Letting our carbon go free
The sustainable management of carbon and blanket peat in the English uplands

An eroded grip in the north Pennines.
Alistair Crowle

Alistair Crowle

Blanket peat is a rare and fragile substrate that forms only under specific and uncommon environmental conditions. With 2.2 million ha (Natural England 2006a), the UK supports about 20% of the global blanket-peat resource (Lindsay *et al.* 1988). About 230,000ha of this are in England (Natural England 2006b), distributed across the English uplands, with the majority found in the North and South Pennines. Approximately 176,000ha of the blanket peat in England have been included within Sites of Special Scientific Interest (SSSIs), the majority also being designated under the European Habitats and Species Directive.

The importance of blanket peat tends to be expressed in terms of its biodiversity interest, in particular its botanical and breeding-bird communities. Unsurprisingly, therefore, most of the concern about the well-being of upland peatlands has focused upon the effects of management on vegetation and birds. An increasing number of studies, however, have found that management and other factors affect the integrity of the blanket-peat resource itself, the water that drains off it and the nutrients released as the peat dries and oxidises. Blanket peat is, of course, an important store of carbon, and it is now more widely appreciated that our activities can have an impact upon the ability of the peat to store this carbon. With our increasing understanding of the potential impact of climate change, the management of blanket peat should, arguably, be viewed first and foremost in terms of its contribution to carbon storage and protection. Nowhere in the world is blanket peat subject to such intense collective pressures as it is in England and, although the component of the world's blanket peat found within England may, at

2%, seem small, the impacts of management upon these areas is likely to have implications for blanket-peat management elsewhere.

National trends in carbon loss

Worrall *et al.* (2004) documented increasing amounts of carbon in solution, known as Dissolved Organic Carbon (DOC), from 1961 onwards in 198 streams and lakes of upland catchments across the UK. They found that 77% of the sites showed an upward trend in DOC concentration. This increase was estimated to produce a DOC flux from the UK of 0.86 million tonnes of carbon for the year 2002 and is increasing at a rate of 0.02 million tonnes of carbon per year. They suggest that the most likely driver for this process is temperature increase, with additional shorter-range increases due to the frequency of severe droughts, which lower water tables and allow oxidation of peat (see below); other mechanisms may act in specific locations. Bellamy *et al.* (2005) used data from the National Soil Inventory of England and Wales to show that, in the period 1978-2003, carbon was lost at a rate of 0.6% per year. These results have been the subject of much debate, and it seems clear that more work is required before consensus will be reached within the science community. The important point is that there is a marked trend towards carbon loss from the existing national resource.

Processes that release carbon from peat

Carbon can be released into the environment as a gas, in solution or in particulate form, depending upon a range of factors. In recent years, research has been focused upon the mechanisms that influence the production of DOC. During the summer months or periods of drought, the water table drops, increasing the volume of peat that is exposed to oxidation. When the water table rises, it flushes out the oxidised peat as DOC into rivers and streams. Worrall *et al.* (2002) found that the critical factor in determining the volume of DOC was the length of time of exposure of the peat to oxygen, which drives the oxidation processes. It has been proposed that an 'enzyme-latch' is in operation (Freeman *et al.* 2001) whereby the phenols that prevent decomposition when the water-table height is regained in autumn are destroyed. Thus, the water table may be restored but decomposition continues for some time, as is demonstrated by the continued increased levels of DOC in the water.

Gorham (1991) and Malmer (1992) make the case for the importance of the release of carbon from peatland in methane (CH_4), and both suggest that increasing temperatures driven by climate change will likely result in increases in the volume of methane being released. Malmer further predicts that increases in the release of carbon dioxide (CO_2) would also take place under this scenario, but it appears that little work has been done on this with regard to blanket peat in Britain.

Whilst the study of the chemical processes involved in the release of DOC is quite recent, studies of the causes and implications of erosion of blanket peat are of longer standing and it is clear that DOC is not the only means by which carbon is lost from the peat resource. Tallis (1964, 1987, 1997) considers that there is good evidence to suggest that erosion is not a recent or necessarily human-induced phenomenon. Labadz *et al.* (1991), investigating sediment yield and delivery in a drainage basin in the southern Pennines, concluded that there was an ongoing serious erosion problem and that the initiation of the gullying that was supplying the sediment was within the previous 200 years, but they did not speculate as to the causes of this process. Evans *et al.* (2006) compared catchments in the North and South Pennines, where they found respective total sediment yields of 44 and 267 tonnes per km^2 per year and organic sediment yields of 31 and 195 tonnes per km^2 per year. The conclusion from this work is that the largest single loss of carbon from these systems is in particulate form.

Warburton (2003) investigated the significance of wind erosion of upland peat on a site that was already bare. On his study site at Moss Flats, in the North Pennines, he calculated erosion rates of 0.46 and 0.48 tonnes per ha. These figures correspond to the lowering of the surface by approximately 3mm over two years. Working in the same geographical area, Evans & Warburton (2001) identified the importance of peat-block transport in upland rivers and streams and concluded that this was an under-reported load component of these systems.

Land-management practices and the release of carbon from blanket peat

Whilst blanket peat within England has been an important resource for man since prehistoric times

(Bartley 1975; Simmons 1990; Simmons & Innes 1996), the intensity with which it is managed has increased considerably over the last 200 years. Sheep numbers have increased hugely (Sansom 1999), burning management for grouse and sheep has become widespread and intensive, and there have been widespread attempts at peatland drainage. This period also saw increases in the atmospheric deposition of a variety of chemical compounds resulting from industrialisation, and this, combined with the intensification of land use, has had a profound effect upon English blanket peat.

Burning

Until recently, when fire was spoken of as damaging it was usually in the context of summer 'wildfires' (e.g. Anderson 1997), when the fire has been the result of carelessness or arson, and relatively little consideration has been given to the effects of routine burning of moorland for agricultural or grouse management purposes. Gimingham (1972) acknowledges that plant diversity is reduced on regularly burned sites compared with unburned ones, and Hobbs (1988) discussed the impact of burning upon certain bryophytes. Allen (1964) burned Heather *Calluna vulgaris* under laboratory conditions and noted that over half of the carbon contained within the Heather was lost in the smoke. It says something of the times that this study was focused primarily upon Na, K, Ca, Mg and P, with the carbon results appearing almost as an afterthought. Burning appears to be particularly damaging in cases where the surface vegetation is completely removed. Imeson (1971), investigating heather-burning practices on the North York Moors, found alarming rates of erosion, with a sediment discharge amounting to 480 tonnes per km^2 per year in the Hodge Beck catchment. He determined that the critical period was the length of time during which the ground was bare. Once the vegetation cover was restored beyond a certain point, erosion was no longer a problem, and Kinako & Gimingham (1980) found a similar pattern in Scotland. Fullen (1983) investigated the differences in air temperature and wind velocity at burned and unburned blocks of Heather on the North York Moors. He found that the temperatures above the burned moor were more extreme and variable and the wind velocities considerably higher than was the case over unburned Heather. He suggested that the changes in air temperature promoted the breaking and fragmentation of the peat surface and that this, combined with higher wind velocities, meant that the exposed surfaces were more prone to wind and water erosion.

Garnett *et al.* (2000) investigated carbon sequestration on long-term experimental burn plots on Hard Hill, at Moor House NNR. These plots comprised combinations of burned and unburned areas along with grazed and ungrazed treatments. The burning took place at ten-year and 20-year intervals, and the results showed that there were no differences in carbon accumulation between lightly grazed and ungrazed plots, but there was significantly less carbon stored in the burned plots.

Researchers at Cranfield University have recently made a link between increased levels of heather-burning and increased levels of DOC in water coming off the catchment (A Yallop pers. comm.). Aside from bringing into question the sustainability of burning on blanket peat as a land-management practice, the findings have significant implications for the management of drinking water regarding the capacity of treatment works and whether they are capable of dealing with the increases in DOC and the associated toxic by-products generated by its treatment.

At the time of writing, 36,834ha of SSSI blanket peat is classified as being in unfavourable condition owing to burning (Natural England 2006c). The recent analyses of aerial photographs of the North Pennines have highlighted the apparent increasing intensity of burning in terms of area and burn intervals that is taking place (Yallop *et al.* 2006). In this area, around 30% of the peat resource on SSSIs is burned at intervals of less than 20 years, the evidence appearing to show that the management of blanket-peat habitats is frequently more intensive than that of upland heath. If this holds true for other upland areas, burning of vegetation on blanket peat is likely to be making a considerable contribution to carbon loss.

Grazing

Blanket bog that is undamaged or unmodified supports a vegetation cover that is generally regarded as being a climax community (Rodwell 1991). As such, grazing (or burning) is not a prerequisite for the attainment of nature-conservation objectives. Whilst light grazing by sheep is compatible with maintaining the botanical interest (Rawes & Hobbs 1979; Grant *et al.* 1985), Welch (1984) and Welch & Scott (1995) illustrate that high stocking densities can adversely affect the structure and diversity of the vegetation communities.

Whilst there is a considerable body of work on the role of sheep in influencing vegetation and the importance of their removal to allow recovery of bare peat (e.g. Gore & Godfrey 1981; Birnie 1993; Mackay & Tallis 1996), less work has been carried out on the physical damage caused by overstocking. Following research in both the Pennines and the Lake District, Evans (1997) put forward the need for a national survey of grazing-initiated erosion as a means of estimating the size of the problem. Van der Post *et al.* (1997) considered that exponential increases in sedimentation rates within Blelham Tarn, in the Lake District, were in direct response to increases in the number of sheep grazing the surrounding land. It seems clear that inappropriately high stocking levels can make a significant contribution to the loss of organic matter from the uplands.

Erosion of blanket peat caused by trampling by sheep. Alistair Crowle

Artificial drainage

The digging of drainage channels (grips) in peat is not a recent practice, but Government grants from the 1950s to the 1980s enabled the use of grip-producing machinery on a large scale (Hudson 1984). Coulson *et al.* (1990) observed that aerial photographs of upland areas in England and Wales indicated that over 50% of the land had been drained in some areas.

Conway & Miller (1960) carried out an investigation into the hydrology of some small peat-covered catchments in the North Pennines. They found that both burning and draining increased the sensitivity to rainfall, with earlier and higher peak flow rates per unit area. They also noted large quantities of silt in the drained catchment, which were absent from the *Sphagnum*-covered catchment that was not drained. Robinson (1985) updated the Conway & Miller study and concluded that artificial drainage by ditching increased peak flows owing to faster storm runoff. He also confirmed that severe burning of the peat increased peak flows and that burning reduced the storage capacity of the soil and lowered dry-weather flows. Holden *et al.* (2006) revisited this study site and found that macropore flow, density of soil piping (naturally occurring underground channels that carry water through the peat mass) and pipeflow were significantly greater in drained peatlands than in intact basins.

Hudson (1992) estimated that a kilometre of moorland with a normal drainage system of drains at 22m intervals would carry in the region of 45.5km of drains that would produce a minimum of 319 tonnes and up to 13,650 tonnes of material per square kilometre over the first three years. Holden (2006) concluded that, at sites which had been drained for 40 years, particulate carbon loss from sub-surface piping was likely to be in the region of 5.8×10^3 kg carbon per km^2 per year over the period compared with that from an undrained slope and this would be in addition to any surface erosion related to ditch channel incision or other surface processes. The key discovery to take from Holden's work is that management in the form of drainage appears to result in increased soil piping and enhanced sub-surface erosion.

Atmospheric deposition and the impact upon peat

Until recently, *Sphagnum* has been all but absent from some blanket peat in the English uplands, especially those in the South Pennines. Here, the loss has been put down largely to the atmospheric deposition of pollutants, mainly sulphur, as a result of the industrial revolution, and it has been proposed that this loss of *Sphagnum* cover has resulted in the exposure and erosion of the peat (Woodin & Farmer 1993; Tallis 1985). Ferguson *et al.* (1978) investigated the response of different *Sphagnum* species to increasing concentrations of sulphur pollutants. They found that the concentrations then present in the environment were lethal to some species and reduced the growth of others. Further work, by Lee *et al.* (1993), concluded that *Sphagnum* species in ombrotrophic mires (mires that receive their water and nutrients from precipitation) are amongst the plants most sensitive to changes in levels of elements as a result of atmospheric deposition.

Whilst the levels of sulphur emitted have fallen in recent years, levels of atmospheric nitrogen have increased (Woodin *et al.* 1987). Press *et al.* (1986) found that concentrations of nitrate and ammonium within the range deposited atmospherically could inhibit the growth and recovery of *Sphagnum*. The recent discovery by Clark *et al.* (2005) that sulphur dioxides play a role in suppressing the production of DOC, and that the reduction in sulphur deposition may result in increases in the release of DOC, emphasises the complex interactions that are taking place on these sites.

Blanket-peat management – options and future directions

Blanket peat is an important store of carbon, and this is being released through both natural and man-made processes. If the research to date is correct, climate change is likely to increase the rate of carbon loss, with potentially serious consequences for society. Furthermore, it is clear that any form of intensive use of blanket peat results in the loss of carbon in one form or another.

Blanket peat has always been of marginal value as pasture and was really intensively used only when subsidies made drainage and stocking worthwhile. Lance (1983) has demonstrated that sheep perform better on serially burned than on unburned blanket bog, but given the importance of blanket peat as a habitat in its own right, as well as its role in carbon storage, there would seem to be little justification for continuing this practice.

Some land-managers are of the opinion that without grazing the whole of the uplands would quickly become covered in trees and scrub. English Nature (2003) investigated sites that have been taken out of management, in some cases for up to 50-60 years, and it is clear that, in many upland areas, management activities or grazing by livestock could cease without any significant change in tree cover for decades, if not centuries.

Many moorland managers now recognise that artificial drainage channels are one of the mistakes of the past, but some are still opposed to taking remedial action. The sheer scale of the drainage channels across the uplands, largely funded by Government drainage grants, is such that the only way to tackle the blocking and management required within a sensible time-frame is to establish a national restoration scheme. Fortunately, we now have modelling tools and data which can be used to prioritise the work required and so target resources effectively.

One of the justifications for moorland burning is to reduce the impact of a wildfire. The irony is that the act of creating a Heather monoculture and drying the peat surface in the process increases the likelihood of a wildfire causing damage, although it is interesting to note that, in the Peak District, Heather was identified as the least vulnerable habitat (McMorrow *et al.* 2005). The Heather monocultures are a phenomenon that date only from the period of industrialisation (Chambers *et al.* 2006). Before that, a range of plants existed together usually in a much wetter state, and, although fire events had taken place previously, Heather had not dominated the landscape to the extent now found across large areas of the uplands. In the light of what we now know about the damaging effects of burning on peat, it seems inappropriate to continue to cause damage on the grounds that it may prevent damage at a later point. The best way to avoid damage by wildfires is to prevent the fire in the first place. However difficult politically or socially, this means establishing more robust protocols for closing upland areas at times of risk, establishing more novel methods of managing visitors, and putting more resources into having personnel on the ground to patrol vulnerable areas.

In order to safeguard the peat resource, we shall need to restore peat-forming processes. If we believe that the continual cycle of burning on peat is unsustainable, then somehow the position must be reached where the Heather is no longer dominant and forms part of a wetter, more diverse blanket-peat community. The blocking of grips has an important part to play in reducing

A severely eroded grip at Bleaklow, Peak District, that has been partially blocked to stop further damage. Mick Rebane

DOC loss (Wallage *et al.* 2006) and perhaps to some degree in restoring the water table, but it seems that, in order to achieve the restoration of blanket peat, we shall have to rely considerably upon new and innovative techniques. As part of this process, it is inevitable that we shall have to re-examine our definition of a restored site.

A key question is that of whether degraded peatlands can once again support *Sphagnum*. Caporn *et al.* (2005) revisited sites that had been first investigated in the early 1980s and found that the numbers of bryophytes recorded on these sites had increased markedly; at Holme Moss, for example, seven species were found in 1983-84 and 24 species in 2005, the latter including *Sphagnum* species that are recognised as being major peat-formers. As this work and that of others (e.g. Tallis 1987) show, some sort of recovery is clearly possible, although we do not know the timescale over which it may operate. The 'Moors for the Future' project in the Peak District has demonstrated that large areas of bare peat can be revegetated and stabilised, albeit with non-natural vegetation, and the next step will be to develop the techniques that allow us actively to promote the recolonisation by *Sphagnum* of upland sites and to restore these sites to favourable condition.

The great challenge over the next few years will be that of persuading land managers to modify practices so that, at the very least, they are not contributing to the loss of carbon and damage of blanket peat. This will need to include the important message that people must take responsibility for carrying out actions that can have impacts many miles away. Increasingly, researchers are starting to turn their attention to catchment-scale experiments, and in the next five years it may be possible to start to quantify more accurately the levels of carbon released by different management activities. Changes to the law affecting heather- and grass-burning in England were introduced on 1st October 2007, along with a revised Heather and Grass Burning Code. This provides a timely opportunity to address some of the concerns regarding the sustainability of burning blanket peat, as it introduces new protection for 'carbon-rich' soils. On the ground, the Higher Level Stewardship agri-environment scheme has options for addressing all of the practices discussed in this article: burning, grazing and drainage. Provided that the scheme is adequately resourced, it could play a vital role in establishing sustainable management in the uplands. Whilst some blanket peat may already be a net source of carbon, the appropriate restoration of these sites may turn them into important carbon sinks.

Acknowledgements

This article has been taken from a review written in the weeks leading up to the formation of Natural England. I am grateful to Andy Brown, Dave Glaves, Richard Pollitt, Mick Rebane, Martin Evans, Joe Holden and Fred Worrall for their discussion and comments. The last three also supplied their most recent papers, which improved the review considerably. The library staff at Northminster House were of great help in sourcing references. Fay McCormack supplied data on designated sites.

References

Allen, S E 1964 Chemical Aspects of Heather Burning. *Journal of Applied Ecology* 1: 347-367

Anderson, P 1997 Fire damage on blanket mires. *In* Tallis, J H, Meade, R, & Hulme, P D (Eds) 16-27

Bartley, D D 1975 Pollen analytical evidence for prehistoric forest clearance in the upland area west of Rishworth, West Yorkshire. *New Phytologist* 74: 375-381

Bellamy, P H, Loveland, P J, Bradley, R I, Murray Lark, R, & Kirk, G J D 2005 Carbon losses from all soils across England and Wales 1978-

2003. *Nature* 437 (8): 245-248

Birnie, R V 1993 Erosion rates on bare peat surfaces in Shetland. *Scottish Geographical Magazine* 108: 12-17

Caporn, S, Lee, J, Studholme, C, & Carroll, J 2005 Recovery of ombrotrophic *Sphagnum* moss in relation to air pollution in the Southern Pennines. Moors for the Future Conference Presentation. http://www.moorsforthefuture.org.uk/mftf/main/Publications.htm

Chambers, F M, Daniell, J R G, Mauquoy, D, Newberry, J, & Thoms, P S 2006 *A Preliminary Examination of the Vegetation History of Moorland in northern England*. Report to English Nature

Clark, J M, Chapman, P J, Adamson, J K, & Lane, S N 2005 Influence of drought-induced acidification on the mobility of dissolved organic carbon in peat soils. *Global Change Biology* 11: 791-809

Conway, V M, & Miller, A 1960 The hydrology of some small peat-covered catchments in the North Pennines. *Journal of the Institute of Water Engineers* 14: 415-424

Coulson, J C, Butterfield, J E L, & Henderson, E 1990 The effect of open drainage ditches on the plant and invertebrate communities of moorland and on the decomposition of peat. *Journal of Applied Ecology* 27: 549-561

English Nature 2003 *Vegetation Change in the English Uplands Following Removal of Management*. Internal Report

Evans, M, & Warburton, J 2001 Transport and dispersal of organic debris (peat blocks) in upland fluvial systems. *Earth Surface Processes and Land Forms* 26: 1087-1102

Evans, M, Warburton, J, & Yang, J 2006 Eroding blanket peat catchments: Global and local implications of upland organic sediment budgets. *Geomorphology* 79: 45-57

Evans, R 1997 Soil erosion in the UK initiated by grazing animals: a need for a national survey. *Applied Geography* 17 (2): 127-141

Ferguson, P, Lee, J A, & Bell, J N B 1978 Effects of sulphur pollutants on the growth of *Sphagnum* species. *Environmental Pollution* 16: 151-162

Freeman, C, Ostle, N, & Kang, H 2001 An enzymic 'latch' on a global carbon store. *Nature* 409: 149

Fullen, M A, 1983 Some changes in air temperature and wind velocity after burning of heather (*Calluna vulgaris*) moor and their relation to moorland surface processes. *Naturalist* 108: 174

Garnett, M H, Ineson, P, & Stevenson, A C 2000 Effects of burning and grazing on carbon sequestration in a Pennine blanket bog, UK. *The Holocene* 10, 6: 729-736

Gimingham, C H 1972 *Ecology of Heathlands*. Chapman & Hall, London

Gore, A J P, & Godfrey, M 1981 Reclamation of eroded peat in the Pennines. *Journal of Ecology* 69: 85-96

Gorham, E 1991 Northern Peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications* 1 (2): 182-195

Grant, S A, Bolton, G R, & Torvell, L 1985 The responses of blanket bog vegetation to controlled grazing by hill sheep. *Journal of Applied Ecology* 22: 739-751

Hobbs, A M 1988 Conservation of leafy liverwort-rich *Calluna vulgaris* heath in Scotland. *In* Usher, M B, & Thompson, D B A (Eds) 339-343

Holden, J, Evans, M G, Burt, T P, & Horton, M 2006 Impact of Land Drainage on Peatland Hydrology. *Journal of Environmental Quality* 35: 1764-1778

Holden, J 2006 Sediment and particulate carbon removal by pipe erosion increase over time in blanket peatlands as a consequence of land drainage. *Journal of Geophysical Research* Vol III

Hudson, P J 1984 Some effects of sheep management on heather moorlands in northern England. *In* Jenkins, D (Ed) 143-149

Hudson, P J 1992 *Grouse in Space and Time – The population biology of a managed gamebird*. Game Conservancy Ltd, Fordingbridge

Imeson, A C 1971 Heather burning and soil erosion on the North Yorkshire Moors. *Journal of Applied Ecology* 8: 537-542

Kinako, P D S, & Gimingham, C H 1980 Heather burning and soil erosion on upland heaths in Scotland. *Journal of Environmental Management* 10: 277-284

Labadz, J C, Burt, T P, & Potter, A W R 1991 Sediment yield and delivery in the blanket peat moorlands of the Southern Pennines. *Earth Surface Processes and Landforms* 16: 255 -271

Lance, A N 1983 Performance of sheep on unburned and serially burned blanket bog in western Ireland. *Journal of Applied Ecology* 20: 767-775

Lee, J A, Parsons, A N, & Baxter, R 1993 *Sphagnum* species and polluted environments, past and future. *Advances in Bryology* 5: 297-313

Lindsay, R A *et al.* 1988 *The Flow Country. The peatlands of Caithness and Sunderland*. Nature Conservancy Council, Peterborough

Mackay, A W, & Tallis, J H 1996 Summit-type blanket mire erosion in the forest of Bowland, Lancashire, UK: Predisposing factors and implications for conservation. *Biological Conservation* 76: 31-44

Malmer, N 1992 Peat accumulation and the global carbon cycle. *Catena Supplement* 22: 97-110

McMorrow, J, Cavan, G, Aylen, J, & Albertson, K 2005 Fire and climate change in the Peak District. Moors for the Future Conference Presentation. http://www.moorsforthefuture.org.uk/mftf/main/Publications.htm

Natural England 2006a Biodiversity Action Reporting System

Natural England 2006b Upland Habitat Inventory

Natural England 2006c English Nature Site Information System

Press, C M, Woodin, S J, & Lee, J A 1986 The potential importance of an increased atmospheric nitrogen supply to the growth of ombrotrophic *Sphagnum* species. *New Phytologist* 103: 45-55

Rawes, M, & Hobbs, R 1979 Management of semi-natural blanket bog in the northern Pennines. *Journal of Ecology* 67: 789-807

Robinson, M 1985 The Hydrological Effects of Moorland Gripping: A Re-appraisal of the Moor House Research. *Journal of Environmental Management* 21: 205-211

Rodwell, J S (Ed) 1991 *British Plant Communities Vol. 2: Mires and heaths*. CUP, Cambridge

Sansom, A L 1999 Upland vegetation management: the impacts of overstocking. *Water Science and Technology* 39 (12): 85-92

Simmons, I G 1990 The Mid-Holocene Ecological History of the Moorlands of England and Wales and its Relevance for Conservation. *Environmental Conservation* 17(1): 61-69

Simmons, I G, & Innes, J B 1996 Prehistoric Charcoal in Peat Profiles at North Gill, North Yorkshire Moors, England. *Journal of Archaeological Science* 23: 193-197

Tallis, J H 1964 Studies on southern Pennine peats I. The general pollen record. *Journal of Ecology* 52: 323-353

Tallis, J H 1985 Mass movement and erosion of a Southern Pennine Blanket Peat. *Journal of Ecology* 73: 283-315

Tallis, J H 1987 Fire and flood at Holme Moss: erosion processes in an upland blanket mire. *Journal of Ecology* 75: 1099-1129

Tallis, J H 1997 The pollen record of *Empetrum nigrum* in southern Pennine peats: implications for erosion and climate change. *Journal of Ecology* 85: 455-465

Van der Post, K D, Oldfield, F, Haworth, E Y, Crooks, P R, & Appleby, P G A 1997 A record of accelerated erosion in the recent sediments of Blelham Tarn in the English Lake District. *Journal of Paleolimnology* 18: 103-120

Wallage, Z E, Holden, J, & McDonald, A T 2006 Drain blocking: An effective treatment for reducing dissolved organic carbon loss and water discoloration in a drained peatland. *Science of the Total Environment* 367: 811-821

Warburton, J 2003 Windsplash erosion of bare peat on UK upland moorlands. *Catena* 52: 191-207

Welch, D 1984 Studies in the grazing of heather moorland in north-east Scotland III. Floristics. *Journal of Applied Ecology* 21: 209-225

Welch, D, & Scott, D 1995 Studies in the grazing of heather moorland in north-east Scotland. VI. 20-year trends in botanical composition. *Journal of Applied Ecology* 32: 596-611

Woodin, S J, & Farmer, A M 1993 Impacts of sulphur and nitrogen deposition on sites and species of nature conservation importance in Great Britain. *Biological Conservation* 63: 23-30

Woodin, S J, Studholme, C U, & Lee, J A 1987 Effects of Acid Deposition on Peatlands. *In* Perry, R, Harrison, R M, Bell, J N B, & Lester, J N (Eds) 554-561

Worrall, F, Burt, T P, Jaeban, R Y, & Shedden, R 2002 Release of dissolved organic carbon from upland peat. *Hydrological Processes* 16: 3487-3504

Worrall, F, Harriman, R, Evans, C D, Watts, C D, Adamson, J, Neal, C, Tipping, E, Burt, T, Grieve, I, Monteith, D, Naden, P S, Nisbet, T, Reynolds, B, & Stevens, P 2004 Trends in dissolved organic carbon in UK rivers and lakes. *Biogeochemistry* 70: 369-402

Yallop, A R, Thacker, J, & Clutterbuck, B 2006 *Mapping Extent of Burn Management in the North Pennines: Review of extent year 2001-2003*. English Nature Research Report 698

Alistair Crowle, Uplands & Grazing Management Team, Natural England, Northminster House, Peterborough