experimental blocks were investigated and a key to the samples is provided in Table 2, showing the reference code describing the experimental blocks (A–D) and treatments (G = grazed; U = ungrazed; B = burnt every ten years).

Sampling procedure

Short peat cores were extracted from the central part of the three treatment plots in each of the four blocks in September 1997 by gently pushing plastic tubes (diameter 10 cm and depth 21 cm) into the peat surface, after first carefully incising an outline of the cores through the top 10 cm of peat with a knife. The cores were

Table 2 Experimental layout of the Hard Hill plots used in the present study, showing treatment reference codes

Block	Burning treatment	Grazing treatment	Reference code
A	Burnt 1954 and every ten years	Grazed	A/GB
A	Burnt 1954 only	Grazed	A/G
A	Burnt 1954 only	Ungrazed	A/U
B	Burnt 1954 and every ten years	Grazed	B/GB
B	Burnt 1954 only	Grazed	B/G
B	Burnt 1954 only	Ungrazed	B/U
C	Burnt 1954 and every ten years	Grazed	C/GB
C	Burnt 1954 only	Grazed	C/G
C	Burnt 1954 only	Ungrazed	C/U
D	Burnt 1954 and every ten years	Grazed	D/GB
D	Burnt 1954 only	Grazed	D/G
D	Burnt 1954 only	Ungrazed	D/U

dug out using a spade, placed in labelled plastic bags and sealed. The base of all cores was above the water table and the aspect, slope, vegetation composition and total depth of peat were recorded for each coring location.

Determination of carbon content

On returning to the laboratory, each core was stored in a refrigerated room (*c.* 4°C) until analysed. The cores were extracted, one centimetre at a time, by gently forcing the core vertically out of the plastic tubing using a wooden piston. One-centimetre thick horizontal sections were taken using a sharp knife, weighed fresh and then wrapped in aluminium foil. A subsample of approximately 20–40 g was removed from each section to determine moisture content. This subsample was weighed while fresh, oven-dried (105°C) for 24 hours, cooled in a desiccator and weighed again to determine the moisture content. The subsample was taken to be representative of the whole section, and, therefore, the total dry mass of the complete section (D_t) could be calculated using:

$$D_t = W_t \times (100–\%M_s)/100$$

where $\%M_s$ was the moisture content of the sub-sample removed from a section with total wet weight W_t.

The C concentration of peat was assumed to be 50% dry mass since this has frequently been reported for peat elsewhere (e.g., Heal and Smith, 1978; Allen, 1989; Immirzi *et al.*, 1992).

Chronological marker

The effects of the treatments on C accumulation were assessed by quantifying the C contained above a layer which was chronologically synchronous across all cores. This layer had to have been formed before the start of the experiment and, to allow small changes in C accumulation caused by the treatments to be identified, the amount of C above the 'fixed point' and below the start of the experiment had to be small to reduce natural variability in C accumulation.

Radiocarbon methods are most frequently used to date peat profiles; however, they are problematic in dating recently formed peats, and were therefore not used in the present study (Tolonen *et al.*, 1993). There were several other candidate chronological markers which had potential as fixed points in the present study although the record of spheroidal carbonaceous particles (SCPs) preserved within peat profiles offered greatest potential since these particles can be rapidly analysed at low cost. The particles are mainly formed from oil and coal combustion and records of their deposition follow the historical fuel consumption of the area where the particles were deposited (Wik and Renberg, 1996). Therefore, a rapid increase in SCP concentrations in surface lake sediments and stratified peat profiles reflects industrialization and the increase in fuel consumption in a region. Although the precise date of this 'take-off' varies between regions due to differences in industrialization (Wik and Renberg, 1996), all the Hard Hill experimental plots are located within a very small area (<1 km^2) and it can be assumed that each received the same historical load of SCP deposition.

To determine the industrial 'take-off' in deposition of SCPs, samples were initially selected at intervals of 4 cm down the profile of each core. The SCP concentration of these 'range-finder' samples was determined and then a second batch of samples at 1 cm intervals selected by choosing the part of the profile which was expected, based on the 'range-finders', to contain the SCP 'take-off'.

The method used to quantify the SCPs in each sample was based on Rhodes (1998): A sample of air-dried peat (0.2 g) was placed in a 250 cm^3 conical flask and 20 cm^3 of distilled water added. The solution was covered and left for 24 hours to allow the peat to rehydrate and then 20 cm^3 of 6% hydrogen peroxide was added to the solution, which was again covered and placed in an oven at 50°C for 48 hours. The solution was filtered through a Whatman Number 1 filter paper, the filter paper contents retained and the liquid discarded. The filtrate was carefully washed into a 9 cm diameter plastic petri-dish using distilled water and returned to the oven (50°C) to evaporate the excess liquid. Another 20 cm^3 of 6% hydrogen peroxide was then added and the lid placed on the petri-dish and replaced in the oven at 50°C for 48 hours. The lid to the petri-dish was then removed allowing the liquid to evaporate after which it was ready to count using a stereo microscope (Wild M3Z, Heerbrugg, Switzerland) at $\times$40 magnification.

Eight transects, covering more than half the petri-dish area, were scanned and the total number of identifiable SCPs counted; it was found from a preliminary investigation that the total amount of SCPs in samples could be accurately estimated by scanning these eight transects.

The SCP 'take-off' is usually estimated simply from the trend in SCP concentration in a profile (Rose *et al.*, 1995). However, in the present study the depth where the concentration first exceeded 100 SCPs was used to provide a more objective definition for the 'take-off'.

Since the dates of experimental burns at the Hard Hill site were known it was suspected that the record of charcoal fragments preserved in the peat profiles may provide additional chronological information. Quantification of charcoal fragments was therefore undertaken for all profiles from blocks A and B, preparing the samples as for SCP counting (Rhodes, 1998). Charcoal fragments were counted at $\times$40 magnification along 16 transects, representing half of the petri-dish area. They were measured using a 10$\times$10 square grid graticule and grouped into three size classes (125–250 μm, 250–500 μm and $>$500 μm).

Statistical analyses

The mass of C contained above the SCP 'take-off' in each core was calculated and an analysis of variance (ANOVA) performed to establish whether there were significant treatment effects. The ANOVA was undertaken using MINITAB version 10.2.

Results

The profiles of SCP concentration for each peat core are shown in Figure 2. The figure is divided into four charts with each experimental block being represented on a separate chart. The values for SCPs ranged from less than 50 at the base of the cores to greater than 1000. The 'take-off' was generally at a greater depth for the unburnt treatments (G and U) than the treatment being burnt every ten years (GB; Figure 2). In three of the blocks the unburnt 'take-offs' centre around a depth of 8–12 cm, though in block D all treatments showed 'take-offs' nearer the surface.

Although the SCP 'take-off' is believed to reflect the increasing deposition of SCPs caused by industrialization, there are other factors which affect concentrations, such as rates of peat accumulation and compaction (Clymo *et al.*, 1990). Although variations in compaction will have influenced the profiles of SCPs in the cores, most of the 'take-offs' are located in the middle part of the cores where compaction during coring and extraction is considered small. Since the basal layer of the peat in the cores had SCP counts of less than 20–30 and the 'take-off' appeared to be signalled by SCP counts exceeding 100, a compaction equivalent to squashing 4 cm of peat into 1 cm would have been required to cause an apparent SCP 'take-off'. The degree of compaction during coring and core extraction was considerably lower than this and was confined to the surface layers of peat.

Similarly, the rate of peat accumulation would have needed to have been reduced by at least a quarter to produce the concentrations of SCPs which could have been misinterpreted as an industrial 'take-off'. There is no stratigraphical evidence to suggest that the peat accumulation rate had changed rapidly at the same time as the SCP 'take-offs', as indicated by distinct layers of increased humification or changes in plant species composition of the peat. Furthermore, the experimental plots were situated on uniform slopes and some distance away from any areas of peat erosion which could have been responsible for a rapid reduction in peat accumulation (through alteration of hydrological conditions). The SCP concentrations below the 'take-off' in each peat core were also relatively constant, with counts of typically 0–30. In several cores, concentrations within this range existed over a large depth interval (e.g., from 6–10 cm and the base of the cores). The rate of peat accumulation over this depth is likely to have fluctuated with variations in the factors affecting peat accumulation (e.g., small changes in climate), but the relatively constant concentrations of SCPs suggest that changes in peat accumulation did not have a major affect on the SCP concentrations.

The reliability of the profiles of SCP concentration also depends on the accuracy of the method used to quantify SCPs. Rhodes (1998) undertook a thorough test of the method using charcoal particles of a similar size to SCPs, and showed that very few particles were lost during preparation. Since the inorganic component of the peat samples was very low and almost all the organic component had been bleached by hydrogen peroxide, the vast majority of SCPs in the petri-dish samples were clearly visible and easily counted.

Clymo and Mackay (1987) have shown that vertical movement of pollen grains may occur in the surface layers of peat and since SCPs are of a similar size (e.g., 10–50 μm) it is possible that some movement of SCPs may have occurred in the profiles. Clymo and Mackay (1987) observed an average movement of pollen in cylinders of *Sphagnum* of 1.5 cm, although even if this movement occurred in SCPs it may not affect the present results since it could have occurred equally in all cores. Furthermore, although the bulk density of the peat profiles was not accurately measured in the present study (see below) it was considered to be much greater than the packed *Sphagnum* cylinders used in the experiments of Clymo and Mackay (1987), which would be expected to further inhibit movement of particles. More recently, Punning and Alliksaar (1997) have investigated the trapping of similar particles to SCPs in the surface of *Sphagnum* peats and concluded that very little movement of fly-ash particles occurred.

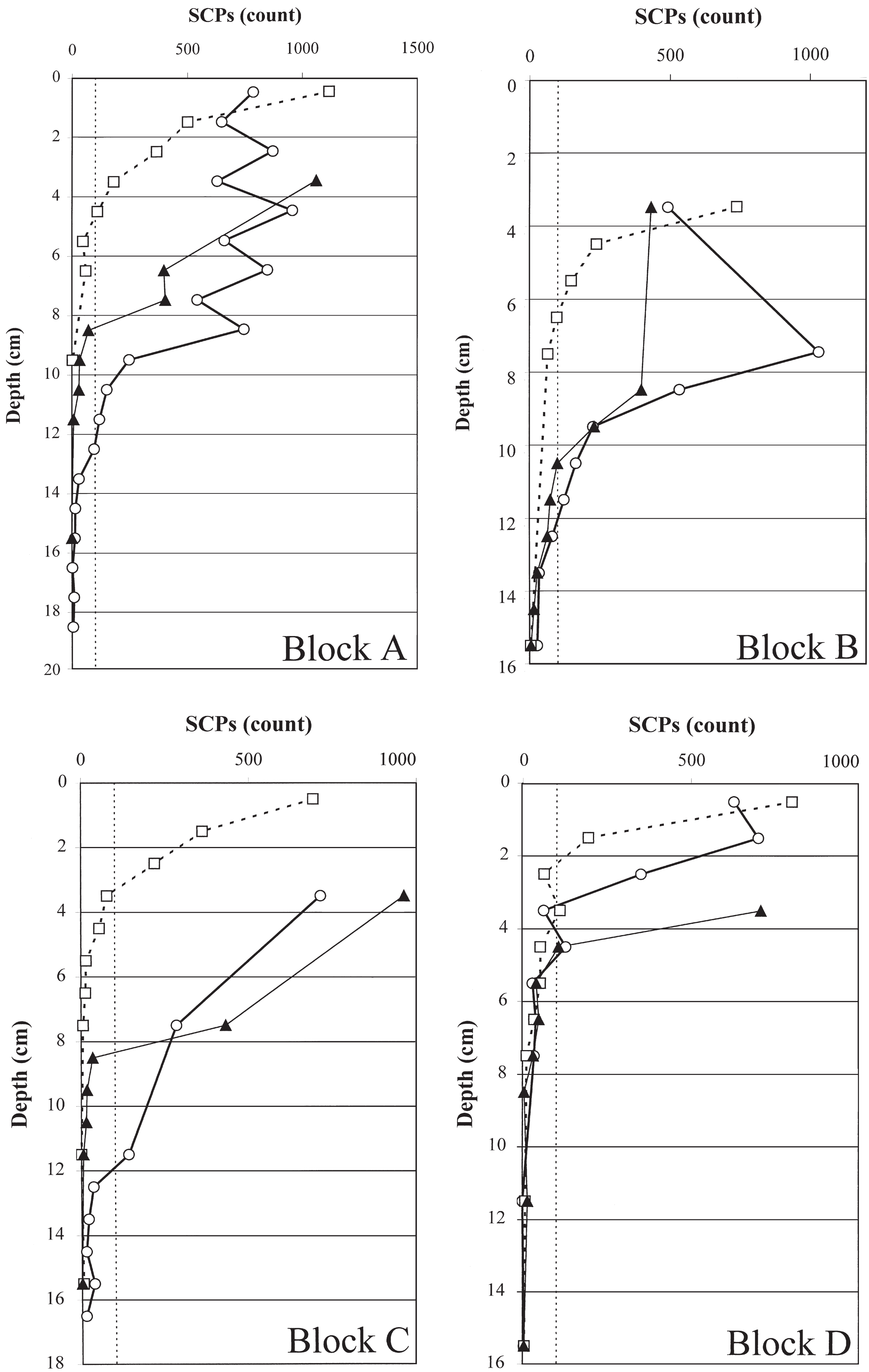

Figure 2 Profiles of spheroidal carbonaceous particle (SCP) counts for each treatment and each block. Blocks are represented as A, B, C and D. The treatments are: G = grazed + unburnt (open circles); GB = grazed + burnt every ten years (open squares); U = ungrazed + unburnt (filled triangles). Dashed vertical line indicates the threshold concentration of 100 SCPs.

The profiles of charcoal concentration are shown in Figure 3 and provide chronological information which supports the SCP records. In the plots which have not been burnt since 1954 (treatments G and U) there is a peak in charcoal concentration just above the SCP 'take-off'. Due to the high concentrations of large charcoal particles at this depth, the charcoal must represent a very local fire as large particles are known to be deposited very close to the burn (Rhodes, 1996). Therefore, we consider that these charcoal peaks represent the most recent known burn on the plots in 1954; charcoal concentrations above this depth were much lower and, where present, probably represent the burning of the adjacent burnt (GB) plots. The charcoal records lend support to the SCP profile since the AD 1940–1950 'take-off' in SCPs, dated in nearby lake sediments (Rose *et al.*, 1995), occurs, as would be expected, slightly below the charcoal peak in the peat profiles.

The SCP 'take-off' occurs at a greater depth relative to the peak in charcoal concentrations in the burnt plots (GB) than in the plots burnt in 1954 only. However, because charcoal concentrations peak near the surface of the burnt profiles, it suggests that very little peat accumulation has occurred on the plots burnt every ten years since 1954. Consequently, it may be that the distance between the SCP 'take-off' and the peak in charcoal is greater in the burnt plots because compaction of the profiles, caused by peat accumulation, has been lower.

Accurate estimates of bulk density could not be determined due to slight compression of the peat during coring and sectioning, and therefore profiles of bulk density have not been presented. Furthermore, measurement of peat bulk density requires accurate measurement of sample volume yet the error associated with slicing the cores was *c.* 10%. However, these uncertainties do not affect the values of C stored above the SCP 'take-off' and, hence, the conclusions regarding the effects of the treatments on C accumulation.

Table 3 shows the estimated depths of the SCP 'take-offs' derived from Figure 2, and the amount of C contained in the peat above this layer. Figure 4 displays the mean values of C stored above the SCP 'take-off' for each treatment, being calculated as the average from each experimental block. The C stored above the SCP 'take-off' layer in the unburnt plots was not significantly different under the two grazing treatments ($G = 5.4 \pm 0.6$ kg C m^{-2}; $U = 4.6 \pm 0.4$ kg C m^{-2}), yet, under grazed conditions, significantly more C was contained above the 'take-off' when the plots were not rotationally burnt ($GB = 3.1 \pm 0.4$ kg C m^{-2}; $G = 5.4 \pm 0.6$ kg C m^{-2}; $P < 0.02$).

Differences in the amount of C contained above the SCP 'take-off' will have occurred as a result both of treatments and natural variability in peat accumulation. That the sites have historically accumulated peat at different rates (at least in terms of height increment) is evident since measurement of the peat depth at each coring location showed total peat depth ranged from 1 m to 2 m (Figure 5). However, although peat depth varied considerably between different blocks, there were predominantly only small differences in total peat depth within the same block under the different treatment plots (Figure 5). Therefore, the past peat accumulation within separate blocks seems to have been very similar across the site. Furthermore, there was no correlation between the depth of the SCP 'take-off' and the total depth of peat for each sample, which would have suggested that natural variations in sampling locations were responsible for the different amounts of C contained above the SCP 'take-offs'.

Although the 'take-off' was arbitrarily defined as the depth where the count exceeded 100 SCPs, calculations based on other thresholds (e.g., 200 SCPs) made little difference to the overall results.

Discussion

Effect of sheep-grazing on carbon accumulation in blanket bog

There are several potential mechanisms whereby sheep-grazing may modify rates of peat accumulation and C sequestration. Grazing may directly reduce C inputs from plant litter (due to removal by grazing) or indirectly by influencing rates of primary production and decomposition. Additionally, trampling by sheep may cause hydrological changes to surface peats since these have low density and are easily compressed (Clymo, 1983); peat accumulation is strongly influenced by hydrological conditions (Clymo, 1984) and any disruption of surface hydrology caused by trampling may affect C accumulation.

The mean mass of C above the SCP 'take-off' in the grazed treatment (G) was 5.4 ± 0.6 kg m^{-2} (SE), whereas the ungrazed treatment (U) contained 4.6 ± 0.4 kg m^{-2}. Although the grazed treatment suggested a greater amount of C, the results of the ANOVA showed this difference was not significant. Consequently, after over 30 years of different management, there was no detectable difference in the C accumulated under the separate treatments.

The results are not surprising since the density of sheep at this site was very low (0.02–0.2 sheep ha^{-1}; Smith and Forrest, 1978) and no significant effect of sheep-grazing had been found on the above-ground biomass of blanket bog vegetation at Moor House under this stocking density (Smith and Forrest, 1978). Although Taylor and Marks (1971) found that grazing did reduce the above-ground biomass of *Rubus chamaemorus*, this species is a minor component of blanket bog vegetation (Forrest and Smith, 1975), decomposes rapidly (Latter *et al.*, 1998), and does not contribute very much to peat accumulation.

Effect of burning on carbon accumulation in blanket bog

Burning is practised regularly on large areas of moorland in upland Britain to provide uneven-aged stands of heather (*Calluna vulgaris*) which provide suitable conditions for red grouse (Hobbs and Gimingham, 1987). Regular burning is also believed to improve the grazing value of heather moorland for sheep, although Hobbs (1984) has questioned this assumption. Few studies have investigated the impact of rotational burning on blanket bogs (Hobbs, 1984), although results obtained from experimental studies at Moor House indicate that this practice caused major changes in the species composition of plant communities (Hobbs, 1984). In addition to direct release of CO_2 to the atmosphere, burning may affect plant productivity and alter hydrological conditions in peats which may consequently affect C accumulation.

The impact of fire on C accumulation in peatlands is poorly understood (Gorham, 1991) yet fire occurs naturally (e.g., lightning strikes; Kuhry, 1994), accidentally (e.g., in recreational areas; see Phillips *et al.*, 1981) and as a management tool on peatlands (Hobbs, 1984). It is of interest that increased fires are expected with global warming (Overpeck *et al.*, 1990; Gorham, 1991) which would provide a positive feedback to warming through increased release of the large amounts of C contained in peats.

The results of the present investigation may be useful in assessing the impact of natural and accidental fires on C accumulation in peats, although there are important differences between these types of fire (e.g., heather burning is only allowed between October and April in England and Wales to prevent fires becoming uncontrollable; Rowell, 1988), which may limit extrapolation of the results.

That burning strongly affects the above-ground biomass on blanket bog is clear since immediately after a burn there is a reduced biomass on the peat surface. Furthermore, Allen (1964)

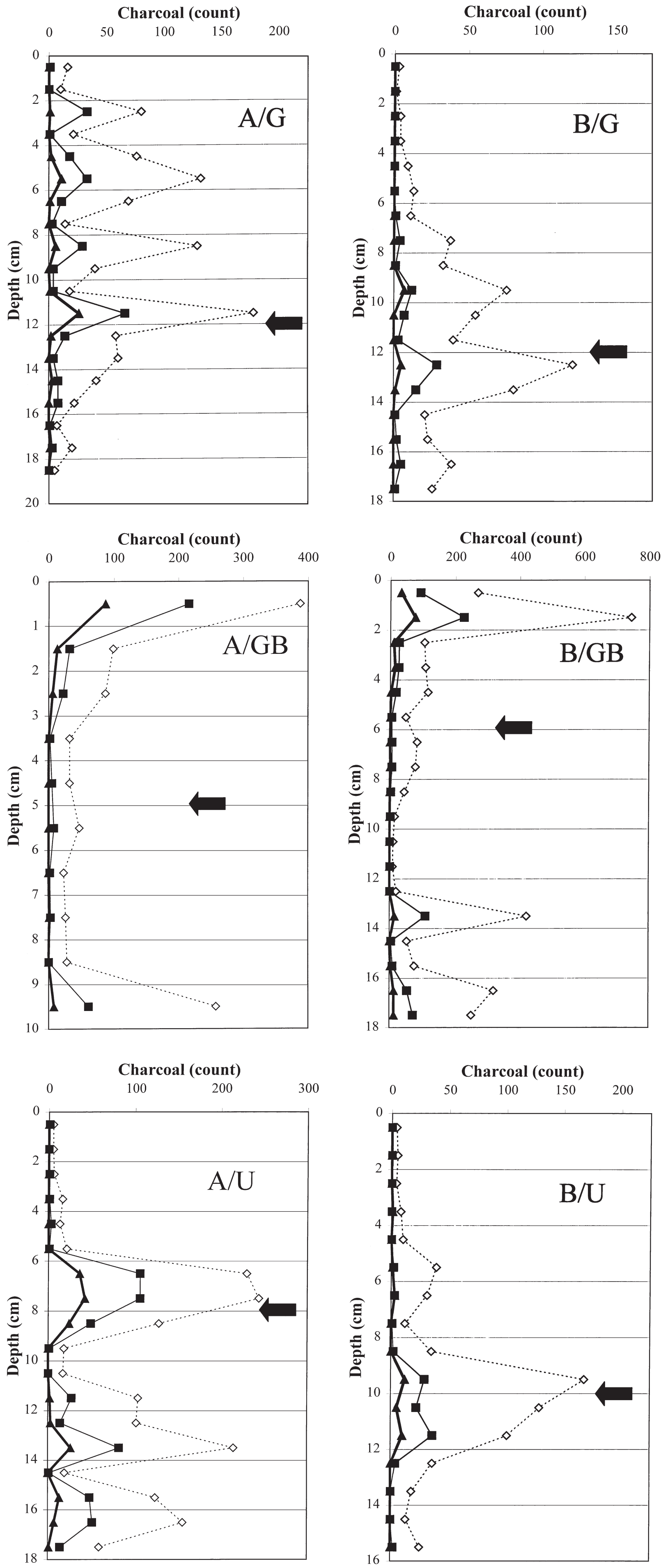

Figure 3 Profiles of charcoal counts against depth for each treatment in blocks A and B, according to particle size. Size classes are: 125–250 μm (open diamonds); 250–500 μm (closed squares); $>$250 μm (closed triangles). Arrows indicate SCP 'take-off' depths.

Table 3 Depths of the SCP 'take-offs' and C contained in the peat above the 'take-offs', for each profile

Block	Treatment	Depth of the SCP 'take-off' (cm)	C in peat above the SCP 'take-off' (kg m^{-2})
A	G	12	6.5
A	GB	5	3.9
A	U	8	4.2
B	G	12	5.7
B	GB	6	3.3
B	U	10	5.4
C	G	12	5.8
C	GB	3	2.3
C	U	8	5.2
D	G	5	3.7
D	GB	4	2.7
D	U	5	3.7

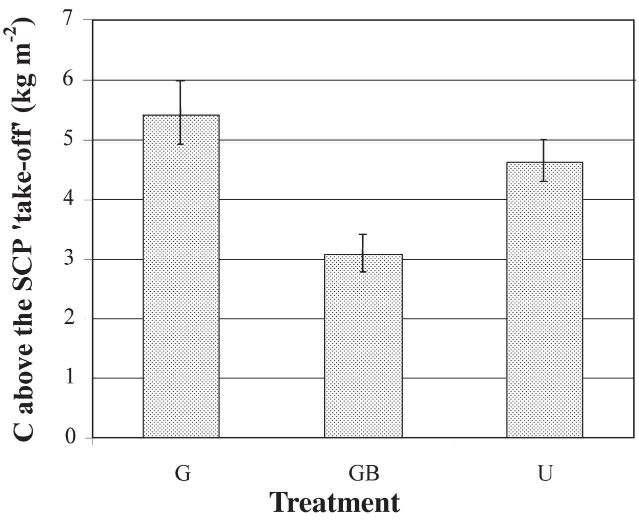

Figure 4 Mean values of C above the SCP 'take-off' layer in peat profiles under different treatments. The only significant difference was between treatments G and GB ($P < 0.02$). Error bars indicate standard error. The treatments are: G = grazed + unburnt; GB = grazed + burnt every ten years; U = ungrazed + unburnt.

conducted laboratory experiments to simulate heather burning and found that, during the burn, 61–68% of the original vegetation C was transferred to the atmosphere. However, since burns rarely remove all former vegetation (woody material and charcoal frequently remain) and because the vegetation recovers rapidly after the burn, and possibly at an increased rate due to the high availability of nutrients left in the ash (Allen, 1964), it is unclear from the literature whether burning should increase or decrease the net total C storage in blanket bog. Furthermore, fire may reduce C accumulation in blanket bogs by directly burning the surface peat (e.g., Maltby *et al.*, 1990), or influencing properties in the surface layers which may alter rates of decomposition or hydrological characteristics of the peat (e.g., bulk density; see above and Rowell, 1988). Hobbs (1984) reported that burning increased the dominance of *Eriophorum* sp. over *Calluna vulgaris* which may affect total primary productivity and the quality of the litter produced.

The results of the present investigation at Hard Hill showed that significantly ($P < 0.02$) less C was contained above the SCP 'take-off' under the treatment which had been burnt every

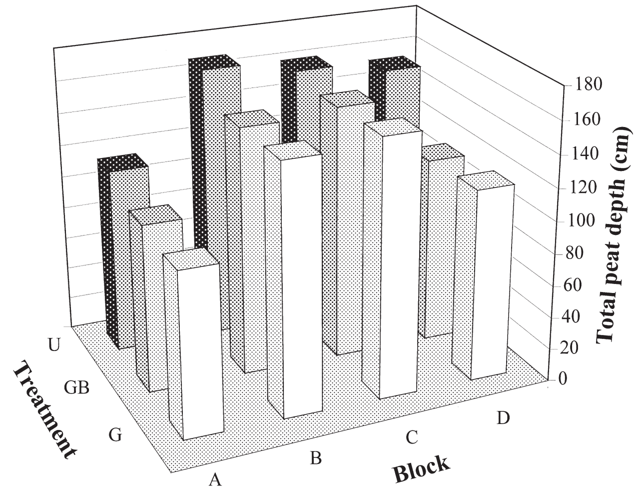

Figure 5 Total depth of peat at each sampling point at the Hard Hill experimental plots. Blocks are represented as A, B, C and D. The treatments are: G = grazed + unburnt; GB = grazed + burnt every ten years; U = ungrazed + unburnt.

ten years when compared with the unburnt treatment (GB = 3.1 ± 0.4 kg m^{-2} and G = 5.4 ± 0.6 kg m^{-2}). These results imply that this management practice contributes to anthropogenic emissions of CO_2 through (i) decreasing the rate of peat accumulation, (ii) stopping peat accumulation, and/or (iii) reducing C stores by burning existing surface peat. It is not possible from the results of the present investigation to establish which of these processes dominated at this site, because it is not possible to establish whether peat formed before the burning treatments began has subsequently been burnt. However, the reduced amount of C stored above the SCP 'take-off' and the single high peak in charcoal concentrations near the surface of the burnt profiles suggest a definite net reduction in peat accumulation caused by burning.

The main purpose of burning as a management tool is to improve the grazing value of moorland vegetation and, assuming that this occurs, areas of vegetation recovering from burning will have been favoured by sheep, and therefore, more intensively grazed. Consequently, a large proportion of vegetation C may have been removed from the burnt (and unenclosed) plots by sheep, which would otherwise have contributed to new peat growth. Although there was no significant effect of sheep-grazing on the blanket bog C in unburnt plots (see above), this is not directly comparable because recently burned areas may have had higher grazing value than unburnt areas and probably received a greater intensity of grazing.

Since the date of the industrial SCP 'take-off' was uncertain (based on other studies it probably lies *c.* AD 1940–1950; Rose *et al.*, 1995), actual rates of C accumulation under the different treatments have not been determined. However, comparative estimates for the average rate at which C stored above the SCP 'take-off' varied across the different treatments can be made because the dates of the start of the experiment and application of treatments are known.

The experiment at Hard Hill was established in 1954 and, initially, the area covering all plots was burnt (Hobbs, 1984). The plots were then defined and different treatments applied. Although the experiment commenced in 1954, the burnt and unburnt treatments have only had a different management treatment from the time of the first ten-year burn on the burnt plots (GB) in 1965 (Hobbs, 1984). Thus, the differences in C above the SCP 'take-off' represent the impact of burning over a period of 32 years. The difference in the amount of C above the 'take-off' layer in the different treatments is equivalent to a reduced C sequestration in the burnt treatment of 73 g m^{-2} yr^{-1} (calculated by dividing the difference between the mean estimates of C stored above the

SCP 'take-off' by the number of years the treatments had differed). The results imply that if the burnt plots, and other similarly managed blanket bogs in the United Kingdom (UK), had not been burnt over the last 32 years, an average extra 73 g C m^{-2} yr^{-1} would have been stored in the blanket bog. Although the area of blanket mire in the UK has been estimated at 1479×10^3 ha (Tallis and Meade, 1998), there is no information on the proportion managed using rotational burning, aggravating attempts to estimate this reduction in C sequestration at the UK scale.

Studies investigating the impact of burning as a management tool (or even as natural or accidental fire) on the C balance of peatlands are rare in the published literature. However, the observed reduced rates of C accumulation under the burning treatment are in agreement with the results of Kuhry (1994). In a study of peat profiles from the boreal zone of Canada he found that peat accumulation was significantly reduced under increasing frequencies of fire, implied from charcoal analysis. Recent stratigraphic evidence from a Finnish mire also suggests that frequent mire fires reduce C accumulation (Pitkänen *et al.*, 1999). Maltby *et al.* (1990) described the complete loss of peat profiles following accidental fires on blanket bog in the North York Moors of England, though these fires penetrate deeply into the peat profiles, unlike the controlled burns used for moorland management.

The investigation at Hard Hill implies that regular burning of the blanket bog at this site has resulted in a reduced C storage in the peat when compared to non-burnt areas, and that consequently the abandonment of this management practice may provide an opportunity to increase terrestrial C storage in similar areas and, therefore, mitigate industrial emissions of CO_2.

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References

Allen, S.E. 1964: Chemical aspects of heather burning. *Journal of Applied Ecology* 1, 347–67.

—— 1989: *Chemical analysis of ecological materials*. Oxford: Blackwell Scientific Publications.

Clymo, R.S. 1983: Peat. In Gore, A.J.P., editor, *Ecosystems of the world 4a*, Amsterdam: Elsevier Scientific, 159–224.

—— 1984: The limits to peat bog growth. *Philosophical Transactions of the Royal Society of London* B 303, 605–54.

—— 1996: Assessing the accumulation of carbon in peatlands. In Laiho, R., Laine, J and Vasander, H., editors, *Northern peatlands in global climate change*, SILMU, 207–12.

Clymo, R.S. and **Mackay, D.** 1987: Upwash and downwash of pollen and spores in the unsaturated surface layer of *Sphagnum*-dominated peat. *New Phytologist* 105, 175–85.

Clymo, R.S., Oldfield, F., Appleby, P.G., Pearson, G.W., Ratnesar, P. and **Richardson, N.** 1990: The record of atmospheric deposition on a rainwater dependent peatland. *Philosophical Transactions of the Royal Society of London* B327, 331–38.

Forrest, G.I. and **Smith, R.A.H.** 1975: The productivity of a range of blanket bog vegetation types in the northern Pennines. *Journal of Ecology*, 63, 173–202.

Gorham, E. 1991: Northern peatlands: role in the carbon cycle and probable responses to climatic warming. *Ecological Applications*, 1, 182–95.

Heal, O.W. and **Smith, R.A.H.** 1978: Introduction and site description. In Heal, O.W. and Perkins, D.F., editors, *Production ecology of British moorlands and montane grasslands*, Berlin: Springer-Verlag, 3–16.

Hobbs, R.J. 1984: Length of burning rotation and community composition in high-level *Calluna-Eriophorum* bog in N England. *Vegetatio* 57, 129–36.

Hobbs, R.J. and **Gimingham, C.H.** 1987: Vegetation, fire and herbivore interactions in heathland. *Advances in Ecological Research* 16, 87–173.

Houghton, R.A. 1995: Land-use change and the carbon cycle. *Global Change Biology* 1, 275–87.

Immirzi, C.P., Maltby, E. and **Clymo, R.S.** 1992: *The global status of peatlands and their role in carbon cycling*. London: Friends of the Earth.

Kattenberg, A., Giorgi, F., Grassl, H., Meehl, G.A., Mitchell, J.F.B., Stouffer, R.J., Tokioka, T., Weaver, A.J. and **Wigley, T.M.L.** 1996: Climate models-projections of future climate. In Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K., editors, *Climate change 1995*, Cambridge: Cambridge University Press, 285–357.

Kuhry, P. 1994: The role of fire in the development of *Sphagnum*-dominated peatlands in western boreal Canada. *Journal of Ecology* 82, 899–910.

Latter, P.M., Howson, G., Howard, D.M. and **Scott, W.A.** 1998: Long-term study of decomposition on a Pennine peat bog: which regression? *Oecologia* 113, 94–103.

Maltby, E., Legg, C.J. and **Proctor, M.C.F.** 1990: The ecology of severe moorland fire on the North York Moor: effects of the 1976 fires, and subsequent surface and vegetation development. *Journal of Ecology* 78, 490–518.

Melillo, J.M., Prentice, I.C., Farquhar, E.-D., Schulze, O.E. and **Sala, O.E.** 1996: Terrestrial biotic responses to environmental change and feedbacks to climate. In Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K., editors, *Climate change 1995*, Cambridge: Cambridge University Press, 285–357.

Milne, R. and **Brown, T.A.** 1997: Carbon in vegetation and soils of Great Britain. *Journal of Environmental Management* 49, 413–33.

Overpeck, J.T., Rind, D. and **Goldberg, R.** 1990: Climate-induced changes in forest disturbance and vegetation. *Nature* 343, 51–53.

Phillips, J., Yalden, D. and **Tallis, J.H.** 1981: *Peak District moorland erosion study. Phase 1 report*. Bakewell: Peak Park Joint Planning Board.

Pitkänen, A., Turunen, J. and **Tolonen, K.** 1999: The role of fire in the carbon dynamics of a mire, eastern Finland. *The Holocene* 9, 453–62.

Punning, J.-M. and **Alliksaar, T.** 1997: The trapping of fly-ash particles in the surfaces layers of *Sphagnum*-dominated peat. *Water, Air and Soil Pollution* 94, 59–69.

Rhodes, A.N. 1996: *Moorland fire history from microscopic charcoal in soils and lake sediments*. Unpublished PhD thesis, University of Newcastle-upon-Tyne.

—— 1998: A method for the preparation and quantification of microscopic charcoal from terrestrial and lacustrine sediment cores. *The Holocene* 8, 113–18.

Rose, N.L., Harlock, S., Appleby, P.G. and **Battarbee, R.W.** 1995: Dating of recent lake sediments in the United Kingdom and Ireland using spheroidal carbonaceous particle (SCP) concentration profiles. *The Holocene* 5, 328–35.

Rowell, T.A. 1988: Burning. In Rowell, T.A., editor, *The peatland management handbook*, Peterborough: Nature Conservancy Council.

Schimel, D.S. 1995: Terrestrial ecosystems and the carbon cycle. *Global Change Biology* 1, 77–91.

Smith, R.A.H. and **Forrest, G.I.** 1978: Field estimates of primary production. In Heal, O.W. and Perkins, D.F., editors, *Production ecology of British moors and montane grasslands*, Berlin: Springer-Verlag, 17–37.

Tallis, J. and **Meade, R.** 1998: Blanket mire degradation and management. In Tallis, J.H., Meade, R. and Hulme, P.D., editors, *Blanket mire degradation: causes, challenges and consequences*, Aberdeen: Macaulay Land Use Research Unit, 212–16.

Taylor, K. and **Marks, T.C.** 1971: The influence of burning and grazing on the growth and development of *Rubus chamaemorus* L. in *Calluna-Eriophorum* bog. In Duffey, E. and Watt, A.S., editors, *The scientific management of animal and plant communities for conservation*, Oxford: Blackwell Scientific, 153–66.

Tolonen, K., Possnert, G., Jungner, H., Sonninen, E. and **Alm, J.** 1993: High resolution ^{14}C dating of surface peat using the AMS technique. *Suo* 42, 271–75.

Wik, M. and **Renberg, I.** 1996: Environmental records of carbonaceous fly-ash particles from fossil-fuel combustion. *Journal of Paleolimnology* 15, 193–206.