Durham E-Theses

The future stability of upland blanket peat following historical erosion and recent re-vegetation

Sarah Clement

How to cite:

Clement, Sarah (2005) *The future stability of upland blanket peat following historical erosion and recent re-vegetation.* Doctoral thesis, Durham University.

THE FUTURE STABILITY OF UPLAND BLANKET PEAT FOLLOWING HISTORICAL EROSION AND RECENT RE-VEGETATION

SARAH CLEMENT

Thesis submitted in accordance with the regulations for a degree of Doctor of Philosophy in the University of Durham, Department of Geography, 2005.

One Volume

0 6 DEC 2005

DECLARATION

I confirm that no part of the material presented in this thesis has previously been submitted by me or any other person for a degree in this or any other university. In all cases, where it is relevant, material from the work of others has been acknowledged.

The copyright of this thesis rests with the author. No quotation from it should be published without the prior written consent and information derived from it should be acknowledged.

Signed: *S. Clements*

Date: 22. 11. 05

ABSTRACT

The importance of fluvial dissection in upland blanket peat erosion is well-established but knowledge of the significance of peatland gully system development is limited. This thesis investigates the stability of upland blanket peat in relation to recent re-vegetation and historical erosion of peatland gully systems. It combines regional morphological surveys in a GIS framework with detailed field and laboratory analyses. Detailed research was carried out at three study areas across Northern England: The Cheviot (Northumberland), Moor House (North Pennines) and Wessenden Head Moss (Southern Pennines).

A regional-scale investigation into gully development at the three sites demonstrated that the end members (Type 1 and Type 2 dissection) in Bower's 1960 classification of dissection types could be identified but a revised dissection classification including a third category of anastomosing dissection was needed. Regional variations in erosion and gully form were observed. The most extensive aerial erosion was on The Cheviot (80 %) and least at Moor House (48 %). Re-vegetation was most well-established at Moor House (80 % of the eroded peat) and least on Wessenden Head Moss (45 % of the eroded peat). The local topography of each site was the key in explaining erosion patterns. Linear dissection dominated on steeply sloping ground and anastomosing dissection on gentle sloping summit areas. Dendritic dissection occurred on intermediate slopes. Approximate slope angles for the dentritic transitional zone vary in relation to the local topography; however, the means for the three study sites are 3.7° (Moor House), 4.9° (The Cheviot) and 1.4° (Wessenden Head Moss).

Local-scale variations in erosion were observed on the interfluves and within existing gully systems. On the interfluves peat accumulation rates were estimated from Spheroidal Carbonaceous Particle deposition. Average rates were 0.5 mm yr^{-1} under moorland grass and 1.2 mm yr^{-1} under heather. Erosion potential of these sites was estimated from rainfall simulation experiments. The potential for erosion was high (243 t km^{-2}, 0.243 mm yr^{-1}), though not atypical of local directly measured erosion rates. However, experimental results showed that sediment production rarely occurred below a rainfall intensity of 12 mm hr^{-1} (high intensity for the Pennines) and with a presence of an intact vegetation cover sediment is only locally entrained and re-deposited and actual erosion under current climatic conditions is likely to be low.

The onset of peat erosion was estimated by comparing eroded and uneroded cores. It is thought the most recent phase of erosion resulted from climatic change and land management and occurred some 570 years ago on Wessenden Head Moss and between 300 – 330 years ago at Moor House and on The Cheviot. Over the last approximate 50-years, infilling and re-vegetation of the bases of gully systems has been observed. The peat within the gully stratigraphy appears to be eroded, re-deposited or grown *in situ*. The future of upland blanket peat will likely involve further stabilisation of the gully systems; however, in severely eroded areas where the peat is totally stripped and surface hydrological regime destroyed, the peat will not recover.

ACKNOWLEDGEMENTS

LIST OF CONTENTS

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

CHAPTER 2: REVIEW OF RESEARCH INTO BLANKET PEAT EROSION AND RE-VEGETATION IN UPLAND BRITAIN

xiii

CHAPTER 4: REGIONAL SCALE INVESTIGATION INTO GULLY DEVELOPMENT

CHAPTER 5: INTERFLUVE PEAT ACCUMULATION

CHAPTER 6: INTERFLUVE PEAT LOSS BY SOIL EROSION

CHAPTER 8: DISCUSSION

APPENDIX 3: TO ACCOMPANY GULLY MORPHOLOGY (CHAPTER 7)

LIST OF TABLES

CHAPTER 5: INTERFLUVE PEAT ACCUMULATION

CHAPTER 6: INTERFLUVE PEAT LOSS BY SOIL EROSION

CHAPTER 7: GULLY MORPHOLOGY

CHAPTER 8: DISCUSSION

LIST OF EQUATIONS

CHAPTER 3: STUDY SITES AND METHODOLOGY

CHAPTER 6: INTERFLUVE PEAT LOSS BY SOIL EROSION

1.0 INTRODUCTION

During the last 50 years erosion of upland blanket peat in Britain has attracted considerable attention. This work has been dominated by that of Bower (1960a; 1960b; 1961; 1962). However, in light of the recent re-vegetation of eroded blanket peat landscapes, a more up to date understanding of the state of the peatlands was required. The broad aim of this research is to assess the erosional stability of upland blanket peat landscapes following historical erosion and in light of the evidence of recent re-vegetation.

1.1 Blanket peat landscapes

What is peat?

Peat is decaying organic matter that has accumulated under saturated conditions (Fielding and Haworth, 1999). It can be defined as 'a substance that is composed of the partially decomposed plant remains with over 65 % organic matter and less than 20 – 35 % inorganic matter' (Charman, 2002). Peat consists of as much as 88 – 97 % water, 2 – 10 % dry matter and 1 – 7 % gas (Heathwaite *et al.*, 1993; Charman, 2002). As a result of its saturated conditions the hydrological setting is important. It contains appreciable quantities of nutrients, for example, when dry it contains 0.4 % calcium, 0.02 % potassium, 0.04 % phosphorus and 1.3 % nitrogen (Crisp, 1966). Peatlands are landscapes made up dominantly of 'peat' (Charman, 2002). The term 'peatlands' has different meanings to different people with interests in these environments, e.g. ecologists, soil scientists, biogeochemists, hydrologists, archaeologists, cultural historians, agricultural and horticultural scientists, foresters and engineers (Charman, 2002). Charman (2002) defined peatlands as 'any ecosystem where in excess of 30 – 40 cm of peat has formed'. There are three main types of peatlands found in the UK: fens, raised bogs and blanket bogs. Fens develop around lake margins and other waterlogged areas where there is a supply of base-rich water. Raised bogs are dome-shaped peat masses, which started as a lake or pond. As they infill with silt the water depth is reduced and this allows the invasion of plants from the margin. The continued growth and decay of the plants leads to the accumulation of peat and bog formation. Blanket bogs consist of large carpets of peat that may extend over very large areas and their only supply of nutrients is from rainfall (Fielding and Haworth, 1999). As a result blanket

1

bogs form where there is high rainfall (> 1200 mm yr^{-1}) and excess moisture. Blanket bogs are also known as blanket 'mires'.

Blanket peat often forms in landscapes that are glacially scarred and smoothed (Tallis, 1997a). As a result of this uneven topography, the depth of the present-day peat varies considerably within a single geographical region. For example, peat covers most of the landscape including mounds, however thins out on slopes (Tallis, 1998; Charman, 2002). In England and Wales peat tends to occur on slopes of less than 18° (Taylor and Tucker, 1970), although where peat depths are greater (approximately 1 m deep), slope angles are usually less than 5° (Burt and Gardiner, 1984). The development of peat depends on special climate conditions, where there is greater than 1200 mm of rainfall, at least 160 wet days per year, a surplus precipitation over evaporation of at least 200 mm for the 6 month period from April to September, and an annual mean temperature for the warmest month of less than 15° C (Moore, 1973): conditions typical of upland Britain. Such areas support bog vegetation, such as *Sphagnum*, which is the dominant component of British peatlands, along with other acid-tolerant plants such as *Calluna vulgaris* and *Eriophorum* (Tallis 1998; Charman 2002).

Dates of peat initiation in the British Isles occur from about 9400 to 800 BP. However, the majority of published dates show widespread peat formation over Britain and Ireland to have developed more recently: 5100 – 3100 years BP (Johnson and Dunham, 1963; Tallis, 1998). Upland Britain over 5000 – 6000 years ago was predominantly covered by forest of birch and pine, along with oak and hazel (except on cliffs, screes, areas of shallow soils, mires, springs, flushes and the most exposed summits), with the tree cover extending probably to altitudes of 700 - 800 m in many upland areas (Pears, 1975). Deforestation of the 'wildwood' by burning, grazing and felling of forest cover for Neolithic Agriculture is historically the greatest change to have affected all but the highest altitudes (Chambers, 1978; Tallis, 1998). Areas where the wildwood once grew have since been replaced by blanket peatlands. Many remains of the 'wildwood' are preserved in the peat stratigraphy (Tallis, 1998); for example, at Moor House and Upper Teesdale National Nature Reserve (NNR), remains of birch, willow and juniper, extend up to 760 m altitude (Godwin, 1981).

Globally blanket peat landscapes cover a significant percentage of land cover in many countries (Warburton, 2003). Tallis (1997a) suggests this is approximately 3 % of the world's land surface, or 4 million km^2. Estimates of blanket peat cover in Britain range from 7.5 % to 14.5 % depending on definition (Hobbs 1986; English Nature 2001a). In a global context the blanket peatlands of upland Britain are regarded as one of the most comprehensive range of mire types in the World, with around 10 – 15 % of the world's blanket peat existing in the British Isles (Tallis *et al.*, 1997). The locations of blanket peatlands in Britain are shown in Figure 1.1.

Figure 1.1: Map showing the location of upland blanket peat in Britain (Source: Tallis, 1997a).

From Figure 1.1 it is clear that blanket peat areas in Britain are in the upland, wet areas of the north-west and not in the lowland, dry areas in the south-east. Upland Britain covers an area of approximately 6.5 million ha or 30 % of Britain (Pearsall, 1950; Ratcliffe and Thompson, 1988).

Blanket peat covered catchments are an important archive of past climate, a major terrestrial stores of carbon (Clymo, 1998) and aid in the reduction of global warming. For all British upland peat the calculation of total organic carbon content suggests a net carbon sink of between 0.15 and 0.29 M t C yr^{-1} (Worrall *et al.*, 2003). Worrall *et al.* (2003) produced the first comprehensive study of the fluvial export of carbon within the terrestrial carbon budget and show the size of the peat carbon sink to be smaller than previous estimated, although sensitivity analysis shows that the primary productivity rather than fluvial carbon flux is a more important element in balancing the carbon budget. The blanket peatlands of upland Britain also play a major role in the overall economy and land use at a major national resource on at least five different criteria: land-use importance, landscape appeal, geomorphological importance, wildlife and conservational value, and archival importance (Heathwaite, 1993; Lappalainen, 1998; Tallis, 1998). The British and Irish blanket peatlands were formally recognised to be of international significance by the International Mires Conservation Group in 1986 and confirmed in a Parliamentary Statement in January 1988. They are thus a major priority in national conservation programmes (Tallis, 1997a) and more recently a national inventory of blanket bog habitats in Great Britain was planned for 2004, to provide an up-to-date picture of the extent of this rare habitat. Blanket bog is listed in the Habitats Directive, and is found only in the north and west of the UK and Ireland. In addition, some are either proposed or already designated as RAMSAR sites under the EC Birds Directive (UK Biodiversity, 2004).

Peat Accumulation

Peat accumulation is the most important process in the development of peatlands (Charman, 2002). Studying peat accumulation provides information on vegetation history; land-use changes; human activity and climate change. The accumulation process is very slow (Clymo, 1983), occurring at an approximate rate of 1 cm every 10 years (1 mm yr^{-1}); however, this rate varies considerably (Tallis 1995a; Charman, 2002). Figure 1.2 from Tallis (1995a) illustrates the variations in peat accumulation rates in blanket peats from the British Isles. This diagram shows that although rates are approximated to 1 mm yr^{-1}, in actual fact accumulation rates vary from 0.1 to 1.2 mm yr^{-1} with the majority of accumulation rates between 0.2 to 0.6 mm yr^{-1}. These

variations in accumulation rates are thought to be a result of there being two distinct layers within a peat profile (Ingram, 1978). There is a clear distinction between the upper layer, known as the 'acrotelm' (where the vegetation is in the early stages of decomposition and contains the water table) and the lower layer, known as the 'catotelm', (where vegetation is less identifiable and permanently waterlogged) (Bragg, 1982).
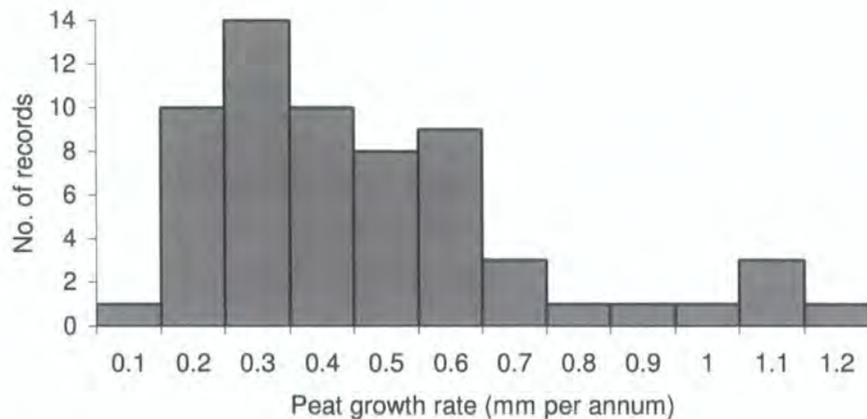
Figure 1.2: Diagram showing the variation in peat accumulation rates from upland blanket peat (Source: Tallis, 1995a).

Peat Hydrology

The presence of peat greatly influences the hydrology of a catchment. Peatlands cover the headwaters of important river systems in many parts of the world, but despite a history of scientific investigation stretching back 70 years, few studies have reported on the spatial or temporal runoff characteristics of these areas. Horton (1933) first discussed infiltration-excess overland flow. He proposed that precipitation is divided between infiltration and overland flow. Overland flow fails to infiltrate the peat and flows rapidly over the surface to generate storm runoff or quickflow in the streams, whilst the infiltrated water, is either lost via evapotranspiration or percolates to groundwater, and then seeps slowly downhill to sustain low flow or baseflow in the streams (Jones, 1997). Figure 1.3 shows an example of a storm hydrograph from Troutbeck at Moor House and Upper Teesdale NNR.
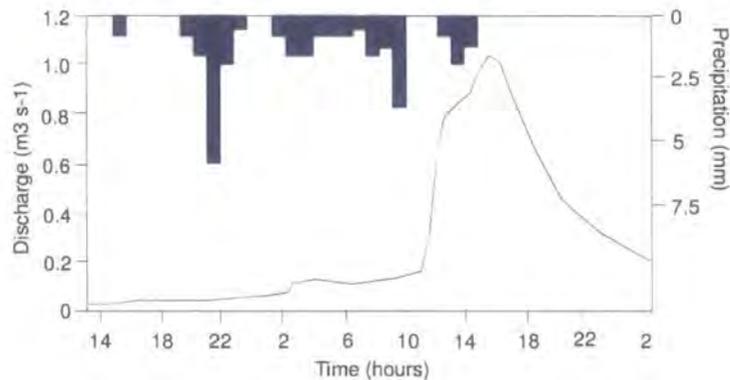
Figure 1.3: An example of a storm hydrograph from Troutbeck at Moor House (Source: Evans *et al.* (1999)).

Figure 1.3 shows a steep rising limb and a gentle falling of the hydrograph following prolonged precipitation. The steep rising limb is a result of overland flow entering the channel quickly, whereas the gentle falling limb is a result of slower throughflow from the infiltrated water. In addition to infiltration-excess overland flow runoff can also be produced by saturation-excess overland flow (Kirkby and Chorley, 1967; Dunne and Black, 1970). This is produced when the storage capacity of the peat is completely filled, so that all subsequent additions of water at the surface, irrespective of their rate of application, are forced to flow over the surface (Kirkby, 1988; Gerits *et al.*, 1990). The division of the two dominant peat layers is critical in terms of peat hydrology (Ingram, 1983). It is rare for the water table to fall below 50 cm of the peat surface. Tomlinson (1979) reported a 'critical level' for the water table at 5 – 6 cm below the bog surface, below which fluctuations were slow, lateral flow almost ceased and runoff sharply decreased (Burt *et al.*, 1990). Holden and Burt (2003a) carried out research into the acrotelm-catotelm model at Moor House and Upper Teesdale NNR, North Pennines. They discovered that the water table was maintained above 5 cm depth for 82 % of the time. This was a similar conclusion to Evans *et al.* (1999) who showed that for a gently sloping peat surface, also in the North Pennines, water tables were within 5 cm of the surface for 83 % of the time, but could drop deeper than 20 cm during drought.

Less dense peats, such as the acrotelm have large pore spaces and therefore high hydraulic conductivity, whereas dense peats, such as the catotelm, with a fine peat matrix and small pore spaces, have a low hydraulic conductivity and water movement is therefore impeded (Ingram, 1983; Charman, 2002). Hydraulic conductivity controls the

infiltration rate and hence, in some circumstances, the relative proportion of water entering the soil and water carried away by surface flow (Rycroft *et al.*, 1975). Holden and Burt (2003b) found a significant variation in the hydraulic conductivity with depth (10 to 80 cm from the surface) using piezometers. They found the mean hydraulic conductivity calculated using the response time charts derived numerically by Brand and Premchitt (1982) to be 2.9 x 10^{-6} cm s^{-1}. The hydraulic conductivity of peat has been considered as one of the more important physical properties that affects the hydrologic features of peatland areas (Boelter, 1965).

The slope gradient is one of the major factors affecting overland flow. The greater the slope gradient, the greater the portion of rain that runs off as overland flow. As more water runs off, the velocity is increased both as a consequence of the steepness of the slope and the greater depth of overland flow. The overland flow process is also strongly affected by the topography of the slopes (Holy, 1980).

The potential of erosion in upland blanket peatlands is therefore affected by peat hydrology and depends largely on the rates of overland flow. Peatlands are at greatest risk because when it occurs, erosion is irreversible in the short or medium term. However, due to a lack of baseline data on historical and contemporary rates of upland erosion the impacts on blanket peatlands by overgrazing, recreational pressures and climate change, for example, cannot be easily evaluated (Grieve *et al.*, 1995). In terms of erosion at-a-site, sediment yields will generally be low because where the vegetation cover is intact (regardless of type) sediment cannot be easily entrained (Figure 1.4). However, changing vegetation type has an important influence on runoff production leading to greater surface runoff. Routing of the surface runoff into concentrated flow paths will result in local erosion often producing incision and gully development. Where the surface cover is disturbed directly by the impact of rain, often in conjunction with wind, high sediment yields can result (Environment Agency, 1998).
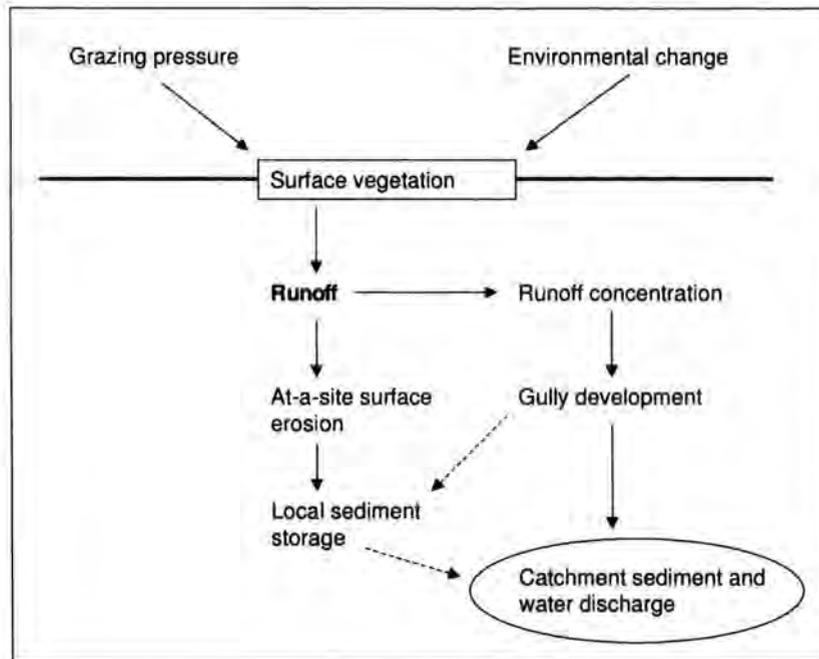
Figure 1.4: Schematic diagram illustrating the links between grazing pressures, runoff and erosion.

Spatial Variation

One characteristic of blanket peatlands is surface patterning. Surface patterning includes depressions and runnels filled with lawns of *Sphagnum* and adjacent raised bog surface with vegetation types such as *Eriophorum* and *Calluna*. They are better known as hollows and hummocks. Hummocks and hollows are persistent features in time and space on the mire surface (Aaby, 1976). Osvald (1923) produced the classic 'Regeneration Cycle', also known as the hummock-hollow theory. 'Regeneration' is the term used to describe the natural development of a peatland into a functioning ecosystem, this is opposite to human intervention towards peat development (rather than natural), which is described as 'restoration' (Charman, 2002). The theory arose after a long period of speculation and imprecise observations on the peat forming process and formation of peatlands (Barber, 1981). The theory, however, was not formally tested until 1961. Osvald stated that 'peat accumulation is greatest in the hollows'. Vertical growth of *Sphagnum*-rich hollow communities leads to peat accumulation raising the former hollow to same level as the adjacent hummock (Svensson, 1988). This is because the hummocks are less waterlogged and the peat more humified. As peat accumulation continues, water seeps from the new hummock, draining it and

8

subsequently flooding the low-lying old hummock (Foster *et al.*, 1988). The process is then replicated as shown in Figure 1.5.
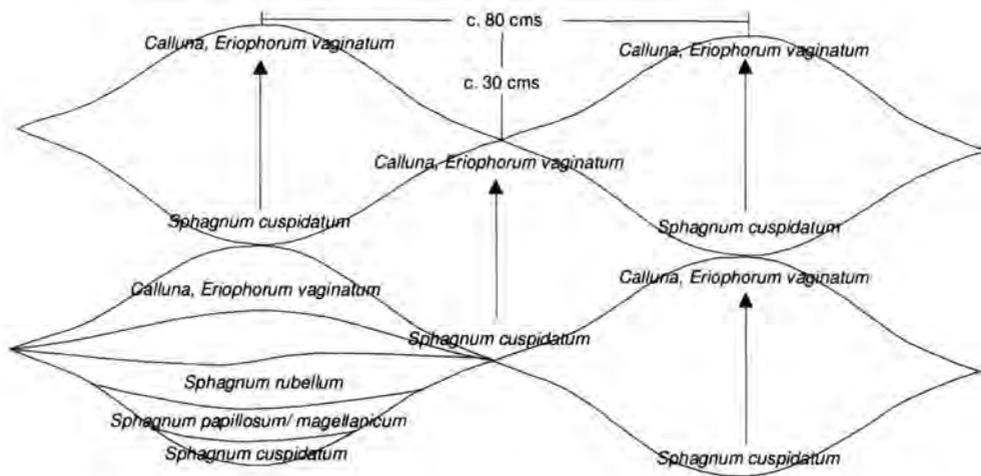
Figure 1.5: The idealised cycle of Regeneration (Source: Charman, 2002).

The cycle of Regeneration shows the vegetation type to vary with the depth of the pool and subsequent waterlogging. One of the most characteristic species of waterlogged hollows is *Sphagnum cuspidatum* (English Nature, 2001a). Finally *Calluna* and *Eriophorum vaginatum* form on the hummock, as they are dry. *Eriophorum vaginatum* is known to colonise fairly wet lawn situations (Osvald, 1923) and to do well in areas where the water level is high in spring but falls in summer (Wein, 1973). Burt *et al.* (1990) noted that where pool-hummock complexes occur, surface runoff might be confined to the pools alone, since the hummocks may be well drained.

Barber (1981) carried out extensive research on Bolton Fell Moss and other Cumbrian sites with the aim of examining the relationship between bog growth and climate change. He hoped to test the 'hummock-hollow theory'. Macrofossil analysis on the hummocks clearly showed 'pure' *Eriophorum vaginatum* hummocks or tussocks, containing abundant *Sphagnum* remains. He suggested that the blanket peat surface was responding all over to changes in surface wetness, growing up in faster and slower phases, but without any suggestion of cyclic processes. Later, Tallis and Livett (1994) looked at the past hummock and pool patterning through stratigraphic records at Alport Moor, Southern Pennines. Their results showed microtopographical diversity of the mire surface into pools, hollows and hummocks to have occurred over the last 2200 years. This was thought to be a result of differential local rates of peat accumulation.

1.2 Key research in blanket peat erosion and re-vegetation

Peat Erosion

Blanket peatlands are sensitive to change. Blanket peat erosion is a three-stage process involving: the removal of the surface vegetation; exposure of the underlying soil; and progressive removal of the peat (Tallis, 1998). Peat erosion is widespread in the uplands (350,000 ha of British and Irish peatlands are affected by erosion (Bragg and Tallis, 2001)) and may, in places, have been ongoing for several hundred years (Bragg and Tallis, 2001; Higgitt *et al.*, 2001). In many ways the sensitivity of blanket peat is analogous to badland erosion (Tallis, 1997a). This sensitivity stems from the potential ability to rapidly destabilise the landscape through accelerated erosion due to small changes in a single environmental factor (Tallis, 1998; Bragg and Tallis, 2001). Although peat erosion can occur as a natural endpoint to blanket peat development (Lewis, 1906; Johnson, 1957), additional causes of erosion can be as a result of: climatic change (Conway, 1954; Bower, 1961); anthropogenic activity, such as grazing (Shimwell, 1974), burning (Pearsall, 1950; Radley, 1965; Stevenson *et al.*, 1990), and atmospheric pollution (Tallis, 1964; Ferguson and Lee, 1983; Rosen and Dumayne-Peaty, 2001).

The natural instability of peatland systems results from its high water content (over 90 %) and the low density of its solid components. The instability becomes more pronounced as peat continues to accumulate (Tallis, 1989). It can easily be chemically destroyed (by oxidisation, solution and burning), physically disaggregated (by frost and drought) and bodily transported as low-density particulates (by water and wind). Only a protective layer of vegetation prevents its rapid erosion (Tallis, 1997a). Several studies have demonstrated the crucial role of vegetation in controlling erosion (Poesen *et al.*, 2003). Thornes (1985) conducted research into vegetation and erosion and found a healthy, well managed vegetation to be capable of withstanding erosion by water, e.g. long grass was found to be a good cover type, not only because its root depth increases with the increased volume of leaf above the peat, but also because in a flood the long grass is laid flat by the force of the water, therefore reducing erosion (Sansom, 1996). Vegetation on blanket peatlands may vary in response to very small changes in water level; however, the underlying peat mass may undergo total degradation when the water table drops. The relative position of the water table within the peat ultimately controls

the balance between accumulation and decomposition and therefore its stability (Thornes, 1985).

Deeply incised gully systems are typical erosion features, which characterise many blanket mire areas of upland Britain (Bower, 1959; 1960a; 1960b; 1961; 1962; Tallis *et al.*, 1997; Tallis, 1998). Gully erosion is defined as 'the erosion process whereby runoff water accumulates, and often recurs in narrow channels and over short periods, removes the soil from this narrow area to considerable depths' (Poesen *et al.*, 2001). Gully systems, although unstable, are regarded as relatively permanent watercourses. They are associated with accelerated erosion and with landscape instability, are found in many parts of the world and form at a break in vegetation cover, or where the underlying material is mechanically weak or unconsolidated (Selby, 2000). Upland environments and gully systems are of interest to geomorphologists because of landscape change; environmental managers because of management practices; soil scientists and ecologists because of vegetation change; and hydrologists because of water resources and reservoir siltation (Tallis *et al.*, 1997). Despite their importance very little work has been done on gully development in peatland systems. In terms of gullying, the timescales of gully initiation vary. There is nevertheless a consensus that points towards peat erosion at a range of sites around 400 – 600 years ago. More recent dates (within the last 200 years) are likely to relate both to the continuing long-term development of gully systems and to accelerated human pressures (Tallis, 1998).

Early research into blanket peat erosion in the UK was first carried out by ecologists (Pearsall, 1941; Osvald, 1949), who commented on the frequency of erosion. Interest was then expressed by Conway (1954) who investigated the stratigraphy of the Southern Pennines using pollen analysis and made assumptions as to the state of the blanket peatlands within the Pennines. Immediately following Conway's paper, a series of investigations were carried out on the processes and the features of blanket peat erosion (Bower, 1960a; 1960b; Radley, 1962) and on the possible causes of their erosion (Bower, 1962; Radley, 1962; Barnes, 1963; Johnson and Dunham, 1963; Tallis, 1964). The first of these detailed studies was presented by Bower (1960a; 1960b; 1961; 1962) who summarised the causes, processes and results of erosion in blanket peat. Bower (1960b; 1961) divided peat erosion into two main types: erosion by water and by mass movement. Following this Radley (1962) suggested that wind erosion was also important. Recent work has confirmed the significance of erosion by wind combined

with rainsplash (Warburton, 2003). Francis (1990) observed deflation of the dry bare peat surfaces to also be an important agent of erosion.

Bower mapped areas of eroded blanket peat and classified gully systems into two distinct types of dissection (Type 1 and Type 2) (Figure 1.6). Both types were considered to form from one of three mechanisms: within the peat mass originating along horizontal or vertical lines of seepage; as runnels on the surface encouraged by vegetation destruction; and by headward erosion of gullies from the margin of the peat. Type 1 dissection is more related to summit erosion and according to Bower (1959; 1960a; 1960b): is 'closely gullied, deep peat areas on flat or nearly flat ground, with an intricate network of branched drainage gullies and bare peat pools encircling dry hummocks'. The earliest reference to peat gullying referred to by Bower (1959) was made by Farey (1811) who described these areas as 'crossed in all directions by gullies and groughs'. Typically Type 1 dissection occurs in peat of 1.5 - 2 m depth on slopes less than 5°. Gully frequency is high and these tend to branch and intersect. Ultimately the peat mass is reduced to a large number of peat islands (Figure 1.7a). Where lateral erosion continues but vertical erosion ceases, expanses of bare peat are produced (Figure 1.7b). Type 2 dissection occurs on more sloping ground with a system of sparsely branched drainage gullies aligned nearly parallel to each other (Burt and Labadz, 1990), typically on slopes exceeding 5° (Figure 1.7c).
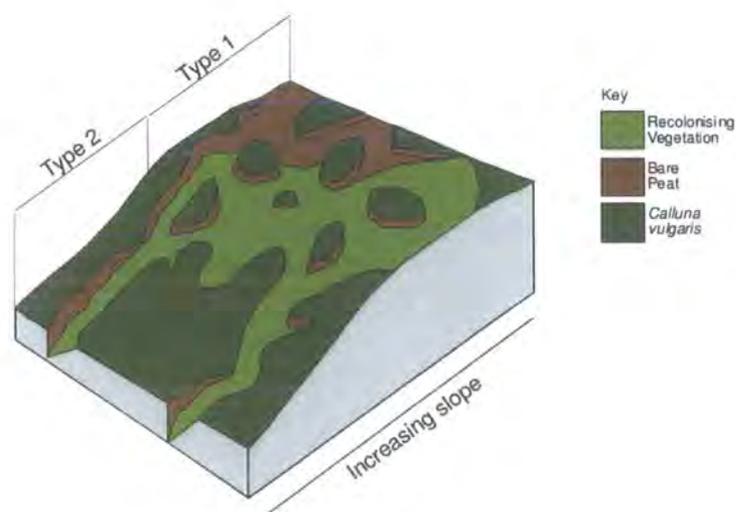
Figure 1.6: Type 1 and Type 2 Dissection of Gully Systems (Adapted from: Bower, 1960b).

A

B

C

Figure 1.7: Photographs showing: A) Type 1 Dissection on gentle sloping ground branched and intersected channels and isolated islands. B) Large expanse of bare peat, now re-vegetating (Moss Flats). C) Type 2 Dissection on sloping ground with aligned nearly parallel channels.

Bower's (1960a; 1960b) classification scheme has been widely employed in the literature on blanket mire degradation. Tallis (1985a) remarked that peat erosion in the Southern Pennines, studied during the 1981 Peak District Moorland Erosion Study (Phillips *et al.*, 1981), conformed well to the scheme of Bower (1960a; 1960b). Others, suggested modifications to the basic scheme (Radley, 1962; Mosley, 1972).

Differences of opinion were found between Bower (1960a; 1960b; 1961) and Radley (1962) in terms of the dominant processes forming the erosional features of peat-covered summit areas. Radley assigned more importance to wind, concluding that, 'wind erosion has an important place in the removal of peat for, although it is quite ineffective while the vegetation cover is complete, wind-scour is possible as soon as the cover is broken, and water erosion can then be effective too. Wind action will be frequent and vigorous on the high, bare, exposed Pennine summit areas'. Radley (1962) agreed with Bower that slope is undoubtedly a factor in the erosion process, but found no direct correlation between slope and the amount of erosion. Radley emphasised anthropogenic activity as the main factor for disrupting the vegetation cover leading to erosion. Furthermore, he disputed Bower's classification of the main types of erosion. Radley distinguished erosion on interfluves (summit erosion) from that downslope.

Mosley (1972) stressed that there was overlap in characteristics between the Type 1 and Type 2 dissection systems. He carried out research on a plateau in Derbyshire, similar to that of The Cheviot and found Bower's (1960a; 1960b) work had drawbacks because of its qualitative nature. Mosley believed a quantitative study could be used to test Bower's conclusions and therefore employed empirical techniques to assess the divisions of dissection systems suggested by Bower (1960a; 1960b). He confirmed that the division of gully systems into two main types is valid, but should be put on a firmer basis by the application of methods and concepts from quantitative and statistical geomorphology. However, Mosley (1972) was unable to assign a particular pattern of dissection to one or other of the two main gully types by reference to its quantitative characteristics and therefore questioned the schemes widespread validity. It was therefore thought that the gully systems produced more of a continuum of forms, and stated that from his analysis there were end-members as a single statistical population and that the vast majority of networks could hardly be placed in one class or the other (Mosley, 1972).

The continuum of form observed by Mosley (1972) has been supported by work of Wishart and Warburton (2002) who carried out an assessment of the erosion of the blanket peat in the Cheviot Hills, Northumberland. Wishart and Warburton's proposed classification scheme of linear, dendritic and anastomosing gully patterns (Figure 1.8) was used to 'avoid preconceived process distinctions'.

Bower (1961) described the development of gully systems, stating that they erode headwards and laterally and eventually incise to the peat base. 'Early stages' refer to cases where most gullies are shallow and contained within the peat, 'advanced stages' are where the main gullies have incised to the peat base but they are very narrow, with V-shaped cross-profiles, and 'late stages' are where gullies are wide and the islands of peat between them small and widely scattered (Bower, 1961). Wishart and Warburton (2002) further discussed this issue, highlighting similar points to Bower (Figure 1.9). Figure 1.9 shows the development of linear and dendritic gully systems in The Cheviot Hills. The processes are shown in the rectangular boxes. Wishart and Warburton (2002) suggested that they develop in a sequential manner.
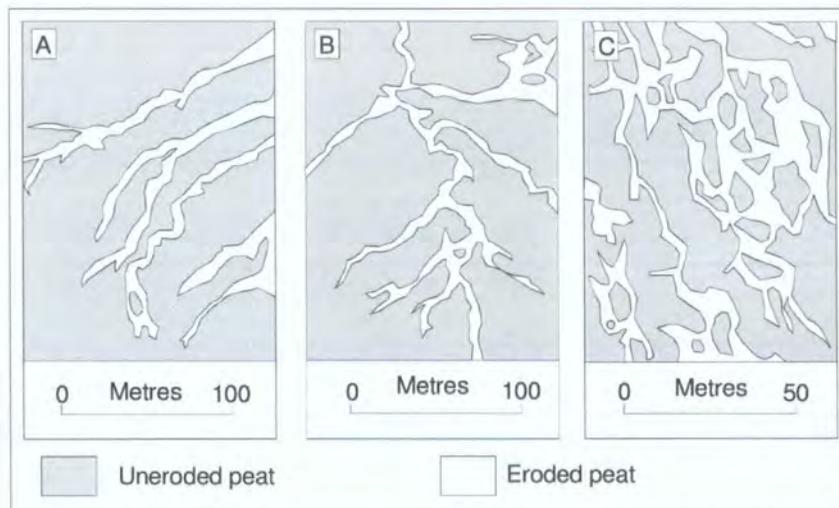
Figure 1.8: Examples of gully erosion types observed in The Cheviot Hills. (A) Linear gullies. (B) Dendritic gully pattern. (C) Anastomosing pattern. (Adapted from: Wishart and Warburton, 2002).

Undisturbed Blanket Peat

▼

Vegetation Destruction

▼

Gully Initiation

▼

Vertical Erosion Dominant

▼

Base of Peat Reached

▼

Lateral Erosion Dominant

▼

Stream Widening and Meandering,
Reduction in Stream Power

▼

Peat Deposition and Re-vegetation

▼

Temporary Stability?

▼   ▼

Localised Erosion and Reworking ⟶ PEAT LOSS
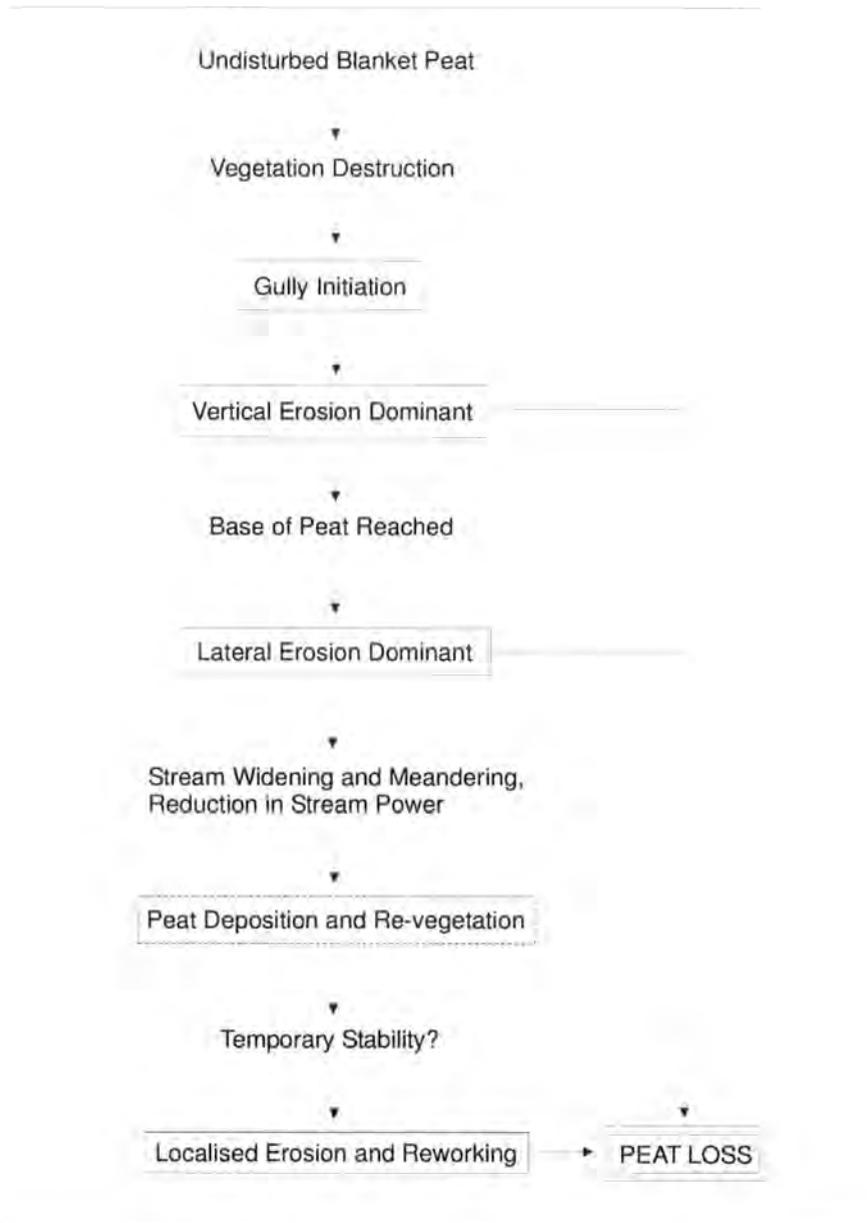
Figure 1.9: Typical sequence of gully development and peat erosion in the Cheviot Hills (Source: Wishart and Warburton, 2002).

Figure 1.9 shows that once the vegetation is disturbed gullies can be initiated (early stages) and rapidly cuts down to produce a 'V'-shaped gully with bare peat walls (advanced stages) and the peat base is reached rapidly as downcutting progresses. The gully floors often composed of poorly sorted drift deposits. In most cases the gully then begins to widen by parallel retreat of the gully walls as downcutting becomes limited by the armouring effect of a lag of rock fragments and bedrock on the gully floor (late stages). The stream power is reduced so erosion reduces. The deposition of peat then occurs followed by re-vegetation. This is occasionally inter-bedded with sand and fine gravel transported down the gully during high discharge storm events (Figure 1.10). This may occasionally be from the development of *in situ* peat in pockets of waterlogged ground, but more commonly re-deposition of peat within the gullies and peat fallen to the base of the gullies from the degraded gully walls. This then acts as a further trap to material being washed down the gully and the gully begins to stabilise. Where gully systems have extensively re-vegetated the active drainage is usually confined to a single channel at the base of the gully, which often hugs one of the gully walls (Figure 1.7c). Although relatively stable, re-vegetated gullies are still active with reworking of re-deposited material occurring during storm events.

Figure 1.10: Evidence of a gully infilled with peat inter-bedded with sand and fine gravel on The Cheviot summit.

Wishart and Warburton (2002) also noted that there is no feedback to undisturbed blanket peat in Figure 1.10 and therefore the timescale implied is shorter than that of complete regeneration. They found there to be no definite time frame of gully

development; however, comparative photography such as Figure 1.11 allows rates of erosion and/or re-vegetation to be approximated.

Figure 1.11: Historical change in the Burnt Hill 1 gully system, Moor House and Upper Teesdale NNR, North Pennines. Left) 1958. Right) 1998 (Source: Higgitt *et al.*, 2001).

The timescales involved in peat formation and the onset of erosion are now beginning to be documented (Tallis, 1998); however, the recent re-vegetation of blanket mires (last 200 years) is very poorly understood. Figure 1.12 suggests linkages between peat formation, the onset of erosion and re-vegetation. This raises important questions regarding the future of upland blanket peat. At present re-vegetation in many UK upland landscapes appears to be occurring and may lead to a recovery stage of the peat and vegetation, eventually leading to stabilisation of the landscape. However, if erosion proceeds once it reaches a critical peat depth, where the peat become unstable, then further erosion may occur (Figure 1.12). One major current concern is that there would be a further loss of blanket peat and an important loss of terrestrial organic carbon (Tallis, 1998).
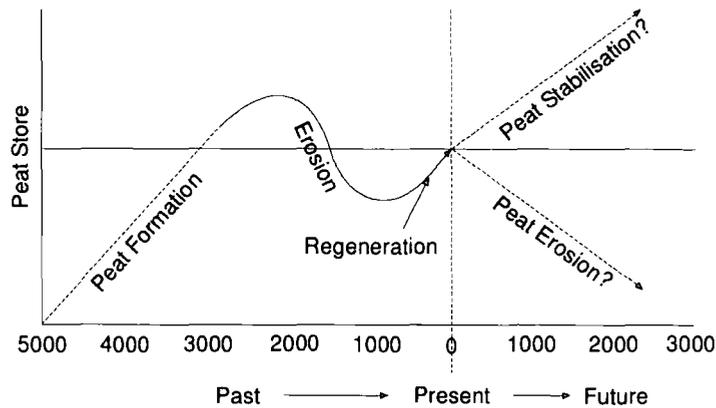
Figure 1.12: Schematic diagram of the past, present and possible future of upland blanket peat.

This research therefore aims to assess the current state of upland blanket peat in light of the recent work on peat erosion and re-vegetation. The classification proposed by Bower (1960a; 1960b; 1961; 1962) and past work is recognised as lacking detail and does not investigate the timescales of re-vegetation and the recovery of dissected peatlands. Predictions of the future stability of upland blanket peat given land management practices and climate change are made.

Bower (1960a; 1960b; 1961; 1962) predicted that, based on observations in the 1950/ 1960s, erosion in the Pennines would continue; however, although spatially variable, this does not generally appear to be the case as some areas are now re-vegetating and regenerating, for example, Moor House and Upper Teesdale NNR (Higgitt *et al.*, 2001; Evans and Warburton, 2005) (Figure 1.7 and 1.11). This suggests re-vegetation of much of the previously eroded peat blanket and raises important questions about the balance between agents of erosion and natural environmental change. Recent work suggests the re-vegetation is associated with changes in nitrogen enrichment, reduced grazing pressures, reduced burning cycles, and positive effects of climate change (Milne and Hartley, 2001). Positive effects of climate change include: species responding by shifting northwards and/or uphill of their current optimum temperature; the type and number of species may change with the ingression of new species; rising temperatures would lead to a more rapid growth in plants due to increased CO_2 carbon and nitrogen levels would then increase in their cell structures and the nutrient status of the habitats would increase. Pepin (1997) also mentioned how climate change in the uplands is important because the peaty soils are significant carbon stores, which may decompose

19

more as climate warms, releasing more CO_2 into the atmosphere and thus providing a positive feedback.

1.3 Plan of research
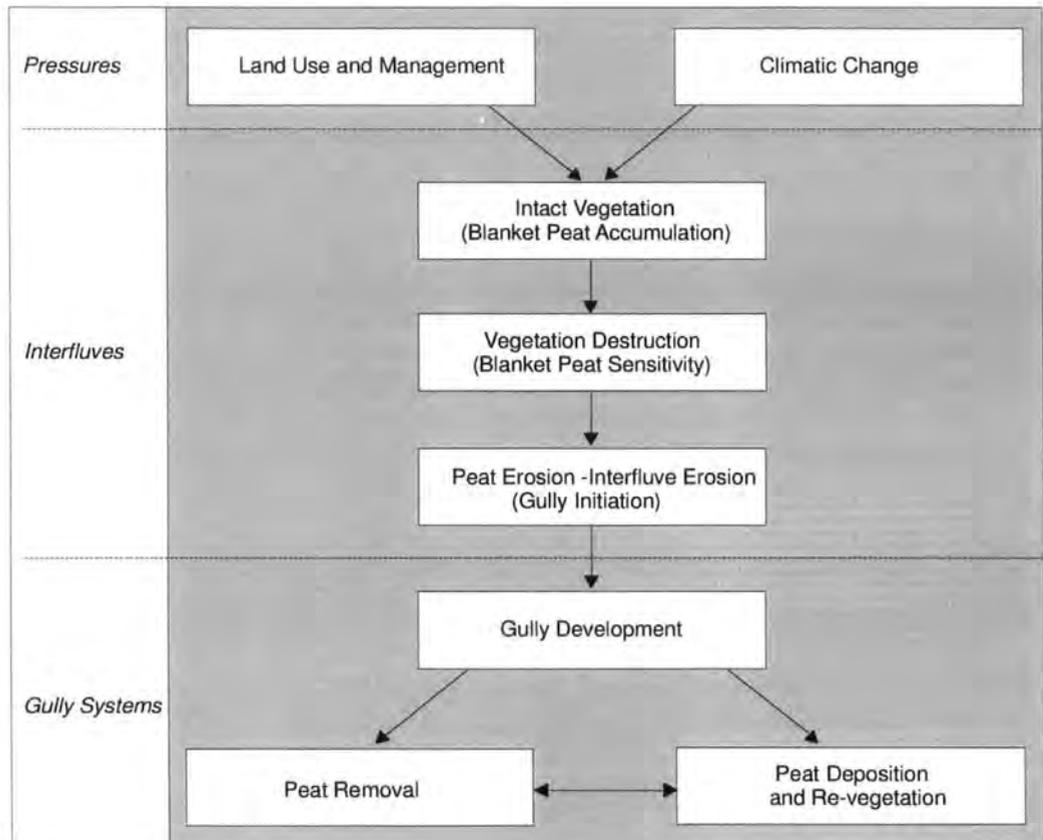
Figure 1.13: Flow diagram of the research topics addressed in this study.

Figure 1.13 summarises how the pressures on UK upland blanket peat landscapes affect the interfluves and gully systems. The pressures on blanket peatlands can lead to an intact accumulating peat profile to become sensitive to erosion. The sensitivity may then lead to a destruction of the vegetation cover and exposure of bare peat. The bare peat is then easily eroded as a result of wind, rain and frost action. This in turn can lead to gully initiation and development. As gullies develop large quantities of peat are removed, they erode the mineral base and then widen before re-deposition occurs and re-vegetation occurs (Wishart and Warburton, 2002). There is limited detailed research on the development of gully systems in upland blanket peat, especially in light of the recent re-vegetation and its impacts on uplands in relation to a long-term sediment budget.

This study investigates regional and local scale variations in gully development and long-term peat accumulation and short-term mechanisms of peat loss in the interfluves (Figure 1.13).

1.4   Research aims and objectives

The overall aim of this research is therefore, to assess the erosional stability of upland blanket peat catchments in light of evidence of recent re-vegetation. The objectives at the centre of this study are:

1. Critically evaluate past literature on the extent of blanket peat erosion in upland Britain and its basic causes.

2. Examine regional variations in extending gully systems across the Pennines from SW to NE (The Cheviot Hills, North Pennines and Southern Pennines) and compare the different extent and patterns of erosion and regeneration that are present.

3. Using sequential air photographs, and historical ground-based photographs assess rates and patterns of erosion and/or regeneration within these regions.

4. Quantify gully form (e.g. width, depth, slope) in relation to local controls and position in the stream network and local site conditions (vegetation, slope and soils).

5. Critically assess the usefulness of Bower's (1960a; 1960b) classification in comparison to quantitative measures of gully form derived using a GIS framework.

6. Use a Spheroidal Carbonaceous Particle (SCP) analysis for dating recent peat accumulation rates of upland blanket peat and examine the regional variations.

7. Use a rainfall-runoff simulation to assess erosion potential on intact vegetation surfaces within the interfluve areas of the blanket peat catchment.

8. Develop a revised conceptual erosion model of gully development and interfluves as a means of discussing the future stability of upland peat gully systems.

1.5   Organisation of the thesis

The thesis is structured into nine chapters. Using a sediment budget framework, Chapter Two presents a detailed critique of existing literature on blanket peat-covered catchments in upland Britain by discussing the types and rates of peat erosion. The potential causes of erosion are discussed: climate change; anthropogenic activity; or a natural endpoint. These causes of erosion are important when considering the future of

21

upland blanket peat. The present state of blanket peatlands (recent re-vegetation status) is then highlighted, especially in terms of the recovery of peat gullies from erosion.

Chapter Three describes the research framework, study sites and methodology of the investigation. A description of the regional setting of the study areas is followed by a description of each study site: Moor House and Upper Teesdale NNR (North Pennines), The Cheviot Hills (Northumberland) and Wessenden Head Moss (Southern Pennines). The description of each site includes notes on: landscape characteristics; geology; soil type; vegetation; climate; land use and management and background data and research. This is followed by a description of the methodology. The methodology can be divided into four main sections: regional assessment of gully erosion and development; long-term, local assessment of interfluve peat accumulation; short-term, local assessment of interfluve erosion and gully initiation and local scale assessment of gully erosion and development.

Chapter Four is the first of the main results chapters and examines the change and development of gully systems over time. This includes the use of sequential aerial photograph analysis in a GIS framework, detailed classification of peat gullies for the three sites and a comparison with Bower's research (Bower, 1960a; 1960b; 1961; 1962). The distribution of the types of gully systems with altitude are then presented, with gully ordering, drainage density and changes in gully development over the multi-decade timescale all discussed. This includes detailed assessments of Burnt Hill gully system and Moss Flats at Moor House and Upper Teesdale NNR, The Cheviot summit and Wessenden Head Moss.

Chapter Five addresses the long-term local variations in interfluve development. Results from Spheroidal Carbonaceous Particle (SCP) dating of peat profiles from the three study sites are presented. The results show the variations in peat accumulation rates over the last 150 years at the three sites and variability in pollution (SCPs are formed from the incomplete combustion of fossil fuels).

Chapter Six addresses the short-term local variations in interfluve development and the erosion potential. Details of the block experiments are presented followed by the results showing the short-term runoff and sediment production rates from exclosure plots during simulated rainfall events at Moor House and Upper Teesdale NNR. Results

highlight the potential of both changes in climate (increased rainfall) and land management (impacts of sheep grazing and burning) in terms of erosion of upland blanket peat.

Chapter Seven presents the local scale development of the gully systems at the three main study sites. Results show variations in the gullies within and between the three study sites. These include observations of gully form, stratigraphy, vegetation and change over time. Results from cores and monoliths are presented from the three study sites, including differences in the macrofossils between cores from the infilled gully bases and adjacent undisturbed interfluves.

Chapter Eight is primarily a discussion chapter. This provides a synthesis of the four results chapters and a comparison of results with previous research. The future stability of upland blanket peat catchments is discussed, based on findings from this study. A revised conceptual erosion model of gully development is developed and a historical sediment budget.

Chapter Nine provides the conclusion to the thesis. The research objectives are reviewed and the major findings discussed. Concluding remarks are made, and finally the chapter addresses the limitations of the research and discusses future work in this field.

2.0 REVIEW OF RESEARCH INTO BLANKET PEAT EROSION AND RE-VEGETATION IN UPLAND BRITAIN

2.1 Scope of chapter

This chapter reviews past literature associated with research into upland blanket peat erosion, and the recent re-vegetation of eroded peatlands. Section 2.2 describes the main mechanism of peat erosion using a sediment budget framework. This is followed by a discussion of the measured rates of erosion (Section 2.3). Section 2.4 then addresses the general processes of erosion. Gully erosion is discussed first; followed by piping; mass movements; frost action and desiccation; wind erosion; and, finally, stream bank collapse and peat block transport. Section 2.5 outlines the factors influencing peat erosion and considers climatic change (Section 2.5.1), anthropogenic activity (Section 2.5.2) and the natural end-point in peat accumulation (Section 2.5.3). Finally Section 2.6 looks at the current state of blanket peatlands and discusses the recent re-vegetation of peatlands including natural re-vegetation (Section 2.6.1) and human induced re-vegetation (Section 2.6.2). An understanding of this is important in terms of the implications of upland blanket peat landscape evolution, especially future management and the impacts of climate change.

2.2 Blanket peat erosion

The main mechanisms of peat erosion are summarised in Figure 2.1, which highlights the importance of peat erosion in the Pennines. The sediment budget shows the production, transport and discharge of sediment (Reid and Dunne, 1996). Dissection (Bower, 1960a; 1960b), piping (Holden and Burt, 2002a), mass movement (Carling, 1986a; Warburton et al., 2003), wind erosion (Radley, 1962; Warburton, 2003) and deflation (Francis, 1990) are all shown to be significant in producing and transporting peat from the hillslopes to the channel systems. As can be seen from the diagram, they are not necessarily mutually exclusive (Tallis, 1985a). In addition, colluvium and bank collapse adds to the in-channel sediment (Evans and Warburton, 2001). Once in the channel, peat is transported in suspension and as low-density blocks. Large quantities of peat stream load lead to reservoir siltation and where severe peat erosion occurs cause problems for reservoir managers (Labadz et al., 1991).

24
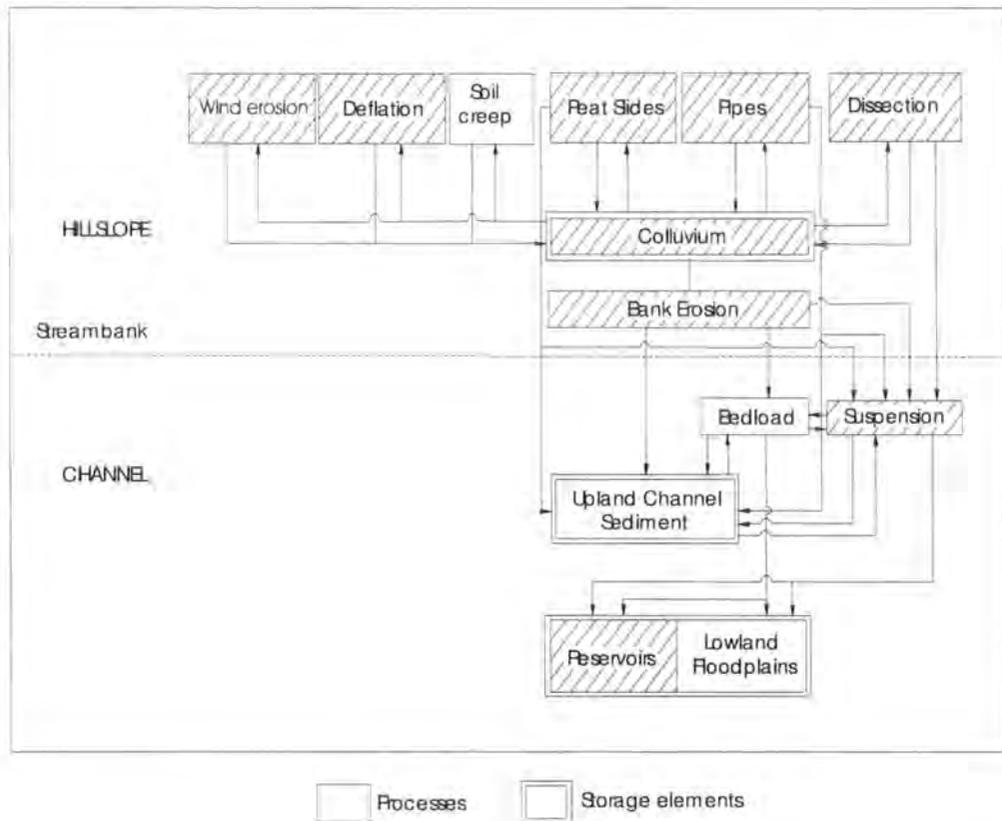
Figure 2.1: General sediment budget structure for the Pennines. The hatched boxes highlight the components of the sediment budget, which tend to be dominated by organic detritus or peat (Adapted from: Warburton, 1998).

2.3   Rates of erosion

Some published rates of erosion measured in the Pennines are presented in Table 2.1. The table shows that rates of erosion can be measured using various techniques. Crisp (1966), Crisp and Robson (1979) and Evans and Warburton (2005) collected water samples from a North Pennine stream (Rough Sike) and estimated the erosion from the amount of peat present in the water. Both in the North Pennines and Southern Pennines erosion pins in the sides of gully walls and peat margins have been used to estimate rates of erosion (Tallis, 1981b; Birnie, 1993; Evans and Warburton, 2005) and in addition sediment traps have been used (Tallis, 1973; Evans and Warburton, 2005) and surveying has been carried out (Carling, 1986a; Evans and Warburton, 2005). Interestingly the results are comparable, e.g. gully wall erosion rates ranged from 0.8 to 1.05 cm yr^{-1} in the North and Southern Pennines. Alternatively, estimates of rates of recent erosion can be attained from dated comparative photography (Figure 1.11),

whereby one photograph was taken in 1958, and since that time approximately 50 cm of peat and sediment had accumulated and re-vegetated in the base of the gully system (1998). Therefore over a 40-year time period, 50 cm of peat has accumulated, either through re-deposition or growing *in situ*. The rate of local accumulation can therefore be calculated to be a rate of 1.25 cm yr^{-1}.

Researcher(s)	Location	Area	Technique	Period	Rate
Crisp (1966)	Rough Sike, Moor House	83 ha	Inputs versus outputs in SSC	1962-1964	46532 kg yr^{-1}
Crisp (1966)	Rough Sike, Moor House	83 ha	Gully erosion through suspended load sampling	1962-1964	560 to 1000 t km^{-2} yr^{-1}
Crisp and Robson (1979)	Rough Sike, Moor House	83 ha	Spot measurements	1963	106064 kg during one storm event (6th July)
Evans and Warburton (2005)	Rough Sike, Moor House	83 ha	Sediment budget	July 1997 – October 2001	37 ± 1.5 t yr^{-1}
Tallis (1981b)	North Pennines		Erosion pins in gully sides		1.05 cm yr^{-1}
Carling (1986a)	Noon Hill Peat Slide, Weardale/ Teesdale		Survey	1983	2720 to 30750 m^3 in one afternoon (17th July)
Tallis (1973)	Featherbed Moss, Southern Pennines		Trap with 0.93 mm mesh		20 to 80 g m^{-2} yr^{-1}
Tallis (1973)	Snake Pass	330 m (length)	Sediment trap in gully base		1000 t km^{-2} yr^{-1}
Tallis (1981b)	Southern Pennines		Erosion pins in gully sides and gully margins		0.8 to 1.0 cm yr^{-1} and 0.5 to 7.4 cm yr^{-1}, respectively

Table 2.1: Selection of measured rates of peat erosion in the Pennines.

2.4 Types of erosion

2.4.1 Gully Erosion (Dissection)

This section builds on the discussion in Section 1.2. The importance of dissection in blanket peat erosion is well known (Figure 2.1) (Tallis *et al.*, 1997) and is probably Britain's major contribution to the global problem of headwater damage (Haigh and Krecek, 1991). Bower (1960a) considered dissection to be the most important erosive process both spatially and in terms of volume of peat removal and had serious implications for conservation of habitats and plant communities, through damage to the flora and fauna (Thompson *et al.*, 1995; Evans, 1997a). Despite this research focused on gully systems is still limited.

One system studied in detail by Bower (1959) was the main gully system on Burnt Hill in Moor House and Upper Teesdale NNR, North Pennines. She produced a long profile for the gully system with seven representative cross-sections identifying changes in slope angle in relation to peat depth (Figure 2.2). A skeletal planform map was produced of the gully system showing the differences in channel frequency between the two types of dissection (Figure 2.3) and the locations of the sites where four detailed study cross-sections. Vegetation was limited on the cross-sections (Figure 2.4). A number of photographs of this gully system used in Bower's research (1959) clearly show how the gully looked at this period (Figure 1.11a).
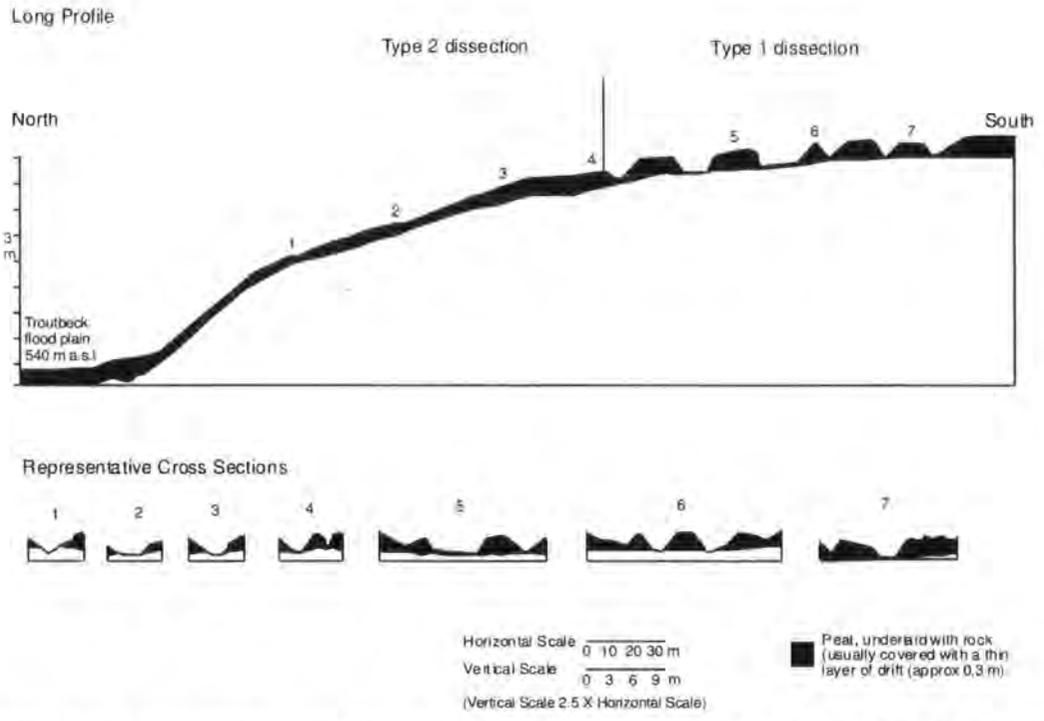
Figure 2.2: Long Profile of the main gully system on Burnt Hill (1957) showing peat depths and the location of representative cross-sections (Source: Bower, 1959).

Figure 2.2 shows variations down the long profile and cross sections in April 1957. In the area of Type 1 dissection at the top of the gully, slope angles were less than lower down the profile in the area of Type 2 dissection. The cross sections are narrower lower down the gully (Type 2 dissection) than at the top (Type 1 dissection). The cross-sections shown in Figure 2.4 are much wider in the area of Type 1 dissection than those in the area of Type 2 dissection. Vegetation is shown to be present in the base of the gully, mostly on the higher ground and on the gully sidewalls. Much of the lower flat ground in the base of the gully is bare with evidence of small-scale desiccation features.
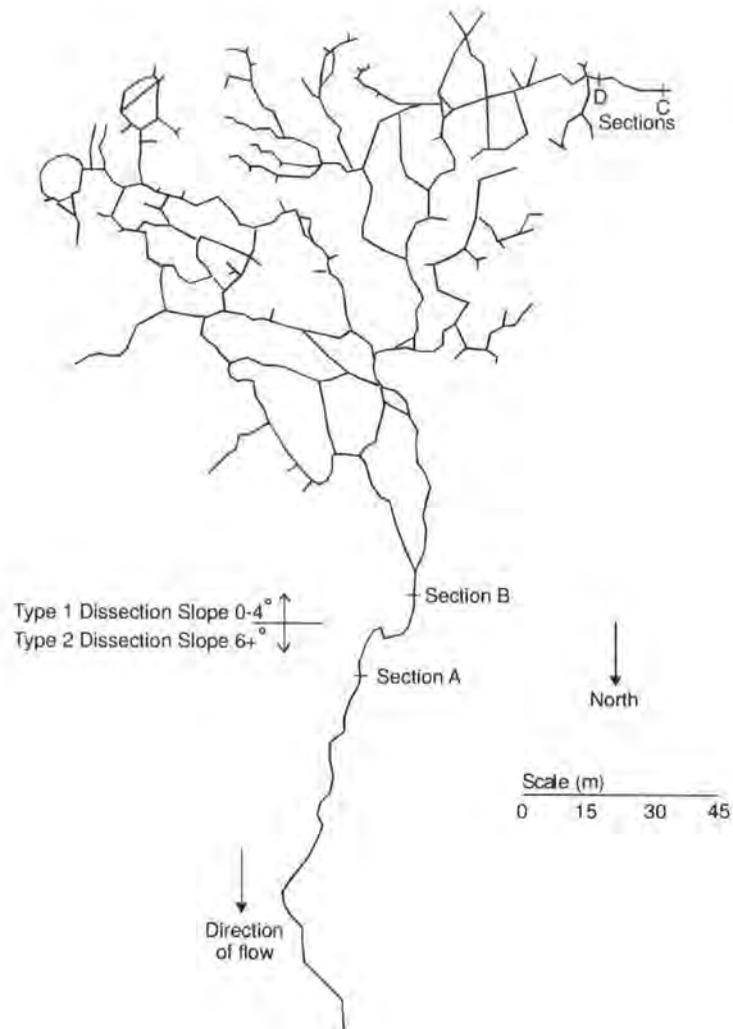
Figure 2.3: Skeletal Planform map of the main gully system on Burnt Hill (1957) (Source: Bower, 1959).
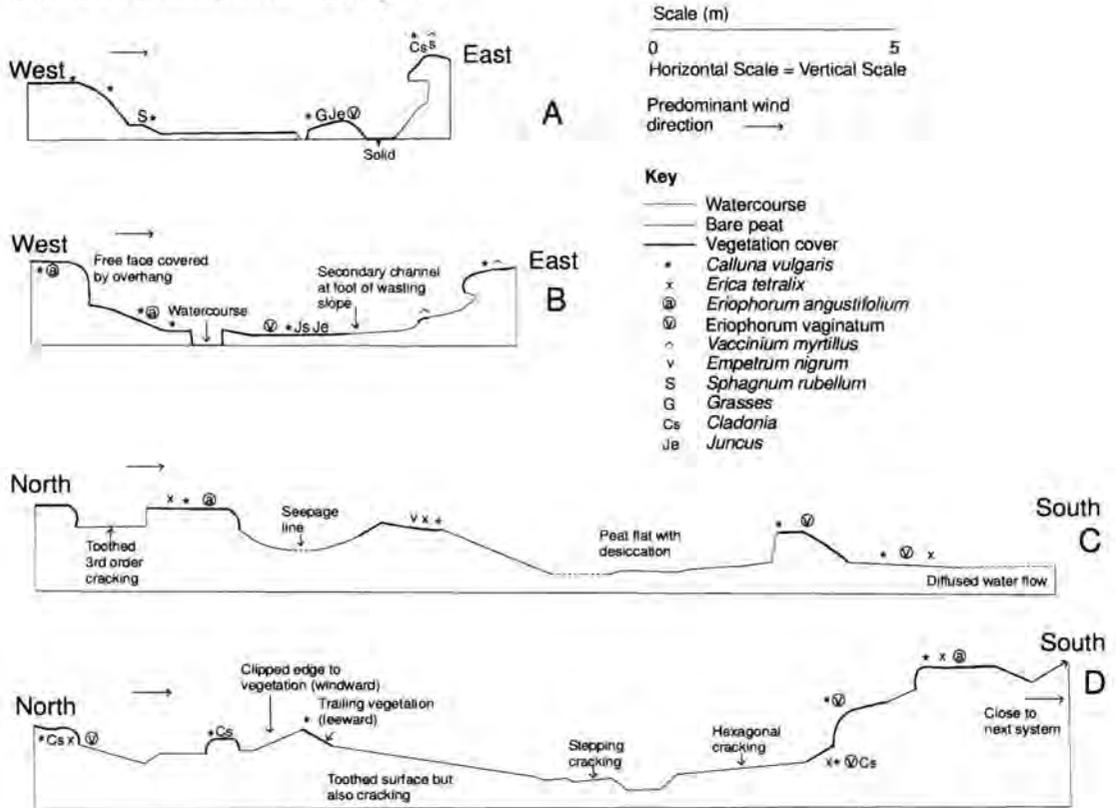
Figure 2.4: Cross-sections in 1957 from the main gully system on Burnt Hill (Source: Bower, 1959).

Detailed research of the characteristics of peatland gully systems and other methodologies and results presented by Bower (1959; 1960a; 1960b; 1961; 1962) have dominated upland blanket peat research in Britain over the last 50 years.

A considerable amount of research has been carried out estimating the extent of peat erosion in various areas of the Pennines (Bower 1961; Anderson and Tallis, 1981; Tallis, 1985a; Wishart and Warburton, 2002). Bower's (1960a; 1960b) classification scheme was used by Bower (1961) to map the distribution of peat erosion across the Pennines and then in the Peak District National Park in the 1981 Moorland Erosion Study, the results of which were presented by Tallis (1985a). Of the three categories, uneroded peat covered 39.4 km^2 (26 % of total peat area), Type 1 dissection covered 19.6 km^2 (13 %) and Type 2 dissection covered 92.3km^2 (61 %). The bare peat areas totaled up to approximately 17 km^2 (11 % of the total peat area) (Figure 2.5). Tallis (1985a) noted eroding peat was not uniformly distributed on the Peak District moorlands; it was more common in the west and at higher altitude (Type 1 dissection

above 550 m altitude). Despite the precipitation being greatest in the west, Tallis thought this was not due to climate but more a result of topography. The west was observed to have more areas of high flat ground flanked by steep slopes, while in the east there are greater expanses of gently rolling moorland.
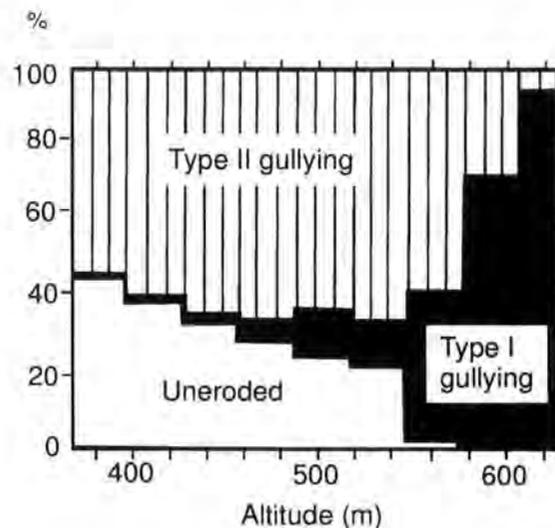
Figure 2.5: The proportion of peat-covered ground at different altitudes of the Peak District that is uneroded or affected by Type 1 and Type 2 dissection (Source: Tallis, 1985a).

Wishart and Warburton (2002) estimated peat erosion to cover 37 % of the high Cheviot upland area. Using their proposed classification, anastomosing erosion affected 7 %, linear 21 %, dendritic 9 % and peat slides less than 1 %. Therefore, in common with the Peak District, The Cheviot Hills showed that linear or Type 2 dissection dominated. There was still a clear difference observed in the percentage coverage of erosion between the two areas. In The Cheviot Hills peat erosion covers 37 % of the total area of blanket peat, whereas in the Peak District, 74 % is eroded: double the extent.

In The Cheviot Hills, Wishart and Warburton (2002) observed the frequency of gully systems to be highest on the most exposed summits and therefore that topography was found to be an important factor influencing erosion patterns. Anastomosing dissection is observed to be restricted to areas of flat or gentle sloping ground, e.g. at an altitudinal range of 800 – 815 m on the summit of The Cheviot. This is typical of Bower's Type 1 dissection. Areas of bare peat were found to be common and surface water flow infrequent resulting in only local peat movement. It was suggested that these areas were

maintained by a combination of wind, rain splash and frost as suggested by Bower (1960a). Linear erosion dominated on areas of steeper uniform sloping ground, typical of Type 2 dissection. The linear pattern changed markedly to a dendritic pattern where topography concentrates drainage toward a central stream (phase between Type 1 and Type 2 dissection, the continuum of forms). On the high Cheviot Hills anastomosing areas were commonly found connected to the linear and dendritic gullies. Where patterns varied within one gully system, for example, the anastomosing pattern found at the top of the gully on the flatter ground and linear and dendritic dissection forming the larger proportion of the erosion lower down the system, this reflected the fact that the hills in The Cheviot Hills are rounded with relatively few flat areas. It was suggested that the anastomosing areas may develop in isolation from linear or dendritic patterns and only become connected where erosion is advanced (Wishart and Warburton, 2002).

Therefore extent of erosion is considered by both Tallis (1985a) and Wishart and Warburton (2002) to be a result of the topography of the areas. Bower (1961) found that topography was not the only influence on the extent of erosion. She found climate, landform and geology all to be significant. She also discovered there was a general relationship between increasing precipitation and elevation: 'the higher the rainfall, the deeper is the peat on a given site'. These factors were said to determine the type and depth of the peat, the processes of erosion (water or mass movement) and the available agents of erosion. She suggested that the relationship between deep peat and extensive erosion at higher altitudes is because the peat is deeper as it has accumulated for longer and probably more rapidly than the thinner peats of lower altitudes. However the results from the Peak District and The Cheviot Hills disagree with this. This is important in this research because precipitation, topography, elevation, peat depth and the extent of erosion vary between the three main study sites. Tallis (1985a) generalised Bower's findings stating that the distribution of eroded peat in the Southern Pennines must account for its location within the Pennines, being affected by the peat growth being at the margins of peat development rather than altitude. This was suggested because the Southern Pennines have developed at the limits of peat growth (see Section 3.3.4)

2.4.2   Piping

Holden (2000) highlighted the lack of measurements of pipeflow and the difficulty finding and defining pipe networks. Pipes occur in a wide variety of environments

including the blanket peatlands of upland Britain. They have been found at the interface between the peat and the underlying mineral layer, solely within the peat itself (usually where there is rapid change in peat properties such as bulk density) (Gilman and Newson, 1980), or entirely within the substrate (Holden and Burt, 2002a). Depths of pipes range from few centimeters below the surface to within the underlying substrate, sometimes up to 3 m deep, with mean diameters ranged from 3 to 70 cm and over 150 m in length (Holden and Burt, 2002a). Once a pipe is initiated it provides a new base level for the local hydraulic gradient. The water flow lines are then concentrated towards the pipe and the rate of pipe flow increases (Thornes, 1980). Pipeflow was suggested by Holden and Burt (2002a) to contribute to around 10 % of the streamflow volume and at times can contribute to up to 30 %, and are therefore an important source of runoff in upland peat catchments.

Pipe locations are often identified mainly by observation of collapse features, water jets emerging from pipes and the sound of flowing water, or visible in streambanks or on gully sides (Jones, 1982). Alternatively change in surface vegetation may often indicate a presence of a pipe (Jones et al., 1991) and traditional methods of locating pipes have involved digging soil pits. Holden et al. (2002) tested a method using ground-penetrating radar (GPR) to identify sub-surface piping in an area of blanket peat at Moor House and Upper Teesdale NNR. The method could not identify pipes smaller than 10 cm in diameter and had a depth accuracy of 20 to 30 cm. Their results did, however, indicate that pipe networks occur over much greater extent than could be detected from surface observations alone. They suggested that GPR provides a non-destructive, rapid technique, which can produce continuous profiles of peat depth and indicate pipe locations across surveyed transects.

Piping plays an important role in the initiation and, to a lesser extent, development of some gully systems. A number of writers have linked piping with gully development by roof collapse and also channel extension (Buckham and Cockfield, 1950; Johnson and Dunham, 1963; Tomlinson, 1981; Higgins, 1990; Holden and Burt, 2002a).

2.4.3 Mass movements

There are two main characteristic rapid mass movements of peatland areas: peat slides and bog bursts (Warburton et al., 2003). Peat slides are important because they mobilize

considerable quantities of peat, have major impacts on stream ecosystems and present a local hazard to humans (McCahon *et al.*, 1987; Higgitt *et al.*, 2001). There are two main zones within a peat slide: the scar area and the run-out zone. The scar area shows exposed mineral substrate with the surface littered with large and small disturbed blocks and rafts, whilst the lower slide zone (the run-out) is where paired peaty levées mark the edge of the flow as it passed over the undisturbed underlying peat (Warburton *et al.*, 2003). With distance down slide peat blocks become more broken up; smaller and more rounded and peat detritus may enter streams and rivers adjacent to the failures. Bog bursts usually involve the rupture of the peat surface or margin due to substrate creep or swelling, whereby semi-liquid basal peat is often expelled at the peat margin or through tears in the surface (Tomlinson, 1981; Carling, 1986a).

Johnson (1957) suggested bog bursts were features of the 'post-mature' stage of peat accumulation and claimed that bog bursts were widespread in the Southern Pennines (Tallis, 1985a). Indeed, reports of both peat slides and bog bursts are widespread in upland Britain (Bower, 1960a; 1960b), e.g. Upper Teesdale in 1983 following very heavy rainfall (104.8 mm in 2.5 hrs) (McCahon *et al.*, 1987), the Hart Hope peat slide, North Pennines in 1995 following heavy rainfall (40 mm and 58 mm on 1st and 2nd February 1995 respectively) and rapid thaw of snow cover (c. 20 to 30 mm of snow) (Warburton *et al.*, 2003) and 40 peat slides on Dooncarton Mountain, SW Ireland in 2003 following localised, short, intense rainfall (80 mm in 45 minutes).

The exact mechanisms of failure are not fully understood, but they involve instability of a peat overburden above a mineral substrate (Carling, 1986b) and all tend to occur in association with heavy and/or prolonged rainfall. Hobbs (1986) suggests that peat bursts involve much more fluid peat than do slides, stating that the latter move *en masse*. There are several key issues that remain unresolved: the hydrological and geotechnical conditions at failure; the knowledge of the location of the failure surface; and the nature of the resulting debris flow or slide (Warburton *et al.*, 2003).

2.4.4   Frost action and desiccation

Regular observations of bare peat surfaces over a year allow variations in the microtopography of peat to be observed. During the winter months the peat is 'puffed up' by frost, and during the summer contracted by desiccation, and buffeted year-round

by wind-driven rain (Warburton, 2003). In winter, the surface layers become corrugated, as the less resistant components of the peat are scoured out from between the cotton grass and woody remains. Observations at Moor House by Evans and Warburton (2001) suggest that formation of needle ice to depths of over 10 cm is common during the winter. They observed that on melting, a friable surface of detached peat is left mantled across peat faces exposed on gully sidewalls (Figure 2.6).

Figure 2.6: A heaved crust, which has undergone desiccation.

The surface generally becomes more uniform through the summer. During drought periods a dried upper crust may form, which can crack into polygonal flakes and be blown or washed away (Figure 2.7). Rain may also penetrate deep into the peat mass down desiccation cracks. This may result in more rapid infiltration down the cracks and changes in the processes that generate runoff. Alternatively, the crusting that occurs on bare, dried peat surfaces might slow infiltration and encourage overland flow and erosion (Holden, 1998).

Figure 2.7: Evidence of desiccation cracks in the peat surface.

Seedlings have difficulty in establishing in such an unstable substrate, and can frequently be found pushed up or washed out completely from the peat. Unless compacted by trampling, this peat is readily degraded by wind (Radley, 1962), rainsplash (Crisp and Robson, 1979; Labadz *et al.*, 1991; Tallis, 1998) and biochemical oxidation (Francis, 1990). At higher altitudes where the peat surface becomes deflated, a layer of peat up to 3 cm thick may be stripped off each year from the bog surface, once the vegetation cover is destroyed (Tallis, 1997a; Bragg and Tallis, 2001).

2.4.5   Wind erosion

Wind erosion is a fundamental characteristic of upland environments in the UK and has long been recognised as a significant factor of erosion of upland peat. Warburton (2003) monitored wind erosion on a 3 ha area of relatively flat, sparsely vegetated peat (Moss Flats) at Moor House and Upper Teesdale NNR, North Pennines. The annual horizontal net erosion flux for 1999 to 2000 was recorded to be 0.46 and 0.48 t ha^{-1} respectively. Results of detailed monitoring over a 10-month period demonstrated that the peat sediment flux collected in windward- and leeward-orientated sediment traps on 10

separate occasions is between 3 and 12 times greater in the windward-facing traps. The concentration of blown peat with height above the surface was shown to decrease rapidly and the majority of the peat was transported close to the ground surface (below 0.3 m) heights. Landforms produced by wind erosion include deflation surfaces, wind-patterned ground, and turf-banked terraces (Figure 2.7). The potential for wind erosion is high in the Pennines, and in the Southern Pennines surface layers of peat have been stripped off over large areas to produce extensive peat 'flats' (Tallis, 1964).

2.4.6   Bank collapse and peat block transport

Peat erosion and weathering is significant in supplying particulate organic carbon (POC) and dissolved organic carbon (DOC) to the geochemical carbon flux of upland rivers (Crisp and Robson, 1979). The stream channel margins of Rough Sike, Moor House and Upper Teesdale NNR, are characterised by undercutting and numerous bank collapses. Turfed and unturfed blocks of peat from these collapses are mobilised during storm events and deposited on bar heads and on the floodplain (Figure 2.8). The largest blocks remain on the channel floor and appear to breakdown *in situ*. The breakdown and dispersal of peat in stream systems is a fundamental geomorphological process. This is important in understanding nutrient cycling in upland streams and reservoir sedimentation, yet despite these concerns the organic flux is an under-reported load component in peatland streams (Francis, 1990; Labadz *et al.*, 1991; Tallis *et al.*, 1997).

Evans and Warburton (2001) carried out research at Moor House and Upper Teesdale NNR on peat blocks. They observed that in narrow peatland streams, such as Rough Sike, the streambed long profiles exhibited step pool sequence, whereby large peat blocks jam in narrow sections of the channel and impounded sediment behind them. The blocks bulk density is close to 1 g cm^{-3}, and therefore the critical depth for block entrainment is low. The blocks are transported by rolling or floating. Smaller blocks at high flow were transported overbank but exhibit little evidence of downstream fining. In larger rivers, such as Trout Beck peat blocks are more actively sorted and show downstream reduction in size from source. This was thought to be a result of the dominance of transport by rolling and the consequent block abrasion. Transport length was shown to increase with flow depth, whilst vegetation and bars play an important part in trapping mobile peat (Evans and Warburton, 2001).

Figure 2.8: Peat stripped from the riverbanks of the Troutbeck, Moor House and Upper Teesdale NNR, during a storm event (30th July 2002), and carried by the flow as blocks. Some blocks were up to a maximum 9 m in length.

2.5   Factors influencing peat erosion

Determining the exact cause of erosion remains a challenge (Higgitt *et al.*, 2001). Over the last few decades the relationship between vegetation cover and erosion has been investigated, e.g. Thornes (1985). As shown in Figure 1.10, once the vegetation cover is disturbed, gully initiation can begin. There are many drivers of vegetation change in the British uplands (Batterbee, 2004); however, there are no simple 'explanations' of degradation and erosion (Tallis, 1997b). Changes in the natural vegetation in many parts of the British uplands have taken place over thousands of years and in the last 200 years the rate of change has been greatly accelerated by the anthropogenic activities (Davies *et al.*, 1996). Tallis (1998) estimates that 82 % (18,500 km^2) of blanket mire in the British Isles is substantially modified as a result of management. In 1997 the British Ecological Society organised a conference specifically to examine the 'Causes, consequences and challenges' associated with blanket mire degradation (Tallis *et al.*, 1997). This was echoed by Mackay (1997) who made an urgent call for a detailed assessment of the condition of UK peatlands requesting information on the types and extent of erosion at present, in order to plan conservation and management practices.

38

The causes of peat erosion can be divided into three broad categories: as a result of climatic change (Conway, 1954; Bower, 1961); anthropogenic activity (Tallis, 1998); or erosion which occurs as a natural endpoint to blanket peat accumulation (Lewis, 1906; Johnson, 1957). Evidence for each of the three main types of erosion is presented below.

2.5.1 Climate change

Recent trends in upland climate

Section 1.2 highlighted some of the positive impacts of climate change on upland blanket peat habitats. Ellis (2004) also considered the negative impacts. These are generally physical impacts and include the impacts from wetter winters and drier summers. The wetter winters and drier summers predicted are thought to affect the structure of the peatlands, increasing peat instability and erosion. Heathwaite (1993) also looked at the impact of climate change on British peatlands and discussed the hydrological changes that may occur. This would include a drop in the height of the water table, affecting the stability of the upland blanket peat and Dissolved Organic Carbon (DOC) release. This raises a number of questions concerning the future of British peatlands, of which the most important will be how this would affect the water balance on a regional scale. Predicted heavier and more frequent downpours will increase overland flow and throughflow and lead to interfluve erosion and flooding of existing channels. Damage to streams, riverbanks and floodplains are likely, which in turn would lead to loss of habitat. Heathwaite (1993) concludes by saying that for peatlands to remain a carbon sink there is a need to remain hydrologically intact and maintain a high water table.

Climatic change has been identified in long-term meteorological records. Gordon Manley began meterorological recording near Cross Fell, North Pennines in 1931, which is the longest upland meteorological record in Britain. Manley (1936; 1942; 1943) considered the climate at Moor House to broadly resemble that of Southern Iceland with strong winds, low summer maximum temperatures, frosts in any month, and long periods of snow cover in winter. Garnett *et al.* (1997) presented data spanning from 1931 – 1995 and found that the 'record-breaking' warmth of the mid-1980s to mid-1990s recorded elsewhere in England was not prominent in the Moor House record

within the context of the last 60 years. Holden and Adamson (2002) have added to this data set of temperature records up to the year 2000. They found new evidence of the recent warming. The temperatures at Moor House had increased over the last decade in the context of the 70-year record, indicating that winters appeared to be becoming milder but summers were remaining constant. Figures for January and February showed mean temperatures to have increased by 1.4 – 2 °C. The onset of mild winters in upland areas are crucial in terms of frost frequencies and days when temperatures are below freezing, linking both the biological and geomorphological processes operating within the region. The reduction in frost occurrence indicates a longer growth period for vegetation as frost controls the length of the growing season in upland Britain and also the potential for erosion and sediment supply (Holden, 2001) (Figure 2.9). Holden (2001) showed at Moor House that the mean number of days with air frost had significantly reduced (by 24 %) and Pepin (1997) presented a climate model for Northern England that predicted a further considerable reduction in frost occurrence as a result of global warming. The impacts of global warming are likely to be observed within the uplands first as demonstrated by Holden and Adamson (2002). They compared the Moor House temperature record with that from Durham Meteorological Observatory, a temperature data series from 1850 and showed that the recent upland warming appeared stronger than the lowland record.
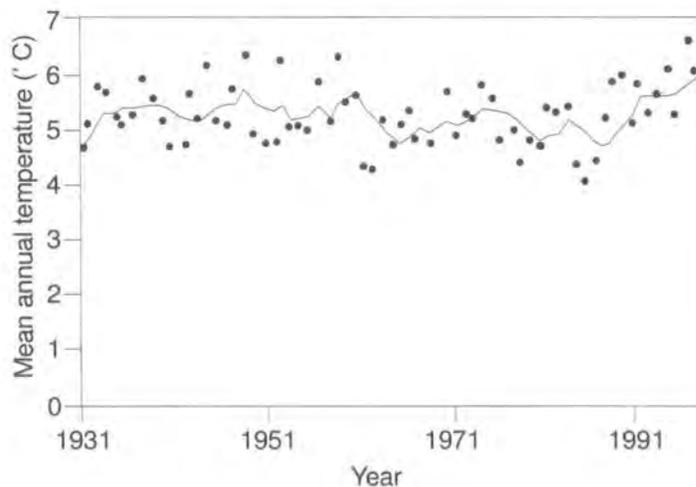
Figure 2.9: Mean annual temperatures for Moor House 1931 – 2000 with a 5-year moving average trend line fitted (Source: Holden, 2001).

Climatic change has been suggested as responsible for the onset of erosion in upland blanket peat in Britain. Bower (1961) was one of the first to conclude that climate is the basic factor behind blanket peat development and peat erosion, followed by topography and geology, which determine the distribution, types and stages of erosion. Evidence of this is, however, hampered by the lack of precise dating. Dating of peat erosion is difficult, as it requires dating a hiatus in the sedimentary sequence.

There are several common approaches in studying blanket mire degradation. These include the examination of lake and reservoir sediments, analysis of pollen stratigraphy, geomorphological form assessment and direct process measurement (Conway, 1954; Barber, 1981; Tallis, 1998). Historical documents have proved useful for reconstructing climate and noting the occurrence of particular storms, but rarely describe geomorphological change, especially in the uplands. A number of peat slides have been described in the literature or in newspaper reports and memoirs written in the late 19th Century have also proved useful. Radiometric techniques have been used, measuring caesium-137 and lead-210 content back to about 50 and 150 years respectively, as well as Spheroidal Carbonaceous Particle (SCP) analysis, which can be used to date peats since the Industrial Revolution. Carbon-14 dates are generally applicable to sediments older than about 300 years, but are complicated where the upstream sediment supply includes eroded peat. There is therefore a gap in the dating from 150 – 300 years ago when both climate change and land use change was likely to have had significant impacts of vegetation cover and erosion and therefore linking erosion to either climate change or land management is difficult (Ballantyne, 1991; Higgitt *et al.*, 2001).

In the Southern Pennines, Tallis (1964; 1965; 1973; 1985a; 1985b; 1987; 1994; 1995b; 1997c), Anderson *et al.* (1996) and Ellis and Tallis (2001) worked extensively on dating peat erosion episodes using intact peat stratigraphy. Pollen and macrofossils can be used to establish the relative wetness of the surface at different periods of time. Tallis (1985b; 1987; 1994; 1995b) and with co-authors such as Tallis and Livett (1994), Mackay and Tallis (1996), Ellis and Tallis (2001) have carried out research on macrofossils at various sites in the Southern Pennines. This work has primarily been concerned with identifying patterns of *Sphagnum* and *Rhacomitrium lanuginosum* in intact peat profiles from directly adjacent to eroded sites or from sites isolated from

erosion. Tallis discusses how those sites immediately adjacent to eroded sites are more drained than those isolated and therefore how the vegetation types vary. The initial point at which variations between the paired profiles occurs can be considered the time of the onset of erosion. One moss species that is important in this research is *Rhacomitrium lanuginosum*.

Rhacomitrium lanuginosum (Woolly fringe moss) (Gordon *et al.*, 1998) gets its common name from the terminating hair-like leaf tips that enable it to trap water droplets and nutrients from clouds. It is very widespread in the bleaker regions of Britain. *Racomitrium lanuginosum* moss dominates in blanket peatlands only under conditions of lowered water table and high atmospheric humidity. Due to its slow growth rate the presence of *Racomitrium lanuginosum* remains in the peat can be used to indicate unusual sets of environmental circumstances, e.g. a wet climate (producing high humidity) but a dry bog surface (resulting from lowered water tables) (Tallis, 1995b). This may be short duration, resulting from lowering over the overall water table, for example, following gully initiation because of a more effective drainage. Therefore an uneroded profile (e.g. a hummock site or gully side) directly adjacent to an eroded site would contain *Racomitrium lanuginosum* remains (Tallis, 1995b) in conjunction with a decrease in *Sphagnum* remains. *Sphagnum* is found in areas of saturated peat and therefore would be lost from the uneroded profile following gully initiation. Tallis (1995b) observed a decrease in *Sphagnum* and predominance of *Racomitrium lanuginosum* in uneroded peat profiles between about AD 1250 and 1450 and again in the mid-18th Century. These drier bog conditions signified drainage associated with gullying (Tallis, 1997a). The full *Sphagnum* record comprises of six 'wet phases' during the last 2800 years, with intervening periods of reduced *Sphagnum* abundance ('dry phases'). An initial stage of degradation and erosion of parts of the peat blanket occurred, either during the 'Early Mediaeval Warm Period' between c. AD 1150 and 1300 (Lamb, 1985) or thereafter. Such drier conditions would therefore lead to a drop in water table depth and would lead to the peat becoming unstable form which then erosion occurs.

Tallis (1995b) was unsure whether other mire areas of the British Isles were also affected by early medieval drought, however thought it unlikely that they would have escaped completely. Research presented by Yalden (1981a) in the North Pennines and Tallis (1965) in mid-Wales supported the suspicion that substantial changes in the

composition of the blanket peat vegetation were brought about by prevailing warmer and drier conditions in the 12th and 13th Centuries. This was followed by a succession of severe winters in the 16th - 18th Centuries, the so-called 'Little Ice Age'. Tallis (1997b) discussed this further and showed that for the last 1000 years the climatic reconstruction in the Southern Pennines is similar to that on Bolton Fell Moss, Cumbria (Barber, 1981) and for Letterfrack, Co. Galway (Blackford and Chambers, 1995).

2.5.2 Anthropogenic Activity

Land use is a major factor that determines the rate at which water runs off the land and thus determines the susceptibility of the British landscape to erosion (Environment Agency, 1998). Heathwaite (1992; 1993) suggested that in Britain alone 45 % of peatlands have been altered through human activity and drainage for agriculture, and forestry may have resulted in 16 – 37 % loss in the carbon sink capacity. There are a number of ways in which anthropogenic activity affects upland blanket peat: through land management practices, such as grazing (Shimwell, 1974), burning (Pearsall, 1950; Radley, 1965; Stevenson *et al.*, 1990) and moorland drainage (Conway and Millar, 1960; Stewart and Lance, 1991); and more generally, through recreation (Northumberland National Park Authority, 1998) and atmospheric pollution (Tallis, 1964; Ferguson and Lee, 1983).

Grazing

Numbers of sheep have increased significantly in most parts of Britain during the 20th Century, doubling to 44 million between the 1940s and 1993 (Sansom, 1996). This has resulted in a significant loss of habitat throughout Britain since the end of the Second World War due to financial incentives available for farmers to improve moorland for agriculture by draining, liming and re-seeding (Fielding and Haworth, 1999). As the number of people employed in agriculture has decreased there has been a decline in labour-intensive management and shepherding and an increase in the use of supplementary feeding, out-wintering and ranging of livestock. This has had a marked effect on upland biodiversity and has led to overgrazing by sheep becoming the principal concern in the uplands (English Nature, 2001a). The damage caused by sheep is well documented.

Evans (1997b) studied soil erosion by grazing animals in Northern England. He identified an increase in sheep numbers in the Lake District in the 1970s, this was some time after the Peak District, where numbers increased after the introduction of headage payments following the 1946 Agricultural Act. In both cases the marked increase in sheep numbers has been associated with a decline in heather cover and an increase in erosion scars. He stated that sheep were capable of initiating heather decline and poorly drained peat was the most sensitive soil type to the impact of sheep grazing. Erosion sensitivity is enhanced through both the damage to the protective vegetation cover (Stevenson and Thompson, 1993) and the compaction of soils by trampling (Evans, 1993, 1997b). This in turn can lead to gully initiation and development, since gully systems form from a break in vegetation or depressions in the ground where runoff collects. Similar findings were noted in the Peak District by Phillips *et al.* (1981).

At sites in Shetland (Birnie, 1993) and the Peak District (Anderson and Radford, 1994), rapid break-up of the blanket mire vegetation and exposure of bare peat is currently occurring at sheep stocking levels of 1.7 and 2.5 sheep per hectare respectively. The impacts may not be immediate but the pressures of continued heavy stocking will gradually change moorland dominated by dwarf shrub heath to one that is grass-dominated and then to species-poor acid grassland completely devoid of heather (English Nature, 2001b). A number of researchers have discussed appropriate stocking densities (Crisp, 1966; Evans, 1997b; English Nature, 2001b; Emmett and Ferrier, 2004). English Nature (2001b) suggest that stocking densities above 1 sheep per hectare need careful vigilance, however according to Emmett and Ferrier (2004) this lies between 0.5 and 2 ewes per ha. Crisp (1966) and Evans (1997b) both suggested that year round stocking densities of about 0.5 ha per sheep was sufficient to cause a decline in heather moorland and subsequently initiate erosion in the form of sheep scars.

Burning

There are two types of burning that take place on heather moorlands. One is burning for heather management and the other is burning through accidental moorland fires (Atherden, 1992). Heather management and the burning regime was introduced in 1911 as a result of the 'The grouse in health and disease' Report. This came about following an increase in popularity of grouse shooting and therefore, economic use of the moorlands in 1850. Grouse shooting covers an area of approximately 320,000 ha in

England and Wales. Direct revenue of approximately £12.5 m is made each year from sales and membership, of which one-third is spent on moorland management and local employment is gained through beating (Atherden, 1992). In contrast with sheep grazing, there has been a decline in grouse shooting since the Second World War; however, it still remains a major land use in the North Pennines, Forest of Bowland, Peak District and North York Moors (Atherden, 1992; English Nature, 2001a).

Burning is important because heather has a distinct life cycle in which management plays an important part. It passes through four distinct development phases: pioneer, building, mature and degenerate (Gimingham, 1972). The aim within the burning practice is to burn the heather before it reaches the degenerate phase and becomes too woody. This then stimulates shoot production from the mature plant and germination of new seedling plants (Gardner *et al.*, 1993). The burning regime evolved as a compromise between the need for older heather for the grouse to nest in and younger heather for fodder (Weber, 2004). Strips or patches are burnt at 10- to 15-year intervals in rotation, producing a mosaic of heather at various stages of development (Atherden, 1992). Grouse moor management aims to establish a continuous supply of heather, at different stages of growth, by means of rotational burning of strips up to ten metres wide, about one-tenth of the land being burned each year (Allaby, 1983).

On the North Yorkshire Moors, Imeson (1971) carried out research on heather burning and soil erosion. His results showed the severity of erosion on recently burnt ground reflected the nature of the ground surface and the presence or absence of conditions favouring surface runoff or needle ice development. Imeson identified most of the *Calluna* moorland in the Hodge Beck catchment to be crossed by shallow intermittent gully systems ranging in depth from a few decimetres to about 4 m. A relationship between gully development and moor burning was suggested by the association of overgrown, partially infilled gully systems with 'mature' and 'degenerate' stands of *Calluna* and by the location of the most actively growing gully systems in or downslope of recently burnt ground. The greater rates of infiltration and throughflow produced by moor burning may explain the location of actively enlarging gullies and seepage faces in or downslope of burnt ground (Imeson, 1971).

Mallik *et al.* (1984) looked at the ecological effects of heather burning. Research was carried out at Muir of Dinnet NNR, N.E. Scotland. They measured water infiltration,

45

water retention and porosity of soils of burned and unburned plots of heathland. On burned plots they found infiltration to decrease by up to 74 % compared to the unburned plot. This was thought to be a result of the ash particles on the burned plot clogging the soil pores in the upper soil layers, therefore reducing the rate of water percolation through the soil and increasing the water retaining capacity and runoff.

An important problem that confronts the re-introduction of enhanced burning management is the presence of extensive areas of old heather stands. These stands have a high wood content and when burnt can produce intense fires, which are difficult to control and can damage the underlying soil structure (Hobbs and Gimingham, 1987). These stands present a particular hazard during accidental summer fires so that regimes that minimise this potential hazard are now an important management goal (Gardner et al., 1993). In addition, research on the North York Moors has shown that the regular burning regime has led to the drying out of the top few centimeters of the blanket peat. This means that it is highly susceptible to being set alight by any unusually hot fire (Atherden, 1992).

The importance of accidental moorland fires in the large-scale degradation of upland peat landscapes has really only recently been realised. Catastrophic fires have been documented across England (Radley, 1965; Phillips, 1981; Tallis, 1981a), e.g. Barrow Fell, Northern Lake District, which occurred in 2003 and burned for five days (2230h 16/04/03 – 21/04/03, devastating an area of over 100 ha (Figure 2.10).

Catastrophic fires have clearly had a major role in generating some of the worst patches of peat erosion, destroying the matrix of peat turning it into ash (Maltby et al., 1990). Subsequent re-colonisation by vascular plants is often slow and usually preceded by the stabilisation of the peat surface by lichen and bryophytes (Tallis, 1981a; Maltby et al., 1990). When fire is followed by drought, or if the surface accumulation of litter is burnt away, the soil is then exposed to rain and wind erosion until the heather has regenerated (c. 6 years) and new hydrological relationships are established (Gimingham, 1960; Radley, 1965; Imeson, 1971; Fullen, 1983; Mackay, 1997).

Figure 2.10: Catastrophic burn above the track on Barrow Fell, Northern Lake District (Source: National Trust, 2003).

Moorland drainage (Gripping)

Moorland drainage was carried out with the purpose of lowering the water table and removing surface water, alleviating flood risk to improve the vegetation for grazing and game, for forestry and horticultural (Holden *et al.*, 2004). The ditches are usually cut parallel to the contour, on wet heath or blanket bog. This was largely a 1960s phenomenon, which is thought to have affected 70 % of the uplands of England and Wales (Emmett and Ferrier, 2004). Conway and Millar (1960) carried out research at Moor House and Upper Teesdale NNR on a grip network adjacent to a re-vegetating gully network. They measured the runoff from a single catchment outlet without looking separately at the processes occurring in the eroded and gripped parts of the hillslope. They suggested that runoff production in blanket peat was extremely rapid; however, relatively uneroded hillslopes could retain significantly more water than drained, eroded or burnt basins. Therefore they concluded that moorland drainage increased flooding downstream and reduced the water storage capacity of the hillslopes.

Some years later, Stewart and Lance (1991) carried out research on the effects of moor draining on the hydrology and vegetation of blanket bog in the North Pennines. They measured the water tables in two moor drainage networks, within and adjacent to Moor

House and Upper Teesdale NNR. Conway and Millar (1960) never established whether moorland drainage significantly affected the water table, but Stewart and Lance (1991) showed that water table was reduced only a few centimetres within 0.5 m of the grips. They concluded that the grips acted mainly to intercept surface runoff and withdrew water from the peat only alongside the grip edge and therefore that both grip network design and soil properties were important in determining the effects of moorland drainage on water storage and runoff generation from blanket peatlands (Holden *et al.*, 2004).

Conway and Millar (1960) and Stewart and Lance (1991) had contradicting views as to the effects of runoff production as a result of moor draining. In addition to the hydrological consequences of moorland drainage, it has been noted that some ditches in Derbyshire have eroded severely in places, quickly becoming deep, wide channels and supplying large amounts of peat material to the channel system. Drains cut to 50 cm depth may erode to several metres, and increase suspended sediment into reservoirs (e.g. Burt *et al.*, 1983, in the Southern Pennines) and possibly contribute to failure and subsequent mass movement (Holden *et al.*, 2004; Warburton *et al.*, 2004). The current state of knowledge is that moorland restoration is important and requires increasing water levels within the peatlands and re-colonising peat forming species, such as *Sphagnum*. Restoration techniques have included grip blocking (see Section 2.6.2); however, moorland drainage rarely occurs in isolation of other management techniques, such as grazing and burning and as a result integrated catchment management is required (Holden *et al.*, 2004).

Recreation

The uplands are used for a variety of recreational activities, including hill walking, fell running and orienteering, mountain biking, horse riding, rock climbing, gill scrambling, caving, para-gliding and hang-gliding, game shooting and birdwatching. Erosional impacts by walkers, bikers, horses and off-road vehicles have lead to erosion threats in upland Britain, especially over the past four decades with the increase in leisure time. Footpath erosion is widespread throughout upland Britain and is most extensive where shallow mineral soils occur on steep sided slopes, initiating gully formation (Anderson *et al.*, 1981; Evans, 1997a) (Figure 2.11). Footpaths were widest on steep unstable slopes or on gentle slopes where wet peat and bog vegetation occurred, e.g. on The

Cheviot (Figure 2.11 and 2.12). Deep incised gully systems form where erodible, coarse-textured stony head was exposed (Anderson *et al.*, 1981). The National Trust has re-surfaced the Pennine Way footpath as a result of erosion from walkers. It has been carried out in the most sympathetic way possible. On level sections stone chippings have been laid and on the slopes or deep peat stone pitching has been used to create a hard, sustainable surface to resist erosion (Northumberland National Park Authority, 1998). Figure 2.11 shows extensive erosion on a steep section of the footpath leading up to The Cheviot summit, and Figure 2.12 is an area on The Cheviot summit where stone pitching has been placed to allow better access to the summit and prevent erosion of the adjacent peat.

Figure 2.11: Unmanaged footpath erosion on The Cheviot, Northumberland.

Figure 2.12: Stone pitching on The Cheviot summit.

Atmospheric pollution

Various human activities over recent centuries have released chemical pollutants into the atmosphere and deposition of this material has affected upland vegetation. Early industrial activity, such as lead smelting would have generated sulphur dioxide and other pollutants, but atmospheric pollution increased greatly at the time of the Industrial Revolution. The Industrial Revolution produced two main pollutants affecting the uplands, killing the vegetation cover; these were sulphur dioxide and nitrogen oxides (Evans, 1997a; Hornung and Langan, 1999), both of which have acidifying effects on the environment.

In particular, sulphur dioxide is probably one of the main pollutants responsible for the dramatic impoverishment of bog vegetation in the Southern Pennines, where there has been extensive loss of *Sphagnum* species (Lee *et al.*, 1988). There are some indications that recent episodes of destabilisation of the blanket peat coincided with the Industrial Revolution, particularly in the Southern Pennines, which is adjacent to the conurbations of Manchester and Sheffield (Stevenson *et al.*, 1990; Higgitt *et al.*, 2001). There is little doubt that the abrupt demise of bryophytes (such as *Sphagnum* and *Racomitrium lanuginosnm*) on Holme Moss and elsewhere in the Southern Pennines was a consequence of air pollution. This is because their decrease coincided with the start of soot contamination in the peat. It is unknown how continuous the carpet was during pre-

industrial times and therefore it would be wrong to associate this demise with the onset of erosion (Tallis, 1987), as in some parts of the Southern Pennines *Sphagnum* was lost 400 – 500 years ago due to reduced surface wetness rather than air pollution (Tallis, 1994, 1998). Skeffington *et al.* (1997) discussed acid deposition in the Southern Pennines. They concluded that the decline in nutrient status may have played an important part in ongoing blanket peat erosion and that restoration of the blanket peatlands required returning nutrients back to the system to allow vegetation to re-colonise (see Section 2.6.2).

Adamson *et al.* (1996) studied soil profiles in the 1960s to early 1970s and again in 1991 at the Moor House and Upper Teesdale NNR. Results showed a general decrease in soil pH over this period, which is likely to have been a result of atmospheric pollution. However, in deeper soils with impeded drainage the pH increased. Although the concentration of pollutants in rainfall is not high in this area, rainfall occurs throughout the year resulting in large deposition fluxes (Adamson *et al.*, 1996). Pollutants were observed to have decreased markedly over the past 30 years (Averis *et al.*, 2004) and levels of air pollution in the Southern Pennines are now much lower than a few decades ago, yet are still thought to be too high to allow the regeneration of *Sphagnum* (Burt and Labadz, 1990).

2.5.3 A natural endpoint

A number of researchers believe that peat erosion is related to the fact that blanket peatlands are inherently unstable systems in which erosion could be the inevitable outcome of accumulation under an upland and northern climate (Pearsall, 1941; Bower, 1961). This idea is based largely on the view that a stable end-point does not seem likely in such an environment (Bower, 1962; Tallis, 1998). A natural endpoint to peat accumulation suggests, the upward growth of peat will ultimately cease at some 'limiting height', which may be determined by the physical properties of the peat mass (Bragg, 1995), by the local climate, or when input of fresh organic material to the peat mass is balanced by cumulative decay of existing material within it (Clymo 1984; Clymo 1991).

Therefore if the naturally unstable peatland environment leads to the degradation of the blanket peat, climatic change and anthropogenic activity become less important, however may contribute indirectly by affecting the rates of peat accumulation.

2.6 The present state of blanket peatlands (re-vegetation)

There are two types of re-vegetation in upland blanket peat areas in Britain: natural re-vegetation and human-induced re-vegetation (Stevenson *et al.*, 1990; Ballantyne, 1991; Gordon *et al.*, 1998).

2.6.1 Natural re-vegetation

Re-vegetation of bare areas is hampered by a series of limitations to plant growth. The native moorland species are slow growing and an effective plant cover may take several years to develop. The slow growth of seedlings makes them particularly susceptible to uprooting or burial by mobile peat and desiccation in shallow mineral soils (Yalden, 1981a). In exposed situations the very mobile peat surface resists re-colonisation by vegetation (Tallis and Yalden, 1983). Erosion such as rainsplash and sheetwash prevents the early colonising plants from developing and also carries away nutrients and the developing surface litter, which can no longer promote further growth and productivity. Gradually, early colonising plants are replaced by more weather-tolerant vegetation and seedlings with a longer life span. Both the average height of the vegetation cover and its total mass, increase exponentially. Ground litter and soil organic content increase more or less in parallel with biomass and are of great importance because of their relation to soil erosion. If erosion occurred, nutrients and organic matter would be removed from the soil, which leads to a further loss of soil moisture and productivity. Water and temperature are the dominant controls on photosynthesis. On a local or regional scale growth is also dependent on non-climatic factors such as soil characteristic and topography (Thornes, 1985).

Re-colonisation occurs in a series of stages with lichens and bryophytes bringing about the initial stabilisation of the substrate and often with grasses such as *Deschampsia flexuosa* preceding the return of heather. Pioneering species such as *Sphagnum* have been lost in the Southern Pennines as a result of atmospheric pollution and slow-growing *Calluna* or *Eriophorum* seedlings may only be capable of establishing in stable

substrates. There is some experimental evidence that deep peat may suffer from a deficiency of certain essential plant nutrients, such that sustained growth is impossible. Nutrient-toxicity in the uppermost soil and peat layers, from heavy metals (lead, zinc, copper etc.) deposited in dust from industrial areas, cannot be ruled out either (Yalden, 1981a).

One of the main conclusions of Bower (1962) was that erosion in the Pennines would continue and in an environment such as the Pennines a stable end-point does not seem likely. However, this has been proved not to be the case, as heavily eroded areas are now regenerating, e.g. Moor House and Upper Teesdale NNR and The Cheviot (Clement, 2001a; Higgitt *et al.*, 2001; Wishart and Warburton, 2002; Evans and Burt, In Press). Godwin (1981) noted that areas sheltered from prevailing weather conditions, for example, between the peat hummocks (hags), vegetation was growing; however, areas of exposed peat flats, exposed to prevailing weather conditions, remained bare or generally scarce of vegetation. More recently, in the Rough Sike catchment at Moor House and Upper Teesdale NNR areas of eroded peat flats appear to be re-vegetating (Clement, 2001b). Also within the basin lower down, in many cases gully floors have re-vegetated (Clement, 2001a; Higgitt *et al.*, 2001). There is no obvious mechanism for transfer of material from the gully walls to the channel and detrital peat accumulates at the base of the gully wall. In some gullies there is sufficient ephemeral flow to maintain an open channel along the gully edge thus linking the gully sediment system to the main channel during flood events (Figure 2.13).

During lower flows these channels connect to the main channel by drainage, which occurs over the cotton grass surface producing peaty fans, which encroach on the floodplain (Figure 2.14 and Figure 2.15). However, on the outer bank of meanders of the main channel, where the channel is eroding into the peat face, tributary gullies discharge directly to the main channel, and are thought to be efficiently linked (Burt *et al.*, 1998; Evans and Burt, 1998; Evans and Warburton, 2001).

Figure 2.13: Gully adjacent to Rough Sike coupled during a flood event on 17th January 2001.

The main gully system on Burnt Hill, Moor House and Upper Teesdale NNR is an example of a re-vegetating gully system. Long profiles, cross-sections and photographic evidence can be used to infer gully change over the last 50 years. Clement (2001a) reproduced the long profile and cross-sections of the gully system in 2001 (previously surveyed by Bower (1957)). Bower's cross-sections were relocated as precisely as possible from photographs and figures in her study (Figures 2.2 – 2.4). This survey indicated major differences in gully form. Cross-sections showed re-vegetation had occurred and this is evident in the images from 1958 and 1988 in the lower section of the gully system (Figure 1.11). This suggests re-vegetation of much of the previously eroded peat blanket is occurring and is important in terms of the balance between agents of erosion (e.g. grazing pressures) and natural environmental change (Mather, 1983).

Figure 2.14: Peat and mineral soils deposited at the break in slope at a gully entrance. The channel is shown to be hugging the eastern bank of the gully. Photograph taken in July 2003.
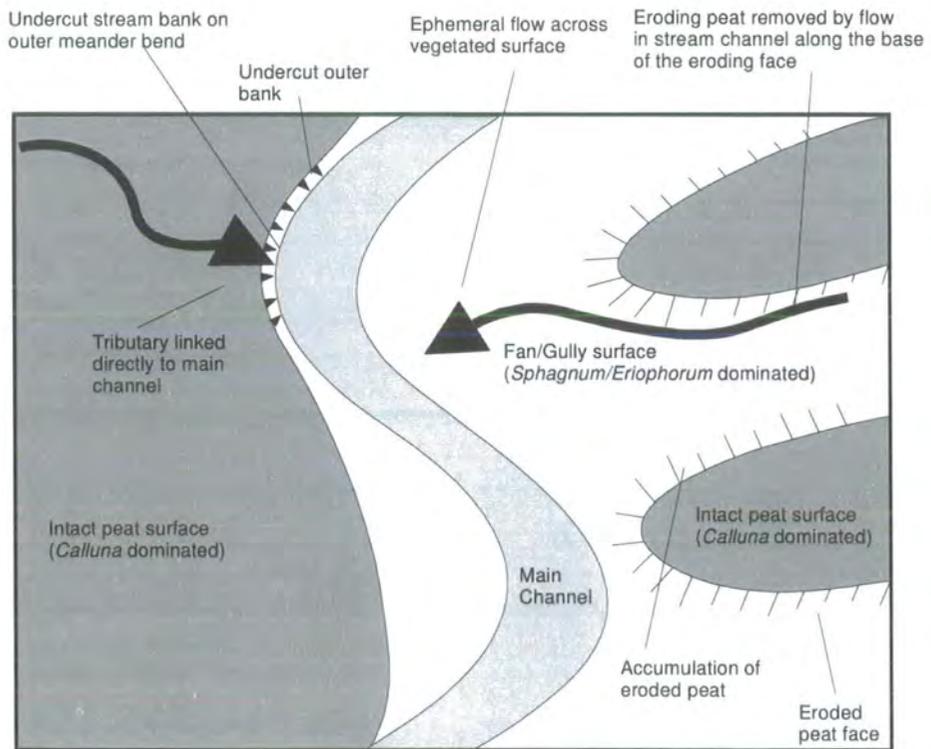
Figure 2.15: Diagram showing the main channel of Rough Sike with erosion and re-vegetation processes operating in the catchment (Source: Evans and Burt, In Press).

Wishart and Warburton (2002) also identified re-vegetation in the bases of the gully systems on The Cheviot. The critical values for re-vegetation were the bank height and the angle of the slope. They showed that with increasing distance downstream the gully systems tended to become wider than they are deep. Dispersed water flow at the base reduced the capacity for sediment transport and peat is re-deposited in the base of the gully. Re-vegetation in the gully base traps material washed down and the eroded peat begins to stabilise. This infilling often leaves topographic depressions in which new gully systems may subsequently develop (Poesen et al., 2001). Wishart and Warburton (2002) also noted that the active drainage is usually confined to a single channel at the base, on one of the walls of the gully (Figure 2.14 and 2.15). Although more stable than the small headwater gully systems, high order re-vegetated gully systems were observed to still be active and reworking re-deposited material was common, especially during storm events (Figure 1.10). Therefore, although gully systems evolve to a more stable state, this does not mean that they cease to contain features indicative of active erosion.

In addition to re-vegetation occurring within the bases of gully systems, natural re-vegetation of moorland grips has also been observed, e.g. Bleaklow and Featherbed Moss, Peak District National Park. This therefore indicates that blanket peatlands within upland Britain are naturally recovering from erosion and disturbance. If the grips are not maintained, they may fill with vegetation and sediment, losing their effectiveness in water removal (similarly to a re-vegetating gully system). Roberston et al. (1968) noted that drains in a Lanark bog had 'ceased to function' owing to the re-growth of *Sphagnum*, such that they can now only be detected by careful inspection. Mayfield and Pearson (1972) also noted that re-colonisation of artificial drainage can be rapid where peat formation is in progress (Holden et al., 2004).

2.6.2 Human induced re-vegetation

The British and Irish blanket mire resource was formally recognised to be of international significance by the International Mires Conservation Group in 1986 and confirmed in a Parliamentary Statement in January 1988. This issue first came to light in the 1960s and attempts were made to protect moorland in the 1968 Countryside Act, but this failed (McTernan, 1993). The Convention on Wetlands (1971) is an intergovernmental treaty, which provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their

56

resources. The Convention's mission is 'the conservation and wise use of all wetlands through local, regional and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world' (RAMSAR, 2004). It came into force in 1975 and is the only global environmental treaty that deals with a particular system. There are presently 141 Contracting Parties to the Convention, with 1376 wetland sites, totalling 122.6 million hectares, designated for inclusion in the RAMSAR List of Wetlands of International Importance (RAMSAR, 2004). More than 1400 wetlands, covering more than 120 million hectares have been included in the RAMSAR List under the EC Birds Directive (RAMSAR, 2004).

Since the Convention on Wetlands there has been concerted efforts to integrate blanket peatlands into the European Conservation Programme for Endangered Species and Habitats. The official recognition of the international importance of blanket peatlands led to the designation of all high-quality sites as Special Areas of Conservation (SACs), Special Protection Areas (SPAs), Sites of Special Scientific Interest (SSSIs) and Natural Heritage Areas (NHAs) under European Law (Thompson et al., 1995; Tallis, 1998).

As a result of the recognition of the importance to conserve blanket peatlands, research and conservation practices are taking place, these include: the removal of sheep; grip blocking; gully blocking; adding fertiliser and re-seeding; and watercourse liming. Such conservation practices are used to promote the growth of vegetation in upland blanket peatlands and to maintain an intact surface vegetation cover, therefore preventing further erosion (Mackay, 1997).

Where areas of common land exist, e.g. in the Lake District and Pennines, temporary fencing to remove sheep is a complicated issue, as permission is generally required from the Secretary of State before fencing can be erected. Although there is a strong presumption against fencing and other works on National Trust common land, the Trust has the power under the National Trust Act 1907 to make 'temporary enclosures' for the purposes of protecting or renovating peat and vegetation. At Moor House and Upper Teesdale NNR a series of long-term exclosure plots have undergone different treatments (grazing and burning). There are thirteen grazing exclosures and four burning exclosures, which were established between 1953 and 1972. Their establishment was to investigate the impact of removing grazing from a variety of upland vegetation types and the data potentially can provide an important contribution to the debates about the

future of our uplands (Adamson, 2002; Adamson and Karl, 2003). The upland vegetation types vary and include: blanket bog and grassland sites such as *Juncus squarrosus* grassland; Limestone grassland; *Festuca ovina* grassland; *Agrostis-Festuca* grassland and *Nardus stricta* grassland. Each site consists of a fenced plot with an adjacent grazed plot, which are monitored by a highly objective pin frame technique. In addition, the exclosure plots vary in altitude (from 488 m to 815 m a.s.l.) and in slope (ranging from 2° to 20°). A number of researchers have carried out extensive studies of both grazing removal and burning (Rawes and Welch, 1964; Welch and Rawes, 1964; Rawes and Hobbs, 1979; Rawes, 1981; 1983; Marrs *et al.*, 1989; Adamson and Karl, 2003).

Welch and Rawes (1964) looked at the early effects of excluding sheep from the high-level grasslands on the Moor House exclosures. They found that the effect of exclosure on the rare species of Pennine grasslands depends on their position in the succession, e.g. some species can exist only where grazing restricts their potential competitors, whereas other species may be excluded by grazing. Rawes and Hobbs (1979) (also on the Moor House exclosures) carried out a study addressing the management of the semi-natural blanket bog. They were concerned with studies relating to low-input, traditional methods of manipulating semi-natural vegetation and observed height variations in vegetation cover over a 22-year period. The significant finding of their research was that differences were shown between the ungrazed and grazed areas. They discussed how these differences might be the result of enclosure or climatic change. For example, they observed a decrease in precipitation by 12 % in the past 12 years compared with the preceding 12 years.

Rawes and Hobbs (1979) also observed that in burnt areas over a 21-year period *Calluna* was found to reach its maximum cover between 11 and 17 years after burning. *Eriophorum vaginatum*, however, recovered from burning immediately and its cover remained consistently high, reaching a maximum about 7 years after burning and then falling to a minimum when *Calluna* cover was at its peak (Figure 2.16). This therefore has an important bearing on the proposed management of upland blanket peat, e.g. *Calluna* re-vegetation became predominant after approximately 14 years without burning, indicating that burning of heather prior to this is ineffective (Welch and Hobbs, 1966). Rawes and Hobbs (1979) concluded that with reference to long-term blanket bog management, light-grazing by sheep (less that 0.55 sheep ha^{-1}), without burning, is

likely to be an acceptable management in the interests of conservation (Holden *et al.*, 2004).
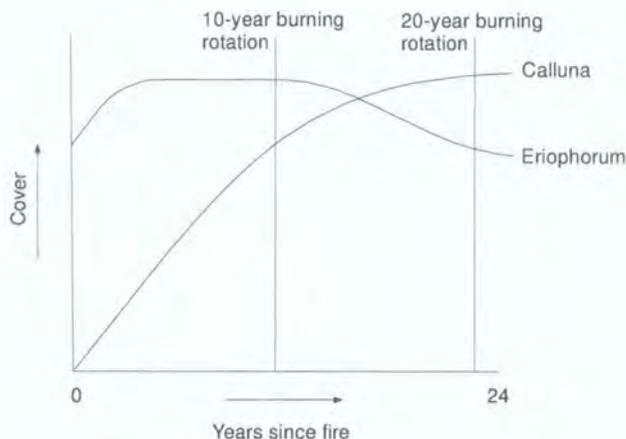
Figure 2.16: Performance and recovery-time of *Calluna* and *Eriophorum* following a burn (Source: Presentation by John Adamson, 2004).

Rawes (1981) continued earlier research on excluding sheep from high-level grasslands at Moor House. Results of this study describe the changes in botanical composition, structure of the grasslands, changes in morphology, nutrient status, plot size, variability and community change. There was an overall decrease in species number over the period of enclosure. Generally, Rawes found that enclosure allows the development of larger plants and allows plants to flower. This was then accompanied by improved rooting and the corresponding likelihood of improved soil conditions. No shrubs or trees had appeared within the exclosures and it was thought likely this was due to the small size of the enclosures. Rawes (1983) continued his research looking at the changes following enclosure. The changes after 15 years of excluding sheep were assessed. Prior to enclosure there was little vegetation cover and erosion was active within the plot, however, following enclosure it was clear that sheep grazing was a cause as the vegetation cover increased and erosion reduced. Similarly to Rawes and Hobbs (1979) however, climate change could not be ruled out as an influencing factor.

Hobbs (1984) carried out some research on the post-fire development of *Calluna-Eriophorum* bog at Moor House. He attempted to provide more detailed information on the composition of the plots after one complete cycle of a long-term burning experiment from 1961 to 1980. This study examined the effects of variation in the length of time

between successive management fires on the composition of the bog community. He concluded that burning every 10 years resulted in increased dominance of *Eriophorum* spp. whilst burning every 20 years resulted in greater abundance of *Calluna vulgaris* and the 'steady-state' composition was re-established (Gore and Olsen, 1967; Rawes and Hobbs, 1979) (Figure 2.16). The large increase in abundance of *Eriophorum angustifolium* in many plots after fire illustrates its ability to invade bare areas by means of rapidly growing rhizomes (Phillips, 1957). Hobbs therefore questioned the usefulness of burning this vegetation type as a management practice.

Further research on the effects of removing sheep grazing at Moor House was carried out by Adamson and Karl (2003), who produced a report discussing the changes in vegetation within the exclosures. Figure 2.17 shows a graph produced by Adamson and Karl (2003) indicating the differences in vegetation cover after 31 years of no grazing inside the plot and grazing outside. The main findings of Adamson and Karl's research was that the impact of removing grazing was affected more greatly at higher altitudes than lower altitudes. On altitudes between 550 and 630 m where deep peat soils were predominant, grazing was light and *Calluna vulgaris* thrived both inside and outside the exclosures. At these altitudes with grassland species and humic soils *Festuca ovina* and *Nardus stricta* was less inside the exclosures than outside, however *Deschampsia flexuosa* and *Carex bigelowii* had benefited from enclosure. At the high altitude sites (690 – 830 m) grazing was the most intensive (especially on mineral soils) and the vegetation cover within the exclosures benefited greatly at both the peat and mineral sites.

Gore and Godfrey (1981) carried out reclamation work at Moor House and Arnfield Moor, Longdendale, Southern Pennines. The effects of fertilizers were examined and the role of sheep grazing in preventing natural re-colonisation was discussed. Their work involved applying fertilizer and/or liming to the bare peat surfaces. Results showed that it was possible to assist plants to colonise a range of types of eroded peat in both the North and Southern Pennines and that it is therefore clear that the inherent infertility and instability of eroded blanket peat prevents natural re-colonisation. A much more rapid development of diverse flora at Moor House suggested there were differences between the blanket peat in North and Southern Pennines (Tallis, 1965).
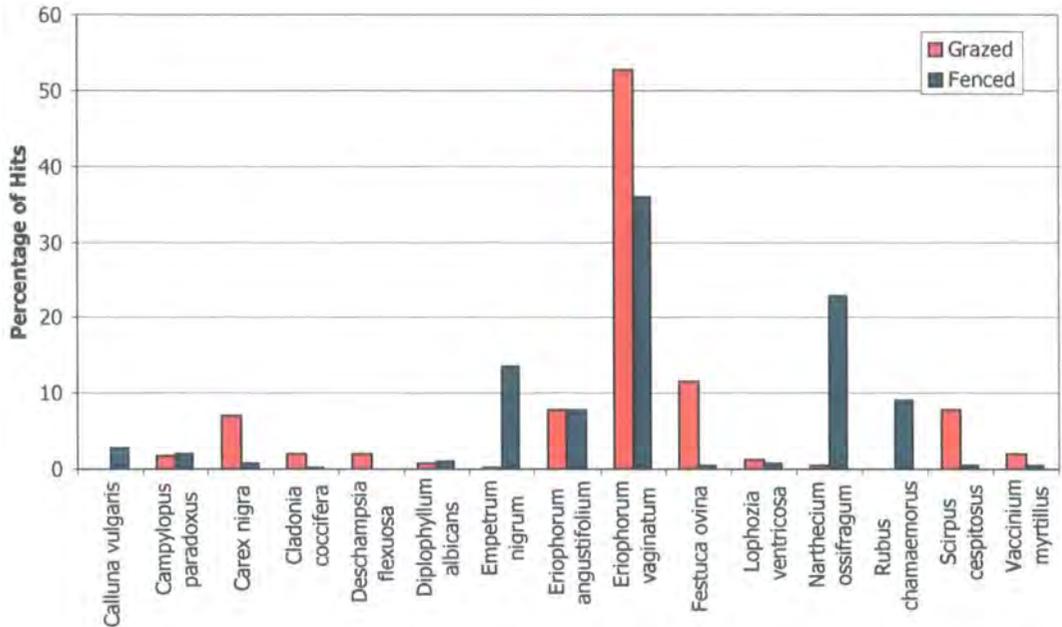
Figure 2.17: Graph showing the difference is vegetation species and percentage cover between the inside and outside of the Silverband exclosure plot, 31 years since enclosure. (Source: Adamson and Karl, 2003).

Reclamation of Damaged Peatlands

A dilemma associated with the re-vegetation and restoration of badly damaged blanket peatlands is that, although the techniques are now available, they are very costly. Government schemes that provide incentives for less-intensive management of blanket mires offer a potentially more viable way to meet our international conservation obligations (Tallis, 1998). Examples of restoration costs come from the restoration work undertaken at Holme Moss. Although successful, the cost was about £6000 per ha for large-scale restoration work. In addition, about £25000 per km^2 was spent on re-surfacing damaged stretches of the Pennine Way and re-vegetation of surrounding trampled ground (Tallis, 1997b). Despite the cost, field trials, government schemes and legislation are still continuing due to the importance of conserving the blanket peatlands.

Phase 2 of the Moorland Erosion Report (1983) concentrated on re-vegetation trials in the Peak District to assess the implications of current rates of erosion and of current land management practices and to examine possible remedial measures (Tallis and

Yalden, 1983). In order to re-colonise the moorland the types of vegetation in each site were studied and choices of re-colonising species made. The sites chosen were on Holme Moss, Doctor's Gate, Cabin Clough and Burbage Moor. Experimental plots within the exclosures were laid out, where vegetation types were added, e.g. *Calluna*. Monitoring then took place whereby total counts of seedlings were made, seedling survival in quadrats, measurements of rates of peat erosion and counts of sheep and people in neighbouring areas of the plots. Results showed the extent of re-vegetation to vary from total failure (at Holme Moss) to a good cover of vegetation (after 3 ½ years at Burgage Moor). Seed mortality appeared to take place during the autumn and winter, when many seedlings were uprooted and left lying horizontally on the peat or soil surface with their roots exposed, or the seeds buried. Uprooting and burial occurred both inside and outside the fenced areas, where sheep or other grazing animals could not be held primarily responsible. Tallis and Yalden (1983) believe frost heave and substrate mobility to be the main causes of high seedling mortality. Movement of the peat (scour and re-deposition) was observed at all sites, particularly during the winter, suggesting that substrate instability was a major deterrent to re-vegetation. Observations of rates of peat erosion using a standard point quadrat suggest that there was a regular annual cycle in the morphology of the peat surface, which also determines the pattern of erosion. Inside and outside exclosures measurements were carried out in order to see the influence of grazing on re-vegetation. Significant differences were found at all sites (similarly to those found on the Moor House exclosures). *Calluna* was observed to perform better inside the exclosure than outside and therefore benefited from a reduction in grazing pressure. Indeed the re-vegetation of bare ground was found to be the most sensitive to grazing pressure (Tallis and Yalden, 1983).

The re-vegetation trials in the Peak District led to a discussion of the possible steps, which ought to be taken in the future (1983). Options included: treatment of footpath erosion before it becomes too severe; proper management of moorland (including the creation of fire breaks); fire prevention (especially by closing the moors, during prolonged periods of drought) and better control of sheep grazing. If the moorland vegetation (especially on peat) is being disturbed, the top 5 – 10 cm should to carefully stripped off, stored and replaced later. To restore grass cover, commercial seed sources, regular lime and fertiliser applications are necessary. Grazing should be limited or excluded for the first 2 – 3 years following a catastrophic event (such as the Burbage Moor fire) to give the immediate seedlings a chance to establish; and finally attention

must be paid to critical topography and the differing seasonal growth patterns of various plants. However, any of the treatments could be ruined by chance erratic events, sudden floods, droughts, fire, strong winds, severe snowfall and thus failure in one treatment on one occasion should not be necessarily regarded as final (Tallis and Yalden, 1983). As a result of sponsored field trials some areas of Holme Moss, Southern Pennines are now recovering as a result of: experimental areas fenced for re-vegetation trials in 1980; areas fenced off under the ESA scheme from 1988 onwards and large-scale re-vegetation within the TV compound from 1984 onwards (Tallis, 1997b).

More recently at the Blanket Mire Degradation Conference in 1997 (sponsored by the BES Mires Research Group) a way forward to combat further degradation was discussed (Tallis *et al.*, 1997). Attempts have been made to re-vegetate the deteriorated moorlands of upland Britain, one example of which is The Moorland Restoration Project of the Peak District (1996). The aim was to overcome the constraints of erosion and reverse the causes of erosion. By 1996 the full project was running and the effects are continuing to be assessed. Progress has been made towards the understanding of rates of change in upland habitats, both in terms of the rates of erosion and the rates of re-vegetation (Anderson *et al.*, 1981; 1996).

As discussed above sheep grazing as often blamed for reducing vegetation cover and causing erosion, as well as preventing re-colonisation. The lifting of access restrictions from the British Countryside following the devastating foot and mouth epidemic (2001) marked a significant milestone and provided an opportunity to start reflecting on the short-term and long-term consequences of reduced sheep numbers from UK upland areas. The Sheep and Wildlife Enhancement Scheme (SWES) was launched (summer of 2003), funded by DEFRA and delivered by English Nature with a budget of £2.5 million, with a further £3 m for 2004. The scheme is designed to encourage farmers to manage their sheep to achieve grazing levels and foddering methods, which will sustain moorland vegetation. The areas targeted within upland habitats are SSSIs. Agreements will run for a period of five years, except where grazing is permanently reduced (e.g. on commons). In return for a one-off, lump sum payment producers will agree to a specified stocking level for the period. Further payments may also be available to support sheep management, e.g. help with shepherding costs to shape the new grazing pattern (English Nature, 2003, 2004).

In addition to the affects of grazing, the problems of moorland drainage in increasing runoff production to the streams has been recognised by MAFF and English Nature who have begun to provide grant aid to block grips, to restore the important blanket bog habitat. There are a number of methods by which grips can be blocked, but the most widely used is to scoop an adjacent bit of vegetation and peat and to place this in the grip channel. Sedimentation then occurs behind the blockage and over time the channel fills in and the blanket bog habitat is re-established. Grip blocking is likely only to reduce the rate of runoff up until the point where the blocked grip is full of water and then water will flow along the blocked grip (River Swale Regeneration Project, 2002). In addition to grip blocking, gully blocking has more recently been carried out. The aim of both is to avoid further scour erosion and allow the ditch or gully to slowly infill with sediment and vegetation (Holden *et al.*, 2004). There are several techniques, which have been used to block gully systems (two are shown in Figures 2.18 and 2.19). Figure 2.18 shows the method of using plastic piling. So far plastic piling is thought to be the most effective method as it holds back more water than other methods (such as that shown in Figure 2.19). It is, however, expensive (£6 per metre) and therefore costs approximately £150 per barrier. Another method which has been used in the same area (Within Clough, Peak District National Park) was using sacks full of sheep' wool. The best method, however, is using cut heather bales, e.g. on Wessenden Moor, Southern Pennines (Figure 2.19). They are thought to be the best method because: the blocks allow water to flow through the bails, but slow the velocity and allow sediment to slowly accumulate; and, heather cutting can be carried out instead of heather burning and therefore is also beneficial to the area from which the heather was removed.

Figure 2.18: Gully Blocking using Plastic Piling by English Nature on Within Clough, Peak District National Park.

Figure 2.19: Gully Blocking using heather bails at Wessenden Head Moss, S. Pennines.

The most recent restoration work to be carried out in the Peak District National Park is the 'Moors for the Future' partnership. The partnership was set up in 2004 and is funded by the Heritage Lottery Fund and partnered with numerous organisations including English Nature, Severn Trent Water, Peak District National Park Authority and National Farmers Union amongst others. In addition to the aim of enhancing badly eroded moorland, the project is developing a range of initiatives to improve the experience of moorland heritage for visitors and local people and is establishing a learning centre to meet a variety of educational and research needs. An important aspect of the project is to develop expertise on protecting moorlands for the future and meet the education and research needs of specific groups and the wider public. Restoration includes re-seeding degraded and damaged moorland, to stabilise and restore the landscape, excluding sheep, gully blocking, monitoring water quality, repairing footpaths, and help in setting up a 'Moor Care Initiative' campaign to raise public awareness of moorland issues such as fires. A new education and learning centre is to be established and a 'Sustainability Baseline' is to be set up to facilitate long-term moorland management and aid decision-making. This involves monitoring techniques and GIS on the extent and condition of moorland vegetation, moorland birds, moorland landscape classification, footpath condition, recreational use of the moors, attitudes and awareness of visitors (Dean, 2004).

2.7   Summary

This chapter reviewed existing literature on upland blanket peat erosion and re-vegetation in Britain. This has been examined within a sediment budget framework.

Past research has highlighted the importance of dissection in terms of upland blanket peat erosion. The basis of this research over the last 50 years has been the methodologies and results of Bower (1960a; 1960b; 1961; 1962). Bower's research has been criticised (Radley, 1962; Mosely; 1972; Wishart and Warburton, 2002) and the need for a more up to date assessment of the current state of the UK upland blanket peatlands is therefore required. The research in this project assesses Bower's classification of gully systems and her research findings, as well as assessing changes in peat erosion in the historical past. A conceptual model of gully development and a conceptual historical sediment budget are developed to aid this evaluation. Other types of peat erosion, e.g. mass movements and wind erosion have significant impacts on upland blanket peat environments (in terms of vegetation destruction and peat removal). These will be addressed in the historical sediment budget indicating how changes in rates of erosion over time impact upon of the wider system.

The causes of peat erosion, both past and present can be divided into three main factors: climatic change, anthropogenic activity and a natural endpoint of peat accumulation. The main cause of peat erosion however is a combination of these effects. The present state of British blanket peatlands suggests re-vegetation of blanket peat has occurred naturally (within gully systems, on peat flats and within grip networks) or by human management activity, e.g. sheep removal and gully blocking. However, regional differences and inconsistencies in available evidence highlight the need to undertake a more comprehensive geomorphological assessment of the current state of upland blanket peat landscapes; a gap in knowledge which this study will address.

Peat erosion is the product of the complex interaction of erosion forces and the resistance of the blanket peat surface to such stresses. Considerable peat research has been carried out on the Moor House exclosure plots in terms of changes in vegetation and soil composition resulting from sheep removal (Welch and Rawes, 1964; Rawes and Hobbs, 1979; Rawes, 1981; Hobbs, 1984; Adamson and Karl, 2003), but less is known about the effects of sheep removal on runoff production and sediment yield from erosion of open moorland and interfluve areas. This will therefore be addressed by carrying out paired rainfall simulation experiments on a number of the Moor House exclosure plots with differing vegetation cover and land management practice. The following chapter outlines the methodology used to investigate current research gaps.

3.0   STUDY SITES AND METHODOLOGY

3.1   Scope of Chapter

This chapter presents details of the study site research framework (Section 3.2) and the study sites (Section 3.3). Each site is discussed: Moor House and Upper Teesdale NNR (Section 3.3.2), The Cheviot Hills (Section 3.3.3), and Wessenden Head Moss (Section 3.3.4). Details include: a general description of the area; the geology; soil type; vegetation type; contemporary climate; land use and management and an overview of some past research at the site. Section 3.4 presents the research framework, while the details of the methodologies are addressed in Section 3.5. These include: the regional variations in gully development (Section 3.5.2); the analysis of interfluve accumulation using a SCP dating technique (Section 3.5.2); the paired rainfall simulation experiments used to assess the interfluve erosion potential (Section 3.5.4) and the gully morphology on the local scale, requiring both field research and laboratory analysis (Section 3.5.5). The field analysis is presented in Section 3.6 and laboratory analysis in Section 3.7.

3.2   The study site research framework

In order to achieve objectives 2, 5, 6 and 7 (Section 1.5) intensive field research was required. Conducting this study in Northern England (The Pennines) allowed direct comparisons to be made with past research by Bower (1960a; 1960b; 1961; 1962) and numerous later researchers such as Mosley (1972), Phillips *et al.* (1981), Tallis (1964; 1965; 1973; 1981a, 1981b; 1981c; 1981d; 1985a; 1985b; 1987; 1989; 1994; 1995a; 1995b; 1997a; 1997b; 1997c; 1998) and Wishart and Warburton (2002). While blanket peat erosion is extensive within the Pennines (Bower, 1961), a selection of representative sites suitable for assessing the extent of blanket peat erosion and re-vegetation in gully systems were required. Three main study sites were selected across Northern England to allow for regional variation along a rough N – S transect (Figure 3.1). These study sites are: Moor House and Upper Teesdale National Nature Reserve (NNR), North Pennines; The Cheviot Hills, Northumberland and the Peak District National Park (NP), Southern Pennines. Within these regions smaller areas were selected to carry out detailed research. Within Moor House and Upper Teesdale NNR, an area surrounding Burnt Hill and the Rough Sike catchment was selected; within the Cheviot Hills, The Cheviot summit area was studied; and within the Peak District

National Park an area known as Wessenden Head Moss was investigated. Their locations within Northern England are shown in Figure 3.1.
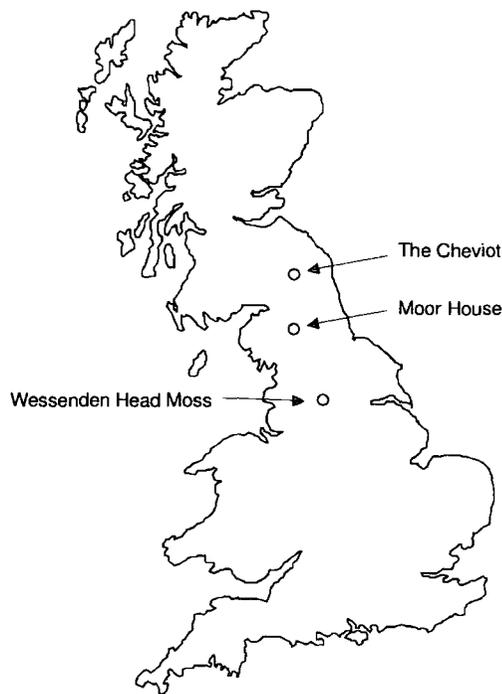
Figure 3.1: Location of primary Study Sites.

The Cheviot (NT 909205) is the most northerly of the three sites and represents the northerly limit of the Pennine range. Moor House (NY 757328) is the central site and is in the North Pennines, whilst Wessenden Head Moss (SE 051063) is in the Southern Pennines and is the most southerly of the three sites. The general characteristics of the three study sites are discussed below and summarised in Table 3.1. Both the geology and the precipitation show marked differences (Figure 3.2 and 3.3 respectively). The geology of the three study areas is dominated by the Carboniferous series (Figure 3.2); however, there is some variability, e.g. volcanic rock on The Cheviot, Namurian sandstones and shales at Moor House, and Kinderscout grit on Wessenden Head Moss (Table 3.1).

Characteristics	The Cheviot, Northumberland	Moor House and Upper Teesdale NNR, North Pennines	Wessenden Head Moss, Southern Pennines
Height	Highest summit: The Cheviot (815 m). Range Studied: 690 m to 815 m.	Highest summit: Great Dun Fell (848 m). Range studied: 520 m to 710 m.	Highest point: 494 m Range studied: 440 m to 494 m.
Precipitation	Rarely exceeding 1100 mm per annum.	1900 mm per annum.	1536 mm per annum (Burt, 1980).
Blanket Peat	Blanket peat covers 48 % and is composed of two units: upper fibrous layer (1 – 2 m) and dark compact layer (c. 0.5 m).	Blanket peat covers 69 % of the reserve. Peat depths vary up to 4 m (generally are < 2 m).	Blanket peat covers 75 % of the area. Peat depths vary up to 6.35 m (generally are between 1.5 - 4 m).
Blanket Peat Erosion	Of the blanket peat 80 % is eroded (20 % intact blanket peat) and consists of 21 % linear, 16 % dendritic and 63 % anastomosing dissection. Of the eroded peat 69 % is re-vegetated (31 % bare peat).	Of the blanket peat 48 % is eroded (52 % intact blanket peat) and consists of 59 % linear, 20 % dendritic and 21 % anastomosing dissection. Of the eroded peat 82 % is re-vegetated (18 % bare peat).	Of the blanket peat 64 % is eroded (36 % intact blanket peat) and consists of 38 % linear, 32 % dendritic and 30 % anastomosing dissection. Of the eroded peat 43 % is re-vegetated (57 % bare peat).
Vegetation Cover	*Eriophorum vaginatum*, *Sphagnum* mosses and patches of *Calluna* in drier areas (Wishart and Warburton, 2002).	Dominated by *Eriophorum* spp., *Calluna vulgaris* and *Sphagnum* spp.	Dominated by *Eriophorum vaginatum*, *Eriophorum angustifolium*, *Empetrum nigrum*, *Rubus chamaemorous*, *Vaccinium myrtillus* (Labadz *et al.*, 1991).
Geology	Volcanic rock predominantly of Devonian age. The Cheviot massif is composed of granite that was intruded into the lavas (Common, 1954).	Carboniferous succession, with alternating strata of limestone, sandstone and shale. The intrusive Great Whin Shale of quartz-doloeritre is exposed on the western escarpment and in the Tees valley.	Interbedded Namurian sandstones and shales. Kinderscout grit predominates in the west.
Main land-use	Sheep grazing and grouse shooting, coniferous afforestation and military use of the area for training.	Low intensity sheep grazing.	Until recently sheep grazing, at present there is no grazing to aid the gully blocking.

Table 3.1: Summary of the main characteristics of the three study sites.

CRETACEOUS, TERTIARY & QUATERNARY

JURASSIC

PERMIAN & TRIASSIC

CARBONIFEROUS

DEVONIAN

CAMBRIAN, ORDOVICIAN & SILURIAN

PRE-CAMBRIAN

IGNEOUS ROCKS OF VARIOUS AGES

The Cheviot

Moor House

Wessenden Head Moss
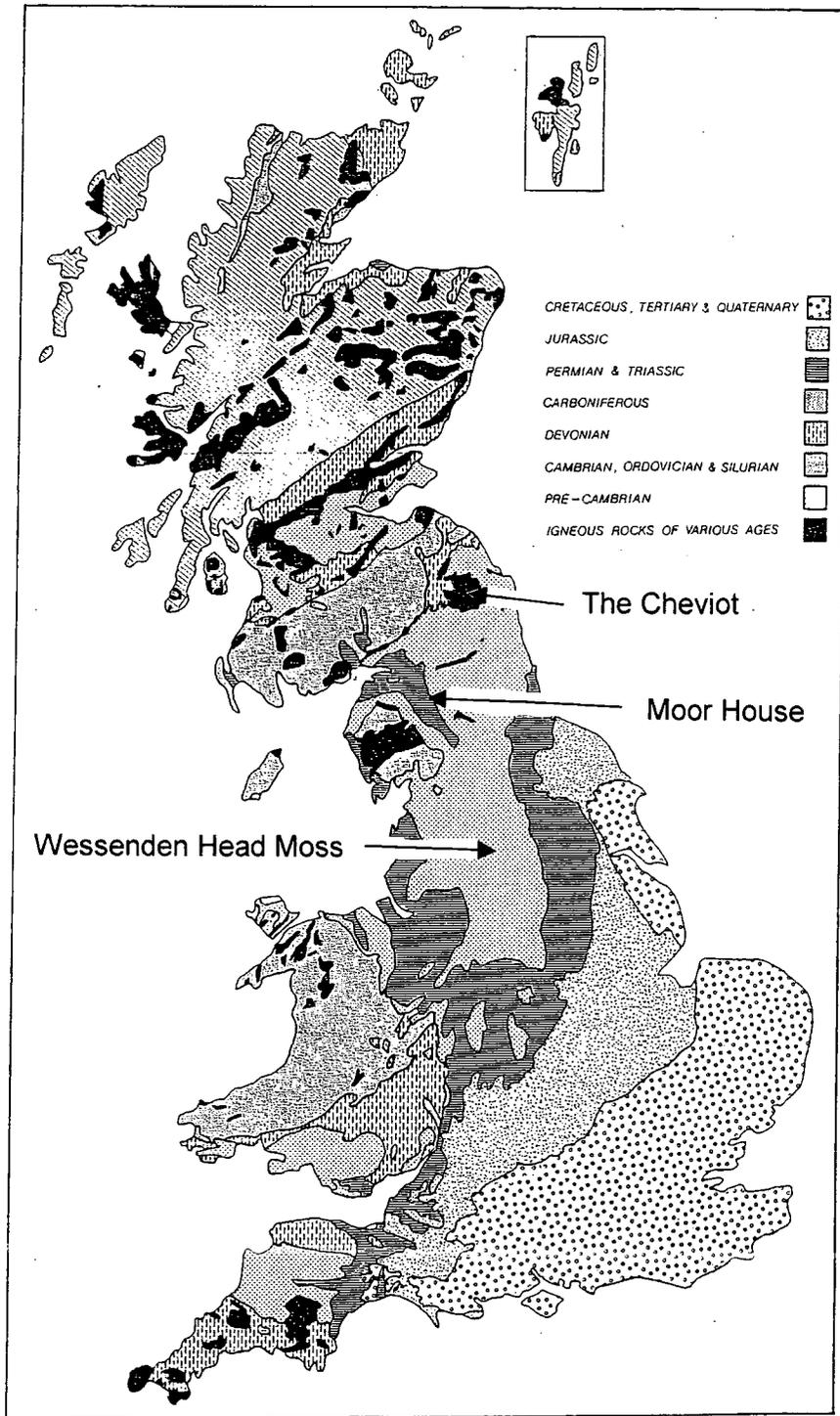
Figure 3.2: Geology map of Britain (Source: Atherden, 1992).
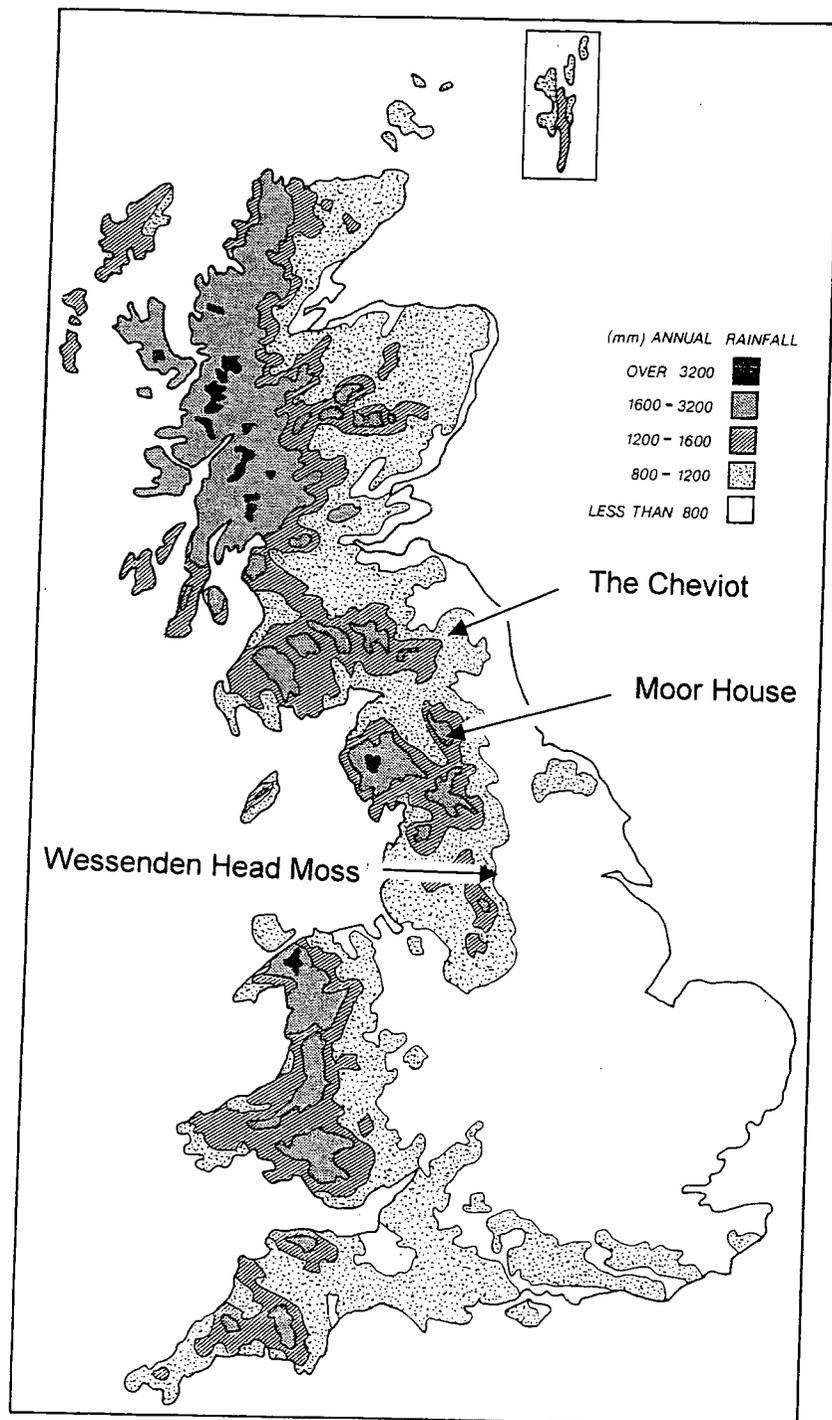
Figure 3.3: Mean annual rainfall (mm), for the period 1941-1970 (Source: Atherden, 1992).

In many respects the precipitation at the three sites (The Cheviot (1100 mm per year), Moor House (1900 mm per year) and Wessenden Head Moss (1536 mm per year)) represent an environmental gradient with respect to the dominant W – E weather systems. This produces different precipitation regimes and is assumed to affect the flux of pollutants into the mires. These totals represent the natural rainfall patterns of the UK (Figure 3.3). Although The Cheviot is the highest of the three study sites, its precipitation is the lowest, which is likely to be a result of it being the most easterly study site.

There are differences in the altitude of the study sites (Table 3.1). In addition to the geology and precipitation this may be a factor significant in controlling the types of erosion. The altitudes of the study areas vary from 440 m – 494 m (Wessenden Head Moss), 520 m – 710 m (Moor House) and 690 m – 815 m (The Cheviot). There is little overlap between the altitudes of the study sites, which enables the extent and types peat erosion in the Pennines to be assessed at the full range of altitudes.

The percentage cover and depth of blanket peat also vary between the three sites. Peat depths are greatest at Wessenden Head Moss (up to 6.35 m), despite the study site being close to the southerly margin of peat growth. It is thought to be a result of their location and their peat depths that may be a cause of their sensitivity (Johnson, 1957; Bower, 1962, Tallis, 1998). Peat erosion is less at Moor House (48 %) than on Wessenden Head Moss (64 %) and on The Cheviot (80 %); however, at all sites has been recognised to be a problem (Garnett and Adamson, 1997; Wishart and Warburton, 2002).

3.3   Study Sites

3.3.1   Moor House and Upper Teesdale NNR

Moor House and Upper Teesdale NNR is discussed first because a more detailed experimentation was carried out here (see Section 3.4). The area forms part of the North Pennines and covers an area of approximately 3900 ha. This is characterised by exposed summits, extensive blanket peatlands, upland grasslands, pastures, hay meadows and deciduous woodlands. The reserve extends from the upper edge of enclosed land in the Eden Valley, over Great Dun Fell (848 m), Little Dun Fell and Knock Fell to the upper end of Cow Green Reservoir on the River Tees. The Tees forms its northern boundary.

Altitudes range from 290 to 848 m a.s.l. It is England's highest and largest terrestrial NNR, a UNESCO Biosphere Reserve and a European Special Protection Area. The Pennine Way crosses the reserve from north to south along the summit ridge of the escarpment (Johnson and Dunham, 1963; Adamson, 2002).

Within the confines of the reserve the almost complete stratigraphical succession of the Carboniferous rocks of the North Pennines is exposed, with alternating strata of limestone, sandstone and shale. The Carboniferous rocks dip eastwards forming level benches and dip-slopes. This is underlain by a sequence of Lower Palaeozoic rocks, which outcrop at the foot of the western escarpment and small areas of these rocks lie within the reserve. The intrusive Great Whin Sill of quartz-dolerite rock is also exposed on the reserve within the Carboniferous succession on the western escarpment and in the Tees valley. Several mineral veins of lead, zinc, fluorite and barites are also exposed on the reserve and owing to the inaccessibility of the region, some of these deposits have never been mined (Johnson and Dunham, 1963; Holden, 2000; Adamson, 2002).

The gently sloping eastern side of the area is overlain by glacial till and boulder clay and periglacial solifluction deposits produce restricted drainage, which has led to water-logging and the development of peat deposits which cover much of the area. The formation of peat started at the Boreal-Atlantic transition about 7500 years ago (Conway, 1954). Figure 3.4 shows an example of an intact peat profile from Moor House (Johnson and Dunham, 1963; Gore, 1965).

The soil type and vegetation types at Moor House can be seen in Figure 3.5, which shows maps of Moor House of (a) topography, (b) the soil types and (c) the vegetation types. As can be seen the western side of the reserve is steeper and the soils and vegetation cover are more variable. The slope angles decrease towards the east of the reserve where blanket peat becomes predominant. On each of the maps the key locations of the main study sites are shown to give context to the present research. The altitudinal range of the study area varies from 520 m – 710 m and is predominantly covered by blanket peat and *Calluna-Eriophorum* vegetation.
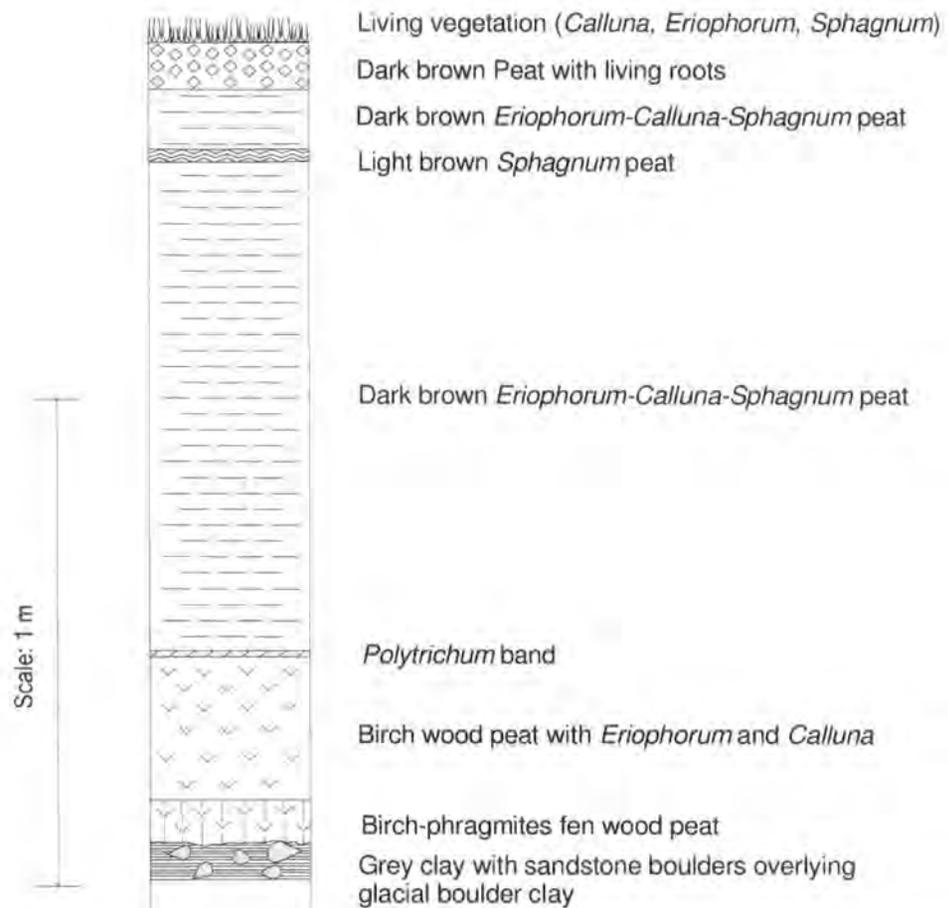
Figure 3.4: Typical Moor House blanket peat profile (Adapted from: Johnson and Dunham, 1963).

Climate is described as sub-arctic oceanic (Heal and Smith, 1978) with a mean annual temperature based on AWS data (at 556 m OD) from 1992 – 2000 to be 5.8 °C, and from annual mean temperatures between 1953 – 1978, at 5.1 °C (Smithson, 1985). This therefore shows an increase of 0.7 °C in temperature between 1953 – 1978 and 1992 – 2000. Temperatures can be extreme with values below –15 °C recorded in most winters. In the context of the 70-year record, the increase in milder winter temperatures over the last decade has been the most significant, increasing by 1.4 – 2 °C (Figure 2.9) (Holden, 2001). Air frost has been recorded in every month of the year and Moor House generally has over 100 days in which the dry bulb air temperature falls below freezing (Evans et al., 1999).
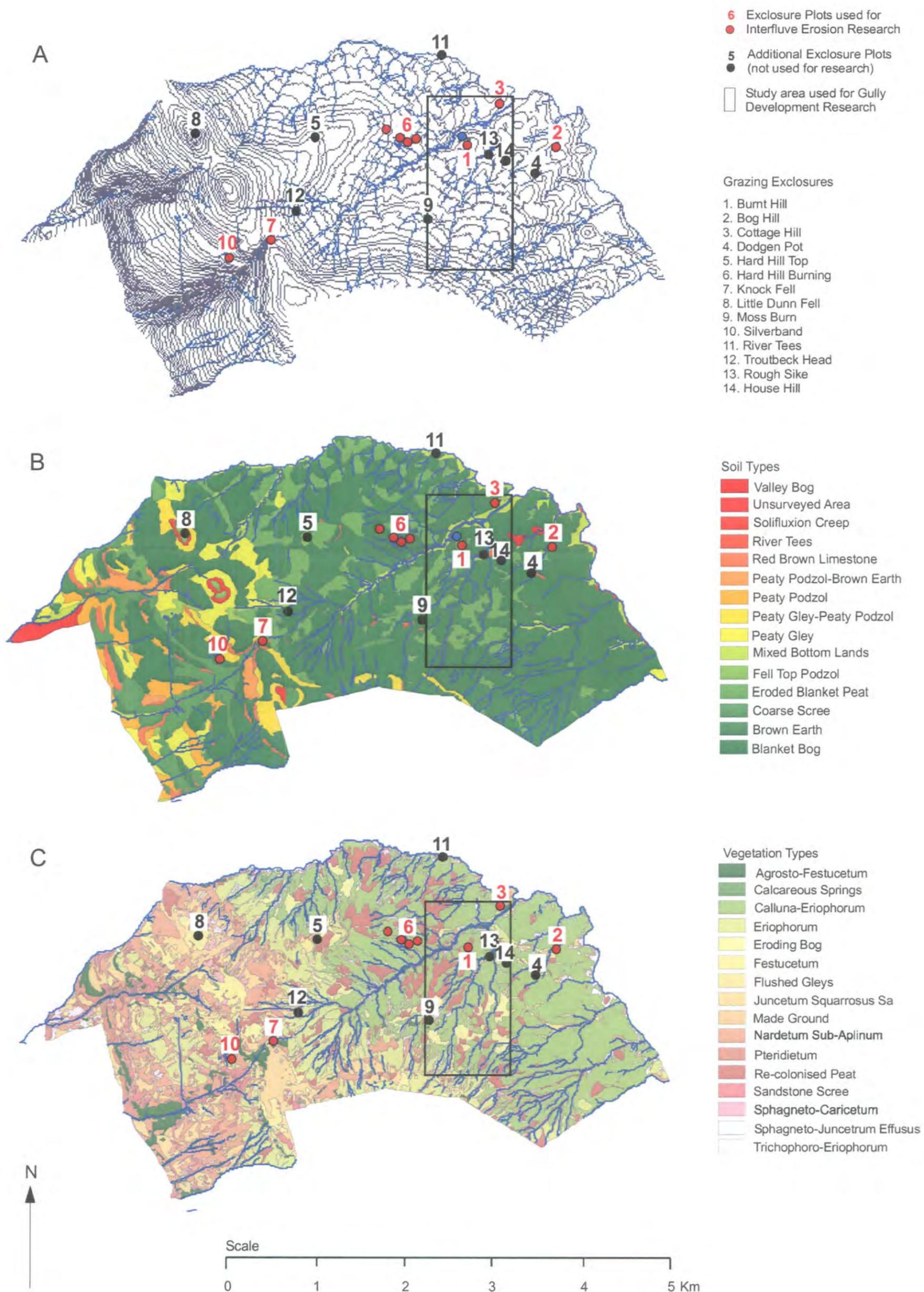
Figure 3.5: Maps of Moor House showing, (A) the topography, (B) the soil types, and (C) the vegetation cover types. Also shown are the locations of exclosure plots and area of gully systems studied in this research. Colour scheme inherited from the GIS (Data obtained from ECN, CEH Lancaster).

Hourly rainfall intensities at Moor House recorded at the AWS shows a dominance of lower-intensity frontal and orographic rainfall. Figure 3.6 shows the natural rainfall intensities from Moor House and Upper Teesdale NNR, North Pennines, during the period of July 2002 to June 2003 (the period of field study); and Figure 3.7 shows the frequency of rainfall events and their magnitudes from 1991 to 2005.
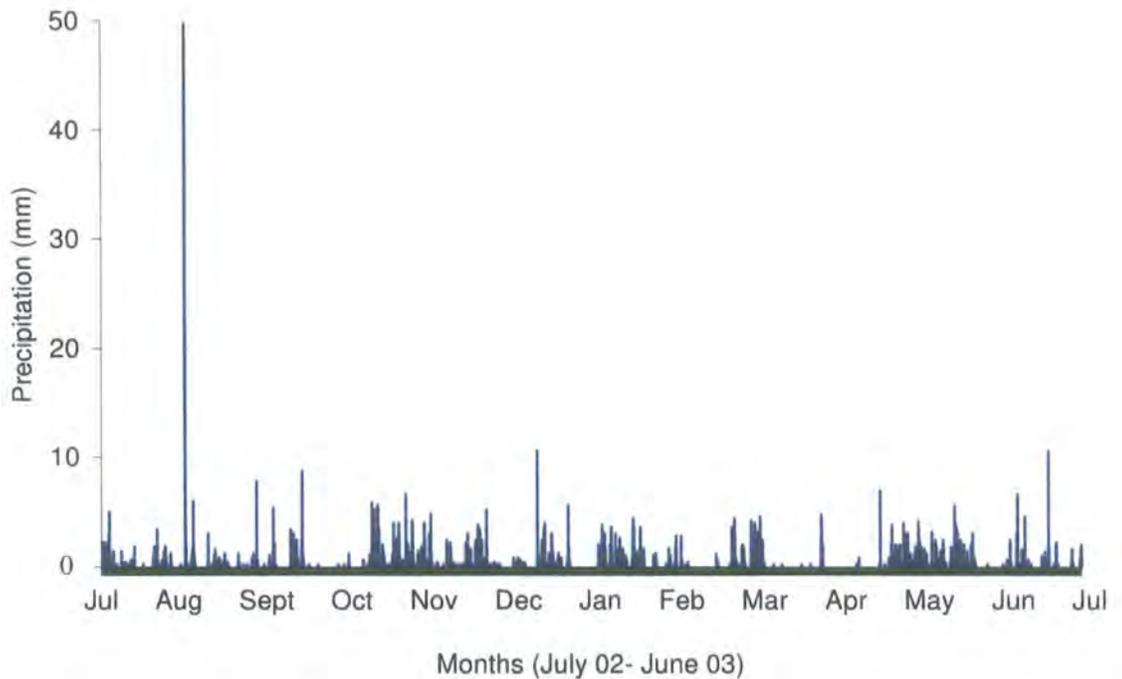
Figure 3.6: Hourly rainfall intensity data for Moor House and Upper Teesdale NNR from July 2002 to July 2003 (Data obtained from ECN, CEH Lancaster).

From Figures 3.6 it is clear that the typical rainfall values for the year vary between 0 mm hr^{-1} and 12 mm hr^{-1}. However, the longer-term record (Figure 3.7) shows that over the last 15 years maximum rainfall intensities reach up to 57 mm hr^{-1}, .In July 2002, during the period of the present study, 50 mm of rain fell in one hour (Figure 3.6). This event caused severe erosion of stream banks and large channel changes (Figure 2.8). The mean rainfall from 1953 – 2000 was 1982 mm per year, with an average of 244 precipitation days per year (Holden and Adamson, 2001). Frosts occur throughout the year and strong winds are common on the exposed fells. Annual average snow cover at 500 m is 55 days and on the summits, 100 days (Johnson and Dunham, 1963; Archer and Stewart, 1995; Burt *et al.*, 1998; Adamson, 2002; Worrall *et al.*, 2003). Westerly

and south-westerly moist air masses from the North Atlantic dominate the climate as indicated by the hourly wind direction data from 1994 – 2000.
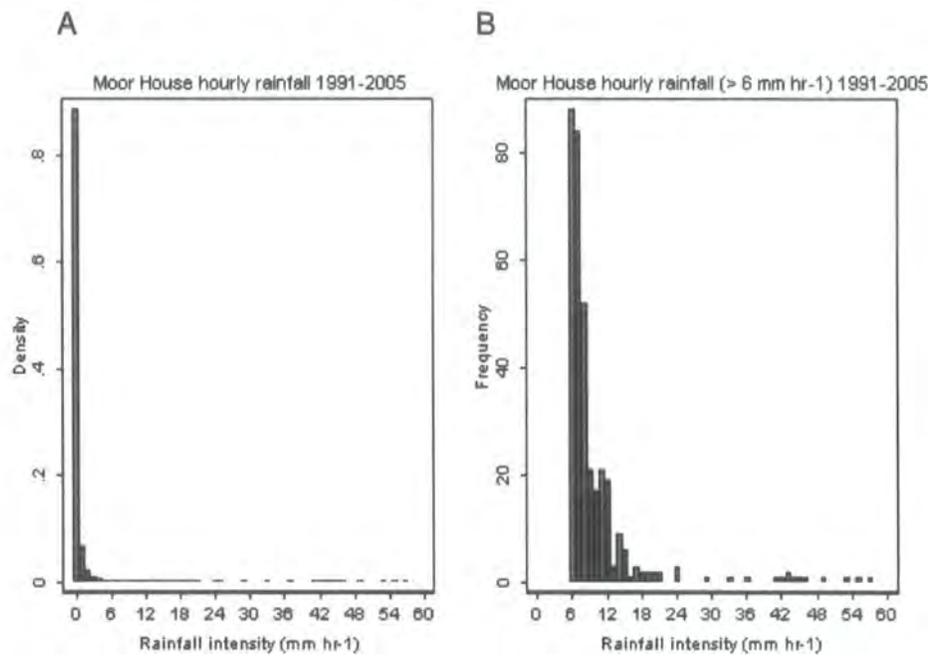
Figure 3.7: Paired histograms showing the frequency of rainfall events against the hourly rainfall intensity for 1991 to 2005: A) rainfall intensity against probability density; B) > 6 mm hr^{-1} rainfall intensities against event frequency.

Research began at Moor House in the 1930s by Universities and Institutes and it was designated a NNR in 1952 with the establishment of a new field station. Nicholson (1957) described the blanket peat at this time as heavily eroded and suggested the erosion to be a result of mismanagement through mining, sheep grazing and burning. The designated Reserve was not simply intended to protect rare or endangered communities of animals or plants but rather as a good example of an upland ecosystem to be used as an 'open-air laboratory' looking closely at moorland management. A wide range of upland issues have been investigated especially the impact of land use change, climate change and the deposition of pollutants, and the functional processes of blanket peatland and streams. Extensive 'grips' were cut in order to drain the moor and experimental plots were established on a variety of vegetation types to examine the impact of sheep grazing intensity on vegetation and soils, either by fencing out sheep completely or by fencing in large numbers of animals (see Section 2.6.2). The location of the exclosure plots within the Reserve are shown in Figure 3.5.

In the 1960s and 1970s the area was intensively studied as part of the International Biological Programme (Adamson, 2002). The Upper Teesdale NNR was designated in 1963 and extended in 1969 to protect the unique communities of arctic-alpine plants and other flora and fauna. From Cow Green Reservoir it extends southwards to the summit of Mickle Fell (788 m) and eastward, down the Tees, to High Force waterfall. Moor House and Upper Teesdale NNR, as it is now known, is a terrestrial and freshwater site, which is part of the UK Environmental Change Network (ECN) monitoring site. The ECN was launched in January 1992. It is a multi-agency long-term research programme to record, analyse and predict environmental changes across the UK from which to obtain comparable long-term data sets. At present, Moor House is owned by English Nature and provides free range common grazing (mainly sheep) for villages in the Eden Valley. Moor House demonstrates that through conservation management eroded blanket peat moorland can be restored. For example, Burnt Hill (a 4.8 ha gently sloping moorland catchment) suffered from severe burning in 1950 and was subsequently named 'Burnt Hill'. At present the vegetation is fully recovered from the burns and the floors of established gully systems have re-vegetated (Figure 1.11) (Higgitt *et al.*, 2001).

3.3.2 The Cheviot Hills

The Cheviot Hills straddle the England–Scotland border representing the northerly limit of the Pennine range. To the south lie the Northumberland fells, to the north the Southern Uplands of Scotland. Generally the hills are smooth and rounded with few craggy outcrops. The hills nowhere achieve the plateau-like form of much of the Pennine range to the south of the Tyne gap (Wishart and Warburton, 2002). The Cheviot Hills are part of the Northumberland National Park (NNP). It is the most northerly, the most remote from urban areas, the least visited and the least populated of all the NPs in England and Wales. The boundary was designated in 1956 and drawn close to the upland limits with any significantly sized settlements remaining outside the area. Except for the river valleys, all the NNP is over 244 m a.s.l, with the highest point being the summit of The Cheviot itself at 815 m (Figure 3.8) (Wishart and Warburton, 2002).

The geology of the Cheviot Hills is largely composed of volcanic rocks of predominantly Devonian age (Common, 1954; King, 1976; The Countryside Agency, 2004). Along with the volcanic rocks, ash, agglomerate and felsite occur locally

(Common, 1954). The lavas are limited in the north and south flanks by boundary faults. They pass under Carboniferous sediments to the east; however, the base of the series and the underlying Silurian sediments are exposed on the high ground to the west. Within these lavas the Cheviot granite covers an area of approximately 55 km^2 of Northumberland and is now considered to be a replacement, probably occupying the major vent of this ancient volcano. The Cheviot massif is composed of granite that was intruded into the lavas (Common, 1954; The Countryside Agency, 2004).

Scale 1:50000
Scale (km)
0   2   4

Location of the main research

N
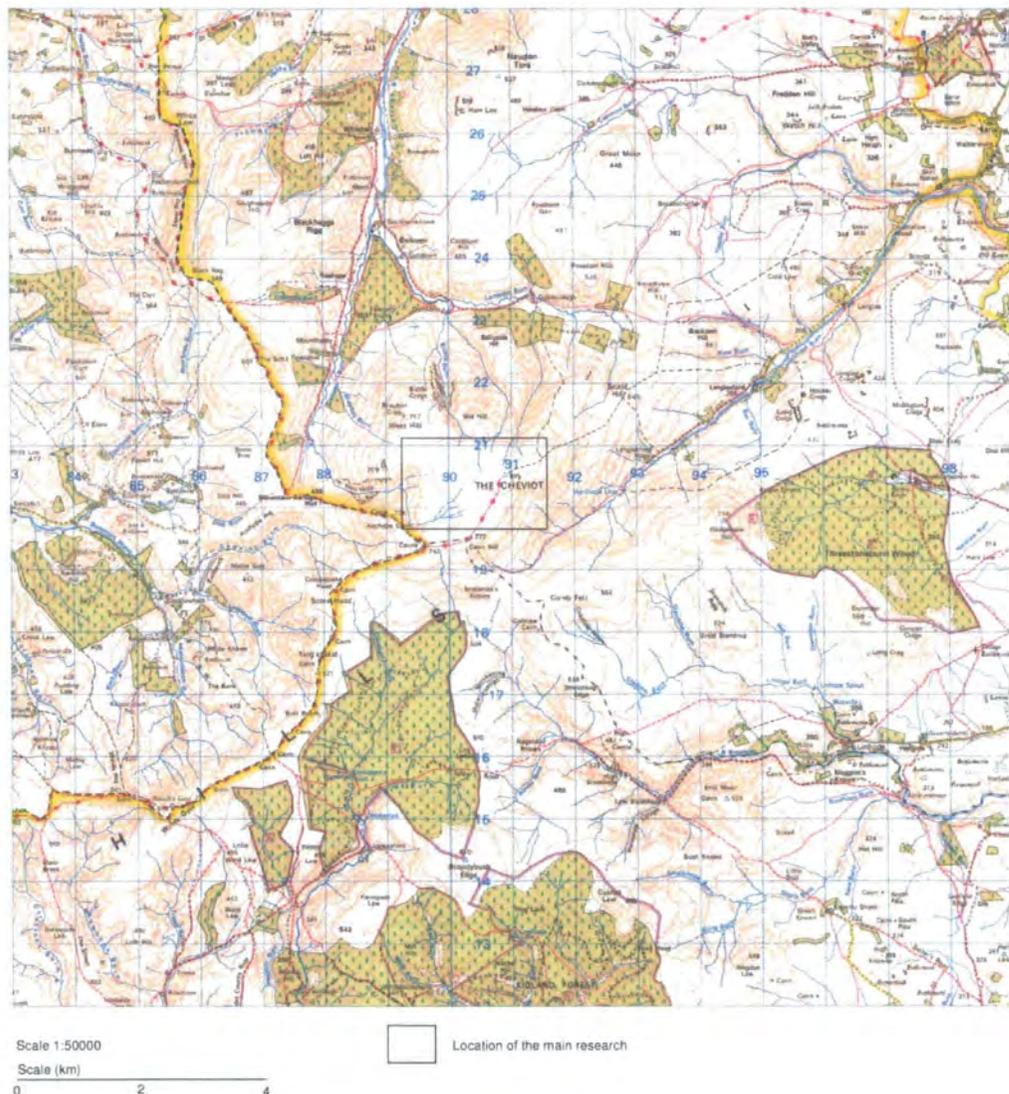
Figure 3.8: Map of The Cheviot and surrounding area (Source: Ordnance Survey, Sheet Number 24, Digimap online).

Blanket peat in the Cheviot Hills is concentrated in the northeast portion of the range. This coincides with the highest and flattest hills. Elsewhere blanket peat, although

extensive, is less continuous. In many areas the peat is underlain by light grey, late-glacial gravel, which is thought to be mainly solifluected till. Figure 3.9 shows a typical intact peat profile from The Cheviot summit. Approximately 70 % of the NNP is wide-open moorland. Within the Cheviots most areas are grassy, with heather cover being relatively sparse (Wishart and Warburton, 2002).

The climate of the Cheviot Hills can be classified as upland maritime, similar to that of Moor House and Upper Teesdale NNR in the North Pennines, although the average annual precipitation is recognised as being approximately half that of the North Pennines, with an average of 1100 mm and is mainly the result of frontal systems approaching from the west. Evapotranspiration losses can be as little as 400 mm (Atherden, 1992; Wishart and Warburton, 2002; The Countryside Agency, 2004).
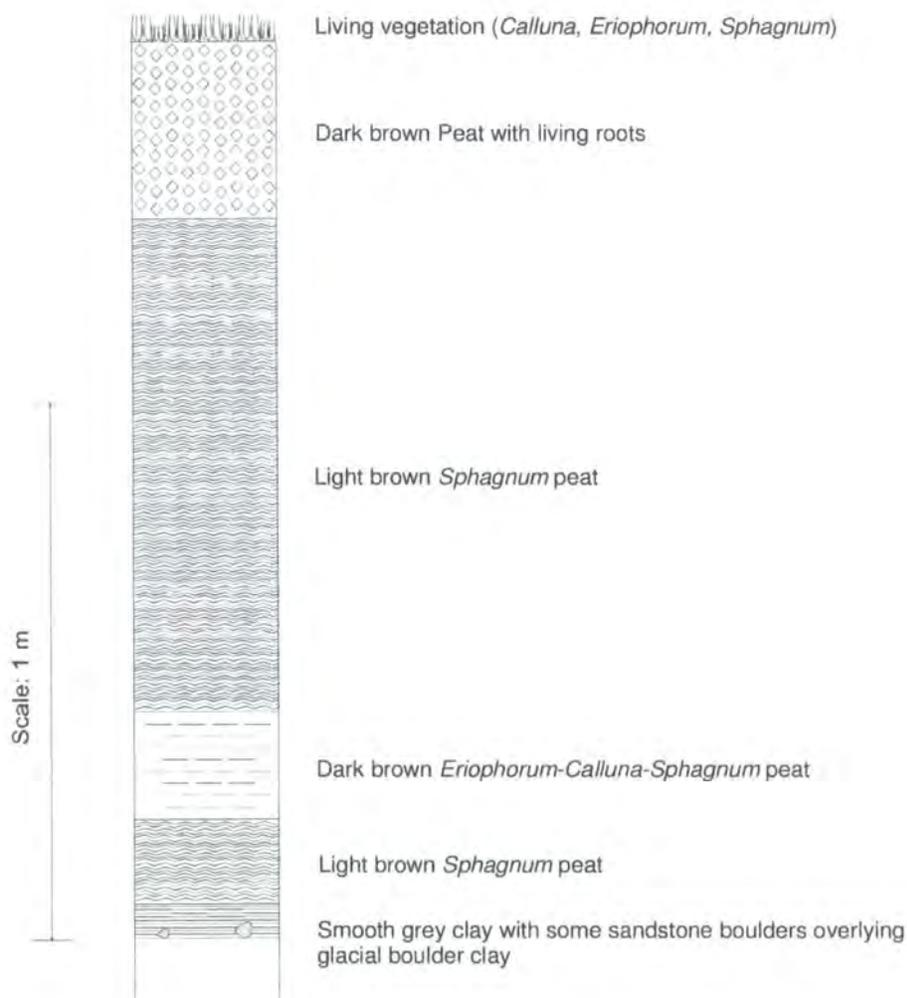
Figure 3.9: Typical Cheviot blanket peat profile, from The Cheviot Summit (c. 815 m).

There are a few substantial blocks of coniferous plantation in the upper valleys of the Cheviots (The Countryside Agency, 2004), which has led to significant areas of moorland being lost. Military use has resulted in heavy-vehicle movements on the Cheviots. Additionally there has been a decline in management of walls, hedges and buildings and increased recreation, which has led to footpath erosion on the Pennine Way. Various organisations such as the NNP, The National Trust, English Nature, College Estate Valleys and the Countryside Agency are working together to combat the problem of erosion. Conservation practices include repairing footpaths through the use of stone chippings and stone pitching on the slopes to create a hard, sustainable surface to resist erosion, replanting mire vegetation and more recently there has been a swing back to grouse moor management (The Countryside Agency, 2004).

Direct reference to peat erosion in the Cheviots is infrequent in academic literature, but has been widely acknowledged elsewhere. Dixon (1903) and The Memoirs of the Geological Survey from 1888 describe a peat slide, which occurred at Lintlands to the north of Bloodybush Edge in approximately 1893 (Muschamp-Perry, 1893). The 1989 Memoir by the same author describes a 'moss burst' (bog burst), which occurred on Caplestone Fell (Clough, 1889). Erosion of the peat by dissection is described in the 1932 Memoir of the Geological Survey, where the peat is said to be 'generally wasting and much furrowed or 'hagged'' (Carruthers et al., 1932; Wishart and Warburton, 2002).

3.3.3   Wessenden Head Moss

Wessenden Head Moss is at the northern end of the Dark Peak and the Peak District NP. It is a 1.5 km^2 area at the headwaters of the Shiny Brook catchment and on the western edge of Featherbed Moss. It is located just north of the main A635 road connecting Huddersfield and Manchester (Labadz, 1988) (Figure 3.10). The Shiny Brook catchment has been researched and discussed in some detail by Tallis, (1964), Gardiner (1983), Labadz (1988) and Burt et al. (1990), whilst Featherbed Moss has been discussed in some detail by Tallis (1985b). The area rises in altitude to 490 m with slopes generally being less than 5 ° except those adjacent to the streams and with angles of less than 1 ° on the interfluves.

Coarse pebbly Kinderscout Grit predominates the geology in the western half of the catchment, where this research took place, whilst on the eastern half of the catchment it is underlain by the more resistant Readycon Dean Sandstone. Often the bedrock is overlain by an impermeable sandy clay head deposit, which may have originated as a result of solifluction processes in the area (Labadz *et al.*, 1991).
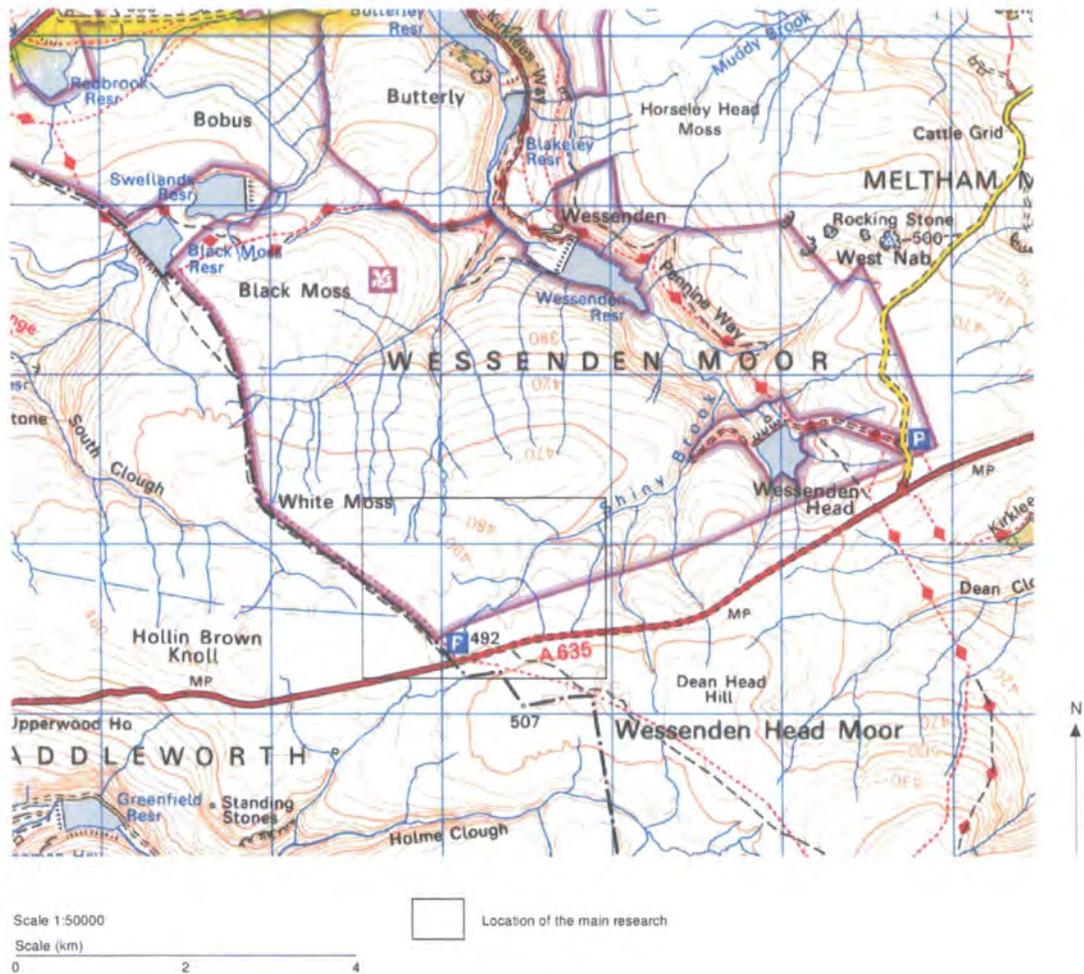
Figure 3.10: Map of the Wessenden Head Moss (Source: Ordnance Survey, Sheet Number 110, Digimap Online).

The area is predominately covered by blanket peat. Figure 3.11 shows a peat profile from Featherbed Moss (Tallis, 1985b). Peat initiation in this area is thought to have occurred at the time of the Boreal Atlantic Transition around 8000 years ago. Within the Shiny Brook catchment field observations of tree remains in the basal peat layer indicates that the earliest accumulations of organic matter may have taken place beneath a cover of alder and birch wood of varying density (Conway, 1954). Tallis (1964) used

pollen analysis to elucidate the relationship between topography and erosion on Wessenden Head Moor (the deep peat interfluve area between Shiny Brook and the adjacent Greenfield Brook catchment to the south). He identified six synchronous horizons within the peat layers (Table 3.2). In general the six horizons conform to the stratigraphic divisions proposed by Conway (1954) from her work in the Southern Pennines and in the absence of carbon dating tentatively dated their inception. Within the area, and in particular the headwater zones, erosion and incision by streams have exposed bare peat in many places. Gully erosion has allowed some drainage of the remaining peat hummocks (Gardiner, 1983).
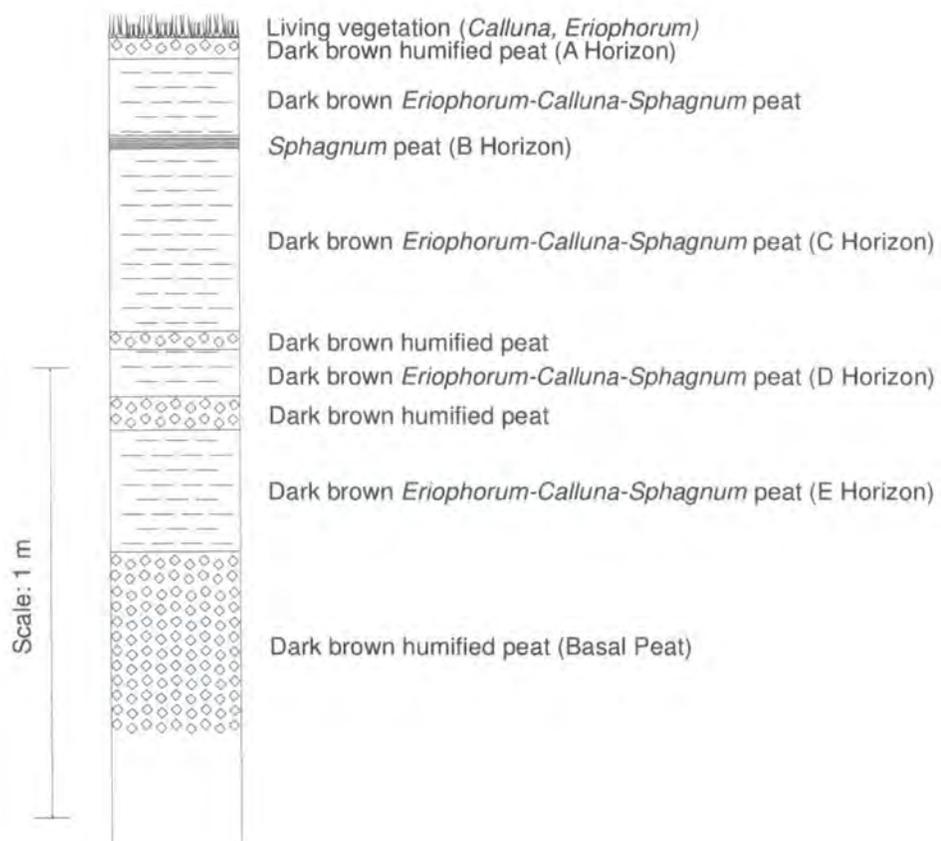
Figure 3.11: Typical Southern Pennine blanket peat profile, from Featherbed Moss (Source: Tallis, 1985b). The locations of the horizons shown in Table 3.2 are presented. The horizons do not fit precisely; however, give some representation of the layers.

i	A Horizon	Maintained almost to the present day surface, marking a change to highly humified peat with an increasing predominance of *Eriophorum vaginatum* remains, associated with the beginning of recent human interference around AD 1000.
ii	B Horizon	A reversal of the process initiated in C to give a fresh band of *Sphagnum*. Possibly due to decreased human interference marked by the end of Roman occupation at around AD 400.
iii	C Horizon	A change from predominantly *Sphagnum* to *Eriophorum* rich peat. Possibly due to human interference on a large represented by Roman occupation at the end of the 1st Century AD.
iv	D Horizon	A prominent band of fresh Sphagnum produced by a further climatic deterioration. The equivalent of Granlunds RY III (Grenz horizant) dated at 600 BC.
v	E Horizon	Occurring at the junction of Conway's Lower and Upper Peat. A thin band of fresh Sphagnum separating the highly humified *Eriophorum* rich Lower peat from the less humified *Sphagnum* rich upper peat. Tallis dated this zone at 1200 BC and tentatively equated it to Granlunds recurrence surface RY IV.
vi	Basal Peat	*Eriophorum* rich peat, conforming to Conway's Lower Peat layer, and initiated later than Conway's estimation of 6000 BC at around 4500 BC to 3000 BC

Table 3.2: Six peat horizons identified by Tallis (1964) using pollen analysis on Wessenden Head Moor (Source: Tallis, 1964).

The climate is classified as upland maritime, similar to The Cheviot Hills in Northumberland, and not too dissimilar from Moor House and Upper Teesdale NNR in the North Pennines. Gardiner's (1983) highest monthly average temperature was 15.1 °C for July, with severe wind exposure and a growing season of only six months. Long-term mean annual temperatures are low, with monthly means for January and February remain close to zero (Labadz, 1988). The average annual precipitation falls between the two other study sites (The Cheviot Hills and Moor House and Upper Teesdale NNR) at 1536 mm (Burt, 1980). Precipitation has an autumn maximum but is distributed throughout the year, being generally associated with the passage of fronts although convectional storms also occur in summer and autumn. Snowfall is a common occurrence, with 45 days per year having snow lying. Frosts are prevalent throughout the winter half of the year, and the low temperatures and high rainfall combined to produce a situation (during Gardiner's study) where rainfall exceeded evapotranspitation in every month.

There is abundant evidence of past land use and management in the area. A Medieval Boundary ditch crosses the Moss. The ditch is now infilled with vegetation, but is still

clearly visible. There is also a linear track that crosses from Wessenden Head Moss over Featherbed Moss. This was thought to be used over 100 years ago for transporting cut cotton. Adjacent to this track is a 0.5 km^2 area of gripped peat. The land use has included sheep grazing and infrequent (on average once every 10 – 15 years) burning of the vegetation. A public footpath crosses the western edge of Wessenden Head Moss from south to north and is regularly used by walkers. The severe erosion typical of the Southern Pennines has led to conservation management. At present the gully systems on the western side and east of Featherbed Moss have been blocked ('gully blocking'). Heather bales have been airlifted into the area and placed in the bottom of gully systems to aid regeneration and re-vegetation of the gully systems. Grazing on the west of Wessenden Head Moss has also been restricted to allow re-vegetation to occur and to prevent trampling or damage to the gullies infilled with the heather bales. Also no burning has taken place in recent years (English Nature, 2004; National Trust, 2004). The various management practices and their locations within the study site are shown in Figure 3.12.
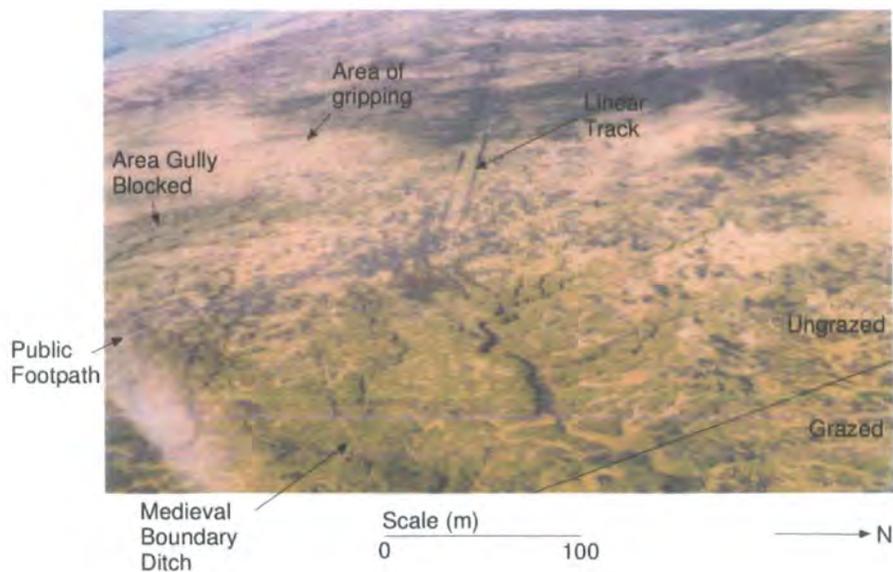
Figure 3.12: Aerial view of Wessenden Head Moss study area with Featherbed Moss towards the back of the photograph. Locations of various land management practices are shown along with the dense network of linear, dendritic and anastomosing dissected gully systems. The photo was taken prior to grazing restriction (Source: Labadz, 1988).

3.4 The methodological research framework

As discussed in Section 1.4 this research investigates both the regional and local scale variations in gully development as well as peat accumulation and peat loss from the interfluves. An integrated framework of field and laboratory research covering three study sites across Northern England was used, involving a combination of traditional fieldwork (surveying and sampling), laboratory analysis (e.g. Spheroidal Carbonaceous Particle (SCP) analysis) and GIS. Table 3.3 presents a general summary of the research conducted at the three sites. The investigation of gully development and the interfluves was the first objective to be addressed. This was assessed on a regional scale, across Northern England at Moor House, The Cheviot and Wessenden Head Moss. Moor House was selected as the main study site where more detailed research was conducted. This is justified because Moor House and Upper Teesdale NNR provides an excellent location due to the amount of research that has been done on the Reserve since the 1950s and the ongoing monitoring operations that continue today. On The Cheviot and Wessenden Head Moss, although they are not researched in the same detail as at Moor House, a similar framework is used throughout. The regional characteristics of the study sites are similar; however, there are some differences. These are intrinsically linked to the natural fabric of the landscape, e.g. altitude and topography and therefore make it impossible to standardise. Using a GIS framework approximately 200 gully systems at Moor House and approximately 50 gully systems on The Cheviot and Wessenden Head Moss were studied in terms of their type, order, length, width and development over an approximate 50-year time period. The variations in the number of gully systems studied were not factors of gully density, but study area, i.e. there were not more gully systems at Moor House, a larger area was studied.

The regional scale analysis is followed by local-scale studies examining peat accumulation from interfluves at the three sites and peat loss from interfluves at Moor House. The peat accumulation research required core samples being removed from the three sites and the rates of accumulation over the last 150 years were inferred using SCP analysis. SCPs are formed from incomplete combustion of fossil fuels and therefore also allowed an assessment of the variations in pollution across Northern England to be inferred. Investigations into potential interfluve erosion (gully initiation) were conducted at Moor House taking full advantage of the unique exclosure plot experiments (Adamson, 2004). This required carrying out paired rainfall simulation

experiments, both inside and outside of the exclosures. This research aimed to identify the potential importance of erosion of blanket peat in relation to land management and climatic change. Finally, and also at the local scale, the morphology of a small number of representative gully systems at each of the three sites were assessed in terms of their development. Again research was focused at Moor House where 12 gully systems were investigated. On The Cheviot and Wessenden Head Moss 3 gully systems were studied. Measurements of the long profiles, cross profiles and stratigraphy were recorded.

Methodology	Moor House	The Cheviot	Wessenden Head Moss	Timeframe
Regional Gully Development	Approx. 200 gullies surveyed	Approx. 50 gullies surveyed	Approx. 50 gullies surveyed	November 2001 – March 2002
Interfluve Peat Accumulation (SCP analysis)	2 blocks removed from which 4 cores were sampled in each	1 core sampled	1 core sampled	March 2002 – December 2003
Interfluve Erosion (Paired Rainfall Simulation Experiments)	5 paired experiments conducted on the grazing exclosures and 1 on the Hard Hill Burning Experiment			June 2002 – July 2003
Local Gully Development	12 gully systems surveyed	3 gully systems surveyed	3 gully systems surveyed	November 2001 – June 2004

Table 3.3: Basic overview of the research carried out at the three study sites.

3.5 Methodology

3.5.1 Research Preparation

The initial phases of this work involved critically examining past research that had been undertaken at the three study sites (Bower, 1960a; 1960b; 1961; 1962). Aerial photographs for all three study areas were obtained and assessed in detail (Table 3.4).

The areas were initially compared in order to assess the future stability of the peat to erosion and to select representative gully systems on which to conduct detailed field research. Bower's research was reviewed in terms of the classification of gully form, the overall extent of peat erosion and predicted future erosion rates in the areas (Bower, 1960a; 1960b; 1961; 1962).

Permission to access the study areas was granted by the National Park Authority (The Cheviot), English Nature (Moor House), and the National Trust (Wessenden Head Moss). As part of this consultation the management history and current practices undertaken at the sites were discussed with each of these organisations. Information on the management of the areas, both past and present was harder to obtain for The Cheviot and Wessenden Head Moss than that at Moor House. Basic data were collected from past research records, the National Park Authorities of the areas (Northumberland NP Authority and the Peak District NP Authority) and also from the National Trust working in the area of Wessenden Moor and Wessenden Head Moss in the Southern Pennines.

A reconnaissance visit was then undertaken at each of the three study sites. During these visits the areas were walked, focusing on the areas highlighted as important from the aerial photographs. The gully systems selected from the aerial photographs were looked at to confirm whether or not they were representative of the whole area. In addition measurements of slope angles and general observations were recorded. In preparation for the rainfall simulation experiments at Moor House, all fourteen of the exclosure plots were considered and the most appropriate plots selected for the experiments to be undertaken.

3.5.2 Regional Scale Investigation into Gully Development

Regional gully development was assessed using a GIS framework. Historical aerial photographs were scanned at 600 dpi and 150 dpi and imported into the GIS using the digitising programme 'Didger' (© Golden Software). The GIS package ArcGIS was selected as it offers a greater degree of flexibility than ArcView. The aerial photographs used are shown in Table 3.4 and the areas in which the main research was carried out are outlined in Figures 3.5, 3.8 and 3.10 (Moor House, The Cheviot and Wessenden Head Moss respectively).

	Moor House	The Cheviot	Wessenden Head Moss
Aerial Photographs	1953	1951	1948
	1975		1976
		1983	1988
	1995		
	2000		
Ground reconnaissance	2001	2001	2002
Field survey	2001		
	2002	2002	2002
	2003	2003	2003
	2004	2004	2004

Table 3.4: Dates of aerial photographs used and periods of ground reconnaissance and field survey for the three study sites.

A limitation of this research is that no recent aerial photographs were obtained for The Cheviot and Wessenden Head Moss, the most photographs recent being 1983 (The Cheviot) and 1988 (Wessenden Head Moss). However, extensive field research confirmed the accuracy of the photographs.

A number of measurements and observations were carried out at each site. These included observation of: dissection types; cover type; gully order; drainage density and changes in gully development over time. The types of observed dissection were compared with the research by Bower (1960a; 1960b) and later researchers such as Mosley (1972) and Wishart and Warburton (2002). For example, the erosion observed on a 1953 aerial photograph by Bower was resurveyed to see if Bower's patterns of erosion fitted that of this research. An appropriate classification scheme of typical gully types in the three study sites was chosen. Cover types at the three study sites were then assessed. This included the extent of blanket peat, the extent of peat erosion and of re-vegetation. All were assessed in terms of differing altitudes and a Digital Elevation Model (DEM) of Moor House showed variations with slope. A distinction between dendritic and anastomosing dissection was based on definitions discussed by Wishart and Warburton (2002) (Figure 1.8). Dendritic dissection was classified where the tributaries formed a branching network of well defined channels. Anastomosing dissection occurs typically on flat or summit area where multiple channel networks,

criss-cross the peat leaving isolated haggs as islands e.g. at the top of the main gully system on Burnt Hill and the top of the main Cottage Hill gully system (Figure 3.17).

The order of the gully systems was investigated in order to see the pattern of gully order was related to gully length and the patterns of erosion. Figure 3.13 shows the basis of the network analysis, following Strahler (1952). The Strahler (1952) system of network analysis is a modification of Horton's (1945) system; however, is less subjective. For the simple gully patterning shown in Figure 3.13a first order magnitude channels have only one source and no tributaries. Where two first, second or third order tributaries join a second, third or fourth order system is produced respectively. For the complex patterning shown in Figure 3.13b, which is typical of many anastomosing systems, e.g. Figure 2.3, first order fingertip tributaries, which consist of fragmented channels with isolated haggs between, are regarded as first order systems.
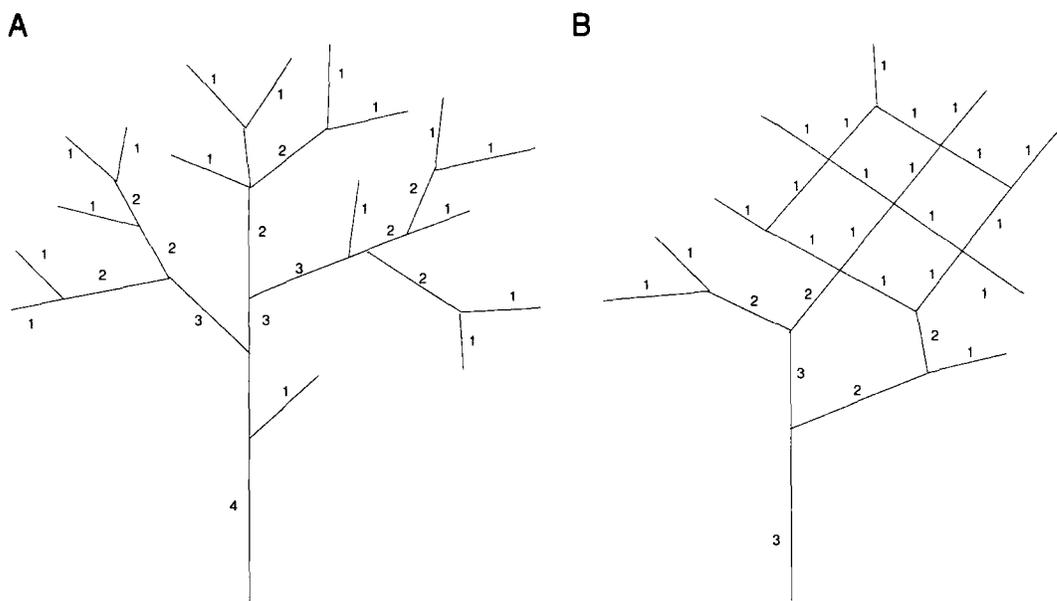
Figure 3.13: Diagram showing the basis of the network analysis (Adapted from Strahler (1952), Haggett and Chorley (1969) and Penning-Rowsell (1969)): A) Simple pattern typical of dendritic and linear dissection; B) Complex pattern showing an anastonosing dissection system.

The drainage density was assessed for the three sites. Gully length and width measurements were used as measures of changes in the gully systems over time, for example from Burnt Hill's main gully system and Moss Flats at Moor House from 1953, 1975, 1995 to 2000. This included any spatial changes in gully type/ form,

changes in the amount of vegetation cover and if during this time period the number of coupled gullies decreases (had decoupled). This was observed within and between the three study sites.

3.5.3 Interfluve peat accumulation - Spheroidal Carbonaceous Particle (SCP) Analysis

SCPs (Figure 3.14) are formed from the incomplete high-temperature combustion of fossil fuels (Renberg and Wik, 1985) and can be transported long distances (>100 km) through the atmosphere to be deposited in remote areas (Renberg and Wik, 1985). During peat accumulation, deposited SCPs are preserved in the soil profile. A profile of concentration of SCPs with depth is shown in Figure 3.15 (Charman, 2002). This profile shows a distinct pattern of change that has been identified in a number of lake sediments in Northern Britain. It shows the onset of SCP accumulation at the start of the Industrial Revolution (1850s); the 'take-off' particularly after 1950 and the peak in SCP concentration in Britain and Ireland in the late 1970s early 1980s (Rose *et al.*, 1995; Yang *et al.*, 2001).
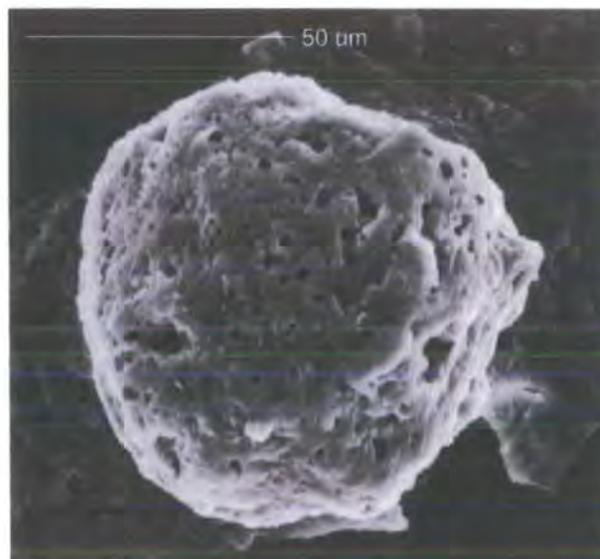
Figure 3.14: Example of a Spheroidal Carbonaceous Particle (SCP) from The Cheviot using the Rhodes (1998) preparation method.

It is reasonable to assume that the SCP profile in an undisturbed and steadily accumulating site will faithfully record historical atmospheric SCP deposition. Therefore SCPs can be used to study the history of atmospheric pollution and as a

potential tool for dating sediment cores (Yang *et al.*, 2001). By establishing the depth of 'take-off' in the trend in SCP concentration in the profile the onset of atmospheric pollution can be determined (Rose, 1995).

SCP Concentration (g DM)

c. AD 1978

c. AD 1950

Depth / Date

c. AD 1850
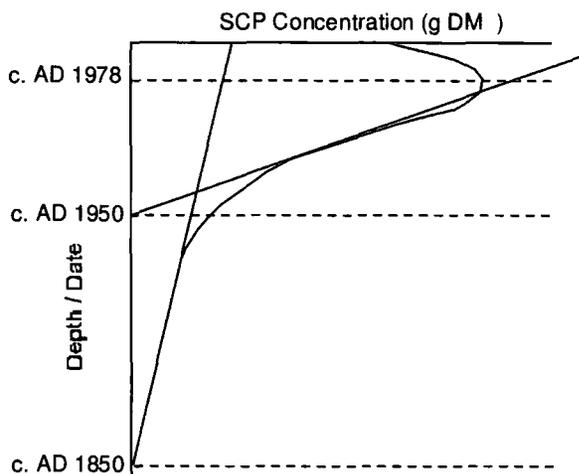
Figure 3.15: Changes in the concentration of SCPs with depth in profiles from lake sediments in Northern Britain. Adapted from Rose *et al.* (1995) (Source: Charman, 2002).

The Pennines are an ideal location to study the deposition of SCPs because it is sufficiently remote from large-scale industrial activity; it is predominantly agricultural (Mackay, 1994) and due to the sensitivity of upland ecosystems they act as 'early warning' indicators for increases or decreases of pollutant input and climate change (Rose *et al.*, 1999). Garnett (1998) carried out research into the impacts of burning and grazing at Moor House. His research used SCPs to identify differences in SCPs concentration inside and outside of exclosure plots. Differences in the profiles were then used to determine peat accumulation rates. Garnett was unable to precisely date the 'take-off' of SCPs, although he believed the SCP 'take-off' corresponded with increased industrial emission of these particles. Garnett reasonably assumed SCP deposition was synchronous across the different exclosure plots due to their close proximity. It was concluded that, differences in grazed and ungrazed vegetation were minimal but burning appeared to have a significant impact on the accumulation of peat.

The analysis of SCPs is rapid and low cost (Garnett *et al.*, 2000) and therefore used to date the peat samples in this study. There are only a few published studies of the use of SCPs in peat (Chambers, 1978; Rose *et al.*, 1995; Garnett, 1998; Barber *et al.*, 1999; Garnett *et al.*, 2000; Yang *et al.*, 2001). The methodologies used in this study are presented alongside the other main laboratory methods presented in this chapter (see Section 3.7).

3.5.4 Interfluve Erosion – Paired Rainfall Simulation Experiments

This aspect of the research took advantage of an established environmental monitoring programme. The database of results, which already exists, was used as background to this present study, much of which was discussed in Section 2.6.2. By comparing the runoff response and sediment production from the long-term vegetation plots at Moor House using a portable rainfall simulator the link between runoff variations and peat erosion (and possible gully initiation) was investigated. This involved a paired (inside and outside the plot) experimental approach on a series of exclosure plots, which have undergone different treatments (grazing and burning).

The Experimental Approach to Rainfall Simulation

Rainfall simulators have been widely used in hydrological and geomorphological research (Bowyer-Bower and Burt, 1989). Meyer (1994) states, 'Rainfall simulators are research tools designed to apply water in a form similar to natural rainstorms. Rainstorm characteristics must be simulated properly, runoff/ erosion data analysed carefully, and results interpreted judiciously to obtain reliable information for the conditions to which the simulated rainstorms are applied.' They allow the amount, intensity and duration of rainfall to be controlled along with other variables such as drop-size distribution and water chemistry, to varying degrees depending on the system of application (Foster *et al.*, 2000). There are several advantages and disadvantages to the technique.

On the positive side the use of rainfall simulators has increased understanding of erosion. This is because experiments can replicate a standard storm numerous times on demand, over any time period and in any location. Natural rainfall events do not guarantee a constant starting condition, e.g. depending on the time between the last storm and the present the ground wetness may be very different. This affects the

outcome of the results and is a problem when undertaking replicate tests. Rainfall simulators can be used to wet-up a plot to a consistent degree allowing accurate replicates to be made. Additionally more control on the characteristics of the rainfall can be achieved unlike natural rainfall events. This is possible by the uniform intensity, duration and drop-size characteristics (Rickson, 2004). Rainfall simulation has led to new approaches in soil erosion research as well as improvements to existing techniques, e.g. infiltration rates can effectively be measured using a rainfall simulator (Holden and Burt, 2002b). The results are obtained by subtracting the runoff rates from the rainfall intensity over a given time period.

Rainfall simulation experiments can be conducted both in the field and laboratory, using the same rainfall simulator. Results are therefore comparable due to the same equipment being used and therefore any discrepancies due to this can be eliminated. There are, still however some discrepancies between field and laboratory results for the same research (Bryan, 1981), with significant differences in results obtained despite identical test procedures between different operators (Luk and Morgan, 1981). The major drawback with rainfall simulators is the scale at which simulations are undertaken and their ability to achieve the characteristics of natural rainfall events given the spatial constraints (Bowyer-Bower and Burt, 1989; Meyer, 1994; Rickson, 2004). Whilst there are relatively large-scale rainfall simulators used in fieldwork, the cost and practicality of such large rigs makes them inaccessible to most researchers. This scale limitation can be viewed as an advantage if the researcher wants to distinguish the operation of different erosion processes, namely sediment detachment and transport. The regularity of simulated rainfall frequency, intensity and energy means that the erosivity is set for any given experiment, allowing variations in other factors to be determined. However, it is thought to be unrealistic because natural rainfall is inconsistent, for example, wind may interfere with rainfall intensities and drop sizes. Providing the results are treated as relative rather then exact then the accuracy with which the simulated rainfall reflects natural rainfall is less important (Rickson, 2004). However, rainfall simulation experiments should not eliminate the need for natural rainfall experiments. This is because they are good for reproducing the short-term mechanisms of erosion; however, they are unable to account for long-term trends in erosion (Meyer, 1994).

'The ideal rainfall simulator would be inexpensive to build and operate, would simulate rainfall perfectly, would be simple to move, and could be used whenever and wherever needed.' (Meyer, 1994)

Early research by Duley and Hayes (1932) used a hand-held watering can to simulate rainfall, but since then two main designs of simulator are now commonly used: the 'spray-type' and the 'drip-type'. The above quotation by Meyer (1994) is not feasible and hence the two types of simulators have different characteristics in order to meet certain requirements. The 'spray-type' simulator closely replicates natural rainfall. This is achieved because raindrop size varies with changing rainfall intensity (Rickson, 2004). The method also has the ability to achieve raindrop impact velocities (terminal velocity) close to that of natural rainfall. This is known as the kinetic energy of rainfall and is very important for erosion and sediment transport. Several researchers in the 1940s carried out research on the fall velocity of different sized raindrops. Laws (1941) found that drops of 1 mm diameter reached terminal velocity after falling for 2.2 m, 2 mm diameter drops reached terminal velocity after falling for 5 m and 3 mm diameter drops reached terminal velocity after falling for 7.2 m. In order for the near-natural rainfall to be achieved the 'spray-type' simulator requires a large amount of water, in comparison to the 'drip-type' simulator. Other disadvantages to the 'spray-type' simulator include large spatial variation in simulated rainfall over large plots and it is hard to get low-intensity rainfall, which is typical of natural rainfall in upland UK (Figure 3.6).

'Drip-type' simulators (Figure 3.16a) have previously been described in detail by Bowyer-Bower and Burt (1989) and Foster *et al.* (2000). Figure 3.16a shows the general set-up of a 'drip-type' rainfall simulator. Here the rainfall simulator is set up above a sloping bounded plot (discussed later in this section). Sloping ground is needed in order for runoff to be generated. The simulator consists of a perspex plate with drop formers and a manometer set at a height of approximately 2 m. Above this is a water supply which feeds water into the Perspex plate at a rainfall intensity set at the manometer. The 'drip-type' rainfall simulator is able to generate a constant low-intensity rainfall rate with drop sizes more easily controlled than the spray systems (Bowyer-Bower and Burt, 1989). 'Tygon' tubing and fishing wire is used to form the drops (Figure 3.16b). The

type of drop former chosen is crucial to determine the drop size relative to the rainfall intensity. This is determined by the outside diameter of the 'Tygon' tubing (2.3 mm). The drop formers are over a fixed grid to produce rainfall over relatively small surface areas. The drop formers need to be raised to a height high enough to allow representative terminal velocities (e.g. 2 m above the ground surface) (Holden and Burt, 2002b). The small 1-m^2 plots over which the experiment takes place is a disadvantage of the 'drip-type' simulator; however, the advantages often outweigh the disadvantages.

Holden (2000) produced a table showing the best design of simulator to be used in upland blanket peat catchments. The 'drip-type' simulator was preferable for eight out of ten attributes over the 'spray-type'. The 'spray-type' simulator was more favourable for its achievement of 'natural' terminal velocity, attainment of desired drop-size relative to rainfall intensity (i.e. flexibility) and adaptability to difficult terrain and vegetation. The 'drip-type's' suitability included being easy to transport, efficiency of water, ability to reproduce low-intensity rainfall and uniformity over the whole plot. The favourable points of the 'spray-type' simulator are therefore disadvantages of the 'drip-type' simulator and vice versa.

For the purpose of this research, the ability of the simulator to be moved with ease across moorland is important. This therefore requires the simulator to be portable both in weight and size. Bowyer-Bower and Burt (1989) designed the 'drip-type' simulator to fit into aeroplane luggage. Simulators should be erected without complicated or lengthy assembly and disassembly at the field site (Rickson, 2004). Water efficiency is important. Reducing the amount of water needed to be carried over large distances is an advantage. Exposed moors are often windy; however, the simulator can easily be covered with a wind and waterproof sheet (Rickson, 2004).
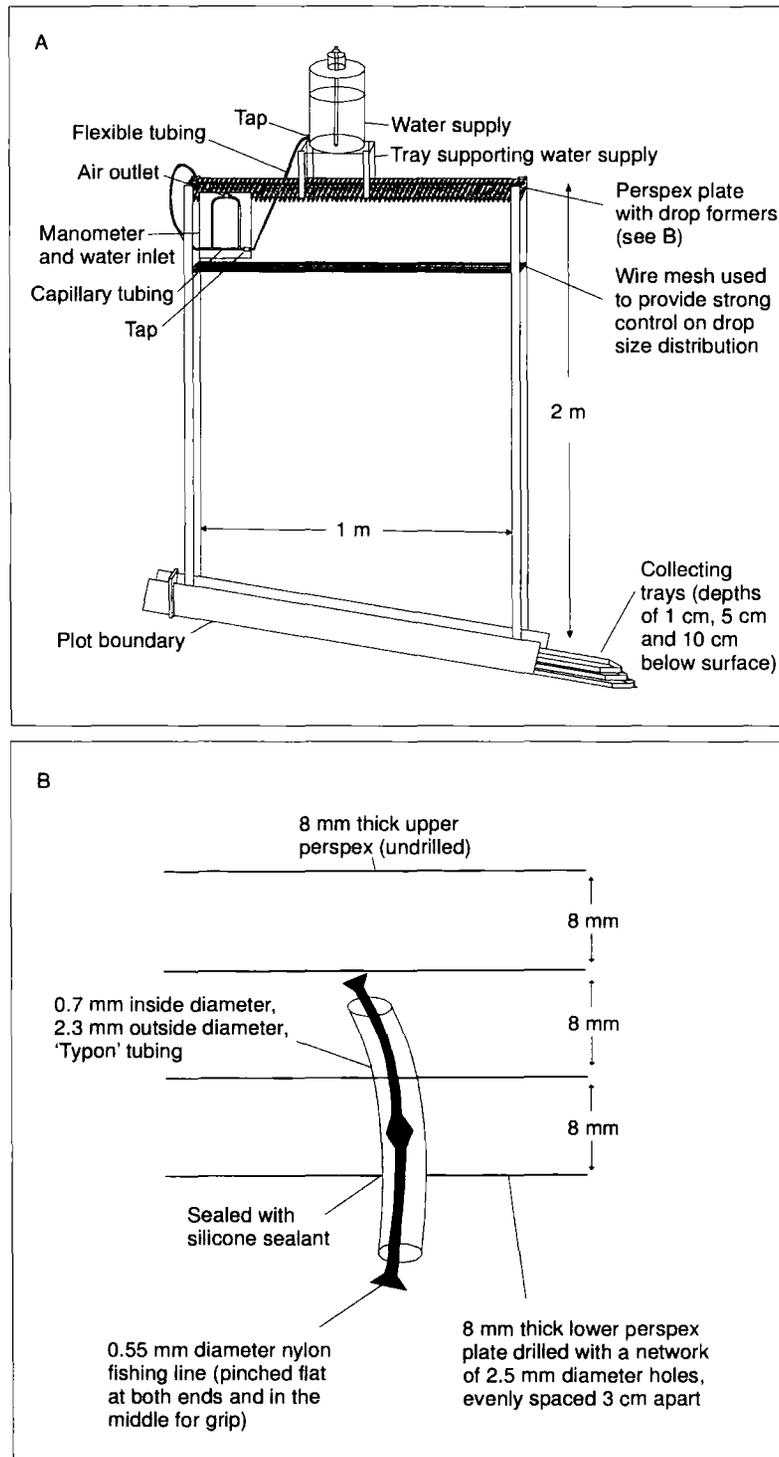
Figure 3.16: The set of the rainfall simulator used: A) the 'Drip-Type' rainfall simulator. B) The drop former for the 'drip-type' simulator (Source: Bowyer-Bower and Burt, 1989).

Based on the previous discussion it was decided that the 'drip-type' simulator was the best for this research. The main reasons for this choice are its efficient use of water (which needs to be transported from site to site), its accuracy in producing and replicating uniform rainfall over the plot area, and its transportability across blanket peat moorland. A great advantage of this system is that it is able to generate a constant low-intensity rainfall with drop sizes more easily controlled than spray systems (Bowyer-Bower and Burt, 1989). A number of researchers have successfully used the 'drip-type' rainfall simulator for blanket peat experiments, for example, Labadz (1988) and Burt et al. (1990) in the Southern Pennines, and Holden (2000) and Holden and Burt (2002b) in the North Pennines. The same simulation had already been used by previous researchers at Moor House (Holden and Burt, 2002b; 2002c; 2003a) and therefore results are comparable.

Calibration, determination of runoff rates and suspended sediment concentration

The simulator was initially run at the four different intensities and rainfall collected at intervals of five minutes and then fifteen minutes. Two runs were carried out to test the uniformity of the rainfall. Calibration allowed the volume of water required for each simulation, at each of the four intensities to be determined (Table A1.1, Appendix 1). In order to calibrate the simulator it was important for it to be level to achieve consistent discharge rates.

Drop size distribution

Drop size distribution was measured at each of the four rainfall intensities. A simple method was used, involving a wooden board (1 m × 0.5 m), covered with a fine layer of flour, of known weight, placed under the rainfall simulator and immediately removed. Raindrops cause the flour to stick. These were then counted and the size of each raindrop measured using a detailed scale, allowing for the calculation of the frequency of each raindrop size. The cover was also calculated by sieving the stuck flour. Trapped flour was weighed and calculated as a percentage of the original weight of the flour. Figure 3.176 shows the results from the four different intensities. A small proportion of drop sizes greater than 5 mm were observed. These were thought to be due to drop coalescing during sampling. As the rainfall intensity increases, so too does the number of drops and the drops sizes resulting from the increased velocity of the raindrop

impacting on the board. The results also show that the percentage cover increases with increasing intensity.
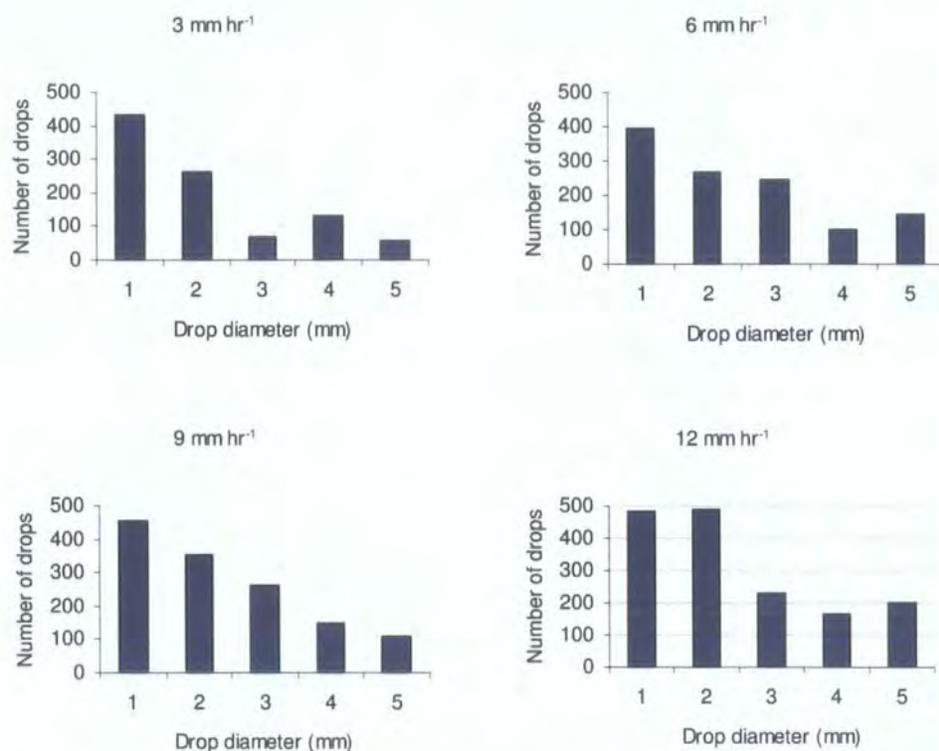
Figure 3.17: Histograms showing the drop size distribution for each rainfall intensity.

Rainfall simulation experiments

Both laboratory and field rainfall simulation experiments were conducted in the same manner (see Chapter 6). Investigations of the variations in runoff and sediment production on different cover types were carried out. In the laboratory, experiments were replicated on a moorland grass block removed from Moor House and experiments were carried out on the block in its natural state (ungrazed), grazed and burnt. In the field paired experiments were carried out at both heather and grassland exclosures, which were grazed and/or burnt. In addition two experiments of bare peat of differing slope angles were carried out. Further details of the block experiments are presented alongside the results in Chapter 6.

With the laboratory rainfall simulations there was more flexibility, for example, the sample could be set at exact slope angles and have numerous replicates carried out with great ease. Since there are unknown discrepancies between field and laboratory results for the same research in the literature (Bryan, 1981), this was investigated. In addition, following the laboratory and field experiments a number of questions remained unanswered. In order to try and solve these questions an additional laboratory experiment was carried out. This experiment was named the 'Throughflow Experiment' as it aimed to allow the understanding of throughflow in the plots, testing the assumption that very little lateral flow occurs at depths greater than 5 cm (Holden and Burt, 2002b; 2002c; 2003a) (see Chapter 6).

Analysis of the surface runoff

Runoff samples were collected as described above and refrigerated at a temperature of 2 °C. The surface runoff from each bottle was filtered in the laboratory in order to determine suspended sediment concentration. The exact volume of the samples in each 500 ml bottle was measured. The water sample was then passed through pre-weighed Whatman GF/C 47 mm Glass Microfibre filter papers that retained particles down to 1 μm using a vacuum filter pump. The filter papers were oven dried overnight and placed in a desiccator to cool. Once cooled the papers were re-weighed to determine the mass of residue sediment. Using the mass of sediment and the volume of the sample, suspended sediment concentrations (SSC) in milligrams per litre (mg l^{-1}) were calculated.

The SSC (mg l^{-1}) is calculated using the following equation:

$$SSC = [(M_{fs} - M_f) / V_{ws}] \times 1000000 \qquad \text{(Equation 3.1)}$$

where

M_{fs} = mass of dried filter paper and sediment (g)

M_f = mass of clean filter paper (g)

V_{ws} = volume of water sample filtered (ml).

Runoff rates were calculated as a volume of runoff collected from the plot over the 5-minute period. The volume was then converted to a rate of mm hr^{-1} so as be comparable to the rainfall intensity. Graphs were plotted with runoff rates at the three depths and the SSC against time. The infiltration rates were also calculated by subtracting the runoff rates from the rainfall intensities. This is only an estimate of the infiltration rate since evapotranspitation is not included in the calculation although this is thought to be minimal over the period of each experiment.

3.5.5   Local Scale Gully Development – Gully Morphology

An important component of this research involves topographic survey of a range of gully systems in the three study areas. The number of gully systems varied between the sites. At Moor House twelve gully systems were assessed (Figure 3.18), on The Cheviot three gully systems (Figure 3.19) and on Wessenden Head Moss three gully systems (Figure 3.20). Surveying involved measuring the gully length and variation in gully width, the contemporary vegetation type and peat depth throughout the systems. In addition, stratigraphic cross-sections provided further details to the gully infill. Monoliths and core samples were removed taken back to the laboratory for analysis. Fieldwork of this nature is essential to this research in terms of looking at gully form and the regeneration of vegetation gully systems. Not only were samples removed from the infilled gully floors but also from uneroded samples (intact peat profiles) directly adjacent to the eroded gullies. Stratigraphic variations of the eroded and uneroded cores allowed an assessment of the possible time of the onset of erosion or regeneration. This work has been successfully conducted by Tallis (1985b; 1995b) in the Southern Pennines.
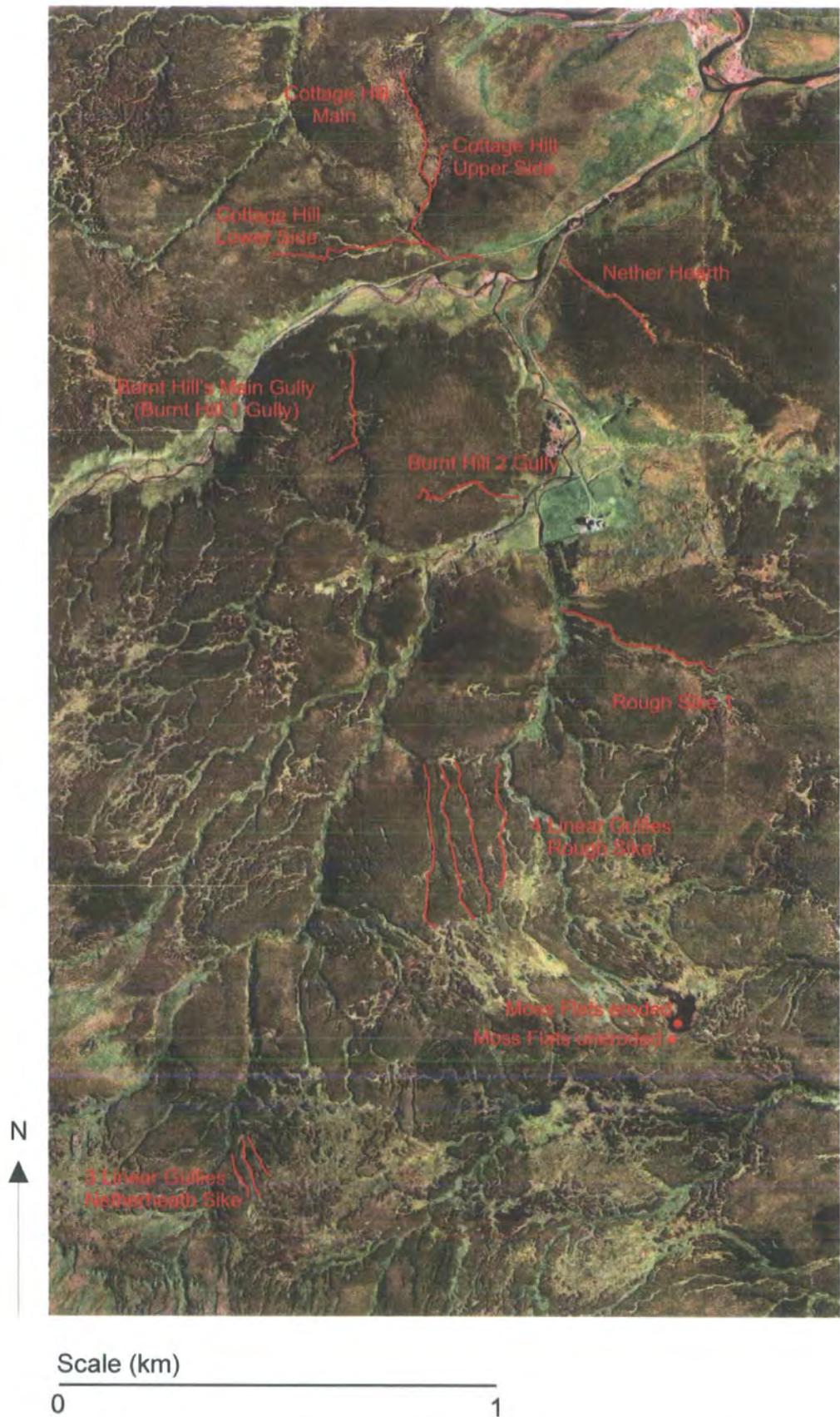
Figure 3.18: Location of the 12 main gully systems at Moor House (Source: Get Mapping, 2000).
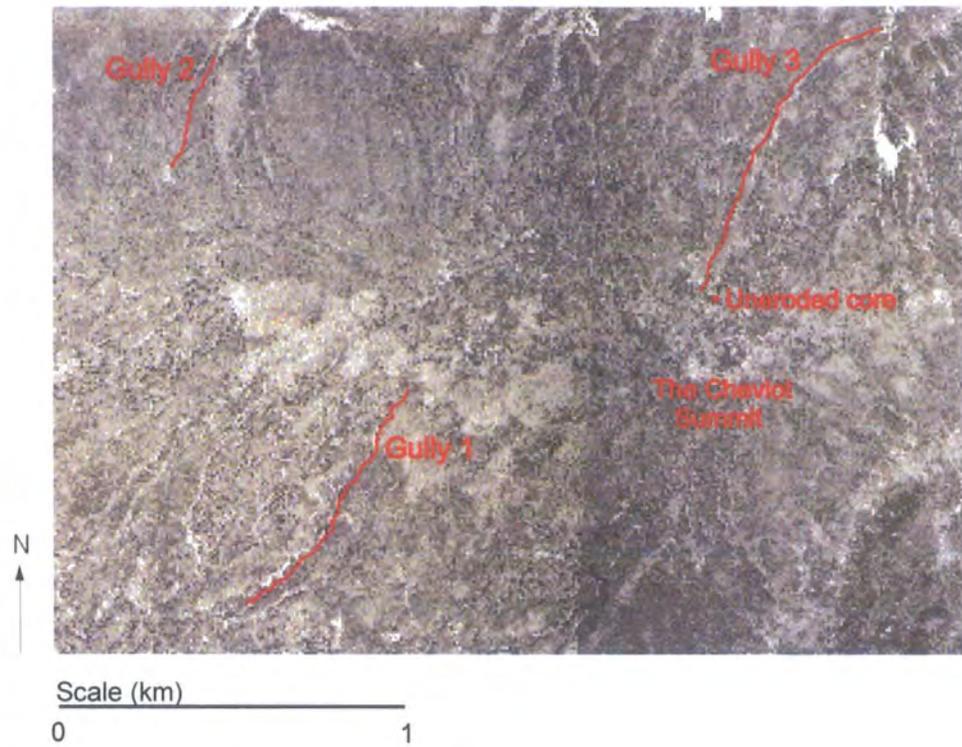
Figure 3.19: Location of the 3 main gully systems research on The Cheviot (Source: ADAS Aerial Photography, Crown Copyright, 1983).
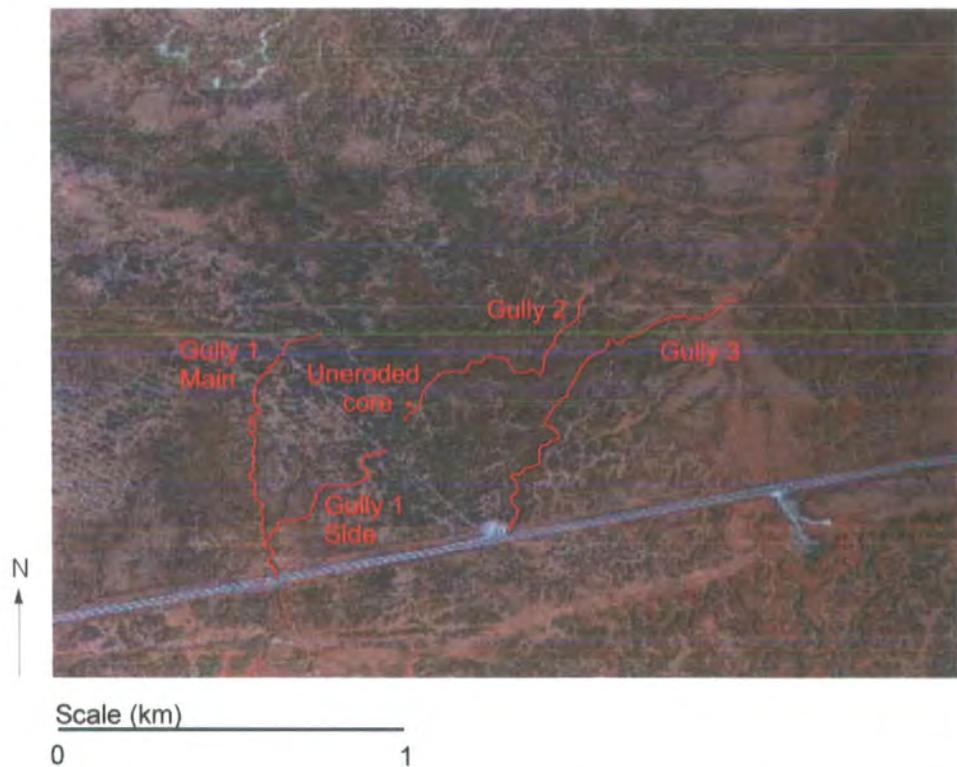
Figure 3.20: Location of the 3 main gully systems research on Wessenden Head Moss (Source: ADAS Aerial Photography, Crown Copyright, 1988).

Both the field research and laboratory analysis carried out to assess the local-scale variations in gully development are shown in Table A1.2 (Appendix 1). The analyses were carried out on eroded (selected gully systems and peat flats) and uneroded sites at the three study sites. The field analysis includes: long profiles; cross profiles; cross-sections; vegetation surveys; and cores, and the laboratory analysis includes: Troel-Smith and von Post classification, bulk density (BD); dry bulk density (DBD); moisture content; loss-on-ignition (LOI); particle shape and form; and macrofossil analysis. The methodologies mentioned are discussed in detail below. The field research section is presented first, discussing the surveying of the gully systems in each of the three study sites and from the intact peat profiles. This is followed by the laboratory analysis, which discusses the methodologies carried out on the samples removed from the field.

3.6   Field Survey Methods and Sampling

This section presents the field methods carried out at selected eroded and uneroded sites at the three study sites. The methods were typically used for the analysis of the local scale variations in gully development and to aid the regional scale research, bringing it up to date.

Long Profile

The long profile of each gully was measured using an automatic level and staff. This was used to identify the vertical change within the gully and peat stratigraphy. At each point surveyed along the profile the peat depth was also measured used a probe in order to assess peat depth variation in relation to slope angle. This was determined in order to evaluate Bower's classification of gully form in relation to slope. Comparisons were made to Bower's research by repeating her 1957 profile of Burnt Hill's main gully system (Burnt Hill 1) (Figure 2.2) and repeating photographs (e.g. Figure 1.11). In addition levelling is necessary for correlating stratigraphy and sample depth at a number of investigation sites (Berglund, 1986).

Cross Profiles

Surveying cross gully profiles allowed changes in peat depth down and across the gully system to be assessed. Generally cross-profiles were measured using a probe to find the

peat depth variation at intervals of 50 cm across a transect. These were repeated at intervals of 20 m along the long profile from the head of the gully systems to the mouth. Cross profiles are useful as they are produced without disturbing the underlying peat and provide a good method of site selection for excavation of trenches and locating cross-sections.

Cross-sections

Two types of cross-sections were surveyed: (1) exposed cross-sections whereby trenches were excavated at six different points across the gully along the long profile in order to look in detail at the stratigraphy; and (2) undisturbed cross-sections whereby cores are removed at selected locations within a cross-profile and the stratigraphic sequence between the cores estimated. In gully systems where it was thought necessary to look at gully regeneration in terms of infill at the base, six transect lines were positioned across the gully systems. Trenches were excavated in order to expose the stratigraphy within the base of the systems and show the changes in peat depth. 'Peat is said to be laid down in a stratified manner and therefore traces of the development of peat can be studied throughout its profile' (Hobbs, 1986). The distance across the gully was measured, surface height variation, peat depth variation and the stratigraphy of the peat recorded. Identifying stratigraphic changes involved studying the newly exposed and cleaned peat surfaces so that the stratigraphy had not been affected by oxidation (Aaby, 1986). Monolith samples were also removed from selected locations within the exposed cross-sections to allow a more detailed assessment of the stratigraphy. Where peat depths were greater than 1 m trenching becomes impractical and therefore coring of sediment was more appropriate (Goudie, 1998). Selected cross profiles are used to investigate undisturbed cross-sections. At a number of locations across a profile core samples were taken. The cores removed are examined in terms of their stratigraphy. Between the cores the stratigraphy was cross-correlated.

Monolith Samples

From the stratigraphic sections in the exposed cross-sections certain sections of the stratigraphy were studied in greater detail using monolith samples. The monolith tins ranged in size from 50 × 10 × 10 cm to 25 × 10 × 10 cm depending on the depth of the peat at the specific site. The tins were gently inserted into a clean face of the excavated

trench. Using a knife, the tin and sample were cut and loosened from the face. Once freed they were photographed, sealed tightly using a plastic sleeve to keep the peat in its field state and taken back and stored in a refrigerator at a temperature of 2 °C until taken to the laboratory for analysis (Barber, 1981). Troel-Smith and von Post classifications were both used to describe the monolith samples. This then provided more detailed analysis of certain parts of the cross-sections, to enhance the stratigraphy identified within the base of the gully. This was particularly useful in the analysis of whether the peat was in-washed (re-deposited) or grown in situ within the gully.

Core Samples

The gouge corer was used to remove sections of peat in the location of undisturbed cross sections within the gully floor. The corer is inserted into the soil, removing firstly a 1 m length of peat. The core sample was photographed and transferred from the steel corer to semi-circular plastic tubing and then sealed tightly using a plastic seal to keep the peat in its field state and taken back and stored in a refrigerator at a temperature of 2 °C until taken to the laboratory for analysis. If the peat depth is greater than 1 m the corer is inserted into the same hole and lowered to 2 m or the appropriate depth. This process is continued until the peat base is reached. Each sample is sealed in the same manner as described above.

The second type of corer used in this study was the D-section Russian corer (with a diameter of 5 cm). This corer has the capability of retrieving extremely well preserved cores from all but the saturated and most fibrous of soft sediments. This produces a clean peat face ideal for looking at the stratigraphy (Goudie, 1998). The reason for this is that unlike the gouge corer the D-section Russian corer seals the peat into the corer before it is removed. This corer was therefore used to sample the peat that was saturated. The samples removed were 50 cm in length and were photographed. Analysis was the same as for the other core samples. An example of where the D-section Russian corer was used was in a large pool complex near the head of the Burnt Hill's main gully system. The area appeared to have infilled from sediments washed into the gully from Burnt Hill. The peat depth was greater than 1 m and the surface of the peat was bare apart from a few sparsely growing *Eriophorum angustifolium*. A core was taken from the central part of the pool in order to assess the stratigraphy in the top section of the gully.

Cores were removed from infilled peat in the bases of gullies but also from uneroded sites. This allowed comparisons to be made between eroded peat and uneroded peat from similar locations. The uneroded peat was removed using a D-section russian corer as the peat towards the base of the profiles was generally saturated, which made using the gouge corer difficult. The same procedures as discussed above were then carried out. Table A1.3 in Appendix 1 provides more detail as to where the monolith and core samples were taken in the field.

Vegetation Survey

The contemporary vegetation within the gully was recorded in order to form a comparison with the past aerial photographs. This could be used to assess the length of time vegetation had been present at that site by relating the results to vegetation succession. A spatial assessment of the vegetation within the gully was carried out by dividing the gully into sections using the most recent aerial photograph. The sections were then walked and the main areas of vegetation noted. For example: areas of bare peat; *Sphagnum* spp.; *Juncus effusus*; *Calluna vulgaris*; *Eriophorum* spp. and grasses such as *Agrostis tenuis* and *Deschampsia* spp. Planform vegetation maps of the gully systems were then produced using the aerial photograph and the vegetation distribution. This allowed the assessment of changes in vegetation down the profile of the gully to be carried out. At each cross-section a more detailed assessment of the vegetation was carried out additionally. This enabled changes in the vegetation pattern to be assessed not only throughout the gully but also how they varied from the gully sides to the centre line.

3.7 Laboratory Analysis

This section presents the laboratory methods carried out on the cores and monoliths removed from the selected eroded and uneroded sites at the three study sites (local scale variations in gully development) and for the analysis of the SCPs discussed in Section 3.5.3.

Classification of the soil types requires a scheme that is broad enough to cover a wide range of deposits likely to be encountered and to separate components found within a deposit (Berglund, 1986). The Troel-Smith and Von Post classifications 'are both widely used methods for describing stratigraphy and therefore the combination of both methods enables the highest quality stratigraphic descriptions to be made from the samples collected' (Berglund, 1986). The Troel-Smith classification provides information on sample darkness and dryness of the sample. The von Post classification provides additional information on the humidity of the sample and fibres within the sample. Along with the two classifications a written description of the sample is given.

The analysis of bulk and dry bulk density, loss on ignition and moisture content

The bulk density is defined as the mass of bulk soil, including solid particles, water and air, contained in a unit volume. Bulk density determination (BD) requires a known volume of soil to be weighed in its natural state.

The BD (g cm^3) is calculated using the following equation:

$$BD = (M_w - M_c) / V_s$$
(Equation 3.2)

where

M_c = mass of crucible (g)

M_w = mass of crucible and sample (g)

V_s = sample volume (cm^3).

The weighed sample was then dried in an oven at a temperature of 105°C overnight. It is then cooled and re-weighed at 25 °C. This enables the mass of dry soil in a unit volume to be identified and is termed the dry bulk density (DBD). This is important in the analysis of peat as the bulk density of peat is low and highly variable with approximately 80 % of the bulk density taken up by water (Berglund, 1986; Hobbs, 1986).

The DBD (g cm^3) is calculated using the following equation:

$$DBD = (M_o - M_c) / V_s$$ (Equation 3.3)

where

M_c = mass of crucible (g)

M_o = mass of cooled crucible and sample post oven (g)

V_s = sample volume (cm^3).

Loss on ignition (LOI) is one of the most important tests as it is used to estimate the organic content of the peat. It is a common and widely used technique and is a useful tool for correlating different sediment cores with distinct LOI variations. The measurement of the organic content is the measurement of the pure, ash-free, vegetable matter and any residual organic compounds from the process of decomposition. Where the ash content is low in a peat the organic content is high and thus the organic content is a good indicator of morphology (Hobbs, 1986). The sample is dried overnight at a temperature of 105°C then weighed, the sample is placed in a Carbolite ashing muffle furnace (OAF 11/1) at a temperature of 550°C for four hours. Once cooled in a desiccator, the crucible and sediment were again weighed and the loss on ignition/ organic content determined.

The LOI (%) is calculated using the following equation:

$$LOI = [(M_0 - M_f) / (M_0 - M_c)] \times 100$$ (Equation 3.4)

where

M_f = mass of cooled crucible and sample post furnace (g).

The Moisture Content (%) is the difference between the DBD and the BD. This provides information on the moisture of the peat prior to the rainfall simulation experiment. This is important prior to simulation because a saturated peat profile may show a greater surface runoff rate, despite similar rainfall intensity.

The Moisture Content is calculated using the following equation:

% Moisture = [(BD – DBD)/ BD] × 100   (Equation 3.5)

The analysis of the monolith and core samples removed from the field included sub-sampling in order to carry out the BD, DBD, LOI, % moisture, particle shape and form analysis and macrofossil analysis. Table 3.5 summarises the laboratory analysis conducted on the gully system samples and Table A1.3 in Appendix 1 provides detail as to the laboratory analysis conducted on the monolith and core samples. The particle shape and form and macrofossil methodologies are discussed below. The samples taken from both the monoliths and cores were 4 × 1 × 1 cm. 4 cm long continuous slices were chosen to represent variations in the BD, DBD, LOI, % moisture following a pilot test. The pilot test was carried out on 1 cm, 2 cm, 4 cm and 5 cm contiguous slices of peat and showed minimal variability in peat types below 4 cm. In terms of the macrofossil analysis, various authors such as Tallis (1985b; 1987; 1994; 1995b) used 4 cm slices in order to carry out the analysis. Particle form analysis was carried out on specific stratigraphic units identified from the Troel-Smith and von Post classifications, e.g. where the peat type changed, possibly by type or degree of humification.

Particle Shape and Form Analysis

Analysis of particle shape and form was carried out in order to show the samples greater detail. The Beckman Coulter RapidVue system was used. This is a video imaging system, which analyses the disaggregated peat sample for size and shape quickly without the size and sphericity constraints of other analysers. The size measures analysed in detail were Equivalent Circular Area Diameter and the Fibre Width. The Equivalent Circular Area Diameter is the most commonly used diameter measure for non-circular shapes and is the diameter of a circle having the same area as the actual shape (Figure 3.21a). The Fibre Width was also used in the analysis as different fibres can have different widths. This is used to analyse long, thin particles common in peat (Figure 3.21b). By carrying out the particle shape and form analysis it was thought that in-washed peats or those grown *in situ* in the bases of the gully systems would be identified and therefore aid in the analysis of the stratigraphy. The laboratory procedure for the preparation of the RapidVue peat samples is shown below.
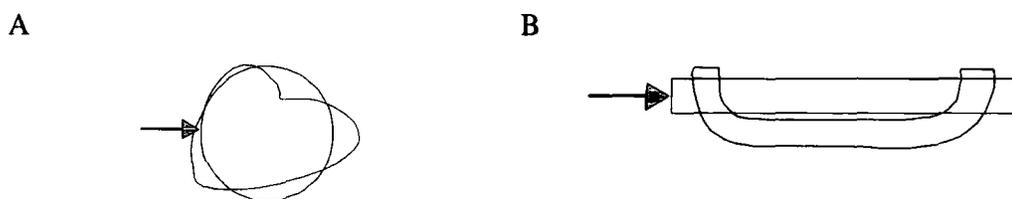
Figure 3.21: (A) The Equivalent Circular Area (ECA) Diameter of a particle (Users Reference), (B) The Fibre Width of a particle (Users Reference).

There are four common methods; wet sieving with centrifuging; wet sieving without centrifuging, wet sieving and sonicate method without centrifuging; and the flushing method. The wet sieving and sonicate method, without centrifuging was used in this study. It was chosen since it was thought to be less destructive the centrifuging method and more rigorous than the wet sieving alone and flushing method. Analysis was conducted on both eroded and uneroded cores and monoliths from Moor House, The Cheviot and Wessenden Head Moss. The appropriate profiles can be seen in Table A1.3 (Appendix 1).

Wet sieving and sonic disaggregation method:

1. Apply 0.5 – 1 g (1/8 cm^3) of sample to 2 mm sieve and wash through with distilled water into funnel emptying into beaker. Do not mechanically sieve, using fingers, treezers for example.

2. Collect the > 2 mm residue into a tube and label 'sample name, > 2 mm'.

3. Spatula the solid from < 2 mm residue into a second tube and label 'sample name, < 2 mm, sonicated'.

4. Place the second tube (< 2 mm residue) on to sonicator and shake for 5 minutes.

5. Use sawn-off pipette (aperture > 2 mm) and extract a representative sample to inject into RapidVue.

6. Carry out the RapidVue analysis.

Macrofossil Analysis

"Macrofossil" is the term used to describe any potentially identifiable fossil preserved in sediments, which can be seen by the naked eye (Birks and Birks, 1980). Macrofossils include animal as well as plant remains, but in this research is restricted to plant

macrofossils, which can consist of almost any part of the plant. Because they are relatively large in size, macrofossils are not usually transported very far from their point of origin. Therefore, in a peat deposit, the local community that formed the peat can be reconstructed. In general, macrofossils are of most value in reconstructing plant communities and environments of wetlands and aquatic habitats. Information provided from macrofossil and pollen grains are largely complementary and thus a study combining the analysis of both sorts of fossils can provide a more complete palaeoecological picture of the past vegetation and environment. Macrofossils have an advantage over pollen in that identifiable remains are often preserved of plants which either produce very low amounts of inefficiently dispersed pollen, or which produce fragile pollen which is not fossilised (for example *Juncus* spp.), or which do not produce distinctive microfossils at all (for example some mosses, excluding *Sphagnum* spp.) (Wasylikowa 1986).

The importance of *Sphagnum* and *Racomitrium lanuginosum* species in macrofossil analysis was discussed in Section 2.4.1; macrofossil analysis can be useful for not only inferring the onset of erosion but also re-vegetation. For example, where abrupt changes in macrofossils occur, this may be a result of peat being re-deposited within the system, followed by peat then grown *in situ*. The re-deposited peat may have been washed down the system when the system was still very active and possibly coupled to lower streams. Additionally sand lenses may be deposited with of above this peat. The *in situ* peat, however, may represent a time of stabilisation within the gully system. This may show a progression from early colonising (e.g. *Eriophorum*) to late colonising species (e.g. *Calluna*).

Macrofossil analysis was conducted on both eroded and uneroded cores and monoliths from Moor House, The Cheviot and Wessenden Head Moss. The appropriate gully systems are shown in Table A1.3 and profiles in Table A1.1 in Appendix 1. There are no standard methods for studying macrofossils; however, techniques such as sieving and mounting of the samples for analysis under the microscope are appropriate (Charman, 2002). The method used by Walker and Walker (1961) and Barber (1981) was adopted in this study. This involved 4 cm slices of peat (Mauquoy and Barber, 1999) (4 × 2 × 2 cm) being placed on a 250 µm sieve and sprayed with a high-pressure jet of water from a narrow plastic pipe connected to a tap, which served to force fine, highly humified material through the sieve and disaggregate the sample. The washing was collected in a

beaker below and the colour of the water used as an estimate the amount of 'unidentified organic matter' (UOM). The material remaining on the sieve was washed into a petri dish and stored in the refrigerator at 2 °C until the analysis was undertaken. The analysis required systematically scanning the petri dish under a Nikon stereozoom microscope (SMZ-10) at × 40 magnification. This was carried out by dividing the petri dish into 10 sections, with each section represented 10 % of the petri dish. Each species was assessed within those sections using the percentage cover, which also included UOM. For those with few species the total number of species identified was also noted. The most common species found in these mounts are shown in Table 3.5. A series of sieve sizes were tested before finally choosing the 250 μm sieve. Initially the 125 μm sieve was going to be used. However, much of the sediment was retained and identification proved difficult. The other sizes tested were 180 μm, 500 μm and 1 mm. The 250 μm sieve appeared to retain all macrofossils but allow sufficient UOM to be washed through the sieve.

Species	Habitat
Calluna vulgaris (heather)	Dry places on bogs, heaths and peaty soils
Erica cinerea (bell heather)	Dry heaths
Erica tetralix (cross-leaved heather)	Bogs and wet heaths
Sphagnum cuspitadum	The north and west of Britain, on acid bogs and moors, or growing as an aquatic in pools and lakes, although mostly along pool margins or in wet hollows and soaks
Sphagnum recurvum	Forming wide lawns in moderately wet, open peatlands. It may even be found indistinctively minerotrophic sites or drier localities, being tolerant of a fairly wide range of chemical and hydrological conditions. Grows mainly in generally weakly minerotrophic conditions
Sphagnum palustre	By streams in wet woodland and moorland, absent from highly calcareous and strongly acid locations. More shade tolerant species
Sphagnum papillosum	Moors and bogs, at the base of hummocks or more extensive carpets. Closely related to *S. palustre* but grows in wetter, more acid habitats
Racomitrium lanuginosum	Hill and mountain districts on acid rock and peat. It forms a mountain-top community in drier areas
Pleurozium schreberi	Dry places on heaths, moors, mountain slopes, sand dunes and screes, never on calcareous ground
Cladonia portentosa	Moors and heaths forming patches among heather stems and on bare ground
Juncus effuses	Bogs, wet woods, pasture, ditches, by rivers and lakes, mostly on acid soils
Juncus squarrosus	Acid soils on wet and damp moorland heaths and bogs, especially where sheep grazing is heavy
Trichophorum cespitosum	Bogs, wet heaths and hill grassland throughout upland Britain
Eriophorum latifolium	Small turfs in wet places, usually on base-rich soils or flushes
Eriophorum angustifolium	The wettest parts of bogs and acid fen
Eriophorum vaginatum	Found on wet peaty soils, particularly blanket bogs, where it forms part of the characteristic vegetation
Deschampsia cespitosa	Wet soils on moorland, damp meadows and ditches throughout Britain
Deschampsia flexuosa	Sandy or peaty soils, often common on moorland or clearings in woodland, drier parts of bogs
Festuca ovina	Poor soils particularly on hills or moorland. Often abundant on hill pastures where it is a valuable part of the diet of sheep
Vaccinum myrtillus	Heaths, moors and woods
Polytrichum commune	Forms dark green deep turfs in wet heaths, bogs, moorland, usually amongst mosses and by streams in woodland
Potentilla erecta	Upland areas
Molinia caerulea	Forming tussocks in heaths and moors
Agrostis tenuis	Grassy places, rough ground and acid soils
Galium saxatile	Dry grassland, open woods on acid soils
Pteridium aquilinum (bracken)	Woods, heaths and grassland on sheltered parts of hills, usually on acid soils and absent from limestone

Table 3.5: The common species found in the blanket peatlands in the Pennines (Source: Phillips, 1994).

Two common procedures for the preparation of SCPs have been used: the methods of Rose *et al.* (1995) and that of Rhodes (1998). No previous publications have compared the two preparation methods; therefore the 'best' method for the preparation of SCPs was unknown at the start of this research.

A pilot project was conducted to test the best preparation technique. In addition, the spatial variability in SCP accumulation on the micro-plot scale was also investigated. Two samples of intact peat (50 × 30 × 30 cm) were collected from adjacent surfaces on Nether Hearth, Moor House and Upper Teesdale NNR (NY 757333). The two samples differed in their vegetation (heather and moorland grass). Each block was sub-sampled into four cores taken from the four corners of the block. The samples were described using the Troel-Smith and von Post Classifications and were then cut into contiguous 1 cm slices for further analysis. The BD, DBD, LOI and % Moisture Content were then calculated for all eight cores. The SCP concentration in the eight cores was also calculated using the two common preparation methods: Rose *et al.* (1995) and Rhodes (1998).

Figure 3.22 shows the comparison in the SCP profile from the same heather sample removed from Moor House, between the Rhodes (1998) (A) and Rose *et al.* (1995) (B) preparation methods. The Rose *et al.* (1995) profile shows the 'take-off' is at a depth of 18 cm. There is no great increase in the number of SCPs. Instead there are a series of small peaks to a depth of 7 cm, followed by a decline in the number of SCPs to the surface. The key differences to note between the two profiles are the number of SCPs, shape of the profiles and the position of the 'take-off'. The Rhodes (1998) profile identifies a much greater number of SCPs, reaching a peak at over 1000 counts, whilst the Rose *et al.* (1995) profile shows there to be a peak of less than 100 counts. This indicates a large difference between the two preparation methods. The 'take-off' for the Rhodes (1998) profile is at a depth of 23 cm. The peak in SCP concentration also varies. The Rhodes (1998) profile peaks at 10 cm, whereas the Rose *et al.* (1995) profile peaks at 7 cm. Following the later 'take-off' and peak in SCP concentrations in the Rose *et al.* (1995) profile there is also a later decline in SCPs to the surface. Generally, the Rhodes (1998) preparation method yields greater numbers of visible SCPs, and produces a more continuously variable record of SCPs through the profile. The Rose *et al.* (1995) method

counts are typically an order of magnitude less and show considerably more internal variability. The Rhodes (1998) method was therefore chosen to be the best preparation technique for the analysis of SCPs.
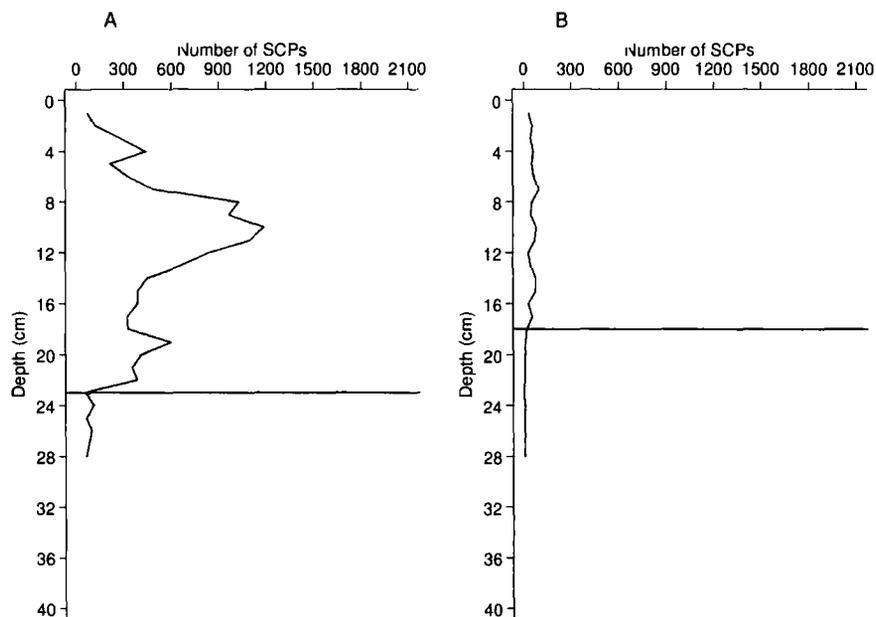
Figure 3.22: The difference in the SCP profile between the two preparation methods using the same heather sample. A) Preparation method by Rhodes (1998), B) Preparation method by Rose et al. (1995).

The preparation technique suggested by Rhodes (1998) required:

1. 0.2 g of air-dried peat placing in a 250 ml conical flask.
2. 20 ml of distilled water adding.
3. Cover the solution and leave for 24 hours to allow the peat to re-hydrate.
4. Filter the solution through Whatman Number 1 (11 μm) Glass Microfibre filter paper, retained the contents and discard the liquid.
5. Wash the solid into a 9 cm diameter petri dish using distilled water.
6. Place the samples in an oven at 50 °C until excess liquid has evaporated.
7. Add 20 ml of 6 % hydrogen peroxide. Replace the lid of the petri dish. Samples are left in the oven at 50 °C for 48 hours or until samples are dry.
8. Remove the petri dish lid to allow the liquid to evaporate before counting.
9. Count the samples using a stereo microscope (× 40 magnification).

Figure 3.23 shows the variations in the position of the 'take-off' on a micro plot scale of the heather samples using the Rhodes (1998) preparation method. The 'take-off' varies from 18 cm to 26 cm. This indicates the results should be treated with caution, as over an 8 cm depth there may be 80 years of peat accumulation (since peat accumulates at an approximate rate of 1 mm per year).

Having established the best technique for the preparation of SCPs and the accuracy of using this type of analysis, individual cores were removed from stable sites on The Cheviot and Wessenden Head Moss. The results from the Moor House samples were compared against the SCP profiles from The Cheviot and Wessenden Head Moss to provide detail as to the regional variations in SCP deposition. All cores were described using the Troel-Smith and von Post Classifications and then cut into 1 cm contiguous slices where the BD, DBD, LOI and % Moisture were calculated. The SCP concentration was then calculated using the Rhodes (1998) preparation technique.
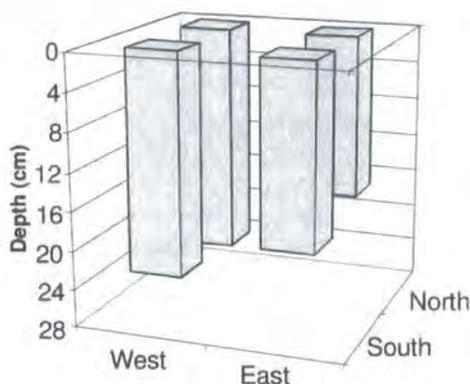
Figure 3.23: Bar charts showing the 'take-off' in SCP concentration against the orientation of the sample using the Rhodes (1998) preparation method for four heather samples.

Any variations in SCP concentration or appearance between the study sites would be analysed further under the Scanning Electron Microscope (SEM). An example of an SCP viewed under a SEM is shown in Figure 3.14. The preparation involves an individual SCP particle being mounted onto a stub. The backscatter waveform was adjusted so that the SCP particle could be distinguished from the background and by altering the light and line scanning an image of an SCP is produced (Watt, 1998). The

controlling image analysis program used is known as EDAX. Watt (1998) has also used a SEM microscope to assess SCPs in fly-ash particles.

3.8   Summary

This chapter has presented information on the study areas and methodologies used in this research. Blanket peat erosion is extensive in the Pennines of Northern England and therefore ideal for conducting this research. Three study sites were selected across Northern England to allow for regional variation along a rough N – S transect: Moor House, The Cheviot and Wessenden Head Moss. The three sites vary in their environmental conditions, altitude, precipitation, geology, peat depths and intensity of erosion.

The methodological framework highlights the importance of this research in terms of the integrated framework of field and laboratory research at three study sites and the novel combination of traditional fieldwork, laboratory analysis and GIS. The initial research indicated that choosing the study sites, gaining permission for access, and planning the research is important. The methodologies were divided into four main sections: Regional scale variations in gully development; Interfluve accumulation (Spheroidal Carbonaceous Particle (SCP) analysis); Interfluve erosion (rainfall simulation experiments); and Local scale variations in gully development.

The regional scale variations in gully development were assessed using a GIS framework. Aerial photographs and field-based research were used to provide information as to how the gully systems and blanket peat areas have changed over an approximate 50-year time period.

An SCP profile can be used to faithfully record historical atmospheric SCP deposition. SCP analysis was carried out on intact peat cores from the three study sites and used to estimate the rates of peat accumulation (interfluve accumulation).

In addition to interfluve accumulation, interfluve erosion was estimated from paired rainfall simulation experiments. A 'Drip-type' simulator was used. The experiments were carried out inside and outside the Moor House grazing (and burning) exclosures.

The detailed methodologies of the experiments are presented alongside the results (Chapter 6).

The field methods involved in the assessment of local scale variations in gully development and to bring the regional scale research up to date were: gully measurements (long profiles, cross profiles, cross-sections and vegetation surveys) and sampling (from both eroded and uneroded sites). The core and monolith samples removed were taken back to the laboratory for further analysis.

The laboratory analysis was used to assess the local scale variations in gully development and interfluve accumulation: Troel-Smith and von Post classifications; bulk density; dry bulk density; moisture content; loss on ignition; particle shape and form analysis; macrofossil analysis; and SCP analysis. The best method for the analysis of SCPs was established: the method by Rhodes (1998).

The results of the research are presented in the next four chapters: the regional variations in gully development over time; the interfluve accumulation; the interfluve erosion; and the variations in gully development observed from ground-based research. The regional variations in gully development are presented in the next chapter. This chapter is the first of the results chapters as it provides an overview of the gully systems at the three study sites and the differences within and/or between the systems at the three sites. These differences include: the cover types (extent of blanket peat, peat erosion and re-vegetation); gully order; drainage density and the changes over time in gully development.

4.0 REGIONAL SCALE INVESTIGATION INTO GULLY DEVELOPMENT

4.1 Scope of Chapter

This chapter presents results of a regional scale GIS analysis of variations in gully development. Section 4.2 assesses the classification scheme used for gully development and develops a revised scheme, which is developed and adapted for use throughout this thesis. Section 4.3 then discusses the differences in the cover types (e.g. peat cover, erosion and re-vegetation) and types of erosion (e.g. linear, dendritic or anastomosing dissection). Gully order and gully length is addressed in Section 4.4 and drainage density in Section 4.5. The morphological changes over time (c. last 50 years) are discussed (Section 4.6) and finally the accuracy of GIS analysis is assessed in Section 4.7. Throughout this chapter the results from each study site are discussed in turn: Moor House, The Cheviot and Wessenden Head Moss.

4.2 The Classification Scheme

A classification scheme of erosion types common at the three study sites was required to assess gully development. As discussed in Chapter 1, the classification scheme proposed by Bower (1960b) is the most widely used; however, this has been questioned by Mosley (1972) and a more recent classification scheme used by Wishart and Warburton (2002) was shown to be more effective in classifying gully erosion on The Cheviot. Figure 4.1 shows an example of the peatland erosion classification schemes. The more recent classification scheme (Figure 4.1b) is shown alongside Bower's (1960b) classification (Type 1 and Type 2 dissection) (Figure 4.1a) and the differences between the two schemes are shown in Figure 4.1c. This more recent classification scheme needed to be tested at Moor House and on Wessenden Head Moss.

The most recent aerial photographs and field research of the three study sites show that Type 1 and Type 2 dissection is important; however, it appears that the dissection at these sites is more complex. Figure 4.2a shows a 1950 aerial photograph from Moor House with Bower's interpretation of the peat erosion (Bower, 1959). Figure 4.2b then shows the same 1950 aerial photograph classified in what was thought to be the best classification scheme to classify the gully systems in this research; used by Wishart and Warburton (2002) (Figure 4.2b). Comparisons can therefore be made between the two

120

classification methods as to the comparability of the classification schemes. Figure 4.2c shows the Wishart and Warburton classification scheme applied to the year 2000 aerial photograph of the same area, enabling comparison of the changes in dissection over time.

As can be seen from Figure 4.2a and 4.2b there are significant differences in the two classifications. Based on this, it is thought that classifying the systems into linear, dendritic and anastomosing systems is better than Type 1 and Type 2 as it is more representative of the range of gully systems at Moor House. Based on aerial photograph interpretation on Wessenden Head Moss the dissection in this area is shown to be more complex than at Moor House and therefore a more sophisticated scheme (linear, dendritic and anastomosing dissection) was thought to better describe the gully systems at this study site also.

Comparing Figures 4.2b and 4.2c shows variations in the extent and patterns of erosion between 1950 and 2000. Over the 50-year period there appears to have been a reduction in the extent of peat margin erosion, anastomosing dissection and dense dentritic dissection. Once densely eroded ground had re-vegetated, leaving less dentritic erosion and linear erosion as the predominant erosion types. Areas are also shown to have totally recovered from erosion. These areas tend to be adjacent to the areas of uneroded ground in 1950 and therefore it is thought that the vegetation cover has spread, re-colonising these adjacent areas.

Within the linear, dendritic and anastomosing dissection classes further divisions could be made. Linear dissection was deemed to be where gully systems are either:

o Single thread channels, therefore 1st order gullies,

o Multiple channels, for example where 1st order channels join to 2nd, 3rd and 4th order channels, but still follow a linear pattern,

o A series of parallel channels of which may be single thread or multiple.

Dendritic dissection varied in the density of the channel networks. They may be represented by a number of channels (1st order) leading into 2nd, 3rd and 4th order channels where densities increase.
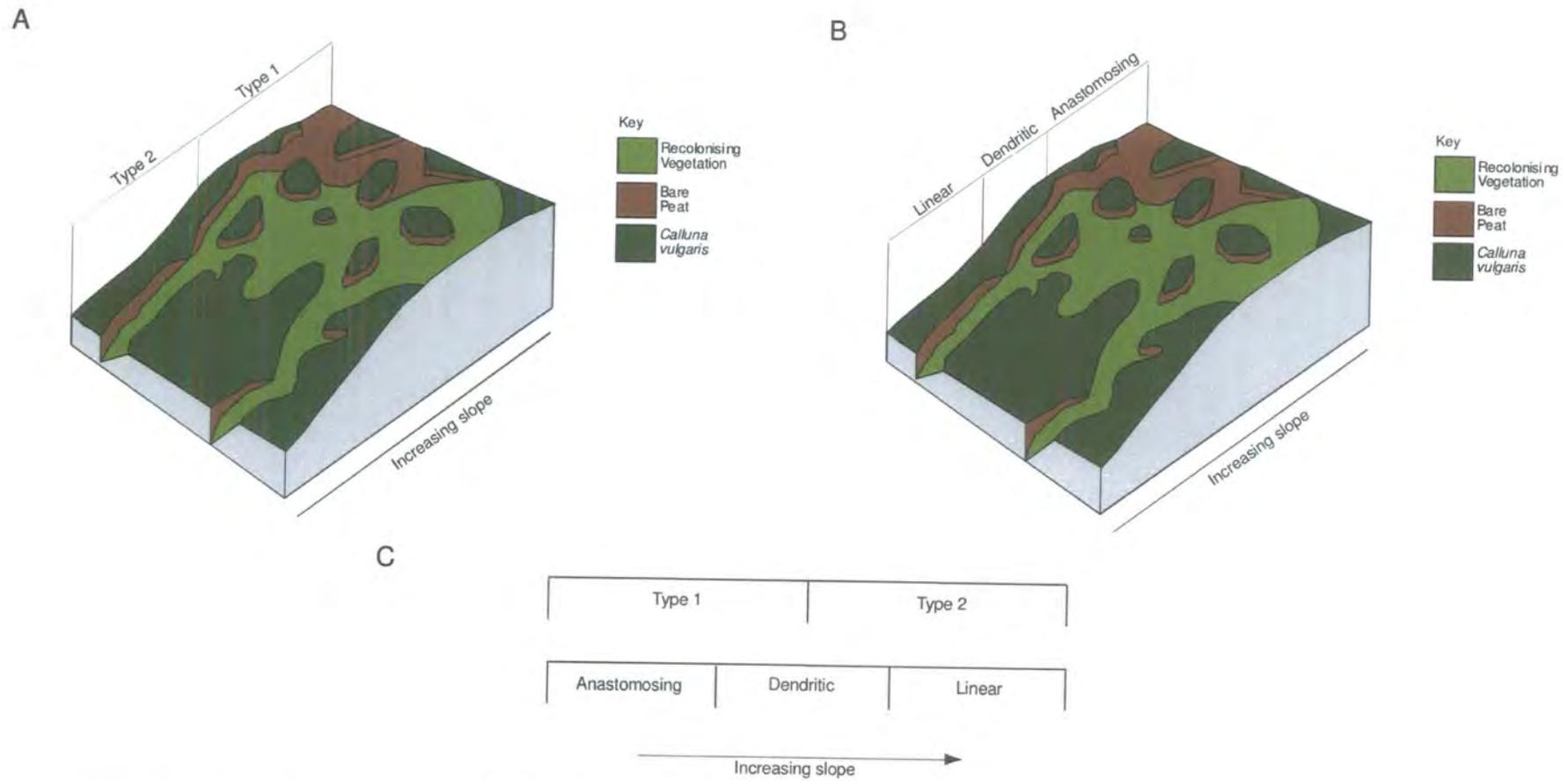
Figure 4.1: The differences between the two classification schemes. A) Bower's (1960b) Type 1 and Type 2 Dissection (as shown in Figure 1.6). B) Modified peatland erosion classification scheme, showing Linear, Dendritic and Anastomosing Dissection. C) The difference between the two based on a priori reasoning.
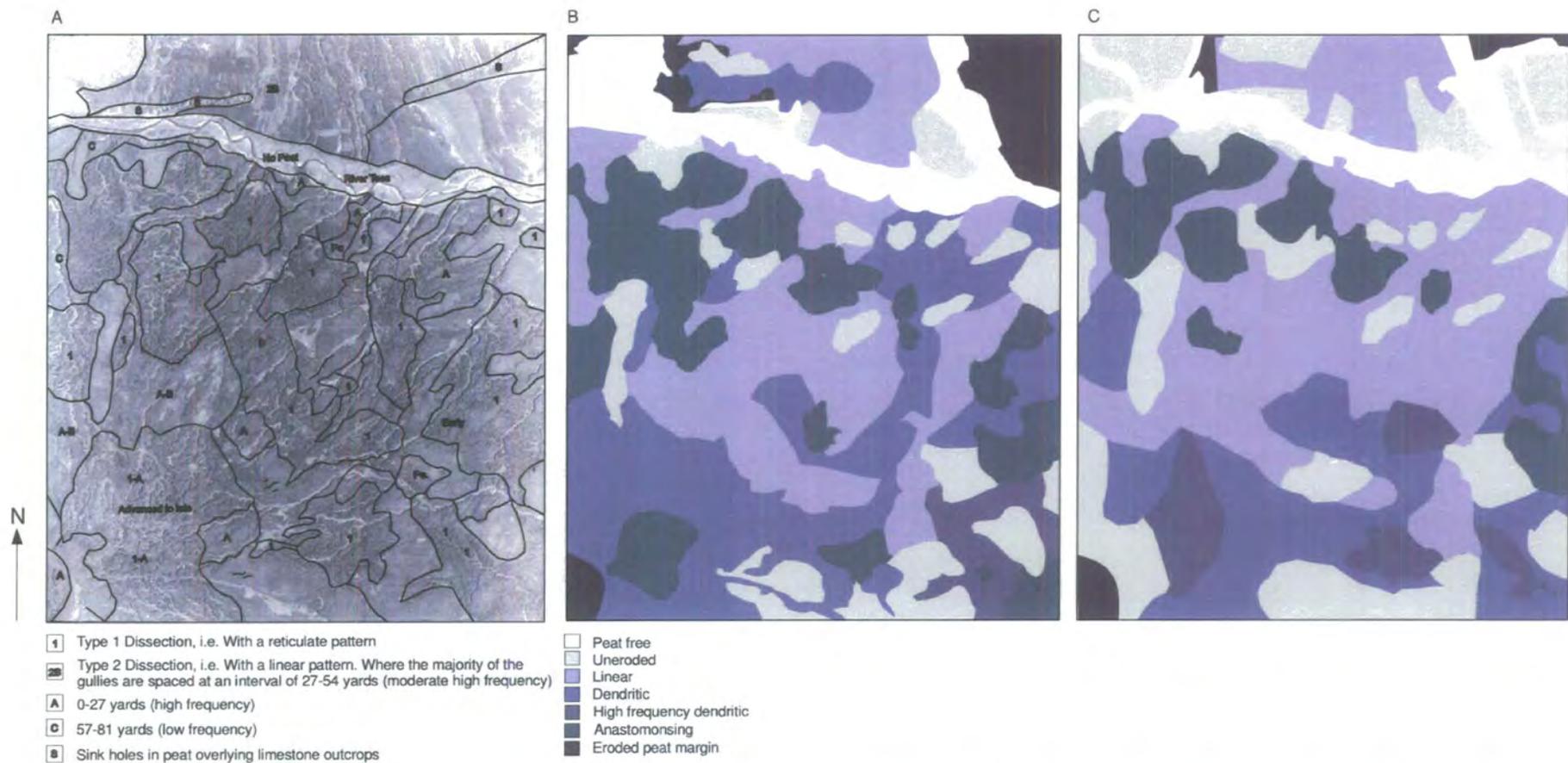
Figure 4.2: Distribution maps of the peat erosion on Hard Ridge, Moor House and Upper Teesdale NNR. A) 1950 aerial photograph with the patterns of erosion mapped by Bower (1959). B) 1950 aerial photograph with the patterns of erosion mapped for this study. C) 2000 aerial photograph with the patterns of erosion mapped for this study.

Anastomosing dissection occurs where the channels become almost indistinct as they are fragmented (1st, 2nd, 3rd and 4th order channels). Field observations of anastomosing dissection are complex. The density of the channel networks varied within and between gully systems and study areas. The peat is poorly drained and where the channels become so dense, haggs become isolated (Wishart and Warburton, 2002). Peat flats are common on the higher altitudes at each of the study sites: Moor House (620 m); The Cheviot (810 m); and Wessenden Head Moss (490 m).

4.3   Cover Types

This section addresses the different cover types at the three study sites. The cover types, at each of the three study sites, discussed in turn throughout this section are:

- o The extent of peat cover.
- o The extent of peat, which is intact or eroded.
- o The extent and type of dissection.
- o The extent of bare and re-vegetating peat.

The data presented are from the most recently available aerial photographs at each site and were backed up by field research.

Cover Type	Moor House (% (km^2))	The Cheviot (% (km^2))	Wessenden Head Moss (% (km^2))
Total study area which is peat covered	69 (40.30)	48 (6.24)	75 (5.55)
Area of intact peat	52 (20.96)	20 (1.24)	36 (2.00)
Area of eroded peat	48 (19.34)	80 (5.00)	64 (3.55)
Area of eroded peat which is bare	20 (3.87)	39 (1.90)	55 (1.95)
Area of eroded peat which is re-vegetated	80 (15.47)	61 (3.10)	45 (1.60)
Area of eroded peat with linear dissection	58 (11.28)	21 (1.30)	37.5 (1.33)
Area of eroded peat with dendritic dissection	21 (4.03)	16 (1.00)	33 (1.17)
Area of eroded peat with anastomosing dissection	21 (4.03)	63 (2.70)	29.5 (1.05)

Table 4.1: The percentage and area of peat cover, erosion (bare and re-vegetated) and the dissection type (Linear, Dendritic and Anastomosing) at the three study sites, Moor House, The Cheviot and Wessenden Head Moss.

As can be seen on Table 4.1 the total peat cover is far greater at Moor House (40.3 km^2) than on The Cheviot (6.24 km^2) and on Wessenden Head Moss (5.55 km^2). The reason for this is generally based on the size of the area researched because percentage of area researched covered by peat was 69 %, 48 % and 75 % respectively (Figure 4.3). This indicates that the greatest cover of peat is on Wessenden Head Moss and the least on The Cheviot. This is expected given variations in altitude between sites. For example, The Cheviot (700 m – 815 m) is at a much greater height above sea level than Wessenden Head Moss (440 m – 494 m) and it is thought that the weather conditions may have limited peat growth. Generally the peat in the Southern Pennines is known to be deeper than that in the North Pennines, therefore the peat is deeper on Wessenden Head Moss than at Moor House and on The Cheviot. In addition, the shape of the Cheviot study area forms a dome, with steep slope angles at the low altitudes and gentler slopes towards the summit. Peat accumulates to greater depths on the gentler slopes (< 20°). By way of comparison Moor House study area forms a basin shape and Wessenden Head Moss is relatively flat (Figure 4.3). This is important in terms of this research since topography controls the distribution of peat in an area and on patterns of peat erosion.
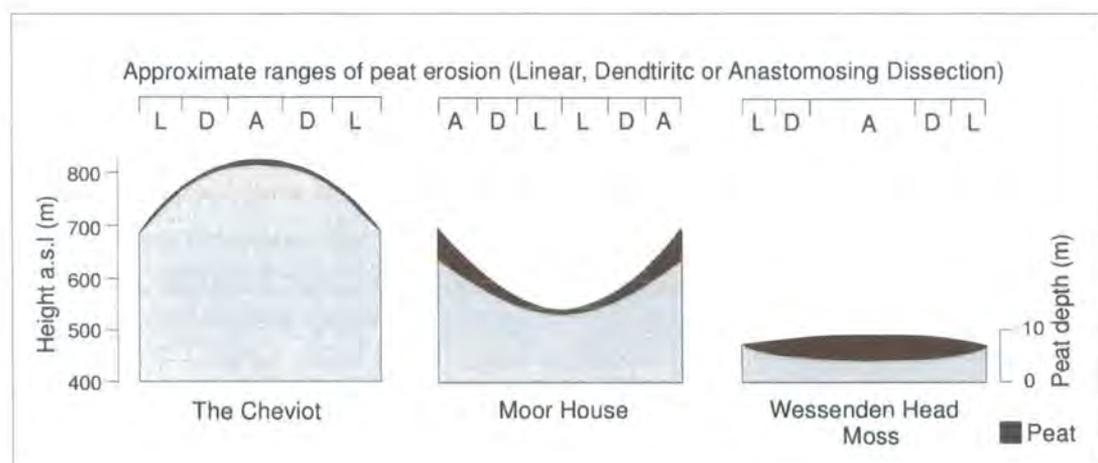
Figure 4.3: Simple diagram showing the shape of the study sites, their height above sea level, peat depths and approximate ranges of peat erosion.

Figure 4.4 shows area-elevation (hypsometric) curves for the three study sites. The Moor House curve indicates a small proportion of the area researched is less than 560 m. The curve is generally convex in shape and therefore the majority of the area researched was in the mid-altitudes of the study area (560 – 670 m). Above 670 m the

curve begins to flatten indicating there to be little area within these altitudes. This emphasises the basin-like shape of Moor House (Figure 4.3). For The Cheviot the curve is more linear with a slight concavity and flattening at the top (800 – 815 m). This indicates that the altitudinal areas researched were of similar size and only the area near The Cheviot summit was smaller, emphasising the dome like shape of The Cheviot (Figure 4.3). The Wessenden Head Moss curve is concave with the largest altitudinal ranges between 470 – 490 m and less at the lower altitudes (< 470 m). This indicates that the majority of the Wessenden Head Moss study area lies above 470 m but as a result of the low slope angles reiterates the relatively flat but dome-like nature of the area (Figure 4.3).
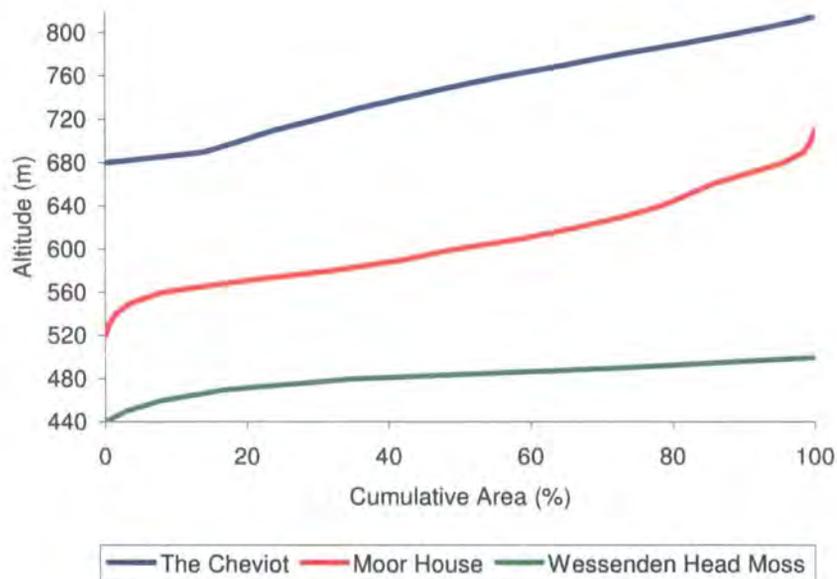
Figure 4.4: Hysometric curve showing area (%) against altitude (m) for Moor House, The Cheviot and Wessenden Head Moss.

Figure 4.5 shows that the proportion of peat cover varies at each site depending on the altitude. The least variation occurs at Wessenden Head Moss where the range in altitude is less (440 m to 494 m). The greatest variations are found on The Cheviot, and below 690 m there is no peat. This is a result of the slope angles becoming too steep for peat accumulation. The largest amount of peat is above 740 m where slope angles decrease. At Moor House there is a decrease in the percentage of peat cover from 520 m to 550 m before an increase to 610 m. The percentage of peat cover then remains high (> 90 %) until 660 m, before decreasing to 690 m. There is then an increase from 690 m to 710

m, before decreasing to its limit at 720 m. The percentage of peat cover is again reflected by the slope angles at Moor House, for example in the mid altitudes (570 m to 650 m) the slope angles tend to be lower, for example, on the top of Burnt Hill (570 m).
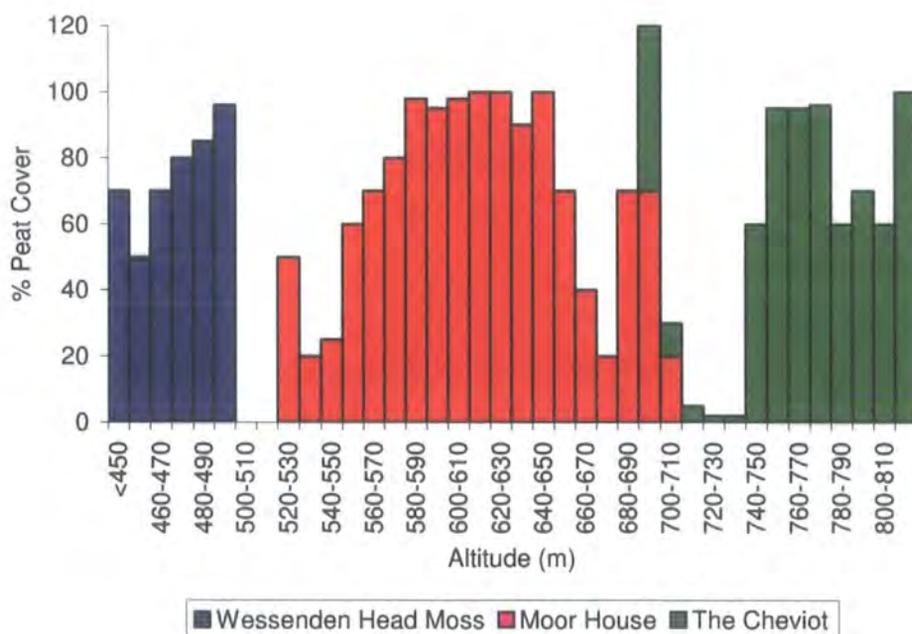
Figure 4.5: Percentage cover of peat at: Moor House, The Cheviot and Wessenden Head Moss. There was little overlap in altitude between the study sites and there are plotted on the same horizontal-axis.

It was expected that the amount of erosion would be greatest on Wessenden Head Moss for a number of reasons, firstly because historical erosion in the Southern Pennines is known to be extensive (Burt and Labadz, 1990; Tallis, 1985a, 1997a; 1997b), secondly, peat in the Southern Pennines is deep (up to 6 m) and is close to the endpoint of peat accumulation (Lewis, 1906; Johnson, 1957) and finally the peat in the Southern Pennines is on the climatic peat boundary, sensitive to change (Tallis, 1998). Table 4.1 however shows that the greatest peat erosion is on The Cheviot, where 80 % of the peat cover is eroded, 64 % on Wessenden Head Moss and 48 % at Moor House. The reason for this could be that despite the thin peat (< 2 m) the study site is higher in altitude and will experience greater influences from weather, such as wind and frost erosion. The precipitation however, is much lower on The Cheviot (1100 mm per year).

Of the erosion at the three sites, the extent of erosion where bare peat surfaces remain and the extent of erosion that has now re-vegetated (past erosion) were measured. Table 4.1 shows that the amount of bare peat is greatest on Wessenden Head Moss (55 %), followed by The Cheviot (39 %) and Moor House (20 %). Therefore the cover of re-vegetated peat is greatest at Moor House (80 %) and least on Wessenden Head Moss (45 %). It was initially thought it may be partially the result of the different years in which the most recent aerial photograph was taken, for example, 2000 at Moor House and 1988 on Wessenden Head Moss, therefore re-vegetation would be expected to be greatest at Moor House. However, field observations (2002 – 2004) indicate that re-vegetation is greatest at Moor House and least on Wessenden Head Moss. In addition, the total amount of erosion at Moor House (48 %) was still less than the amount of peat erosion with bare cover on Wessenden Head Moss (55 %). Therefore there would have been less even if in 1988 in the whole area of Moor House there had been no re-vegetation. The reasoning behind the differences in the extent of erosion are therefore thought to be because Moor House is predominantly in a topographic basin and is thought to be less exposed to prevailing weather conditions and for the last 50 years has not been affected by poor management practices. In addition it has been noted that the Southern Pennines is severely eroded as a result of the loss of *Sphagnum* due to the Industrial Revolution (Tallis, 1998). Industrial impacts are greater at Wessenden Head Moss than Moor House and The Cheviot and therefore the *Sphagnum* on Wessenden Head Moss is sparse. *Sphagnum* is an early colonising species in upland blanket peat and as a result of its absence from the site re-vegetation can be reduced but not eliminated due to other early colonising vegetation types such as *Eriophorum* of which are less affected by industrialisation.

Within the eroded areas at each of the three study sites the three main types of dissection were observed (Table 4.1). At Moor House the main type of dissection is linear dissection (58 %), whilst the extent of dendritic and anastomosing dissections is similar (21 % and 21 % respectively). On The Cheviot the main dissection type is anastomosing (63 %), followed by linear (21 %) and dendritic (16 %) erosion. On Wessenden Head Moss the dissection types are more evenly divided, with 37.5 % linear, 33 % dendritic and 29.5 % anastomosing. The overall peat cover, the amount that is uneroded or eroded by linear, dendritic and anastomosing dissection is shown graphically in Figure 4.4 (as well as in Table 4.1), which shows how these proportions vary with altitude at the three study sites.

Table 4.1 and Figure 4.6 show the proportion of ground at each altitudinal range that is peat free or peat covered. Of the peat covered areas those uneroded or dissected by linear, dentritic or anastomosing dissection are shown for the three study sites. Figure 4.6 demonstrates the least peat cover is on The Cheviot and most on Wessenden Head Moss and that the peat free areas on The Cheviot are those where the slope angles are steep at the lower altitudes (Figure 4.3). Figure 4.7 shows similar diagrams; however, it does not include the areas of no peat and therefore shows more clearly the area of uneroded peat and the patterns of dissection. Both Figures 4.6 and 4.7 reiterate that the areas of uneroded peat are greatest at Moor House and least on The Cheviot. The greatest proportions of uneroded peat are shown to be at the lower altitudes at Moor House and on Wessenden Head Moss, however on The Cheviot anastomosing dissection also occurs extensively at lower altitudes (690 m to 740 m). Figure 4.7 shows the proportion of anastomosing dissection as misleading compared with higher altitudes because of small area of peat cover at the lower altitudes (Figure 4.6). Once the peat cover increases (740 m) the peat is mostly uneroded or affected by linear dissection, followed by dendritic dissection (760 m) and anastomosing dissection (780 m). Generally linear dissection appears to occur at all altitudes at the three study sites, whilst dendritic and anastomosing dissection occurs at altitudes where the peat cover is most extensive, except for The Cheviot where anastomosing dissection is the greatest (63 %). Here linear dissection and the majority of uneroded peat is in the mid altitudes (740 m to 790 m) and dendritic and anastomosing dissection occurs at higher altitudes.
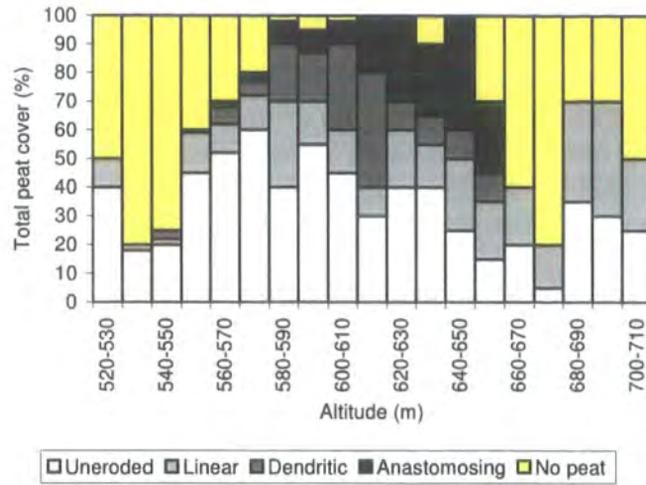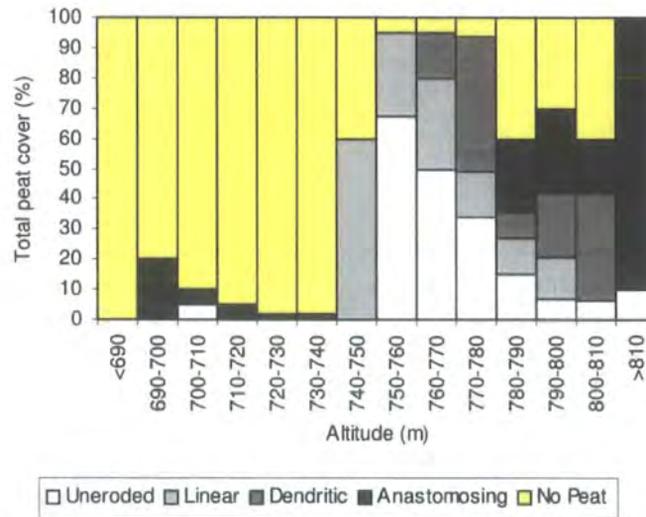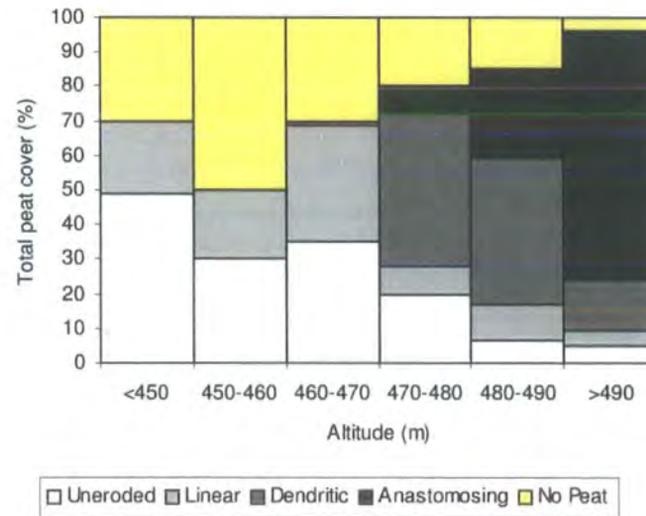
Figure 4.6: The proportion of ground at different altitudes on, A) The Cheviot, B) Moor House, C) Wessenden Head Moss, that is peat free, peat-covered, uneroded or affected by linear, dentritic or anastomosing dissection.
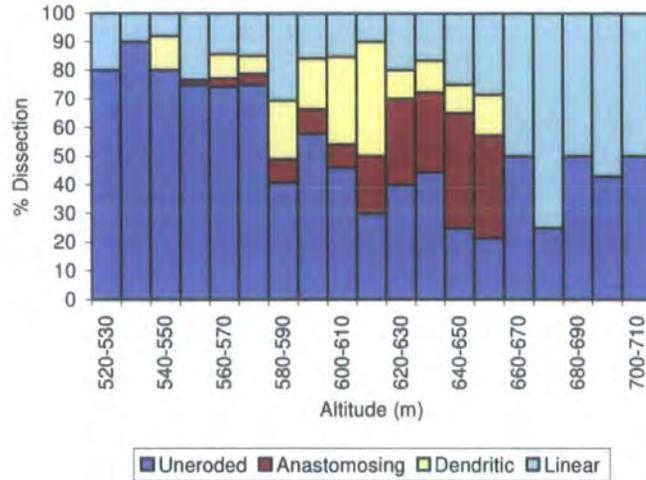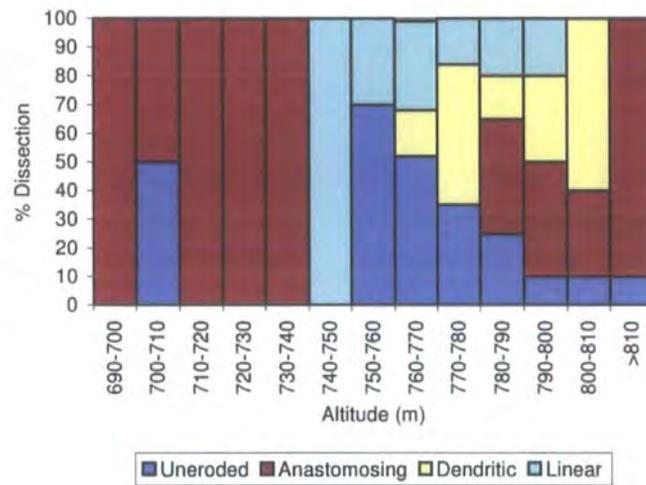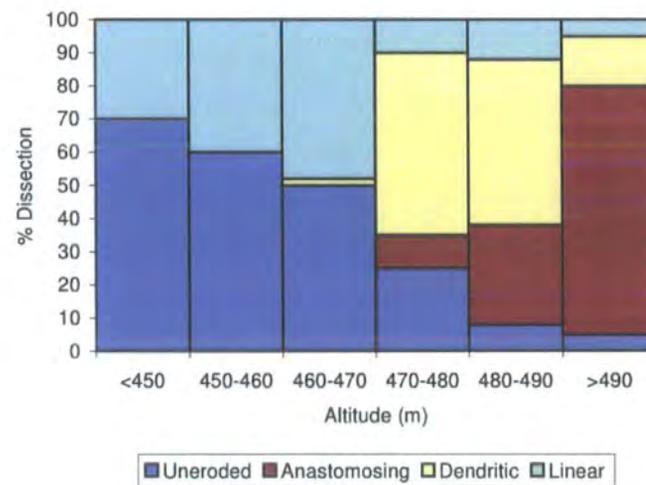
Figure 4.7: The proportion of peat-covered ground at different altitudes of: A) Moor House, B) The Cheviot, and C) Wessenden Head Moss, that is uneroded or affected by linear, dentritic or anastomosing dissection.

Within the areas of linear, dendritic and anastomosing dissection, the percentage of re-vegetated ground was measured (Table 4.2). Table 4.2 shows that at each of the three study sites anastomosing dissection is the least re-vegetated. This is the result of anastomosing dissection occurring on the flattest, highest ground (summit type erosion) with the shortest growing season. At Moor House re-vegetation is the most extensive on all three dissection types. Of the three dissection types, linear dissection shows to be the most extensively re-vegetated (73 %), followed by dendritic (70 %) and then anastomosing (44 %). This is interesting in terms of the future of upland blanket peatlands, as those areas with the most extensive anastomosing dissection may take longer to recover from peat erosion than those with mostly linear dissected gully systems. It was expected that linear dissection would be the most re-vegetated because they are better drained with less erosion and deposition occurring; however, on Wessenden Head Moss, dendritic dissection is the most extensive re-vegetated. This is likely to be a result of large linear gullies to the North of the study area, which are eroded to the peat-mineral base. They are on relatively steep sloping ground compared with the rest of the study site and appear to be active. Due to their steep profiles vegetation may be unable to establish because it would be washed through the systems during a storm and therefore re-vegetation is unable to take place.

% Erosion which is Re-vegetated	Moor House (2000)	The Cheviot (1983)	Wessenden Head Moss (1988)	Mean
Linear	92	84	44	73
Dendritic	89	62	58	70
Anastomosing	60	39	34	44
Mean	80	61	45	62

Table 4.2: Percentage of erosion, which is re-vegetated within each of the dissection types (Linear, Dendritic and Anastomosing) at the three study sites (Moor House, The Cheviot and Wessenden Head Moss).

4.4 Gully Ordering

Mosley (1972) stated that the divisions of Type 1 and Type 2 dissection were valid from aerial photograph analysis; however, he was concerned about the qualitative nature of Bower's (1960b) study and classification and thought it ought be tested quantitatively. Section 4.2 showed linear, dendritic and anastomosing dissection to be more effective in

classifying gully erosion at the three study sites, than Type 1 and Type 2 dissection. This section quantitatively assesses the gully systems at the three study sites. Similar to the work by Mosley (1972), gully order was assessed. The *law of stream numbers* states that the number of streams of different orders decreases with increasing order in a regular way and the *law of stream lengths* is the length of stream of different orders increases with increasing order in a regular way (Horton, 1945).

Gully Order

Figure 4.8 shows the number of gully systems decreases with increasing gully order along a logarithmic trend line at all three study sites. The equation shows the slope to be greatest at Moor House and least on Wessenden Head Moss. This indicates the rate of change from order to order is greatest at Moor House. Each have varying R^2 values: 0.99 at Moor House; 0.96 on The Cheviot; and 0.99 on Wessenden Head Moss. Mosely (1972) stated that there would be two distinct groups of branching if there was a major distinction between Type 1 and Type 2 dissection. These results lie along a straight line with no major discontinuities, which do not support a simple division between Type 1 and Type 2 dissection (as shown in Section 4.2). The main differences between the study sites are the number of surveyed systems. This is not a function of drainage density but rather on the size of the area surveyed (see Section 4.5).

As discussed in Section 4.3, 1st and 2nd order gully systems tend be anastomosing gully systems, 2nd and 3rd order tend to be dendritic gully systems and 3rd and 4th order systems tend to be linear. This is because the dissection types do not occur in isolation of each other along one gully system (Figure 4.1c). There is some overlap between gully order and dissection type because not all the gully systems start in an area of anastomosing dissection and end linear. Figure 4.8 therefore indicates there are more 1st order, anastomosing systems than 4th order, linear systems. This does not, however, suggest there to be more areas of anastomosing dissection (as discussed above) because low-order streams tend to be shorter in length than high-order streams.

A
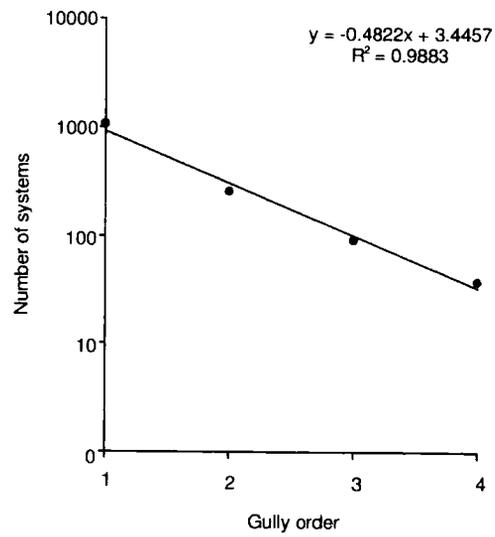
B
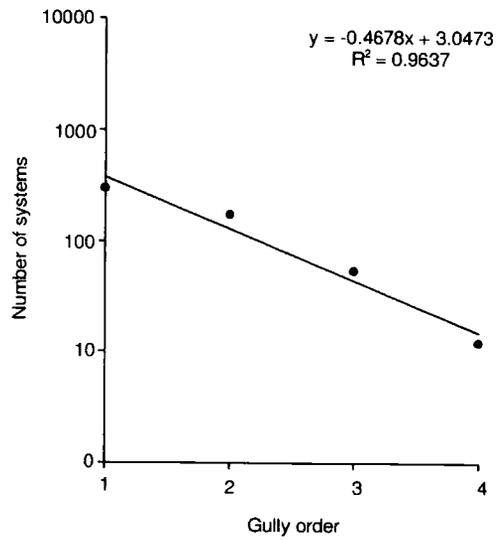
C
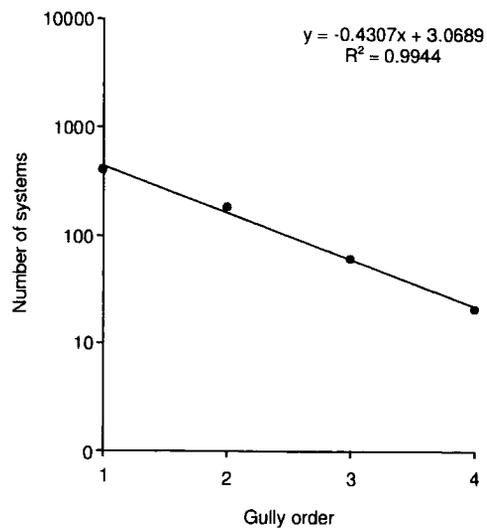
Figure 4.8: The relationship between gully order and number of systems on a logarithmic scale at: A) Moor House, B) The Cheviot and C) Wessenden Head Moss.

Figure 4.9 shows the relationship between gully length, number of systems and gully order for the three study sites. Variations occurred in the length of the gully systems in relation the number of systems and the order of the systems. The 1st order gully systems show a large number of gully systems with lengths less than 50 m. The number of 1st order systems are of much shorter length than 4th order systems, for example, the maximum length of a gully system of 1st order magnitude at Moor House was 420 m, on The Cheviot was 450 m and on Wessenden Head Moss was 350 m whereas of the 4th order systems the maximum length at Moor House was 750 m and on The Cheviot was 550 m. On Wessenden Head Moss the 2nd order gully systems were shown to be the longest in length followed by the 3rd order, 4th order and the 1st order (least). This is thought to be a result of a few anomalies because Table 4.3 and Figure 4.10c show gully order to increase with gully length when plotted against the mean gully length.

Gully order	Gully length (m)	Moor House	The Cheviot	Wessenden Head Moss
1	**Mean**	57.8	99.4	63.3
	Standard deviation	61	82.4	48.5
2	**Mean**	100.3	149	125.3
	Standard deviation	84.9	102.1	108.2
3	**Mean**	135.8	180.4	215.9
	Standard deviation	88.2	112.9	175.6
4	**Mean**	241.6	339.2	265.2
	Standard deviation	207.8	204.6	192.7
Total	**Mean**	133.9	192	167.4
	Standard deviation	110.5	125.5	131.3

Table 4.3: Summary of the means and standard deviations of the gully lengths with gully order at the three study sites.

Figure 4.10 and Table 4.3 show gully order to increase with mean gully length at all three study sites. Based on the law of stream lengths, the law of gully length would state that if the mean gully lengths of different orders were plotted against stream orders, the result would usually be a more or less straight line (Goudie 1998). All plot virtually along a linear trend line with R^2 values of 0.93, 0.87 and 0.99 for Moor House, The Cheviot and Wessenden Head Moss respectively (Figure 4.10). The equation of the line shows the slope is greatest on The Cheviot and least at Moor House, indicating the rate of change from order to order is greatest on The Cheviot.
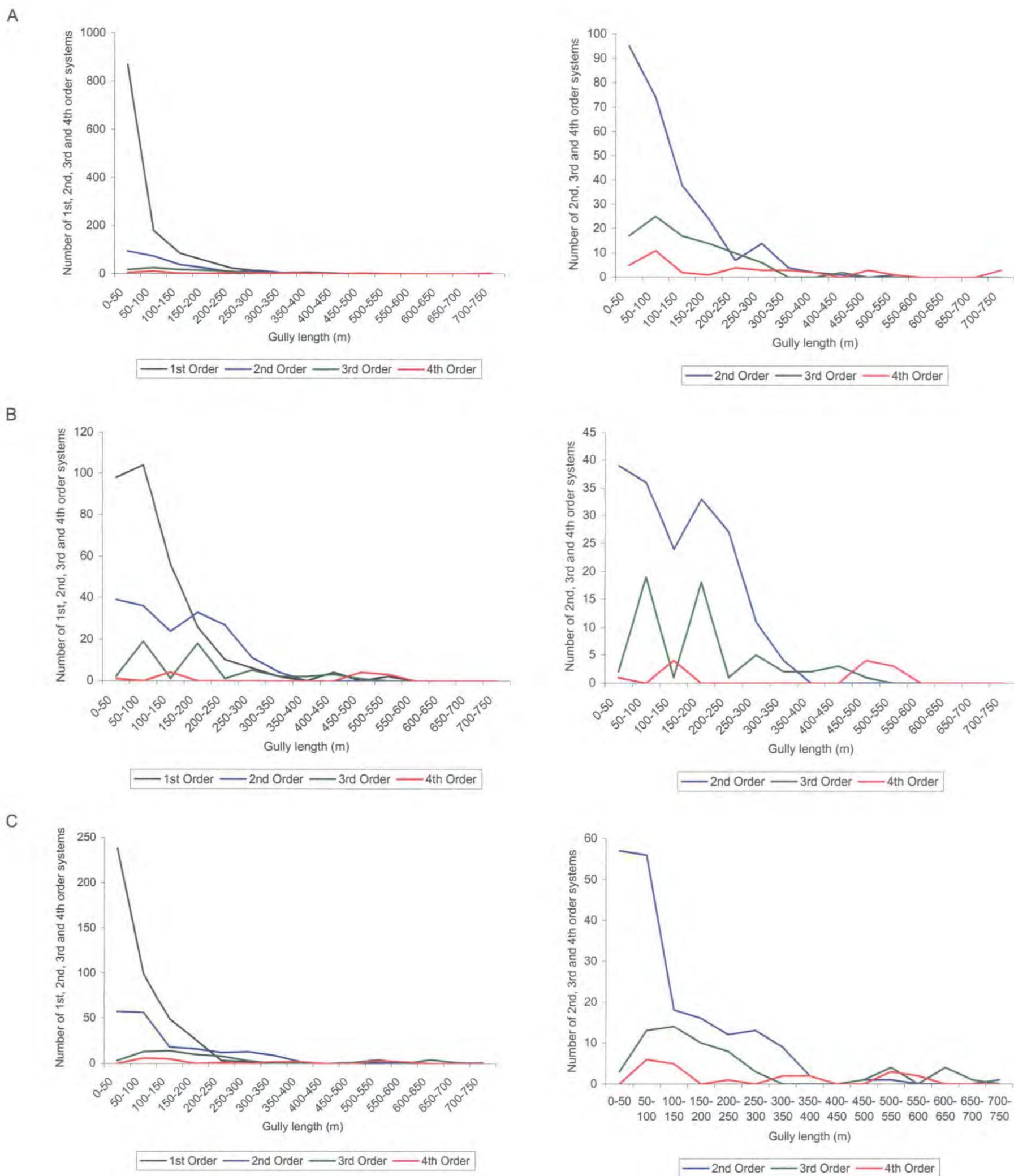
Figure 4.9: Relationship between gully length, number of systems and gully order at: A) Moor House, B) The Cheviot, and C) Wessenden Head Moss.
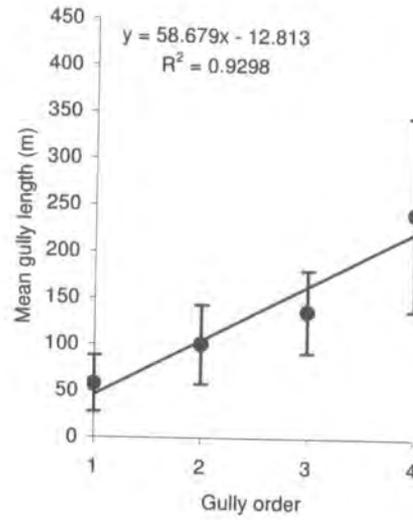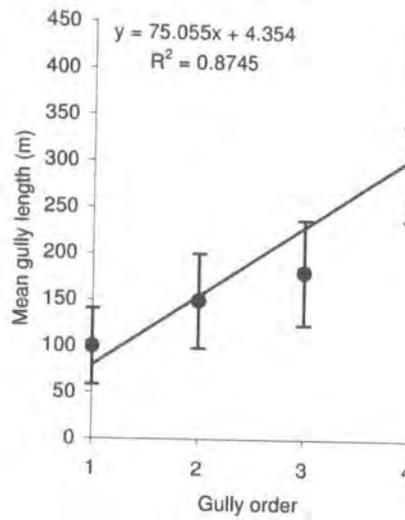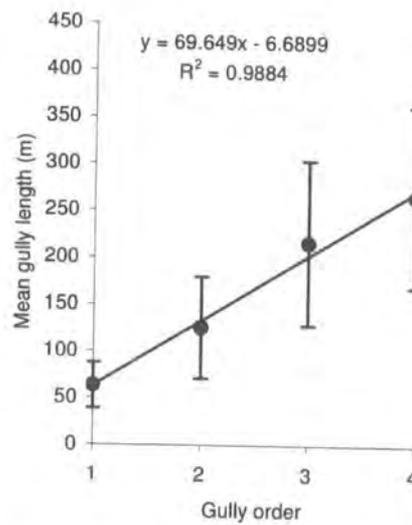
Figure 4.10: The relationship between gully order and mean gully length at: A) Moor House, B) The Cheviot and C) Wessenden Head Moss.

4.5   Drainage Density

The drainage density is used to give an indication of amount of dissection at the three study sites. It is recognised as a topographic characteristic of fundamental significance. In Britain the values of drainage densities are usually less than 5 km km^2 (Gregory and Walling, 1973). For stream systems, low drainage densities are in areas where gully lengths are long, slopes are flat and channels far apart, as opposed to high drainage densities where gully lengths are short and slopes steep. For gully systems, however, this is expected to be slightly different because linear dissected gullies, which are expected to have the lowest drainage densities are on the steepest slopes. Table 4.3 shows the drainage densities for the three study areas: Moor House; The Cheviot and Wessenden Head Moss.

	Moor House	The Cheviot	Wessenden Head Moss
Total Gully Length (km)	118.8	72.1	67.7
Drainage Area (km^2)	41.2	11.4	6.9
Drainage Density (km km^2)	2.88	6.32	9.81

Table 4.4: Drainage density of the three study sites.

Table 4.4 shows the drainage densities to vary between the study sites. Moor House with the least extent of erosion is also shown to have the lowest drainage density (2.88 km km^2). This is thought to be a result of the large extent of linear dissected slopes at Moor House and the shape of the area (Figure 4.3), given that slopes are not steep and tend to be convex and relatively long in profile (approximately 500 m). On The Cheviot the drainage density is higher than at Moor House (6.32 km km^2) but interestingly not as high as on Wessenden Head Moss (9.81 km km^2). Total gully lengths appear to be longer on both The Cheviot and Wessenden Head Moss (see selected gully systems in Figures 3.22 – 3.24). Despite their drainage densities both being high, the topography of both sites are very different (Figure 4.3), with steep slopes on The Cheviot and low slope angles on Wessenden Head Moss. The extent of erosion at these sites is greater than at Moor House, which reflects in the drainage densities. It is thought that the densities are greatest at these sites because of the greater extents of dendritic and anastomosing dissected areas (Table 4.1). Although overall gully lengths are long (approximately 800 m) the large extent of smaller gully systems, which join the longer systems, increase their drainage density and also increase their erosion. This is because

139

a large number of gully systems joining cause much scour and widening of the gully. These gully systems are also those that take the longest to infill and re-vegetate (see Section 4.7).

Burt and Gardiner (1984) discussed the changes in drainage density in the Shiny Brook catchment on Wessenden Head Moss. 1968 and 1976 aerial photographs showed the drainage density to be 4.2 km km^2. This is approximately half of that calculated in this study; however, Burt and Oldman (1986) suggested field surveys were essential due to the difficulty of checking low order stream from OS maps and aerial survey. Using both the 1980 aerial photograph and field surveying Burt and Oldman calculated a drainage density of 11.15 km km^{-2} for the Shiny Brook catchment, Wessenden Head Moss. This is 1.34 km km^{-2} greater than the drainage density calculated in this study and therefore may indicate a reduction in drainage density, because more up to date aerial photographs (1988) and ground surveying (2002 – 2004) were used in this study. Yeloff et al. (2005) discussed a drainage density of 9.92 km km^{-2} for the March Haigh reservoir catchment, Southern Pennines. This was suggested to be low for the Southern Pennines and is very similar to the drainage density calculated for Wessenden Head Moss in this study and therefore indicates there are other areas in the southern Pennines that are more severely eroded, e.g. Bleaklow and Kinder Plateaux.

4.6   Change in gully systems over time

This section addresses the development of the gully systems over an approximate 50-year time period at the three study sites. Aerial photograph analysis has shown that areas of eroded peat have changed very little over the last 50 years, for example there were no major changes in the pattern and dimension of the gully systems. There are exceptions where bank collapse may have occurred locally and therefore a small area of the gully may have increased in width as a result. Since there has been very little change over this time this indicates that the gully systems are much older than 50 years. They are likely to have developed over longer periods of time (several hundreds of years) or have developed during a period of more intense geomorphic activity (Wishart and Warburton, 2002). The main change, which has occurred during this approximate 50-year period, is an increase in vegetation cover density and type at all three study sites. Re-vegetation in the bases of many of the gully systems, on peat flats and on the interfluves, has occurred. An important observation at all three study sites is that the

140

wide linear dissected gully systems are those areas with the greatest re-vegetation. It appears the systems reached a width at which the channel at the gully base was too small to continue eroding the gully floor. The channel tended to meander across the gully floor, but as the slope increased would hug one side of the gully. The examples presented throughout this section show that the preferred side of the gully where the channel is found tends to be that which was affected by the wind direction (Figure 4.11).

Moor House

The gully systems at Moor House provide excellent examples of the transition from Stage 3 to Stage 4 (Figure 4.11) over the last 50-year period. Many of the gully systems are re-vegetated (82 %). One example of a gully system, which has re-vegetated over this period, is the main gully on Burnt Hill (Burnt Hill 1 gully) (Figure 4.12). Figure 4.12 shows the changes over time and was produced using the aerial photographs from 1953, 1976, 1995 and 2000 (with further field checking in 2001, 2002, 2003 and 2004).

As can be seen in 1953 much of the gully system was bare or eroded to the mineral base. In the area of linear dissection towards the mouth of the gully all peat had been totally removed from the system. Ground-based photographs support this (Figure 1.12) and this is confirmed by further ground-based research and re-photographs, which are presented in Section 7.2.3. Towards the head of the system is a large area of bare peat, which is likely to be highly dynamic. Despite this it is thought that the gully system may not have eroded to the peat-mineral base as a result of the low slope angle and extensive waterlogging; however, this is only a presumption because the aerial photographs do not go far enough back to provide specific evidence. The justification of this is addressed further in Section 7.2.5. The channel within the gully base first becomes visible where the gully narrows and slope angle increases. Here there is evidence that the peat has been removed since the gully is eroded to the mineral layer.

Prevailing wind direction

Vegetation
Peat
Mineral

Stage 1: Small depression.

Stage 2: Gully developing, eroded down through the peat to the peat/ mineral base.

Stage 3: Gully developed, started to eroded laterally, channel in the gully floor becomes laterally disconnected and begins to meander.

Stage 4: Channel in the gully floor has meandered and observed to hug the gully side affected by the prevailing wind direction. The channel erodes into the gully side wall and the gully floor begins to re-vegetate.

Figure 4.11: Schematic diagram showing the development of a gully system typical of the Pennines. Many of the gully systems at the three study sites are or have developed from Stage 3 to 4 over the last 50 years.

1953   1976   1995   2000

Mineral Base

Bare peat

Early stage of revegetation, i.e. *Sphagnum*

Mid stage of revegetation, i.e. *Eriophorum*

Late stage of revegetation, i.e. *Calluna*

Uneroded vegetation, i.e. *Calluna*

N Flow

Scale (m)

0   80

→ Prevailing wind direction
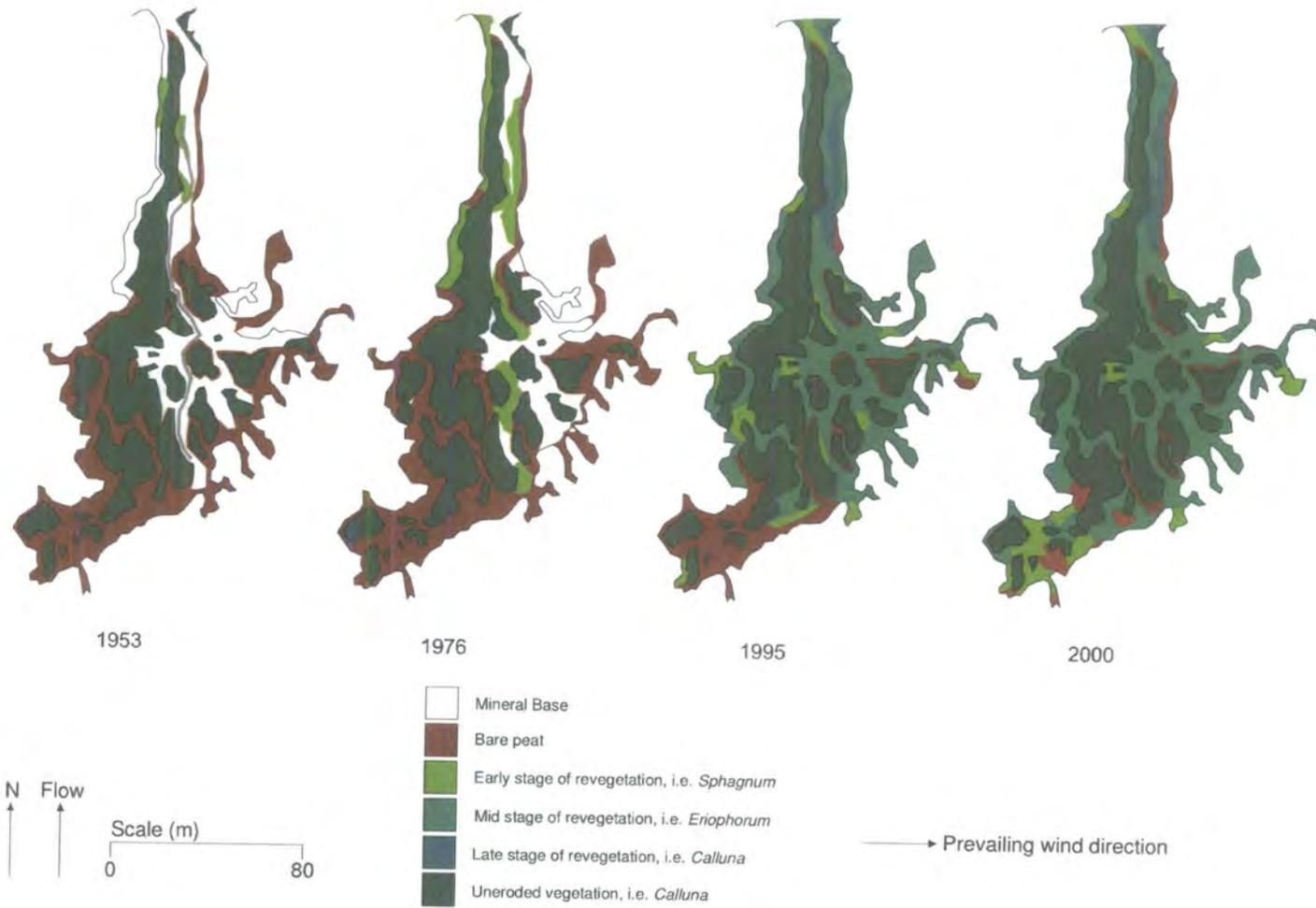
Figure 4.12: Re-vegetation in Burnt Hill 1 gully system from 1953 to 2000.

Rough Sike

1953

Rough Sike

1976

Rough Sike

1995

Rough Sike

2000

Saturated bare peat
Bare peat
Vegetated Hagg
Revegetated peat

N

Scale
0   100 m
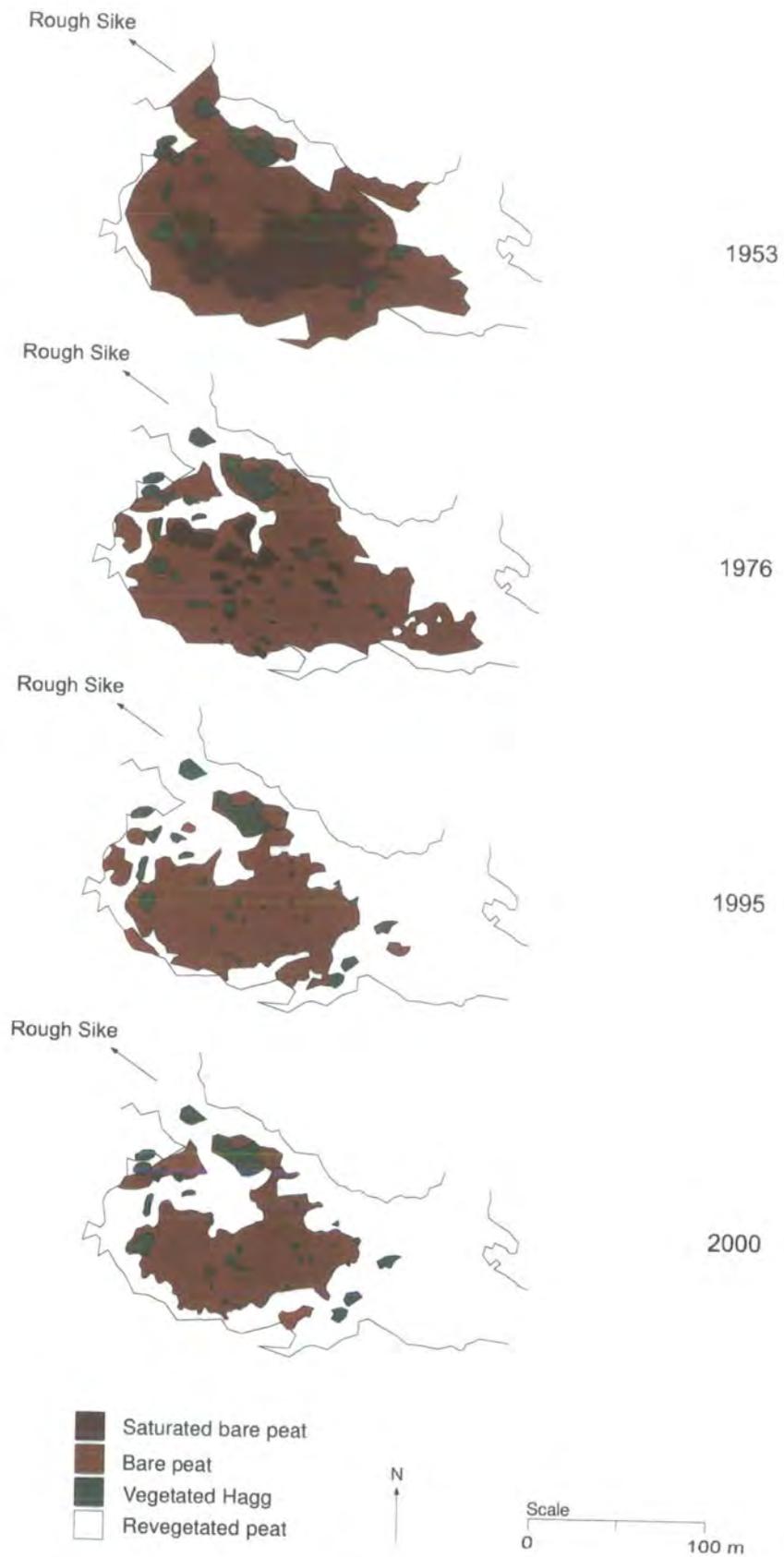
Figure 4.13: Distribution of maps showing the changes in peat from 1953 to 2000.

By 1976 the channel is not fully visible and pockets of re-vegetation have started to occur. The area at the head of the gully still remains bare. The small channel to the west of the main system had fully re-vegetated and become inactive during this period. Over the 19 years from 1976 to 1995 extensive re-vegetation in the base of the gully system occurred. The head of the system still remained bare; however, some evidence of re-vegetation was visible. By 2000 virtually all of the gully system had re-vegetated. The vegetation cover towards the mouth of the gully system was in the late stages of development with the growth of *Calluna vulgaris*. The head of the system had re-vegetated extensively over the 5 years from 1995 to 2000, mostly with *Sphagnum* spp. and *Eriophorum angustifolium*.

In addition to gully systems such as the Burnt Hill system, large areas of peat flats have also shown evidence of re-vegetating at Moor House. One example is Moss Flats, a 3 ha peat flat to the west of Rough Sike (Figure 4.13). Figure 4.13 shows the changes over time using the aerial photographs from 1953, 1976, 1995 and 2000. As can be seen the area of bare peat decreased from 1953 to 2000. In 1953 there was a large saturated area of peat in the centre with a channel draining to the northwest towards Rough Sike. By 1976 much of the saturated peat had gone and the channel had re-vegetated. Towards the west of Moss Flats small areas had began to re-vegetate also. In 1995 the peat flat had reduced dramatically in size. Re-vegetation had occurred around the whole peat flat and the peat flat became isolated from the drainage system. Small areas of bare peat remained towards the west and east of the flat. The channel had further re-vegetated and was virtually unrecognisable and there are no areas of saturated peat. In 2000 further re-vegetation of the peat flat was observed. Haggs became further isolated in the re-vegetated areas and the channel had further re-vegetated. It appeared that most of the re-vegetation is taking place to the north and west of the peat flat. This is likely to be a result of the drainage towards Rough Sike within the peat mass because areas of drained peat re-vegetation more rapidly than saturated areas (as shown in Figure 4.12 where the lower, more drained section of the main Burnt Hill gully was in the later stages of re-vegetation).

The coupling and de-coupling of gully systems with streams is an important change over time. This was investigated in the Rough Sike catchment. Table 4.5 shows the number of gully systems joining Rough Sike and of those that were coupled to the main

stream channel. Those originally coupled and then de-coupled are generally gully systems, which have infilled and re-vegetated.

Year	Number of gully systems observed to be joined to Rough Sike	Number of gully systems coupled	Number of gully systems de-coupled
1953	25	25	0
1976	26	12	14
2000	26	3	23

Table 4.5: Number of gully systems joining Rough Sike, which were coupled to and de-coupled from the active stream.

As can be seen from Table 4.5, 25 gully systems were observed to directly join Rough Sike in 1953, all of which were coupled, e.g. Rough Sike 1 Gully. All the gully systems appeared eroded to the peat-mineral base and were fully connected to Rough Sike. In 1976, 26 gully systems were observed, however only 12 were coupled. This included Rough Sike 1 Gully. Generally the coupling in 1976 consisted of single narrow channels hugging one of the gully sidewalls and running across the floodplain of Rough Sike. Despite the general de-coupling an increase in gully systems from 25 to 26 in the catchment infers gully development occurred also. By 2000 there were still 26 gully systems observed to join Rough Sike; however, only 3 were coupled. This shows that 23 gully systems had become de-coupled in the last 50 years, one of which was Rough Sike 1 Gully, which appeared to have largely re-vegetated. This pattern appeared not only in the Rough Sike catchment but also in other areas within Moor House, for example, in 1950 Burnt Hill 1 and Burnt Hill 2 gully systems were coupled to Troutbeck and Nether Hearth Sike, respectively. The Nether Hearth gully system however was not. By 1976 both Burnt Hill 1 and Burnt Hill 2 gully systems were de-coupled and therefore showed signs of re-vegetation (Figure 4.12) and therefore has significant implications for sediment delivery within the overall peatland sediment budget (Evans and Warburton, 2005).

In general the changes that occurred at Moor House were of infilling and re-vegetation of existing gully systems and re-vegetation of bare areas of peat. The pattern of the systems and gully lengths and widths showed little or no change on the regional scale, therefore indicating that the area was recovering from erosion. Section 4.2 observed

some changes in gully pattern, although they appear to be the result of recovery processes or local adjustments in gully development. There was one observed anomaly, whereby in the Rough Sike catchment one gully had further eroded, although this as questionable is a result of the aerial photograph quality from that period.

The Cheviot

Much of the change that had occurred at Moor House also appeared to have occurred on The Cheviot. The change was mainly in the extent of vegetation cover rather than changes in the pattern and dimensions of the gully systems. Figure 4.14 shows a comparison of aerial photographs between 1951 and 1983 for one of the areas studied on the Cheviot and Figure 4.15 shows the changes over time (1951 – 2004) in Gully 2.

The area shown in Figure 4.14 is directly to the west of the Cheviot summit and the main stream is known as College Burn. This is an area of extensive dissection within the peat. The area to the northwest of both the main photographs shows there to be no peat (A). This is expected as the slope angle increases to the stream and therefore peat is unable to form. For this analysis the colour tone of the photographs have been used to analyse changes over time. Based on this, the large area of bare soil (A) appears to have reduced in size and has been re-vegetated by grasses from 1951 – 1983. Much bare soil is evident in the base of many of the larger gully systems on both aerial photographs indicating that they are likely to have eroded to the peat-mineral base. The large areas of dendritic dissection show there to be much bare peat in the 1951 aerial photograph. By 1983 extensive dissection is still evident; however, areas of bare peat and severe erosion appear to have re-vegetated (this pattern was also observed in the field (2004)). To the northeast the large interfluve area (B) shows no change. This therefore indicates that the gully systems do not appear to have extended headward over the last 50-year period. In addition to this, there appeared to be no changes in the gully patterns and gully widths. This was also observed by Wishart and Warburton (2002), who also stated there to be no major changes in the pattern and dimensions of the gully systems. Despite the general re-vegetation further erosion occurred mainly by walkers using the footpath from The Cheviot to Auchope Cairn (to the southwest of the photograph, Area C). As shown in Figure 4.14 this is undetectable on the 1951 aerial photograph, but visible on the 1983 photograph and was visible in the field (2004).
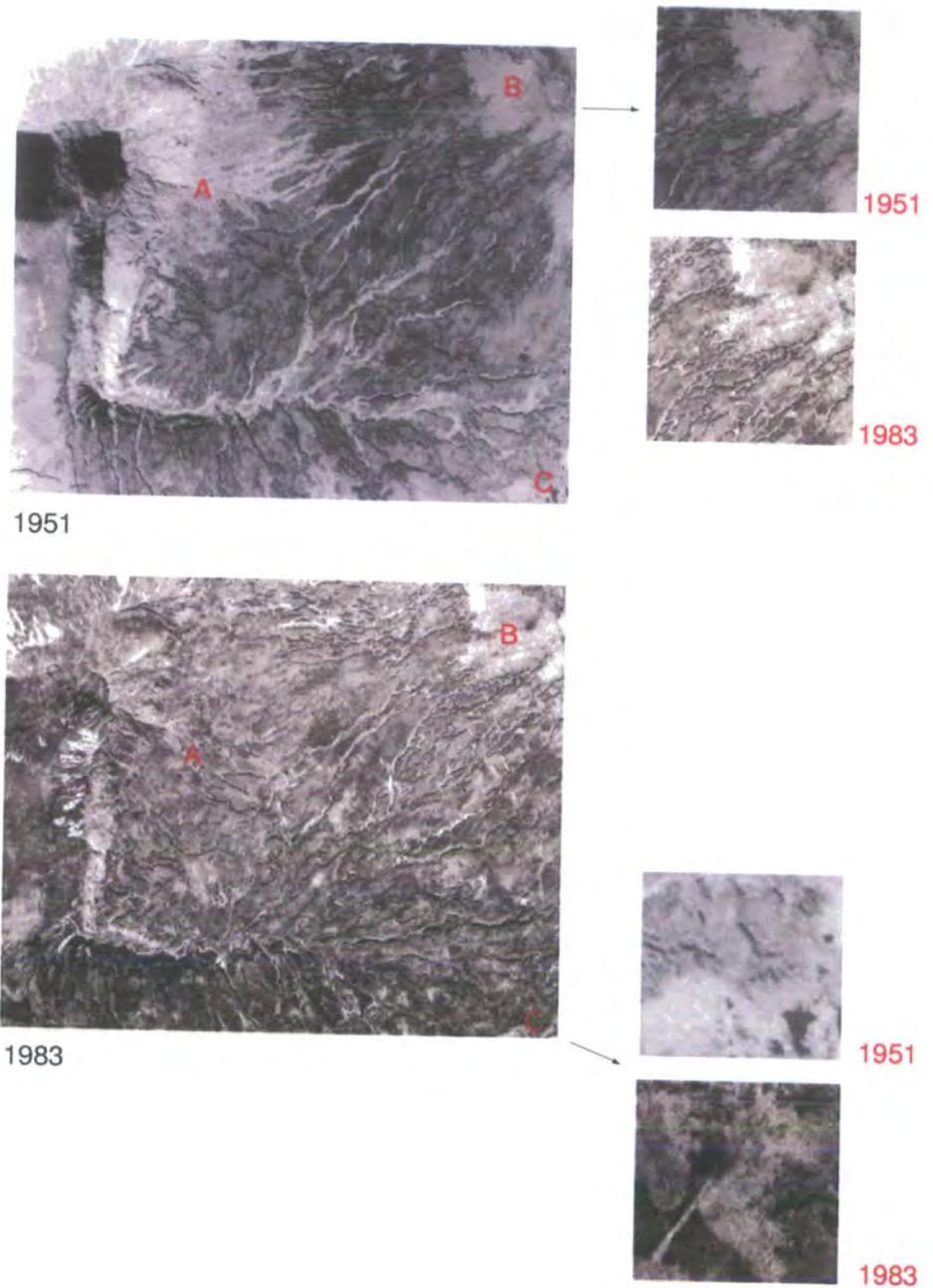
Figure 4.14: Comparison aerial photographs of the Cheviot from 1951 (© Crown Copyright/ MOD. Reproduced with the permission of Her Majesty's Stationery Office) to 1983 (ADAS Aerial Photography. Crown Copyright).

Legend:
- Bare peat
- Early stage of revegetation, i.e. *Sphagnum*
- Mid stage of revegetation, i.e. *Eriophorum*
- Late stage of revegetation, i.e. *Calluna*
- Uneroded vegetation, i.e. *Calluna*

Scale (m)
0 — 70

N Flow

1951   1983   2004
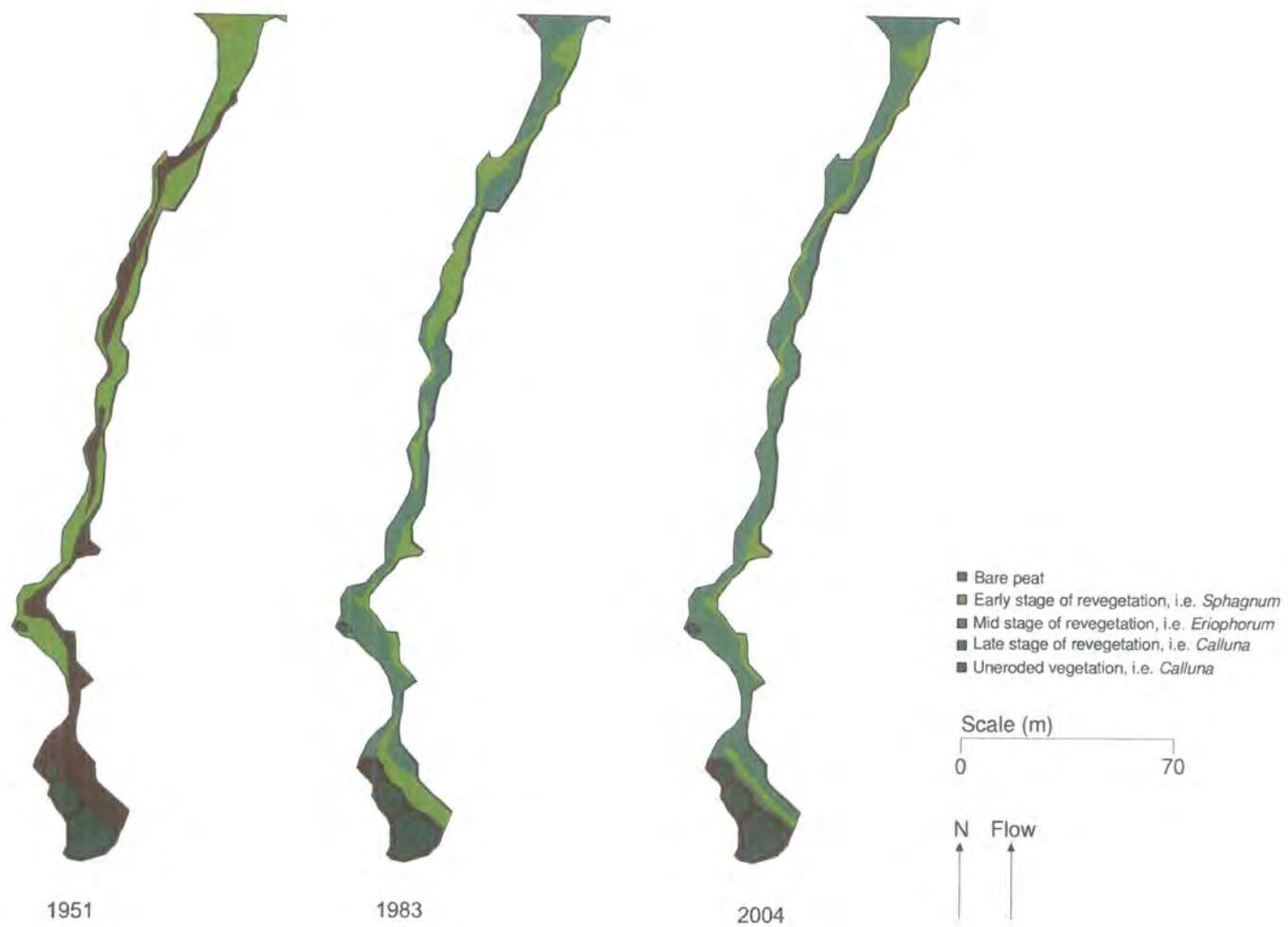
Figure 4.15: Re-vegetation in Gully 2 from 1951 to 2004.

Figure 4.15 shows the changes over last 50 years within Gully 2. Re-vegetation has occurred in the gully system from 1951 – 2004. In 1951 the gully was largely bare towards the top of the system, where the slope angle was least. Throughout the gully system re-vegetation was occurring and appeared to be in the early stages predominantly covered by *Sphagnum* and isolated areas of *Eriophorum*. Bare peat was evident where the channel was present on the gully floor. The channel hugged the east bank of the gully in the upper and lower gully system, however was meandering through the middle of the gully profile. By 1983 re-vegetation was extensive and in the early to mid stages. *Eriophorum* and grasses were predominant. Areas of bare peat were only evident on or adjacent to the gully walls. The channel present in 1951 followed a similar pattern, however, was in the early stages of re-vegetation. By 2004 the re-vegetation in the gully system was in the mid stages to late stages. *Eriophorum* and grasses dominated. Again the channel followed the same pattern, however, was less evident (more re-vegetated) than in 1951 and 1983. The re-vegetation of Gully 2 is discussed in more detail in Chapter 7.

Wessenden Head Moss

Variations from 1948, 1976 and 1988 were observed from aerial photograph analysis and from 2002 – 2004 by field observations. Towards the north of the study area on Wessenden Moor large linear gully systems draining to the north are eroded to the peat-mineral base on all the aerial photographs. Figure 4.16 shows the head of some of the gully systems in 1988. As can be seen in Figure 4.16 approximately one third of the wide systems are eroded to the mineral base and the remaining systems show re-vegetation within the gully base. The vegetation looks to have grown over bare mineral soils with possibly a thin peat layer given that areas of minerals can be seen between the vegetation. In 1948 and 1976 this area looked very different, the extent of the mineral gully bases were far more extensive and there was only small areas of vegetation encroachment in 1976.

Flow N

Scale (m)

0   500
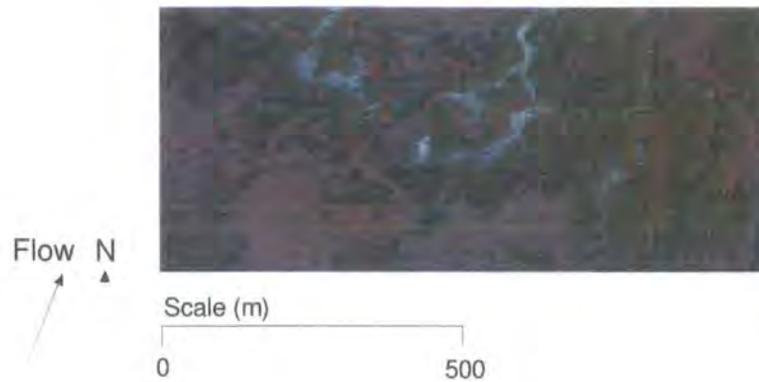
Figure 4.16: Extent of erosion on Wessenden Head Moss in the area of dense wide linear dissection to the north of the study area (Source: ADAS Aerial Photography, Crown Copyright, 1988).

Over the general area of the study site in 1948 the majority of the gully systems were bare with some eroded to the mineral base (Figure 4.17). By 1976 there was some evidence of re-vegetation occurring in the bases of the gullies. This tended to be in the shallower systems (e.g. the bottom of Gully 2) rather than those of which were eroded deep into the peat mass (e.g. Gully 1). Figure 4.17 shows the changes in the large gully system, which drains Gully 2, and changes within Gully 2 itself. In 1948 the gully systems were bare and the large gully was eroded to the mineral base by the drainage channel towards the bottom of the system. By 1976 the wider lower sections of the gully systems began to re-vegetate. This would be a result of the channel having insufficient power to erode the whole gully floor. A channel filled approximately one-third of the gully floor (Gully 2) and hugged the left hand bank (looking up the system) of the gully system. The larger gully system was shown to have a meandering channel in the gully floor visible because of the scour of the bare peat and mineral soil. In 1988 further re-vegetation had occurred. The large gully looked to have infilled over the last 12-years since there was no evidence of exposed minerals and the channel although still meandering tended to hug the south bank (left hand bank looking up the system). Re-vegetation had also occurred further up the system towards the gully sides. Gully 2 had also re-vegetated further and the channel in the base was less visible, though it was still coupled to the larger system from which it joins. From the field observations (2002 – 2004) it was clear this re-vegetation had continued. The bottom half of the system vegetation covered much the gully floor and the channel was virtually invisible and in the top half of the gully vegetation was dominated by isolated areas of *Eriophorum*. The re-vegetation in this gully is discussed in more detail in Chapter 7.
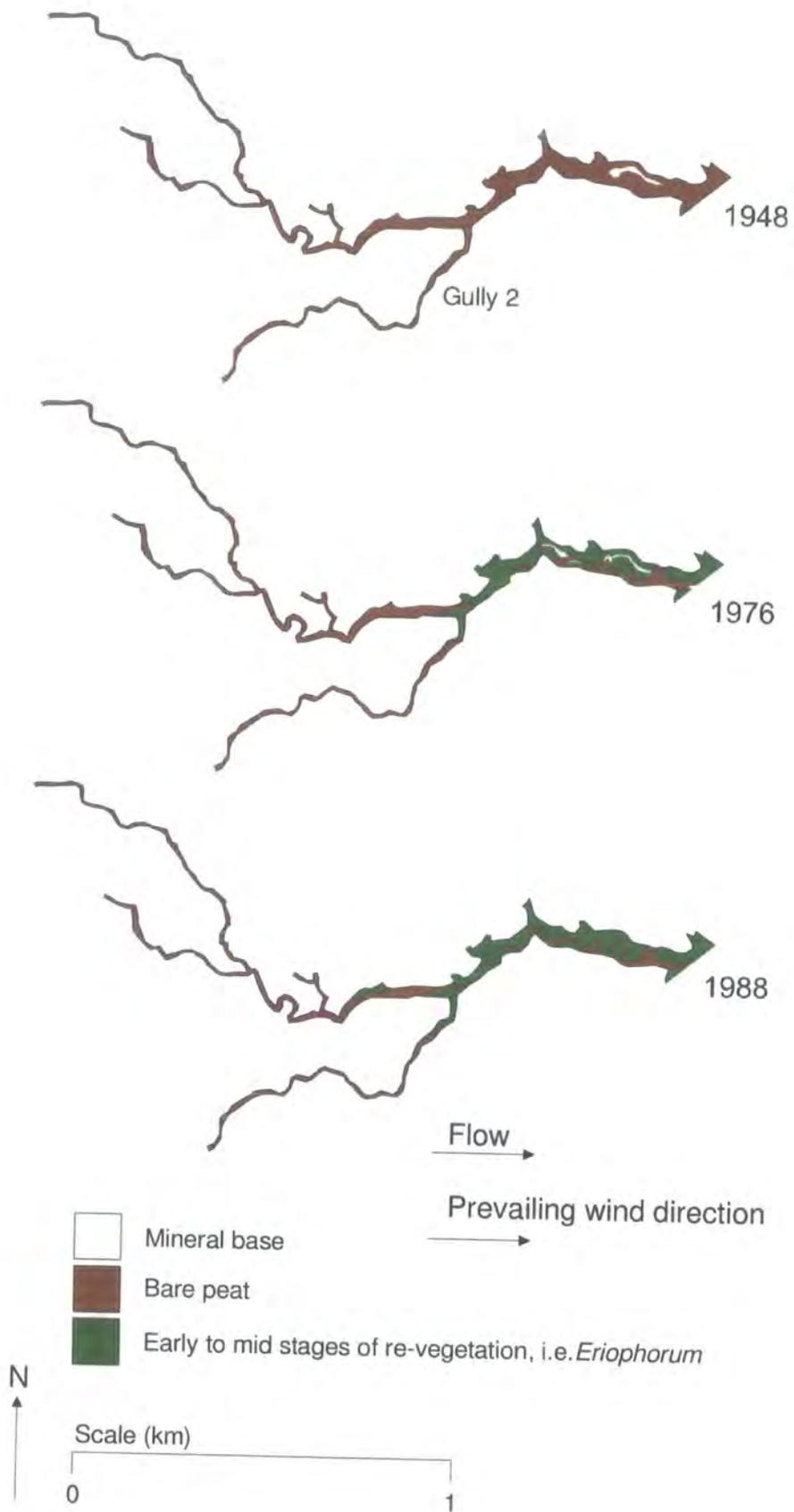
Figure 4.17: Distribution of changes in Gully 2 and its large draining system and from 1948 to 1988.

The extensive peat flats at the head of many of the gully systems were largely bare and showed little change from 1948 – 2004. Only one gully was observed to have further eroded from 1948 – 1976, but by 1988 had re-vegetated at the top and bottom although the middle area remained bare. An additional observation was that the car park and footpath across the moor was evident on the 1988 aerial photograph and in the field but not on the earlier photographs (1948 and 1976). This is interesting in terms of the present stage of the vegetation, especially in the area of the car park and footpath, as this would have lead to increased walking and recreation in the area. Generally there was no evidence of major changes in gully lengths, widths and gully pattern between 1948 and 2004.

4.7   Accuracy of the GIS

The accuracy of the GIS was tested by comparing gully length and width data obtained from the GIS with that obtained in the field from the long profile measurements (see Chapter 7). Table 4.6 shows the variability in the data obtained at the three main study sites. Figure 4.18 shows scatter plots of gully lengths and width between the GIS and field research. As can be seen from Figure 4.18 variation in gully lengths had an R^2 value of 0.98 (Figure 4.18a) and gully widths, 0.94 (Figure 4.18b).

Those measured in the field are thought to be the most accurate given that it is easier to determine where measurements should start and finish, e.g. base of gully banks. This was harder to define using the GIS given that the top width and bottom widths of the gully systems are often different. The variability was greater between the gully widths than gully lengths. This is thought to be again a result of discrepancies between gully banks and gully floors especially in bare peat gullies.

Despite this the GIS method is far faster than the field research. Regional variations in gully lengths and widths can be measured in the time taken in the field to measure one whole system. Both methods therefore have pros and cons. Given the variations are relatively small it is thought that the GIS is the most affective method to use for such measurements, however, field-based measurements are also vital for other research (as demonstrated in Chapters 6 and 7).

Study Area	Study Site	Gully length (m)		Gully width (m)	
		GIS	Field Research	GIS	Field Research
Moor House	Burnt Hill 1	284	272	14	13.5
	Burnt Hill 2	303	290	9.5	8.7
	Nether Heath	426	427.5	8	8
	Cottage Hill main	614	568	11	10.6
	Cottage Hill top side	92	87	3	-
	Cottage Hill lower side	268	260	9	-
	Rough Sike 1	554	561	15	14.95
	Rough Sike Gullies 1	167	159.3	10	8.5
	Rough Sike Gullies 2	183	179.2	9.5	9
	Rough Sike Gullies 3	271	271.9	10	9.3
	Rough Sike Gullies 4	378	378.4	8	8.5
	Netherheath 1	115	119	14	13.5
	Netherheath 3	139	138.7	8	9.9
	Netherheath 3	106	94.7	7.5	7
The Cheviot	Gully 1	621	707.5	7.5	6.8
	Gully 2	278.85	282.9	6.9	7
	Gully 3	575	582.4	10.5	10.35
Wessenden Head Moss	Gully 1 main	341	346	4	3.65
	Gully 1 side	198	208	1.44	-
	Gully 2	334	327.5	5.5	5.25
	Gully 3	495	503.4	8	7.4

Table 4.6: Gully lengths and widths measured both with the GIS and in the field using an Automatic Level.

A

B
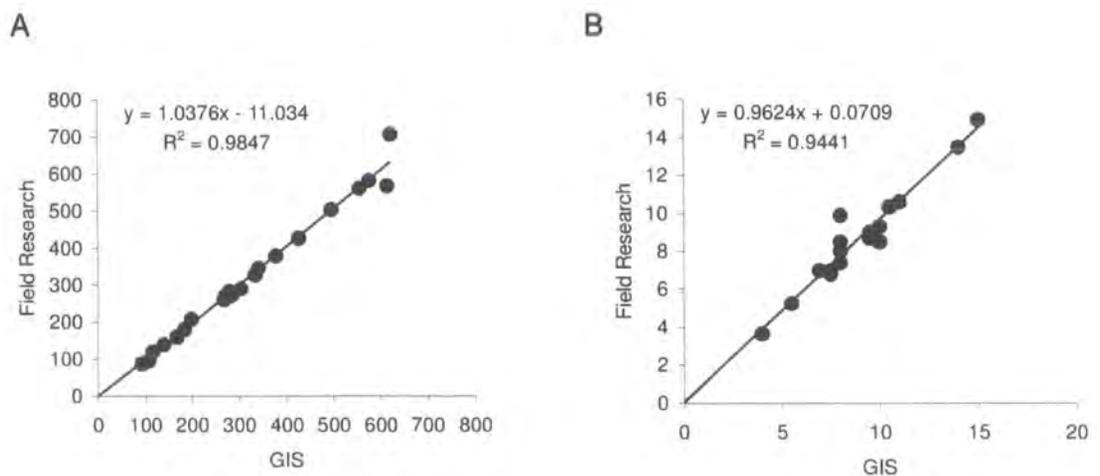
Figure 4.18: Scatter plots showing the variations between the GIS and Field Research for: A) Gully length measurements. B) Gully width measurements.

4.8   Summary

The classification scheme proposed by Bower (1960b) oversimplifies the complex dissection at Moor House, on The Cheviot and at Wessenden Head Moss. The revised classification scheme of linear, dendritic and anastomosing patterns of dissection was adopted for this research because a continuum of form was observed rather than a distinct division between Type 1 and Type 2 dissection (Mosley, 1972), thus a more sophisticated scheme provided better characteristics of these features. The key to this was the slope angle as it varied down the system.

Peat cover was observed to be greatest on Wessenden Head Moss and least on The Cheviot. This was hypothesised as a function of the variations in slope at the sites. The Cheviot appeared to have suffered from the greatest extent of erosion, followed by Wessenden Head Moss and then Moor House. It was thought this was a result of weather conditions or long-term management practices. Re-vegetation within the eroded areas was shown to be greater on The Cheviot than Wessenden Head Moss. In terms of the dissection at the three study sites, at Moor House the linear dissection was greatest. Proportionately linear dissection was also greatest on Wessenden Head Moss, which was not expected given the low slope angles at this site; however, the differences in types of dissection were slight. The Cheviot had the greatest amount of anastomosing dissection, which was not expected given the steep slope angles, however, this may be a result of much erosion being in the area of The Cheviot summit, where the slope angles are low especially in relation to the general slopes. It was expected that the greatest extent of re-vegetation within the dissection types would be in linear dissected areas, followed by dendritic and anastomosing. This was proved right with 73 %, 70 % and 44 % of the dissection types respectively being re-vegetated. This is thought to be the result of the processes of active erosion and deposition in areas of dendritic and anastomosing dissection, improved shelter from the gully sidewalls in areas of linear dissection in particular and shorter growing seasons at higher altitudes.

Each of the three study sites showed that the number of gully systems decreased with increasing gully order. Fourth order gully systems were found on the three sites. The number of systems studied varied; this was affected by the aerial extent of peat surveyed at the three sites. For example, more gully systems were observed at Moor House than on The Cheviot and Wessenden Head Moss; however, it is known that extent of erosion

at Moor House is less than the other two sites, but the greatest area was studied at Moor House. The gully lengths increased with increasing order. This therefore shows that the two concepts work for not only streams but also when extended to upland gully systems within blanket peat (*law of gully numbers* and the *law of gully lengths*), although this might be expected since gully systems are an extension of streams.

Change in the gully systems over time was most noticeable in the extent vegetation cover (the re-vegetation in the bases of the gully systems, on peat flats or on interfluve areas). At Moor House two examples were shown of how changes in the extent of bare peat occurred from 1953 to 2000. It was interesting to see that in 1953 and 1976 the Burnt Hill gully system was relatively bare and eroded to the peat/ mineral base; however, by 1995 and 2000 the majority of the system was infilled and re-vegetated. Moss Flats (a peat flat) also showed signs of re-vegetation from 1953 to 2000. Again the greatest change had occurred from 1976 to 1995. Within the Rough Sike catchment many of the gully systems had become de-coupled from the main stream from 1953 to 2000. In 1953 all the systems were coupled to Rough Sike, with many of them eroded to the peat-mineral base. By 1976 approximately half remained coupled. The bases of the gully systems by this time showed signs of re-vegetation. Only a channel hugging one of the gully sidewalls before flowing across the Rough Sike floodplain coupled many of the systems. By 2000 only 3 systems remained coupled to Rough Sike. The remainder, which included Rough Sike 1 gully had re-vegetated and the channel had become de-coupled from Rough Sike. This is important in terms of the sediment budget as less water, sediment and organic matter will enter upland streams (Evans and Warburton, 2005).

On The Cheviot and Wessenden Head Moss the changes were similar to that at Moor House. From 1951 – 2004 on The Cheviot, areas of bare peat and soil had re-vegetated and the bases of the gully systems over this time had infilled and re-vegetated. On Wessenden Head Moss infilling and re-vegetation had occurred in the bases of wider and shallower gully systems particularly from 1976 - 2004. The large bare peat flats showed little change from 1948 – 2004. Re-vegetation at Wessenden Head Moss was not as extensive as The Cheviot and Moor House. Generally there were little/or no changes in gully pattern, length and width over these time periods suggesting that apart from local adjustments general changes in gully development are not detectable over these timescales (Wishart and Warburton, 2002).

Given the clear topographic controls at the three study sites (Figure 4.3) the changes that occurred at the three sites seem predictable. This is because Moor House, although having a high rainfall rate, is relatively sheltered due to the basin relief and therefore the erosion extent would be expected to be the least and recovery greatest. The location and management of the sites is also important. The Cheviot is high (815 m) with steep slopes. The peat at this site is therefore thin and vulnerable to erosion as a result of the altitude effect. Wessenden Head Moss was interestingly not the most eroded site, but was the least recovered. Recovery at this site was expected to be the least given the lack of *Sphagnum* in the areas for early re-colonisation. The site is also very flat with average slope angles of < 2°. The extent of anastomosing and dendritic erosion and low recovery is thought to be the result of the processes of active erosion and deposition occurring in these areas of dissection.

Regional variation in topography and altitude are thought to be the main controls on the variations in erosion extent and pattern and change over time at the three study sites.

This chapter has provided a regional variation in gully development. Chapter 7 addresses each of the study sites in more detail and expands on much of what has been discussed here. This will include the influence of slope on dissection at the three sites, variations in gully length and width, changes over time using ground-based photography, and from stratigraphic sequences in the infilled bases of the gully systems.

Chapter 5 follows by focusing on the interfluve areas. This is the first of the local-scale studies and addresses the rates of peat accumulation at the three study sites. This research can then be compared with interfluve erosion and upscaled to aid in the assessment of the future stability of peat in upland Britain.

5.0   INTERFLUVE PEAT ACCUMULATION

5.1   Scope of Chapter

This chapter focuses on peat accumulation at the three study sites using SCP analysis from sites of intact peat. The analysis of both Moor House heather and grassland samples are outlined and variations in peat accumulation rates between vegetation cover types discussed. Microscale (local) variations in peat accumulation rates are examined using replicate samples obtained from small peat blocks. Results from individual grassland cores taken from The Cheviot and Wessenden Head Moss are also presented allowing regional scale variations in peat accumulation rates to be made. The chapter outlines: The stratigraphy and parameters of the intact peat (Section 5.2); the SCP profiles and the position of the 'take-off' (Section 5.3); rates of peat accumulation (Section 5.4); the implications for terrestrial carbon storage (Section 5.5); and the spatial distribution of SCP deposition. This is carried out for each study area in turn: Moor House, The Cheviot and Wessenden Head Moss.

5.2   Stratigraphy and parameters of the intact peat

Knowledge of the variations in the rate of decay within the acrotelm and catotelm is important for the study of SCP accumulation and concentration within the peat profiles as it may have large implications on the number of SCPs found at depth. This section discusses the stratigraphy, densities and loss on ignition values of the samples removed from the three sites. The locations of the intact blocks from Moor House and the intact cores from The Cheviot and Wessenden Head Moss are shown in Figures 3.17 – 3.19. The areas from which the samples were removed were all relatively flat and therefore topography will not affect the results. The stratigraphy from the Moor House samples remained virtually the same within the area of the heather and moorland grass blocks and therefore only one stratigraphy is given for each despite there being four separate cores. Variations were observed in their densities, loss on ignition and SCP profiles and are highlighted in the appropriate sections.

The heather samples are 28 cm in depth. The depth was adequate for this research given the rates of peat accumulation and depth of the 'take-off' determined in other research (e.g. Garnett *et al.* (2000) observed 'take-offs' in SCP profiles between 4 and 14 cm in depth). The top 6 cm consists of the contemporary vegetation cover, the decomposing vegetation (the acrotelm) reaches from 6 cm – 15 cm and below this, is the catotelm, where the vegetation is virtually fully decomposed (15 cm – 28 cm). The heather samples show large differences between the acrotelm and catotelm (Table 5.1a). The moorland grass samples were collected up to a depth of 22 cm in the peat for the same reasons as suggested above. The stratigraphy of the moorland grass samples was visibly more consistent through the profile than the heather samples (see Table 5.1b). The top 5 cm is living vegetation followed a 1 cm of decomposing vegetation (the acrotelm). Below this the peat was well decomposed (the catotelm) from a depth of 6 cm – 22 cm (Table 5.1b). The implications of these variations for the SCP profiles are greater for the heather samples than the moorland grass samples given that the acrotelm in the heather samples is 9 cm in depth whereas in the grass sample is 1 cm in depth.

Figures 5.1 and 5.2 show results of the bulk density, dry bulk density, loss on ignition determination and the SCP profiles. They were produced using the mean of the four samples from each peat sample (heather and grassland). The general trend for both samples shows bulk density to increase with depth. As expected from both peat profiles the bulk density is lower where vegetation exists as a result of the macroscopic plant remains. This is also apparent in the acrotelm, compared with the catotelm. The acrotelm in the heather samples (above 15 cm) show variations in bulk density from 0.1 to 0.8 g cm^{-3}, whereas in the catotelm (below 15 cm) variations range from 0.3 to 1.8 g cm^{-3}. The mean density in the acrotelm is 0.5 g cm^{-3}, and in the catotelm it is 1 g cm^{-3}. Variations are greatest towards the top of the catotelm, where there are a large number of wood fragments. In the moorland grass samples (Figure 5.2) the bulk density is much lower in the acrotelm (above 7 cm) than in the catotelm (below 7 cm). Variations in bulk density range from 0 to 0.8 g cm^{-3} in the acrotelm and 0.4 to 1.4 g cm^{-3} in the catotelm. The bulk density increases rapidly with depth in the acrotelm, whereas in the catotlem it is much more even down the profile, averaging 1 g cm^{3}.

A

Depth (cm)	Troel-Smith Classification				Von Post Classification				Written Description
	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres (0-3)	Coarse Fibres (0-3)	Wood remnants (0-3)	Shrub (0-3)	
0-6	Th^4	Nig^2	$Sicc^4$	H^2	0	2	3	3	Living vegetation – *Calluna vulgaris* and *Sphagnum*
6-15	$Tl^3\,Tb^1$	Nig^{2+}	$Sicc^3$	H^4	1	3	1	2	Decomposing vegetation
15-20	Sh^4	Nig^4	$Sicc^2$	H^8	3	1	0	1	Dark brown peat with very fine fibres
20-28	$Tb^3\,Sh^1$	Nig^3	$Sicc^2$	H^6	3	2	2	2	Brown, stratified herbaceous peat, fibrous

B

Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres (0-3)	Coarse Fibres (0-3)	Wood remnants (0-3)	Shrub (0-3)	Written Description
0-5	Th^4	Nig^2	$Sicc^4$	H^2	0	3	0	0	Living vegetation - grasses
5-6	$Th^3\,Tb^1$	Nig^{2+}	$Sicc^3$	H^4	3	3	0	2	Decomposing vegetation
6-10	Sh^4	Nig^4	$Sicc^2$	H^7	3	2	0	1	Coarse, dark brown peat
10-17	$Sh^3\,Dh^1$	Nig^{3+}	$Sicc^2$	H^8	3	3	0	1	Brown peat with fine fibres /
17-22	$Sh^2\,Dg^2$	Nig^3	$Sicc^2$	H^8	3	3	0	0	Light brown peat with fine fibres

Table 5.1: Field stratigraphy sheets for the Moor House Nether Hearth uneroded samples, used for SCP analysis. A) The heather samples, B) The moorland grass samples.
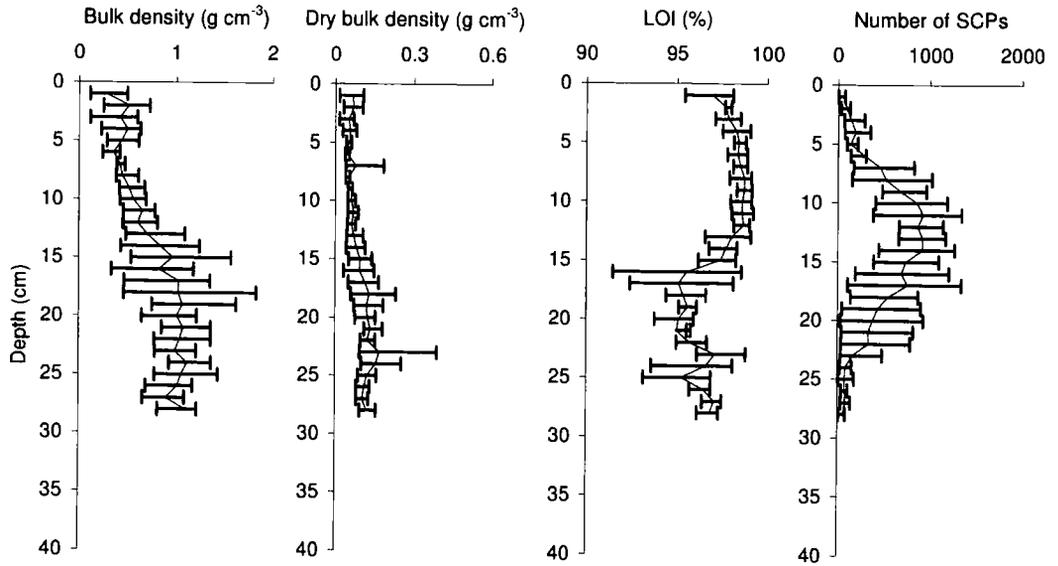
Figure 5.1: The bulk density, dry bulk density and loss on ignition in relation to the SCP profile for the Moor House Nether Hearth uneroded heather samples. The error bars represent the variability in the block.
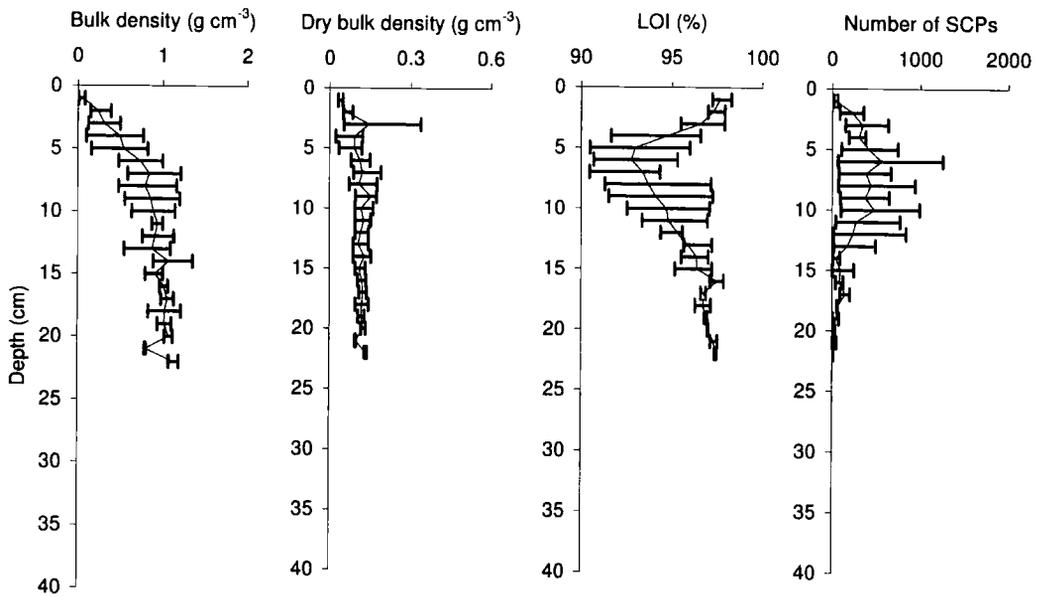
Figure 5.2: The bulk density, dry bulk density and loss on ignition in relation to the SCP profile for the Moor House Nether Hearth uneroded moorland grass samples. The error bars represent the variability in the block.

The dry bulk density profiles show changes throughout the profiles, but much less variation than the bulk density samples. The means in the heather samples vary between the acrotelm and catotelm, and as with the bulk density, the dry bulk densities increase with depth down the profile. There are three large variations in the heather samples at depths: 7 cm; 18 cm; and 23 cm (due to wood fragments), and one large anomaly in the moorland grass profile at a depth of 3 cm, where partly decomposed vegetation is adjacent to more humified peat. The general trend in the profile of the heather samples shows an average dry density of 0.06 g cm^{-3} in the acrotelm and 0.1 g cm^{-3} in the catotelm. Apart from the top 2 cm of vegetation in the moorland grass samples the dry density profile is more even throughout, averaging at 0.1 g cm^{-3}.

The loss on ignition profiles show there to be a greater amount of organics in the heather samples compared with the moorland grass samples. Large differences are evident between the acrotelm and the catotelm in both the heather and moorland grass samples. The percentage organics in the acrotelm is much higher than in the catotelm. Mean values in the heather samples vary from 98 % in the acrotelm down to 96 % in the catotelm. Variations in the means are also greater in the catotelm and although the average is around 96 % there are variations from 91 to 99 %. The moorland grass samples show a very different pattern. The organics start high (98 %), but decrease to a value of approximately 93 % by a depth of 7 cm. Variations above the mean in the moorland grass profiles are related to the division between the acrotelm and catotelm. Interestingly these variations are not picked up in the bulk and dry densities, as they are in the loss on ignition. The bottom 5 cm of the moorland grass samples is very interesting as the percentage organics increase again up to approximately 97 %, with low variability.

The Cheviot

The core sample removed from The Cheviot was a depth of 40 cm to allow for the full SCP profile to be shown. Table 5.2 presents the results from the stratigraphy of the individual core. The vegetation consisted of dense moorland grass (13 cm in height). The acrotelm was shown to be 2 cm in depth and the catotelm was observed from 15 cm – 40 cm, though variations in the stratigraphy were observed throughout the core, i.e. a transition from grass peat to *Sphagnum* peat at a depth of 30 cm (Table 5.2).

Figure 5.3 shows variations in the bulk and dry bulk densities down the profile. The densities increase greatly below 15 cm. This is at the transition between the living vegetation, acrotelm and catotelm. The densities are greatest between 17 cm and 25 cm, before gradually decreasing. There are few variations in the loss on ignition (from 93.8 % to 98.9 %); the majority of the values are between 97 % and 98 %.
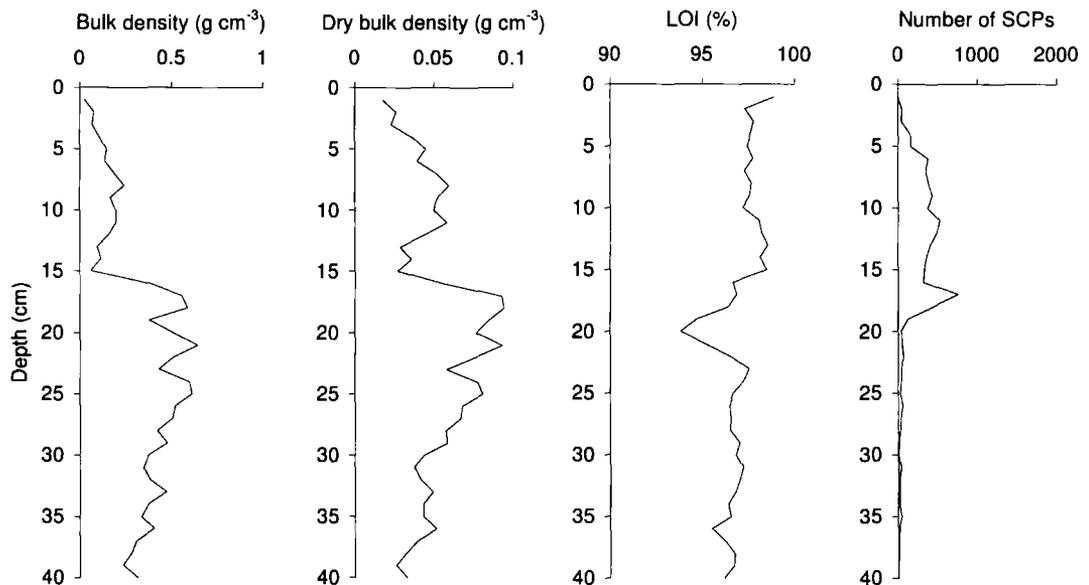
Figure 5.3: The bulk density, dry bulk density and loss on ignition in relation to the SCP profile for The Cheviot uneroded sample.

Wessenden Head Moss

The core was 40 cm in depth. Table 5.3 presents the results of the stratigraphy from Wessenden Head Moss. The living vegetation is moorland grass (2 cm in height). There was little evidence of an acrotelm; however, there was a graded decrease in the number of grass roots to a depth of 12 cm. The stratigraphy remained similar throughout the profile with predominantly brown peat with many coarse and fine fibres (12 cm – 40 cm) (Table 5.3).

Troel-Smith Classification				Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres (0-3)	Coarse Fibres (0-3)	Wood remnants (0-3)	Shrub (0-3)	Written Description
0-13	Th^2 Tb^2	Nig^2	$Sicc^2$	H^3	2	3	0	2	Vegetation – grasses
13-15	Tb^4	Nig^2	$Sicc^2$	H^4	3	3	0	0	Decomposing grasses
15-24	Sh^{2+} Th^1 Dg^+	Nig^4	$Sicc^3$	H^6	3	3	0	0	Dark brown/ black smooth peat with coarse and fine roots
24-30	Sh^3 Dh^1	Nig^{3+}	$Sicc^3$	H^7	3	3	0	0	Dark brown/ black smooth peat with some coarse and fine roots
30-38	$Sh^{2+}Dh^{1+}$	Nig^{3+}	$Sicc^{3+}$	H^7	3	3	0	0	Transition to *Sphagnum*/ less humified peat, saturated
38-40	Dh^4	Nig^3	$Sicc^{3+}$	H^5	3	3	0	0	Saturated *Sphagnum* peat, fibrous

Table 5.2: Field stratigraphy sheet for The Cheviot uneroded sample, used for SCP analysis.

Troel-Smith Classification				Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres (0-3)	Coarse Fibres (0-3)	Wood remnants (0-3)	Shrub (0-3)	Written Description
0-2	Tb^4	Nig^2	$Sicc^2$	H^3	2	2	0	0	Vegetation – grasses
2-12	Sh^{2+} Tb^{1+}	Nig^4	$Sicc^4$	H^7	2	2	0	0	Dark brown saturated peat with fine grassy roots
12-20	$Sh^{2+}Dg^{1+}$	Nig^3	$Sicc^{3+}$	H^7	1	3	0	0	Brown fibrous peat with coarse and fine leafy roots
20-30	$Sh^{2+}Dg^{1+}$	Nig^3	$Sicc^3$	H^7	2	2	0	0	Brown fibrous peat with coarse and fine fibres
30-40	Dg^4	Nig^{3+}	$Sicc^3$	H^8	2	2	0	0	Dark brown fibrous peat with coarse and fine fibres

Table 5.3: Field stratigraphy sheet for Wessenden Head Moss uneroded sample, used for SCP analysis.

The bulk density shows a sharp increase in density from the surface to 4 cm depth (Figure 5.4). The densities then remain similar, fluctuating between 1.3 g cm^{-3} to 2 g cm^{-3}. The dry bulk density shows a sharp increase to a depth of 5 cm to a peak in the density (0.28 g cm^{-3}). There is a decrease in density from 14 cm to 18 cm, which is likely to be a result of the fibrous nature of the peat. The loss on ignition values show a decrease from the surface to a depth of 4 cm, before increasing lower down the profile. The range in percentage loss on ignition is between 95 % and 100 %. Based on the densities and loss on ignition, although the density of roots decreases gradually to a depth of 12 cm, an acrotelm depth of 2 cm seemed likely (between 2 cm and 4 cm in depth).
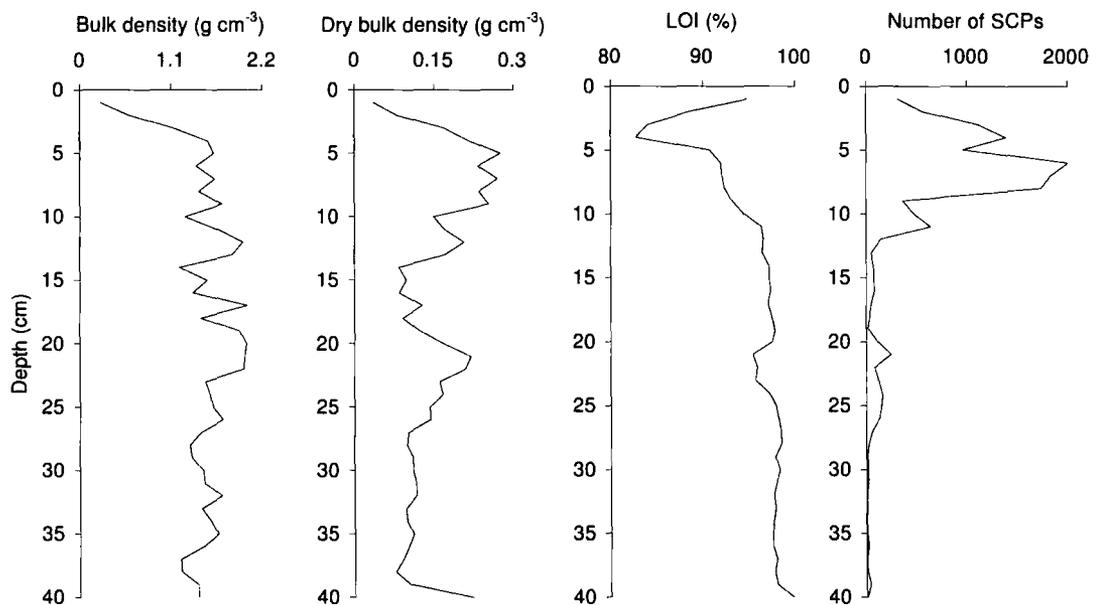
Figure 5.4: The bulk density, dry bulk density and loss on ignition in relation to the SCP profile for the Wessenden Head Moss uneroded sample.

5.3 Spheroidal Carbonaceous Particles Profiles

Results of the SCPs are presented as depth – SCP concentration profile graphs. The profiles show SCP concentrations (number of SCPs per sample). The relationship between the stratigraphic divisions, the bulk density, dry bulk density, loss on ignition and the SCP concentrations were shown in Figures 5.1, 5.2, 5.3 and 5.4.
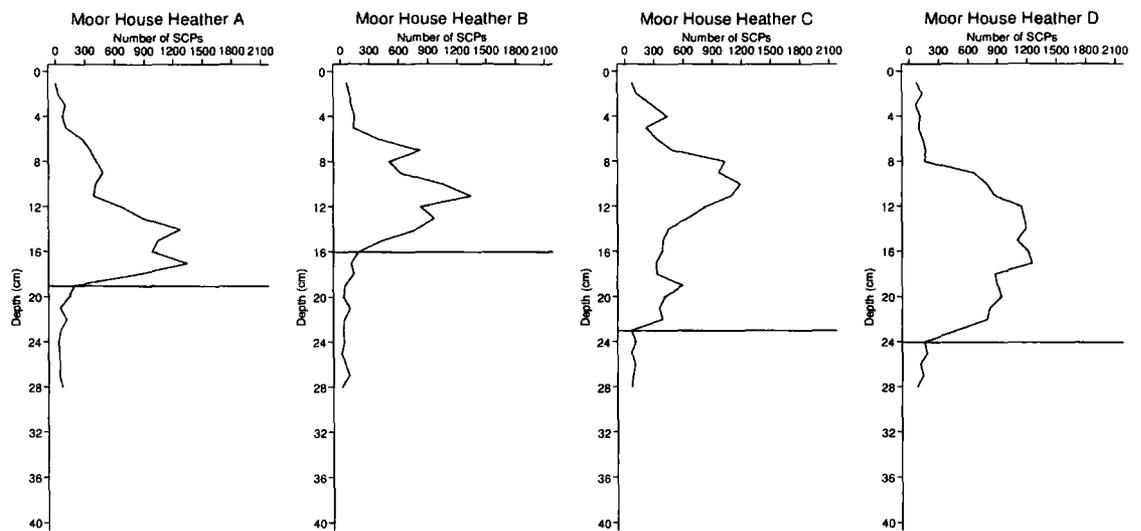
Figure 5.5 (A-D): The SCP profiles for the heather samples.

Figure 5.5 shows the SCP profiles from the four heather samples from Moor House. The 'take-off' (denoted by the red line) in Figure 5.5a is apparent at a depth of 19 cm. Here the numbers of SCPs sharply increase. The peat at this depth can be assumed to represent the 1950s increase in industrial activity within the Industrial Revolution. The peak in SCP concentration occurs 2 cm above the 'take-off', at a depth of 17 cm. This may well be representative of the 1970s – 80s peak in industrial activity in Britain and Ireland (Charman, 2002). There is a second peak, followed by a sharp decrease in the number of SCPs. This is likely to be linked with the stratigraphy, because at a depth of 15 cm (the start of the acrotelm) the peat becomes less dense towards the surface. Figure 5.5b shows the 'take-off' at a depth of 16 cm. Similarly to Figure 5.5a the SCP concentration sharply increases. The peak is much higher up the profile in Figure 5.5b, at a depth of 11 cm, and the decrease in SCP concentration is much later, at a depth of 5 cm. Both Figures 5.5a and 5.5b show a drop off in the number of SCPs at 5 cm, the stratigraphy indicates that this is where the living vegetation occurs in the sample. Figure 5.5c shows the 'take-off' at a depth of 23 cm. This is very early in the profile compared to Figures 5.5a and 5.5b, however, not in comparison to Figure 5.5d. There is no sharp increase in the number of SCPs until around 14 cm. The peak in SCP concentration is therefore, much higher in the profile at a depth of 10 cm, followed by a relatively steep drop in the number of SCPs. Figure 5.5d shows the profile is slightly different in shape from Profiles A, B and C. There is a steady increase in SCPs until the 'take-off', at a depth of 24 cm. This is very early in the profile. There is then a rapid

166

increase in concentration until a depth of 17 cm. Followed by a relatively steep decline in the number of SCPs until 8 cm, when there is a steady decline to the surface.

Figures 5.6 presents the SCP profiles from the moorland grass samples from Moor House. Figure 5.6a shows the 'take-off' is at the depth of 14 cm. There is then a steep increase in the number of SCPs. There are two peaks, the first at 10 cm and the second at 6 cm. After the second peak there is a steep decline in SCP concentration to the surface. This ties in with the stratigraphy, whereby the top 5 cm of the profile is representative of the living vegetation and is therefore less dense. Figure 5.6b shows a profile depth of 15 cm. The 'take-off' is very high up the profile, at the depth of only 5 cm. This is questionable because throughout the whole of the profile, SCP concentrations are relatively low. This may well be a result of counting of the SCPs, as there was a large amount of plant debris still remaining on the petri dish, which may have covered a number of SCPs (see Table A2.1, Appendix 2). Figure 5.6c shows the profile to be similar to Figure 5.6b, reaching a depth of 15 cm. The 'take-off' is at the depth of 12 cm. This is closer to the 'take-offs' from Figures 5.6a and 5.6d, however, the SCP concentration remains relatively low throughout the profile. This is not a result of plant debris on the petri dish, and therefore, remains unexplained. Similarly to the other moorland grass profiles, there is a decline in SCP concentration to the surface, which begins at 5 cm in depth. Figure 5.6d shows the 'take-off' in the profile to be at a depth of 12 cm. There is then a steep increase in the number of SCPs, to a peak at 8 cm. There is no decline in SCP concentration until around a depth of 3 cm, which again ties with the stratigraphy, whereby this is in the top vegetated layer of the profile.

The SCP concentrations are generally presented against the depth (Figure 5.5, 5.6 and 5.7); however they can also presented against cumulative dry mass as a result of the variations in the densities throughout the cores (Rose and Harlock, 1998) (Figure 5.8). A number of researchers have presented the SCP concentrations in units of 'number of particles per gram dry mass of sediment' (gDM^{-1}) (Rose et al., 1994; Rose et al., 1999). The results in gDM^{-1} are presented in Table A2.1 and summarised in Table 5.5.
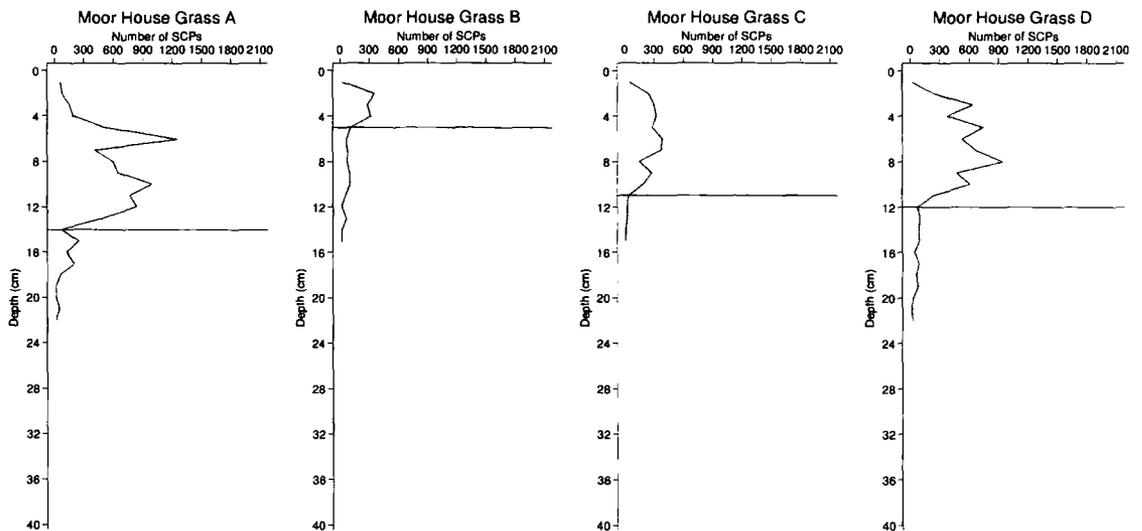
Figure 5.6 (A-D): The SCP profiles for the grass samples.

Figure 5.7 and 5.8 show the variations in the SCP profiles for Moor House, The Cheviot and Wessenden Head Moss. The mean heather sample is the most representative of Moor House and is considered here along with the mean moorland grass sample given that both The Cheviot and Wessenden Head Moss samples were moorland grass samples. The shape of the profiles were altered; however, varying the y-axis (Figure 5.7 and 5.8) did not affect the determination of depth of the 'take-off' and is therefore only useful for discussing the results in terms of rates of peat accumulation. Figure 5.7 shows the four SCP profiles to vary in the number of SCPs, the shape of the profile and the position of the 'take-off'. The Cheviot and Moor House profiles have fewer SCPs than the Wessenden Head Moss profiles. The Cheviot profile shows there to be little variation in the number of SCPs until a depth of 19 cm (the 'take-off'). The number of SCPs rapidly increases to a peak in concentration at a depth of 17 cm. There is then a decrease in the SCP concentration followed by a further increase to a depth of 11 cm, then a decrease to the surface.
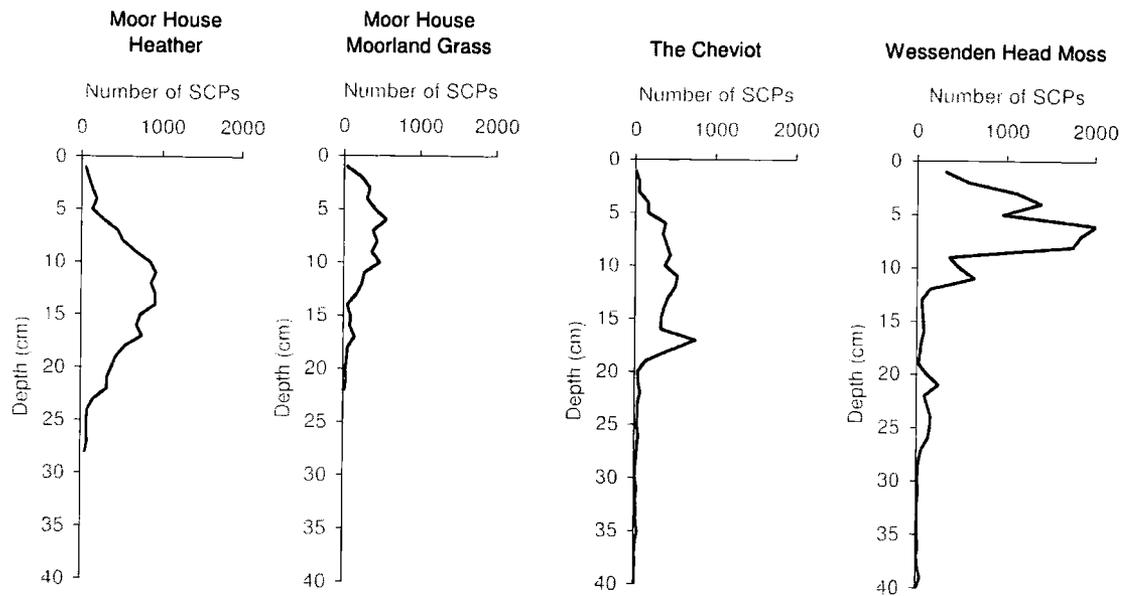
Figure 5.7: SCP Profiles of moorland grass samples from The Cheviot, Moor House and Wessenden Head Moss with depth (cm) on the y-axis.
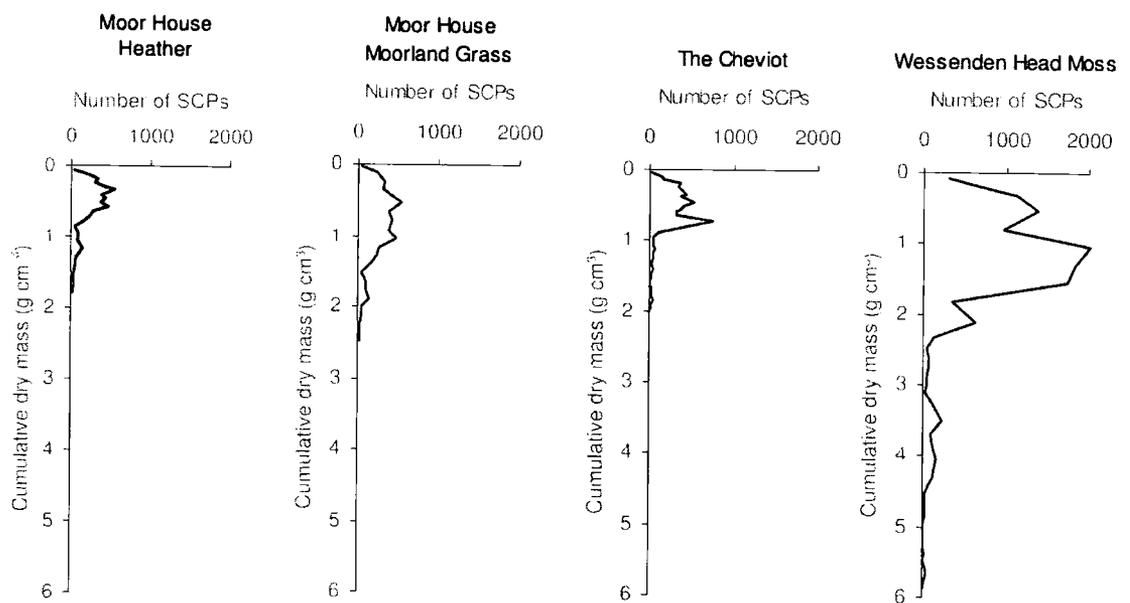
Figure 5.8: SCP Profiles of moorland grass samples from The Cheviot, Moor House and Wessenden Head Moss with the cumulative dry mass (g cm^{-3}) on the y-axis.

The Wessenden Head Moss SCP profile shows the largest concentration of SCPs. The 'take-off' in SCPs (12 cm) and the peak in concentrations (6 cm) are high in comparison to Moor House and The Cheviot, which indicate that the peat accumulation rates on Wessenden Head Moss are slower than the other sites. This was expected given that Wessenden Head Moss is adjacent to the large conurbations of Manchester and Sheffield, which has led to slower rates of peat accumulation in recent times due to the loss of *Sphagnum*. The cumulative dry density for the Wessenden Head Moss profile is much greater than the other sites, which may also be a result of the reduced *Sphagnum* cover. The SCP concentration then decreases from 4 cm to the surface.

All profiles show this decrease to the surface. There are two possible hypotheses for this: 1) the concentration of SCPs decreases to the surface as a result of the decline in SCP emissions since the late 1970s; or 2) the density decreases in the heather sample acrotelm above 8 cm whereby a reduction in the density of the peat and corresponding increase the peat accumulation rate (mm yr^{-1}) may result in a reduction in the concentration of SCPs. Figure 5.8 shows that the decrease in SCP concentration is not a result of decreases in density to the surface but a result of the decrease in SCP deposition since 1980s (Charman, 2002). This is further assessed in Figures 5.9, which show scatter plots between the main stratigraphy, i.e. division of the peat profile and SCP concentration. It is postulated that because the stratigraphy shows clear differences between the acrotelm and catotelm in both the heather samples and the moorland grass samples, the concentration of SCPs in the profiles may also be affected by the changes in density from the acrotelm and catotelm. The red points on the scatter plots represent the acrotelm (e.g. for the heather samples, a depth of 0 to 15 cm). The black points on the scatter plots represent the start of the catotelm (below 15 cm) to the 'take-off'.

Figure 5.9 shows the acrotelm (red) and catotelm (black) points to be clearly distinguishable. It was expected that the density of the acrotelm would be less than the catotelm. The relatively flat trend lines shown for the catotelms of both Moor House samples (Figure 5.9a and 5.9b), the acrotelm of the Moor House heather sample (Figure 5.9a) and the catotelm from the Wessenden Head Moss moorland grass sample (Figure 5.9d) indicate that the stratigraphy of the samples is independent of the density. The acrotelm of the Moor House moorland grass sample (Figure 5.9b) shows a sloping trend line and therefore is dependant on the stratigraphy as is both the actotelm and catotelm from The Cheviot and Wesssenden Head Moss acrotelm moorland grass samples

(Figure 5.9c and 5.9d). Variations are shown between the study sites, these are in the density of the peat, depth of the acrotelm and relationship between SCP concentration and changes in stratigraphy.
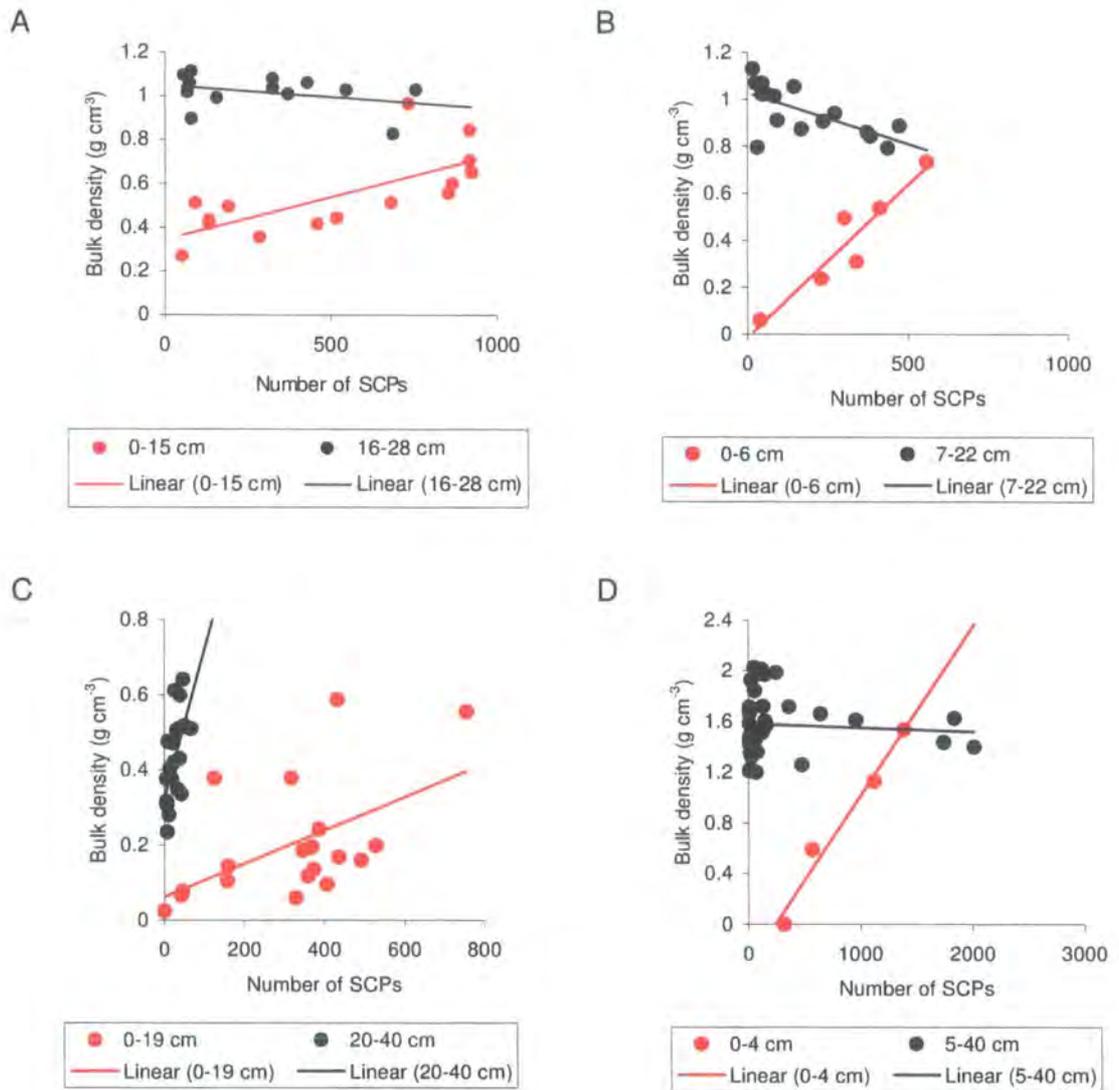
Figure 5.9: Scatter plots showing the relationship between: A) Mean of the Moor House heather samples. B) Mean of the Moor House moorland grass samples. C) The Cheviot moorland grass sample. D) Wessenden Head Moss moorland grass sample.

5.4   The spatial distribution of SCP deposition

Variations in SCP concentration at the three study sites correlate with regional patterns of SCP emissions in relation to the industry in the North of England (Figure 5.10). Figure 5.10 shows there are a greater number of fossil fuel power stations in the area of Wessenden Head Moss than near Moor House and The Cheviot. Moor House is shown to be on the edge of the $10 - 20,000$ gDM^{-1}, The Cheviot is thought to have < 10,000 gDM^{-1} and Wessenden Head Moss is thought to have between $20 - 40,000$ gDM^{-1} emissions. Based on the results in Table A2.1 the total concentration of SCPs in gDM^{-1} was calculated above the 'take-off'). Results show the concentrations in this study are greater than the emissions suggested by Rose and Harlock (1998); however, the relative spatial distributions are as expected, with The Cheviot having the lowest concentration and Wessenden Head Moss the greatest and Moor House in between.
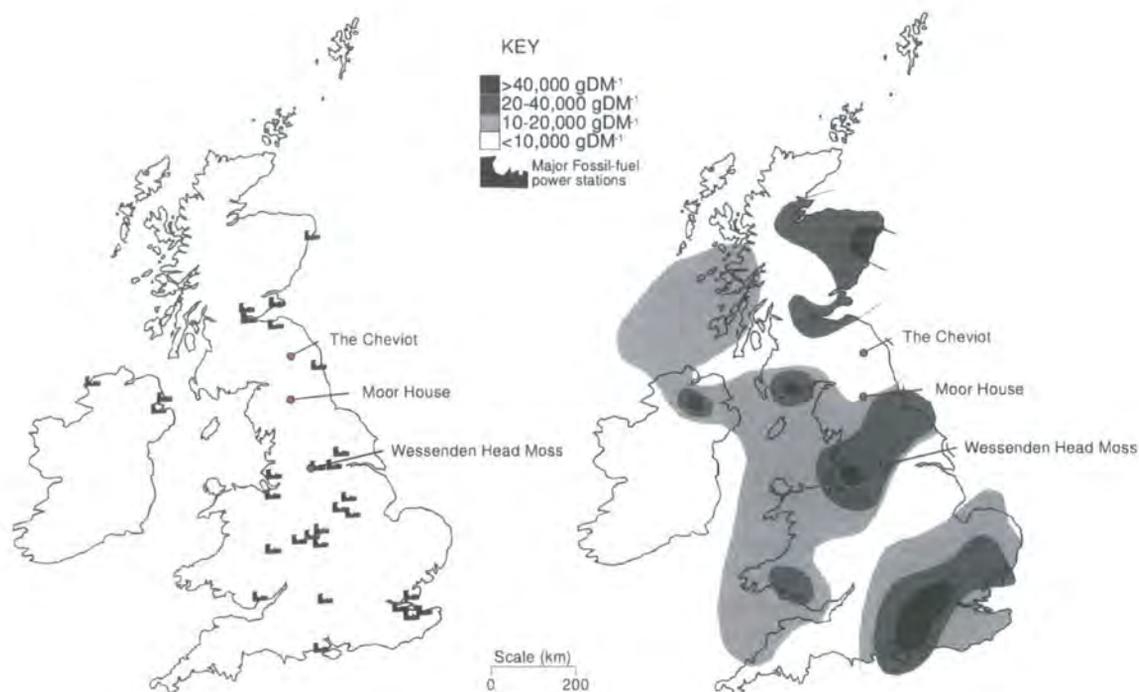
Figure 5.10: Location of the major fossil fuel power stations in Britain and their emissions (Adapted from Rose and Harlock, 1998).

5.5   Summarising the SCP data and results from peat accumulation rates

The SCP profiles constructed here do not ideally fit the typical SCP depth concentration curve (Figure 3.14). In all profiles there are multiple peaks in SCP concentration of

differing size, rather than the one single peak. In general however clear 'take-offs' in the profiles can be observed along with a clear decrease in SCP concentration towards the surface of the profile. The cause of these may be a result of local rather than regional industry. In order to evaluate this, the industrial history of the area needs to be known as well as the age of the peat at the different depths. Peat accumulation models can be used to infer age, based on ages obtained from other dating techniques (Charman, 2002). This is where the information from the typical SCP curve can be used to infer the 'take-off' in SCPs as being at the increase in industrial activity in Britain and Ireland, 1950.

However, as discussed in Section 1.2, peat accumulation rates are very variable. Based on knowledge of peat accumulation rates combined with the depth of 'take-off' in SCP concentration from the profiles studied in this research, it is possible to infer the age of the peak, secondary peaks, and the drop off in SCPs to the surface. In order to do this, a surface zero datum needs to be defined. This is done by examining the stratigraphy (Tables 5.1, 5.2 and 5.3). Living vegetation is not included in the calculations as it represents the present day growth. The zero datum line therefore starts at 6 cm, 5 cm, 15 cm and 2 cm respectively for Moor House heather, Moor House grass, The Cheviot grass and Wessenden Head Moss grass (Table 5.4). Table 5.4 shows the recalculated depths to the 'take-off' for each sample. From this information peat accumulation rates (mm yr^{-1}) were calculated (presented alongside rates from Tallis (1995) (Figure 5.11)).

Sample	Depth to 'take-off' (mm)	Rate of peat accumulation given a 1950 'Take-off' (mm yr^{-1})	Rate of peat accumulation given an estimated 1850 'Take-off' (mm yr^{-1})
Moor House Heather	180	3.3	1.2
Moor House Grass	90	1.7	0.6
The Cheviot Grass	60	1.1	0.4
Wessenden Head Moss Grass	80	1.5	0.5

Table 5.4: The depth of 'take-off' for each sample and the calculations of the peat accumulation rates since the 'take-off', first with an inferred age of 1950 and second, with an inferred age of 1850.

A

Tallis (1995a)

B

1950 'Take-off'

C

Estimated 1850 'Take-off'
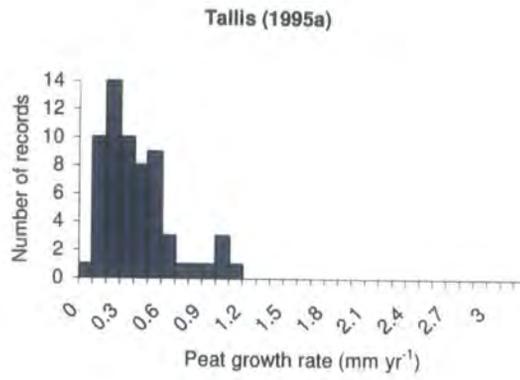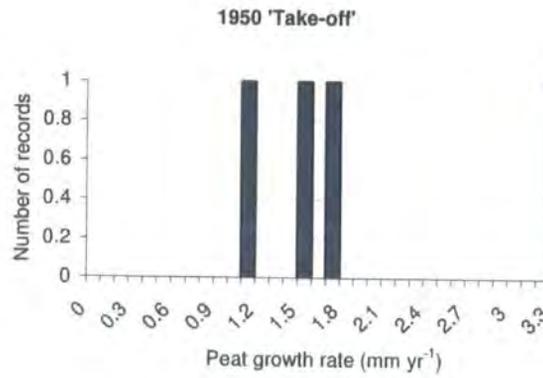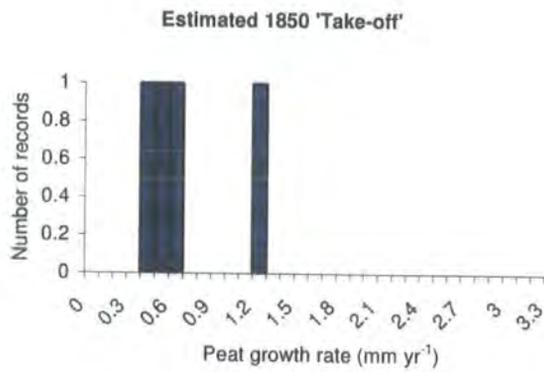
Figure 5.11: Histogram showing peat accumulation rates by Tallis (1995a) and peat accumulation rates with the 'take-offs' at 1950 and estimated 1850.

The table shows variability in the depth of the 'take-offs'. Using the inferred age from 1950 the peat accumulation rates vary from 1.1 to 3.3 mm yr^{-1}. These rates are generally too high for blanket peat. However, if the age of 'take-off' is assumed to be 1850 (the start of the Industrial Revolution rather than where industrial activity increased within the Industrial Revolution), the rates become more realistic, varying from 0.4 to 1.2 mm yr^{-1}. These accumulation rates are presented alongside those from Tallis (1995a) (Figure 5.11).

There are a number of concerns with the estimated 1850 date of the 'take-off': 1850 is supposed to represent the start of the accumulation of SCPs, not the 'take-off', and; past researchers have always discussed the 1950 'take-off' in SCP concentration, including Moor House profiles (e.g. Rose *et al.*, 1995; Garnett and Stevenson, 2000; Garnett *et al.*, 2000; Yang *et al.*, 2001b). Below the 'take-offs' however the number of SCPs are low and given the size of the SCPs it was thought that there could be some hydrological and mechanical processes causing vertical movement of the particles within a profile. A number of researchers have looked at the movement of fly-ash particles (Punning and Alliksaar, 1997) and pollen grains (Clymo and Mackay, 1987) but found little movement. Yang *et al.* (2001a) also stated that it is reasonable to assume that plant roots do not disturb SCPs in peats. Another consideration relates to local industrial activity which may have lead to peaks, for example, in 1870 there was a peak in metal mining in NE England which may have produced a local source rather than regional, which would have had impacts on the 'take-off'. Due to the uncertainty of the SCP 'take-off', and given SCPs are time markers and often used in conjunction with other techniques, an independent dating technique is needed to confirm the results from the SCP analysis. For example, ^{210}Pb is useful in dating peats less than 200 years old and bomb carbon, ^{241}Am and ^{137}Cs are useful in dating peats less than 50 years old. Garnett and Stevenson (2004) showed ^{14}C bomb records and SCP analysis both could be used in conjunction to date the surface layers of blanket peat, though there was some uncertainty since the profile of ^{14}C concentration with depth did not accurately follow the known atmospheric record and other interpretations of the ^{14}C results were possible.

The variability in the peat accumulation rates between the acrotelm and the catotelm is important. Figure 5.8 shows variability in the densities of the peat at the three sites. The cores were removed from uneroded sites and are therefore representative of uneroded peat profiles in the three areas. The heather sample at Moor House and The Cheviot

sample was less dense than the moorland grass sample at Moor House and the Wessenden Head Moss sample. This therefore affects the depth of the 'take-off' (Figure 5.12). The less dense peat (deeper actotelm) samples were those with the greatest depth to the 'take-off'. Despite this those peats which are most dense are shown to have accumulated at generally a rapid rate for a 1950 'take-off' and therefore given SCPs are time markers, an independent dating technique required to be used in conjunction. These results; however, provide the best estimate of peat accumulation rates.
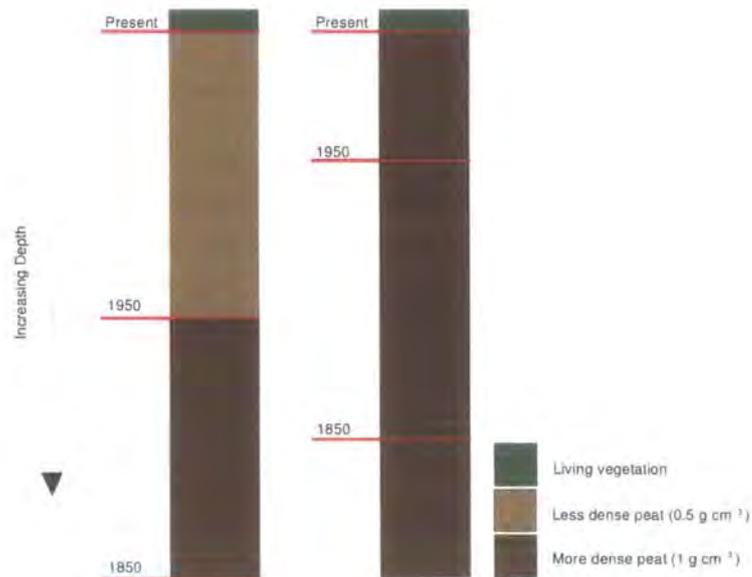
Figure 5.12: Simple diagram showing the depths of the SCP 'take-offs' depending on the density of the peat.

5.6   Implications for Terrestrial Carbon Storage

Knowledge of the rates of peat accumulation are important within upland blanket peatlands given that much carbon is stored within peatlands and erosion of these areas leads to a loss of important carbon stores (Garnett *et al.*, 2000). Given that SCPs can be used to help in the study of terrestrial carbon storage, using the 'take-off' in SCP concentration as a time horizon it is possible to calculate the amount of C deposited since this time. Table 5.5 shows the depths of 'take-off' against the C concentration for the three study sites. Also included is the amount of C Garnett *et al.* (2000) calculated from research he carried out also at Moor House and Upper Teesdale NNR, in a different area of the reserve. The method used for the C determination was the same as that by Garnett *et al.* (2000). This method assumed the C concentration in peat to be 50

% of the dry mass. Prior to this research a test was carried out in C determination using another well-known method. This method was by Bol *et al.* (1999) and looked at the bulk density and LOI results (see Bol *et al.*, 1999). The results showed both methods to produce similar C concentrations and therefore in order to be comparable to Garnett *et al.*'s research at Moor House his method was adopted for this research.

The C content in this research at Moor House for the moorland grass and heather sample lies between that of Garnett *et al.* (2000). The C concentration is shown to be far higher from Wessenden Head Moss than Moor House and The Cheviot (which showed to have the lowest concentration). This is likely to be a result of the greater density of the peat at this site in comparison to the other sites.

Study area	Cover type	Depth of SCP 'take-off' (cm) (not including living vegetation)	C in peat above the SCP 'take-off' (kg m^{-2})	Garnett *et al.* (2000) C in peat above the SCP 'take-off' (kg m^{-2})
Moor House	Heather	18	8.9	
	Grasses	9	5.5	5.4
The Cheviot	Grasses	6	2.4	
Wessenden Head Moss	Grasses	10	10.9	

Table 5.5: Results of carbon storage above the 'take-off' for the SCP profiles from Moor House, The Cheviot and Wessenden Head Moss, a profile by Garnett *et al.* (2000) at Moor House.

5.7   Summary

Peat type and vegetation type appear to influence SCP concentrations within the profile. The stratigraphy of the samples showed to have an effect on the SCP concentration and therefore changes in SCP concentrations were influenced by changes in the stratigraphy as well as changes in SCP deposition.

It is hypothesised that the initial 'take-off' in SCPs may be an approximate 1850 'take-off' rather than 1950 given the rates of peat accumulation, although there is a need for dating the recent peats to test this. The proposed 1850 'take-off' in SCP concentration estimates rates of peat accumulation at the three sites to vary from 0.4 mm yr^{-1} to 1.2

mm yr^{-1} (similar to rates calculated by Tallis (1995a)). This is interesting when estimating dates of: specific peat horizons; peat erosion; and the removal of the most recent layers of peat (see Chapter 7). Given the uncertainties with the rates of peat accumulation estimated from the SCP concentration, the rates suggested by Tallis (1995a) are used in Chapter 7 to estimate the onset of erosion.

Within and between the Moor House blocks local variations in the SCP profiles were noticeable and are interesting in that it highlights that SCP concentrations differ greatly over very small areas. These findings imply there is a significant potential uncertainty in the SCP methodology when assessing recent peat accumulation. This has large implications for the estimation of carbon storage in upland peat when point samples are upscaled to larger areas.

At the regional scale, variations in the SCP concentrations were identified. The spatial distribution of SCP was greatest on Wessenden Head Moss and the lowest on The Cheviot. This was expected since Wessenden Head Moss is located between the large conurbations of Sheffield and Manchester.

The results from this study can also be used to estimate dates of active peat deposition and used when considering the sediment balance on interfluves and sediment budgets, for example, the overall sediment balance. Chapter 6 addresses interfluve erosion and estimates the loss of peat from the interfluve areas at Moor House.

6.0   INTERFLUVE PEAT LOSS BY SOIL EROSION

6.1   Scope of Chapter

This chapter highlights the differences in runoff and sediment production of interfluve areas. Section 6.2 discusses the laboratory rainfall simulation experiments. Section 6.2.1 shows the experimental set-up and Section 6.2.2 presents the results. Section 6.3 discusses paired rainfall simulation experiments on the Moor House exclosure plots and Burnt Hill gully system. The experimental design is shown in Section 6.3.1 and the results in Section 6.3.2. Section 6.4 discusses the throughflow experiment; a laboratory experiment designed to explain findings from Sections 6.2.2 and 6.3.2. Section 3.5 shows a conceptual model of runoff production in upland blanket peat and finally Section 3.6 summarises.

6.2   Laboratory Experiment

The laboratory experiment undertaken addresses the effects of no grazing and simulated grazing and burning on an intact peat block removed from Moor House. The experiments were used to test the effects on runoff production and sediment yield of:

- o   The order in which the rainfall was applied.
- o   Differing times between experimental runs.
- o   Differing slope angles.

The results were used to save time in the field and increase the accuracy compared to field experiments. Direct comparisons between the laboratory experiments were made to the field experiments.

6.2.1   The Experimental Set-up

This set of experiments used an intact peat block (1 m × 0.5 m) covered with predominantly *Deschampsia flexuosa* and *Eriophorum angustifolium* vegetation, which was removed from the field at Moor House. The block was supported in a box to prevent the peat from becoming disturbed. Prior to being placed in the box a sample of the peat was cut from the block to be analysed further in the laboratory. This block was then placed inside an open box and covered in a sheet of plastic in order to catch all runoff from the peat block (Figure 6.1). The box was designed so the peat block could

be inclined at differing slope angles. Aluminium runoff troughs were inserted in the front of the peat block at depths of 1 cm, 5 cm and 10 cm. Containers were placed below each runoff tray and below the plastic sheet. The 'drip-type' simulator was then positioned over the top of the block (Figure 6.1) at a height of 2 m to allow the velocity of the drops to be as close to that of natural rainfall as is possible.
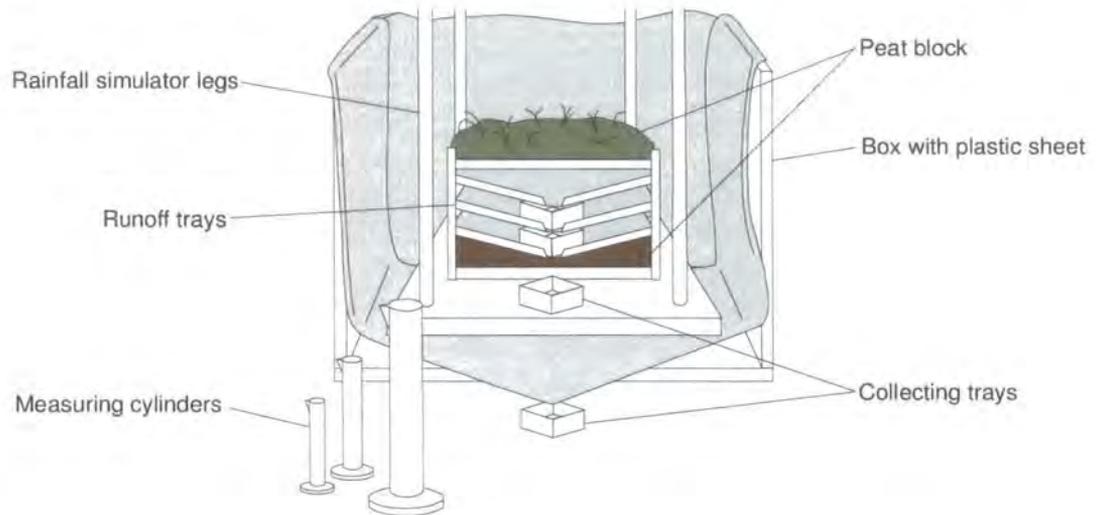
Figure 6.1: The set up of the laboratory peat block. The block is enclosed in the box to enable the base flow to be collected.

The laboratory peat block was first inclined at a slope of 2.5°. Rainfall simulations at 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} intensities were applied to the block in its natural state. Firstly the 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} runs were carried out with a day in-between each run to allow for the plot to drain (the 'discontinuous' experiments). Following the termination of rainfall the runoff was still collected until it also ended, which took less than 1 hour for each run. A continuous set of runs was then carried out at 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} intensities with 1 hour between each run (the 'continuous' experiments). This was carried out to see if there were any differences in runoff volume between the discontinuous and continuous set of runs. It was thought that there would be little difference in the results as sufficient time was left between runs to allow for the plot to drain. The continuous runs were similar to the procedure carried out in the field. The benefit of doing continuous runs of 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} intensities was that it would replicate to some extent natural storm conditions whereby rainfall ramps up in intensity as the storm builds. It was therefore decided in the field to

use the 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} intensity pattern. Holden and Burt (2002b) altered the order of the runs by choosing a decreasing series (12 mm hr^{-1}, 9 mm hr^{-1}, 6 mm hr^{-1} and 3 mm hr^{-1} intensities) in order to reduce the effect of any antecedence, which might bias mean values. This was therefore tested in the laboratory to see if there were any differences in mean values when the pattern was altered.

The slope angle was then increased to 5° and a discontinuous set of runs of 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} intensities followed by a continuous set of runs of 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} intensities were carried out. It was decided not to replicate all the tests carried out on the 2.5° plot as the results from that would be sufficient to evaluate any differences. The slope angle was then increased to 10° and the same discontinuous and continuous set of runs undertaken. These slope angles were chosen because they are typical of slope angles at Moor House (e.g. the field exclosure plots are established on varying slope angles (see below)). These angles are also important slope angles in terms of erosion because 2.5° seems to be representative of the transition between Type 1 and Type 2 Dissection of the blanket peat.

The vegetation on the block was then manually cut (close cropped) to represent a grazed state and set at a slope angle of 2.5°. A continuous set of runs was then carried out. This was followed by the block being burnt at the surface (using a blow torch) and the same set of runs carried out once more. The ungrazed, grazed and burnt states represent the different management practices of many blanket peat moorlands in Britain and are tied in with the long-term monitoring of the thirteen experimental plots at Moor House, for example Knock Fell Plot (grazing) and Hard Hill Plots (monitoring grazing and long-term rotational burning) (Marrs *et al.*, 1989).

Experimental rainfall intensities were selected to be representative of storm rainfall events at Moor House because it is the larger rainfall events which are responsible for the majority of peat loss (Evans and Warburton, 2005). Large storm events are becoming more frequent in the uplands. For example at Moor House and Upper Teesdale NNR, North Pennines in 2002, 50 mm of rain fell in just 60 minutes (Figure 3.6); on Dooncarton Mountain, SW Ireland in 2003; 80 mm of rainfall fell in 45 minutes; in the Shetland Isles in 2003, 100 mm of rain fell in 180 minutes; in the Northern Lakes in 2004, 110 mm of rain fell in 60 minutes; and in the North York

Moors in 2005, 70 mm of rain fell in 165 minutes. Although these are extremes, there is a range of larger events in the 10 – 30 mm hr^{-1} range which occur in the Moor House record (Figure 3.7). Therefore intensities of 12, 16, 20 and 24 mm hr^{-1} were selected in these experiments. This range of values is also useful for examining the response of peat in the mid range between the only two other studies of rainfall simulation on peat by Labadz (1988) and Holden and Burt (2002b).

Runoff production was measured manually every five minutes during the simulation at the surface and two depths and sediment-laden runoff from the surface was retained for sediment concentration determination. Simulations lasted between 90 and 110 minutes depending on the applied rainfall intensity, which was the time taken to allow steady-state runoff to be achieved. The 'steady-state' runoff is achieved when runoff volumes become stable for at least 15 minutes (steady or fluctuating over a mean rather than increasing or decreasing). Philip (1957) produced a theoretical infiltration curve allowing the mean of the quasi-steady state infiltration values to be identified. This can also be applied to runoff values. Table 6.1 presents the time taken to reach steady state runoff (average of 72 minutes for all the plots). Generally the greater the intensity the shorter the simulation as steady-state runoff was achieved over a shorter time period. Rather than using mean and peak in runoff and infiltration rates to characterise the hydrological response, results are more instructive when using 'steady-state' values (Holden and Burt, 2002b; 2003a). The block was covered following each simulation in order to keep it in a moist state. This is necessary to minimise drying and shrinking of the block, which may affect the results.

Depth (cm)	Rainfall Intensity (mm hr^{-1})				
	12	16	20	24	Mean
1	83	74	67	63	72
5	84	70	67	55	69
10	83	74	74	72	76
Mean	83	73	69	61	72

Table 6.1: The mean time to reach steady state runoff (minutes).

6.2.2 Results of Experiments on Runoff and Sediment Production

The results are discussed in terms of runoff production, suspended sediment concentration and soil conditions. The ungrazed laboratory peat block is presented, followed by the grazed and burnt laboratory peat blocks.

Ungrazed Block

Figure 6.2 shows the results of the ungrazed laboratory peat block. Runoff production and sediment concentration vary with differing rainfall intensity, time between runs, order of the runs and slope angle (Figure 6.2). Figure 6.3 compares the steady-state runoff rates of the experiments, e.g. discontinuous and continuous (varying time between runs, 1 day and 1 hour respectively), order of runs (12, 16, 20, 24 and 24, 20, 16, 12) and differing slope angles (2.5°, 5°, 10°). Figure 6.4 graphically presents a summary of the water balance equation, which is shown to have an effect on runoff production. The water balance equation for the laboratory peat block is shown in Equation 6.1 where the output (O) is the dependent on the sum of not only the rainfall input (I), but also less loss (L) and storage (S)

$$O = I - L - \Delta S$$
<div align="right">Equation 6.1</div>

Figure 6.2 shows the 5 cm depth runoff rate to be greatest in all the experiments. This is thought to be due to the dense vegetation mat allowing more rainfall to infiltrate into the peat rather than flow over the surface (approximately 70 %) (Figure 6.3a). Once beneath the surface the water moves laterally as throughflow within the 3 cm acrotelm and is collected on the 5 cm runoff tray. The ungrazed experiments at 12 mm hr^{-1} and 16 mm hr^{-1} rainfall intensities show the runoff rates to increase in parallel with the rainfall intensity (Figure 6.3), indicating that the rainfall rate is having a direct impact on the runoff rate.
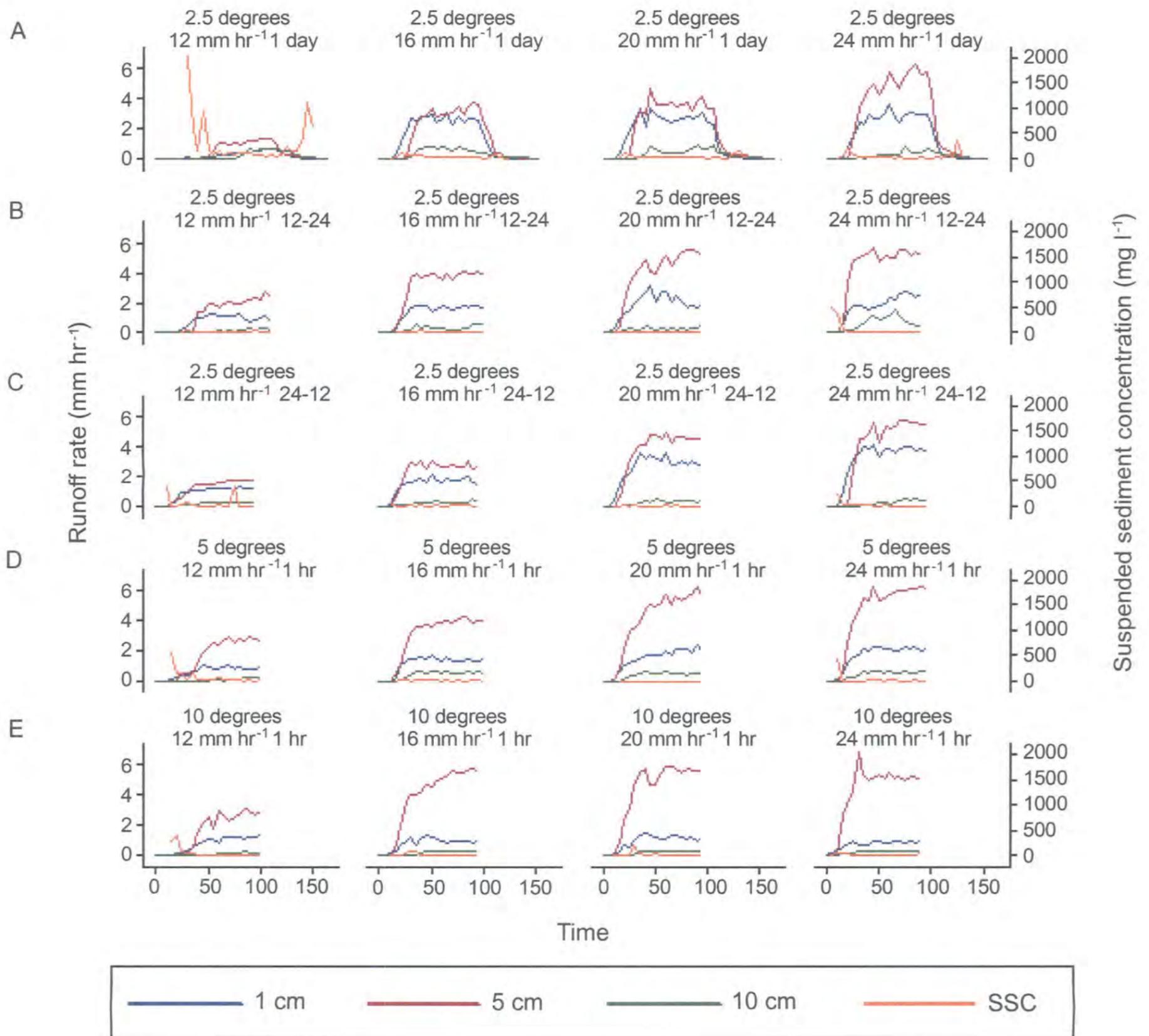
Figure 6.2: Laboratory rainfall simulation results from the Moor House intact peat block in an ungrazed state, A) Slope angle of 2.5°, order of runs were 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} and between runs the block was left to recover for 1 day (discontinuous). Runoff production was measured after the rainfall had terminated, until the runoff terminated. B) Slope angle of 2.5°, order of runs were 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} and between each of the runs the block was left to recover for 1 hour (continuous). C) Slope angle of 2.5°, order of runs were 24 mm hr^{-1}, 20 mm hr^{-1}, 16 mm hr^{-1} and 12 mm hr^{-1} and continuous. D) Slope angle of 5°, order of runs were 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} and continuous. E) Slope angle of 10°, order of runs were 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} and continuous.
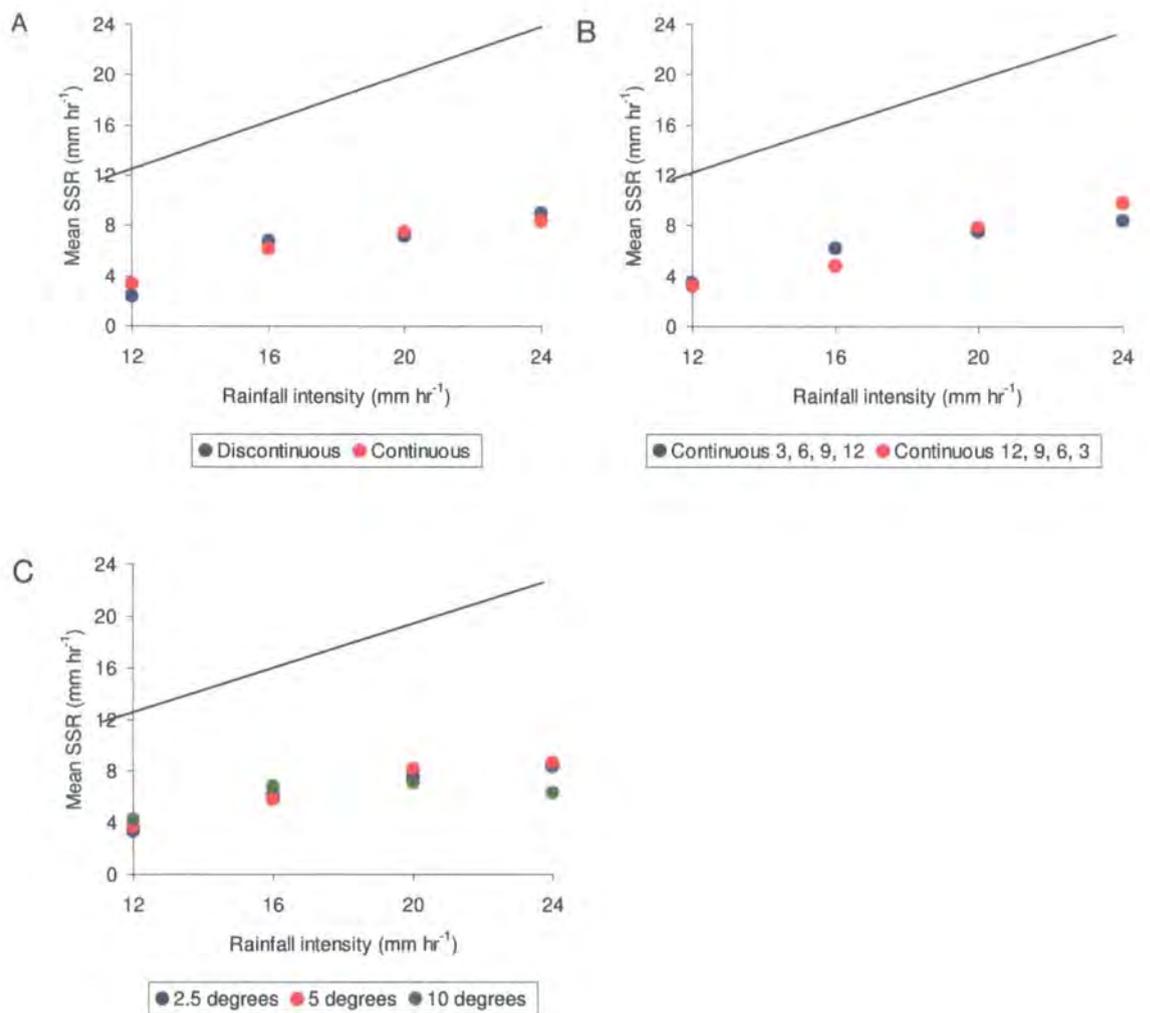
Figure 6.3: Graphs showing the mean steady-state runoff against rainfall intensities for each of the ungrazed laboratory peat block experiments, A) discontinuous and continuous, B) continuous 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1}, 24 mm hr^{-1} and 24 mm hr^{-1}, 20 mm hr^{-1}, 16 mm hr^{-1}, 12 mm hr^{-1} and C) continuous 2.5°, 5° and 10°. The 1:1 (O = I) line is shown.
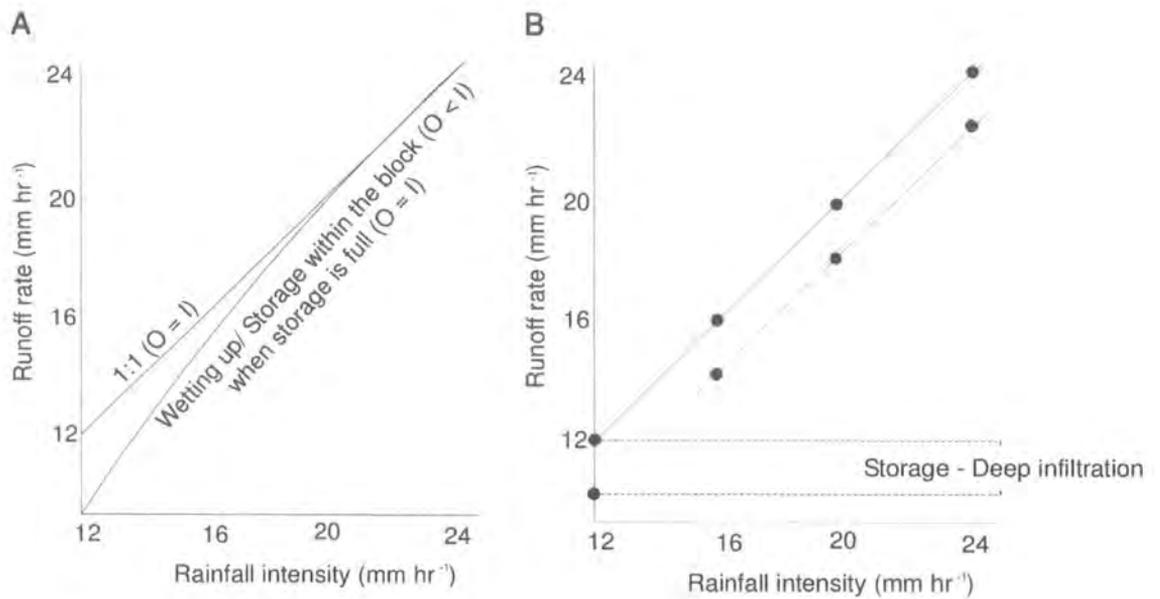
Figure 6.4: Summary of the water balance. A) Example of the possible trend lines in the results and what they signify. B) Example showing how the storage within a block/ plot can be calculated.

It is well known that the infiltration capacity declines through a storm event as the soil wets up. This is the effects of surface sealing whereby a thin surface zone develops during the course of a rainfall event due to the breakdown of the soil structure by the impacting raindrops (Burt and Slattery, 1996; Ward and Robinson, 2000). This appears to be the case throughout these experiments until the SSR is reached (Figure 6.3 and 6.5a).

Unlike the 12 mm hr^{-1} and 16 mm hr^{-1} rainfall intensities, the 20 mm hr^{-1} and 24 mm hr^{-1} rainfall intensities show the infiltration rates to increase as the rainfall intensity increase. There are a number of possible explanations for this. For example, Figure 6.4 shows how the effects of storage or deeper percolation can affect the runoff rate; Bowyer-Bower (1993) in a semi-arid soil observed an increase in infiltration at the higher rainfall intensities and thought it to be the result of the greater energy of the high intensity rainfall (Figure 6.5b). Holden (2000) envisaged similar processes would occur on blanket peat. Figure 6.5 shows that during the individual experiments the infiltration rate decreases but as a whole the infiltration rate increases. Ponding can occur on the surface of the peat particularly at higher rainfall intensities because the rainfall does not have sufficient time to infiltrate into the peat. The hydraulic head of the increases the

infiltration rate. Hawkins (1982) demonstrates numerically, mean infiltration rate over a 0.5 m^2 plot, which is inherently non uniform, will increase with rainfall intensity simply because there is a greater flux of water through the parts of the plot surface that have higher relative infiltration capacities.

It is thought that the increase in infiltration rate at higher rainfall intensities in the ungrazed laboratory peat block may be a result of ponding on the surface of the peat as this was evident throughout the course of the experiment at the higher rainfall intensities.

It was interesting to find that the $2.5°$ discontinuous experiments (where the block is left to drain for a day to fully drain) and $2.5°$ continuous experiments (where the block is left for 1 hour to drain or until there was no runoff from the trays) showed very little difference in runoff rates from the three depths and at all four rainfall intensities (Figure 6.3a). This indicates that more than one run can be carried out over a day, which is important for the field experiments. It was thought that the water table height would rise during the course of the experiment and may affect the results of the runoff rates. This however is not the case because the 24 mm hr^{-1} and 20 mm hr^{-1} 1 cm runoff rates are greater where the order of runs is reversed. The 5 cm runoff rate is still the greatest and shows very little difference with the previous set of runs. If runoff rates were affected by the order of application, in this case, the 3 mm hr^{-1} runoff rate would be higher. Figure 6.3b shows there was virtually no difference in the mean steady state runoff regardless of the order. The 1 cm runoff rate and 10 cm runoff rates are similar to the runs starting with 12 mm hr^{-1} rainfall intensity but the 5 cm runoff is lower. This therefore showed that as long as the block is left to drain for a sufficient period of time (>30 minutes) then the order in which the intensities are applied has little bearing on the results. Considering this, it was decided that starting with 12 mm hr^{-1} and building up to 24 mm hr^{-1} was preferable because it follows the pattern of natural rainfall most closely.

A
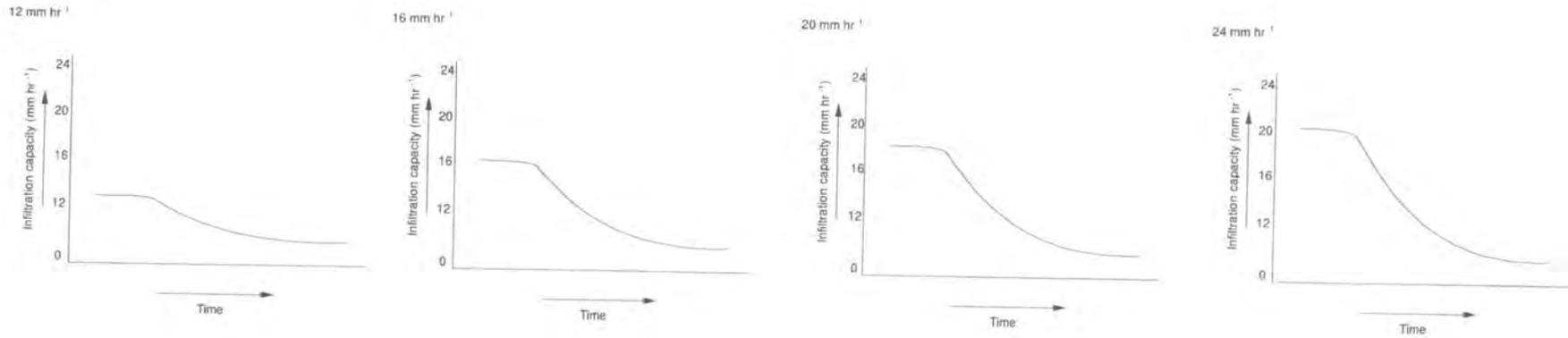
B
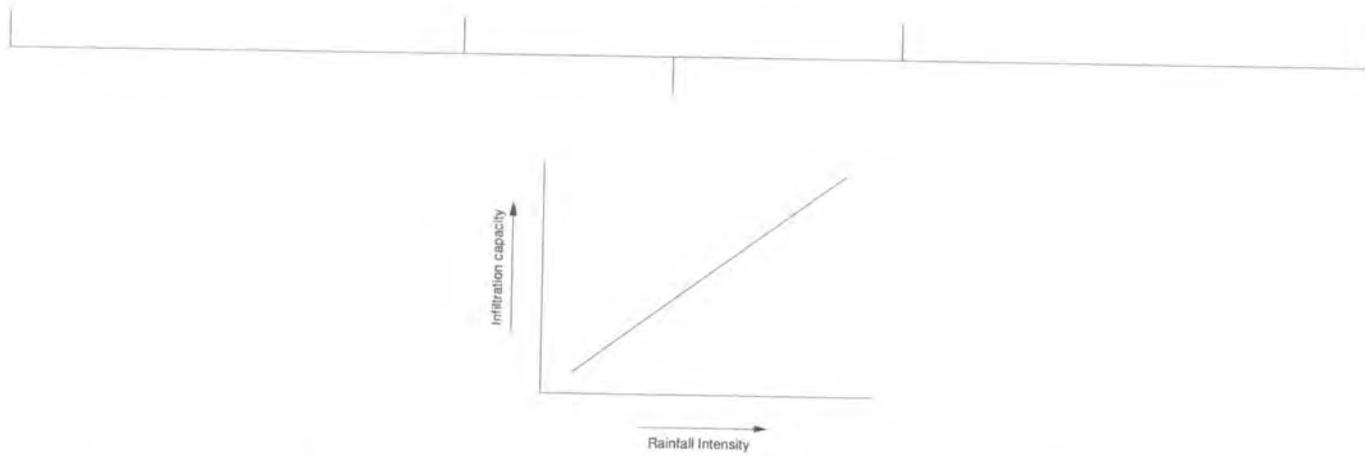
Figure 6.5: Simple diagram showing the effects on infiltration during the course of the experiments.

Differing slope angles of 2.5°, 5° and 10° were compared and the results showed the 2.5° had the highest surface runoff and 10° the lowest, which was not expected as it was thought that as the slope angle increased the runoff rates would increase as there would be less time for the surface water to infiltrate into the peat and therefore would run off the surface. The 5 cm runoff rates were relatively high throughout all the experiments and increased with rainfall intensity. The 5° and 10° slope angles showed similar runoff rates at the 5 cm depth and very little differences in the runoff rates were observed between the 2.5° and 5° slope angles for the 1 cm and 10 cm depths (Figure 6.2 and 6.3c). Figure 6.3c shows the mean steady-state runoff rates to increase in parallel with the 12 mm hr^{-1} to 16 mm hr^{-1} rainfall intensities then begin to stabilise from 20 mm hr^{-1} to 24 mm hr^{-1} where approximately 60 % of the rainfall was infiltrating into the plot at the 24 mm hr^{-1} rainfall intensity. The 5° slope angles show to have the highest steady-state runoff rate at the higher rainfall intensities and the 10° the lowest. This is because at 24 mm hr^{-1} the mean steady-state runoff rate was lower than both the 16 mm hr^{-1} and 20 mm hr^{-1} runoff rates.

The SSCs from the small-scale experimental block are generally low because the vegetation cover is intact and sediment cannot be easily entrained. This is because the slope length is short (1 m) and there is little concentration of flow.

Figure 6.6 shows the mean suspended sediment concentrations from the ungrazed block. The initial flush of sediment from the first run (Ungrazed, 2.5°, 12 mm hr^{-1}, 'Discontinuous') is not included in Figure 6.5a because the mean SSC was 369 mg l^{-1} and the result of loose sediment on the surface. This was an anomaly in comparison to subsequent runs, where the mean SSC did not exceed 84 mg l^{-1}. The block was thought to have been prepared for subsequent runs. At the start of each experiment there was an initial flush of sediment, though much smaller than that observed from the first run (Figure 6.6) and in addition as the rainfall intensity increased towards the end of the experiments sediment production occurred (Figure 6.6 and 6.7).
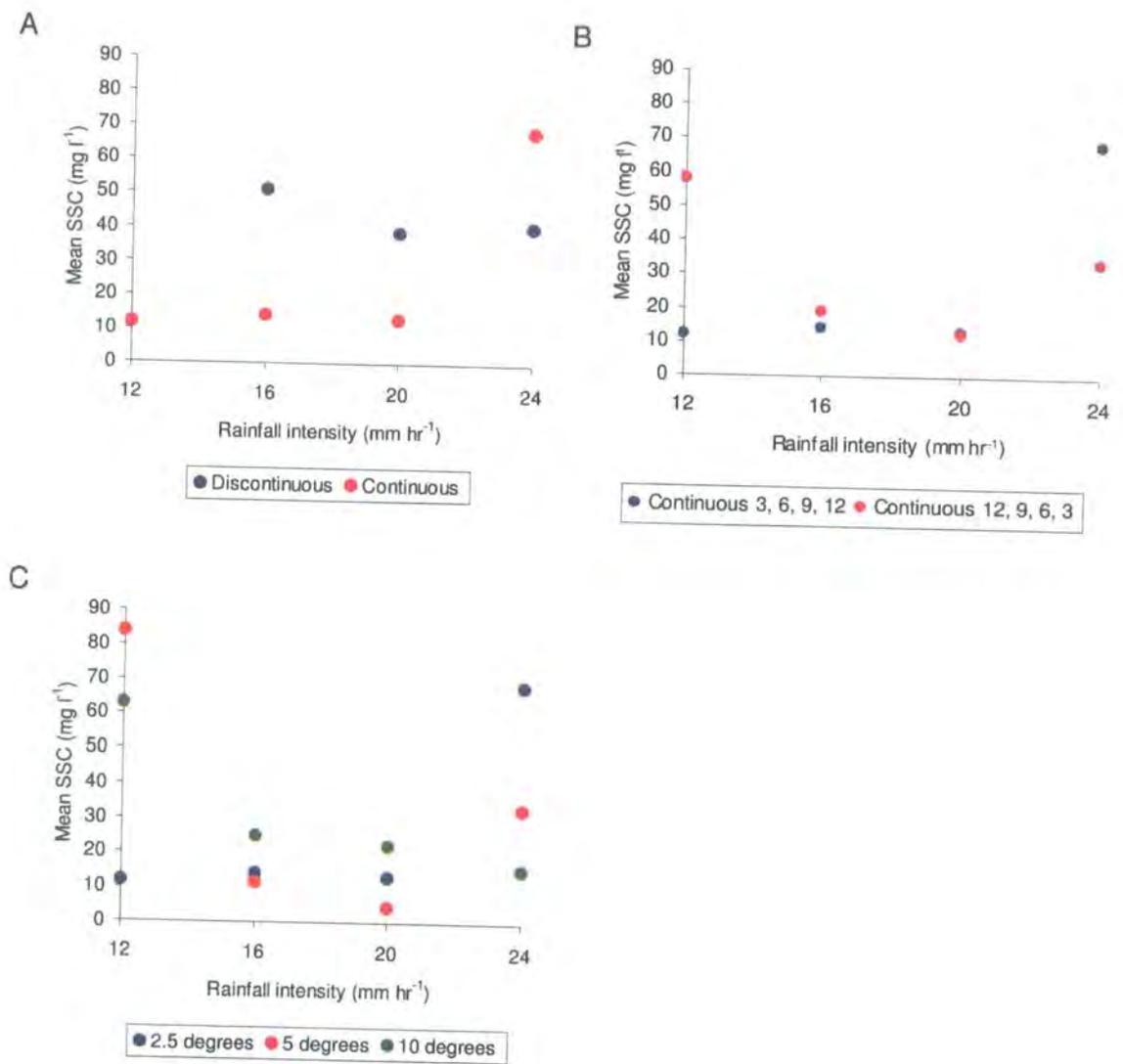
Figure 6.6: Graphs showing the mean suspended sediment concentration against rainfall intensities for each of the ungrazed laboratory peat block experiments, A) discontinuous and continuous, B) continuous 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1}, 24 mm hr^{-1} and 24 mm hr^{-1}, 20 mm hr^{-1}, 16 mm hr^{-1}, 12 mm hr^{-1} and C) continuous 2.5°, 5° and 10°.
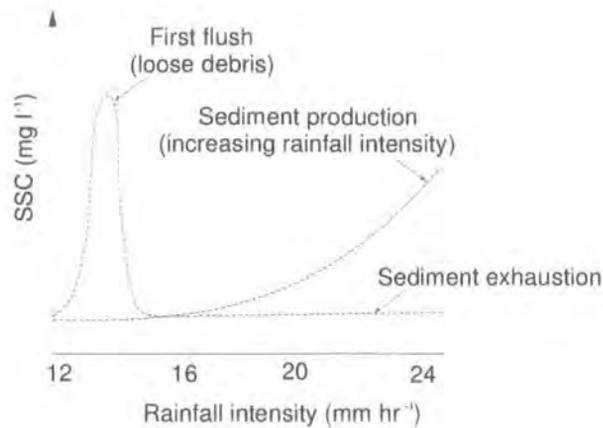
Figure 6.7: Simple diagram showing the controls on sediment production during an experiment.

Figure 6.7 shows a simple diagram explaining the initial flush of sediment, resulting from the detachment of loose debris at the start of an experiment. This is followed by sediment exhaustion due to the reduced supply. As the rainfall intensity then increases sediment production occurs and further detachment of sediment.

At the 10° the SSC and 10 cm runoff remained low. Two important observations that were made from Figures 6.2 and Figure 6.6b and 6.6c was that the order in which the runs are carried out has no implication on the SSC and that changes in the slope angle do not appear to influence the SSC.

Table 6.2 presents the slope angles, stratigraphies, bulk density, dry bulk density, moisture content and loss on ignition of the laboratory and field experiments. The measurements on the laboratory peat block are comparable with the field experiments in terms of soil moisture contents of the upper horizons (0 – 10 cm). The soil moisture content is slightly higher between 5 – 10 cm (83 %) than 0 – 5 cm (80 %), which may explain why the 5 cm runoff is consistently the highest (especially in the ungrazed experiments).

Site	Slope (degrees)	Depth (cm)	BD (g cm⁻³)	DBD (g cm⁻³)	% MC	LOI (%)	Written description
Laboratory Peat Block	2.5, 5, 10	0 to 5	0.74	0.52	80.39	99.47	*Eriophorum vaginatum* vegetation, brown peat with lots of roots
Experiment		5 to 10	0.51	0.09	82.91	97.75	Dark brown/ black with with some roots, smooth
Moorland Grass Exclosures							
Knock Fell Inside	3	0 to 5	2.64	1.01	61.80	85.66	Thick vegetation root mat, db/ b soil, high root content, plasticity high, large stones occasionally, slightly gritty, brown mottling in places, typical brown earth
		5 to 10	2.47	1.00	59.41	86.37	Stones, up to 15 cm, platy and angular, fine db mottled matrix. Some gritty sand lenses
Knock Fell Outside	5	0 to 5	1.82	0.32	82.51	98.94	2 cm turf and root mat grades into black 3 cm peaty soil horizon with fine crumb structure and many fine rootlets
		5 to 10	3.06	2.01	34.21	72.70	Brown clayey silt, gritty texture
Silverband Inside	4	0 to 5	1.19	0.18	84.47	99.75	Dense *Eriophorum vaginatum*, grasses, flowering, soil dark peat
		5 to 10	1.43	0.21	85.60	99.73	Reddish peat with dense root system, similar to Burnt Hill Outside
Silverband Outside	3	0 to 5	0.65	0.06	90.92	99.94	Saturated *Sphagnum* / leafy, *Eriophorum angustifolium*, tan brown peat with lots of roots
		5 to 10	0.67	0.08	88.29	99.75	Saturated *Sphagnum* / leafy, tan brown peat with lots of roots
Cottage Hill Inside	15	0 to 5	0.70	0.13	82.10	99.47	Very dense vegetation mat, *Sphagnum* and grass, peat beneath, moderataly dark
		5 to 10	0.51	0.08	84.80	99.72	Lighter peat, few roots extending below the acrotelm
Cottage Hill Outside	15	0 to 5	1.82	0.32	82.51	98.94	Peat very similar to that inside, more rootlets extending deep into the peat, vegetation mat one third as thick, similar veg, less *Sphagnum* and more grass
		5 to 10	3.06	2.01	34.21	72.70	Lighter peat, few roots extending below the acrotelm
Blanket Bog Exclosures							
Burnt Hill Inside	0.5	0 to 5	0.48	0.06	86.87	99.25	Dark brown/ black fibrous peat, *Polytrichum commune* and other *Sphagnum*, leafy structures
		5 to 10	0.58	0.07	88.60	99.76	Dark brown some red saturated fibrous peat, more grassy roots
Burnt Hill Outside	2.5	0 to 5	1.51	0.32	78.60	97.72	Dark brown peat with lots of coarse roots saturated
		5 to 10	1.58	0.24	84.50	99.78	Coarse dark brown peat with lots of coarse roots saturated
Hard Hill Burning Experiment							
10 years Inside	8	0 to 5	1.81	0.20	88.92	99.76	Thick root mat extending to 20 cm, veg 3 cm, db/ b peat with lots of roots, very smooth
		5 to 10	1.91	0.17	91.20	99.91	Dark brown/ black peat with lots of roots, very smooth
10 years Outside	7	0 to 5	0.72	0.05	93.24	99.92	Black peat, lots of roots
		5 to 10	1.19	0.06	95.06	99.95	Black peat, lots of roots
20 years Inside	13	0 to 5	1.05	0.12	88.62	99.88	Dense vegetation mat and black peat
		5 to 10	0.89	0.09	89.46	99.94	Dark brown/ black peat
20 years Outside	4	0 to 5	1.43	0.15	89.27	99.84	Dense *Calluna* and *Eriophorum angustifolium*, mosses, water drips off end of grasses, black peaty soil
		5 to 10	1.24	0.12	90.53	99.92	Peat slightly lighter
Burnt 1954 only Inisde	5	0 to 5	1.39	0.16	88.39	99.88	Black peat, lots of roots
		5 to 10	1.45	0.08	94.44	99.93	Brown peat, lots of roots
Burnt 1954 only Outside	8	0 to 5	0.96	0.12	87.67	99.85	Very leggy *Calluna*, peat with dense veg mat
		5 to 10	0.69	0.09	86.50	99.92	Less dense root system
No Burn (Grazed only) Outside	5	0 to 5	1.52	0.18	88.50	99.90	*Calluna* becoming leggy, db peat with dense root system
		5 to 10	1.36	0.14	90.02	99.94	Dark brown/ black peat with roots, smooth
Bare Peat Experiments							
Burnt Hill gully floor (bare plot)	5	0 to 5	0.63	0.10	83.78	99.89	Dark brown/ black air dried bare crumbly, some small root structures
		5 to 10	1.68	0.21	87.54	99.89	Dark brown/ black smooth peat with some v fine fibres
Burnt Hill gully wall	20	0 to 5	0.60	0.11	81.11	99.73	Very dark brown peat, air dried
		5 to 10	0.84	0.20	75.73	99.88	Red holocene peat, clayay

Table 6.2: The slope angle stratigraphy, bulk density, dry bulk density, % moisture content and loss on ignition of the laboratory block and field exclosures.

The results from the grazed laboratory block are shown in Figure 6.8 and summarised in Figure 6.9. The results generally show the runoff rates to be greater when left for 1 day (discontinuous) rather than 1 hour (continuous), with the exception of the surface runoff rates, which were similar. The reason behind this is thought to be a result of crustal sealing or the development of macropore pathways within the peat. Figure 6.9a shows the mean steady-state runoff rates increase slightly with rainfall intensity; indicating that infiltration rates are increasing at the higher rainfall intensities, for example, at 12 mm hr^{-1} the infiltration rate is approximately 8 mm hr^{-1}, whereas at a rainfall intensity of 24 mm hr^{-1} the infiltration rate is approximately 19 mm hr^{-1}. Similarly to the ungrazed block, ponding occurred on the surface of the grazed block at the higher rainfall intensities in both the continuous and discontinuous experiments. In addition to this other effects of the impact of the raindrop on the surface, deep percolation and variations in the surface topography may also have affected the results. The discontinuous experiments show the runoff rates to be approximately 2 mm hr^{-1} greater than the continuous experiments for all rainfall intensities. This is unusual as it is expected that the runoff rates would be equal to or higher than the continuous experiments. Since both increase at the same rate throughout the experiment it indicates that there was an initial storage of approximately 2 mm hr^{-1} within the block (Figure 6.4b).

The continuous experiment shows the 1 cm and 5 cm runoff rates are very similar and very little increase in runoff rates from the 12 mm hr^{-1} to 24 mm hr^{-1} rainfall intensities were observed. The 10 cm runoff rates were much lower than the 1 cm and 5 cm runoff rates, however increased with increasing rainfall intensity. In comparison to the ungrazed results the 1 cm runoff rates were very similar and 5 cm runoff rates less. This indicates that more rainfall is infiltrating into the peat and is stored or lost below the 10 cm runoff tray. The collected baseflow from the block indicated that the flow was greater from the grazed block than the ungrazed and therefore rapid infiltration is likely to have occurred during the experiment.

Figure 6.8 and 6.9b shows the SSCs for the grazed laboratory block to be low, similar to the ungrazed block. It was expected that the SSC would increase with a decrease in vegetation cover as there is more chance of erosion; however, the results show the

opposite and this is thought to be a result of the sediment exhaustion given that all the experiments were carried out on the same block. The SSC results from inside and outside the exclosure plots will therefore give a better indication of the effects of grazing on SSC and potential erosion. It appears that despite the SSC being low there are some intensity variations. The SSC is higher for the first run, i.e. when the block is left to rest before the next run takes place. This is shown in all the runs where the block is left for 1 day ('Discontinuous'), because the SSCs are greater than those left with 1 hour in-between ('Continuous'). There is still however a decreasing trend in SSC from 12 mm hr^{-1} to 24 mm hr^{-1} indicating that sediment exhaustion is still occurring despite the large loss in sediment from the first run.
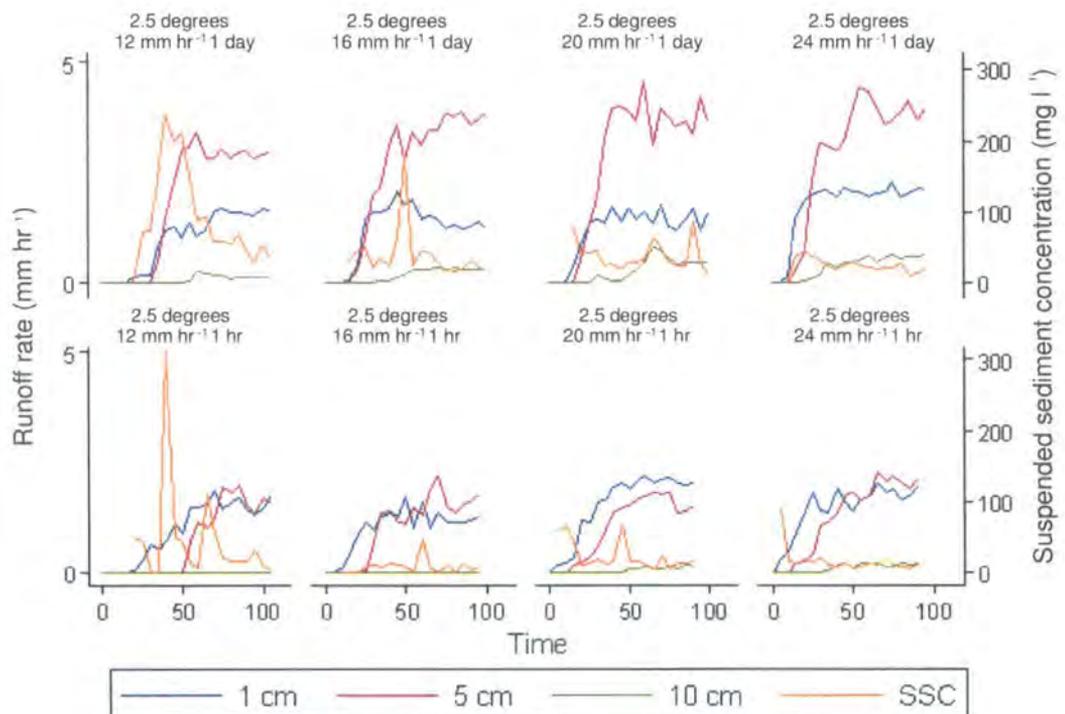
Figure 6.8: Graphs showing the results of the grazed laboratory peat block. Upper) Slope angle of 2.5°, order of runs were 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} and discontinuous. Lower) Slope angle of 2.5°, order of runs were 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} and continuous.
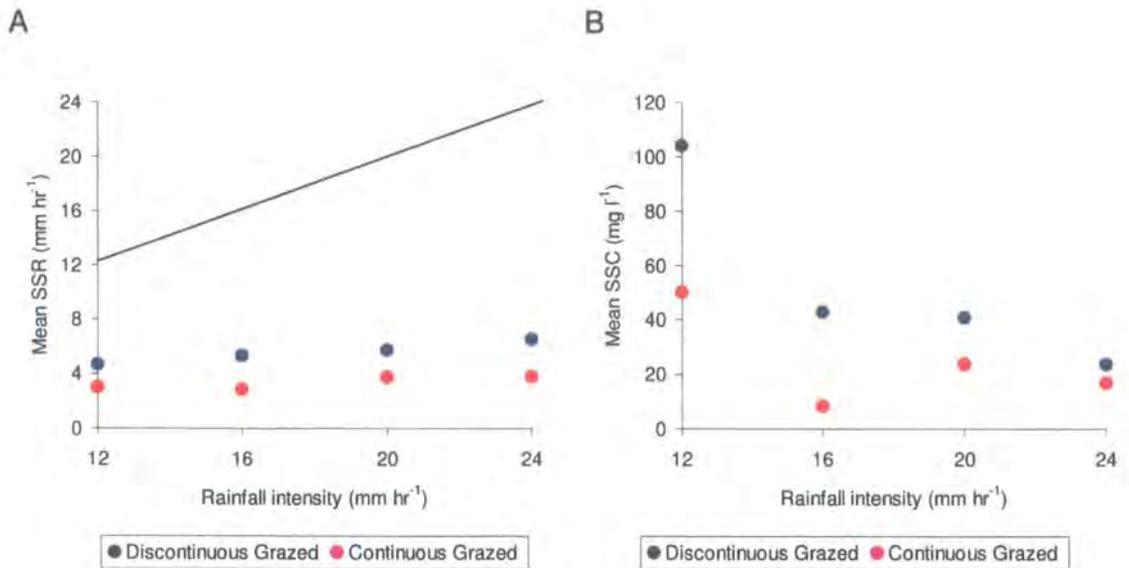
Figure 6.9: Graphs showing the grazed discontinuous and grazed continuous experiments for, A) mean runoff production and B) mean suspended sediment concentration, against rainfall intensities. The 1:1 (O = I) line is shown in 6.9a.

Burnt Block

The same experiments are presented for the burnt laboratory peat block as were presented for the grazed block. The results are shown in Figure 6.10 and summarised in Figure 6.11. The general trend in runoff production once the block had been burnt showed a slight increase in runoff rates at all three depths with increasing rainfall intensity (Figure 6.10 and Figure 6.11a). The only exception to this is the peak runoff rate for the 16 mm hr^{-1} rainfall intensity on the continuous tests is greater than the peak for the 20 mm hr^{-1} (Figure 6.10). This again shows an increase in infiltration rates throughout the course of the experiments, i.e. as the rainfall intensity increases. The cause of this is thought to be the same as for the ungrazed and grazed laboratory peat block, where ponding was observed on the surface of the peat as the rainfall intensities increased. The 1 cm runoff rate is generally greater than the 5 cm and 10 cm runoff rates, with the exception of the 20 mm hr^{-1} and 24 mm hr^{-1} discontinuous runs, where the 5 cm runoff is equal to or greater than the 1 cm runoff rate. The runoff rates from the burnt peat block are low in comparison to the grazed block and slightly less than the ungrazed block. This was surprising as burning is thought to reduce infiltration in peat (Mallik *et al.*, 1984). A likely reason for these results is that the surface has become

cracked from burning allowing the water to infiltrate into the peat to a greater depth. Results from the deep infiltration (> 10 cm) highlighted this because the runoff rates were high (double those from the three runoff trays). The runoff rates at the 1 cm and 5 cm depths were flashier than on the grazed and ungrazed peat block and it took longer for steady-state runoff to be reached. Figure 6.11a shows the results of the discontinuous and continuous experiments are similar, which indicates that leaving the block to drain for one hour was a sufficient time to not affect the results.
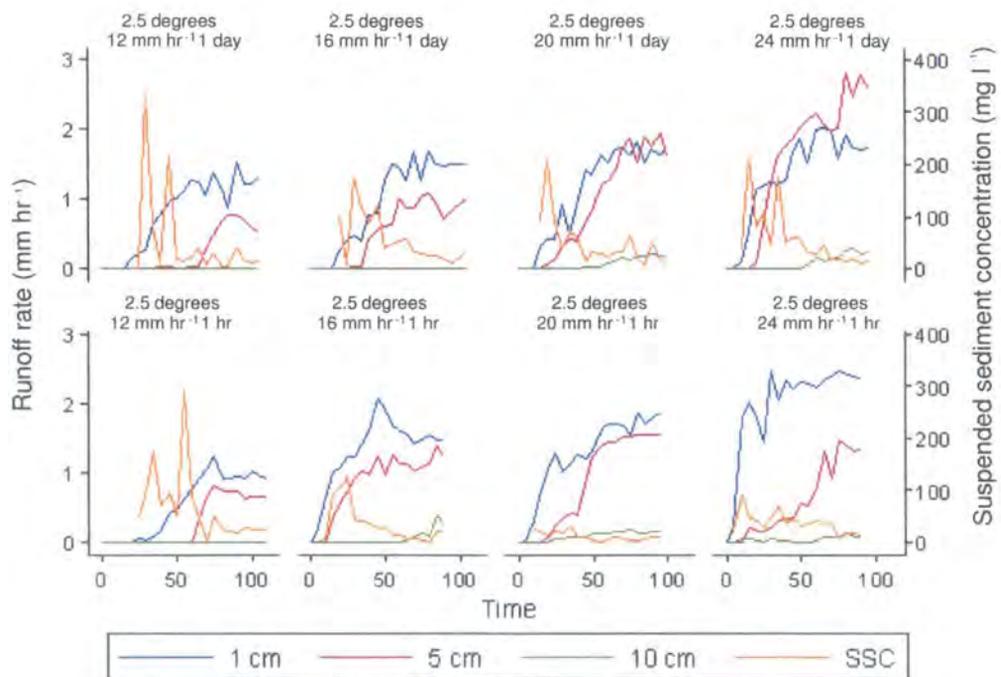
Figure 6.10: Graphs showing the results of the burnt laboratory peat block. Upper) Slope angle of 2.5°, order of runs were 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} and discontinuous. Lower) Slope angle of 2.5°, order of runs were 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} and continuous.
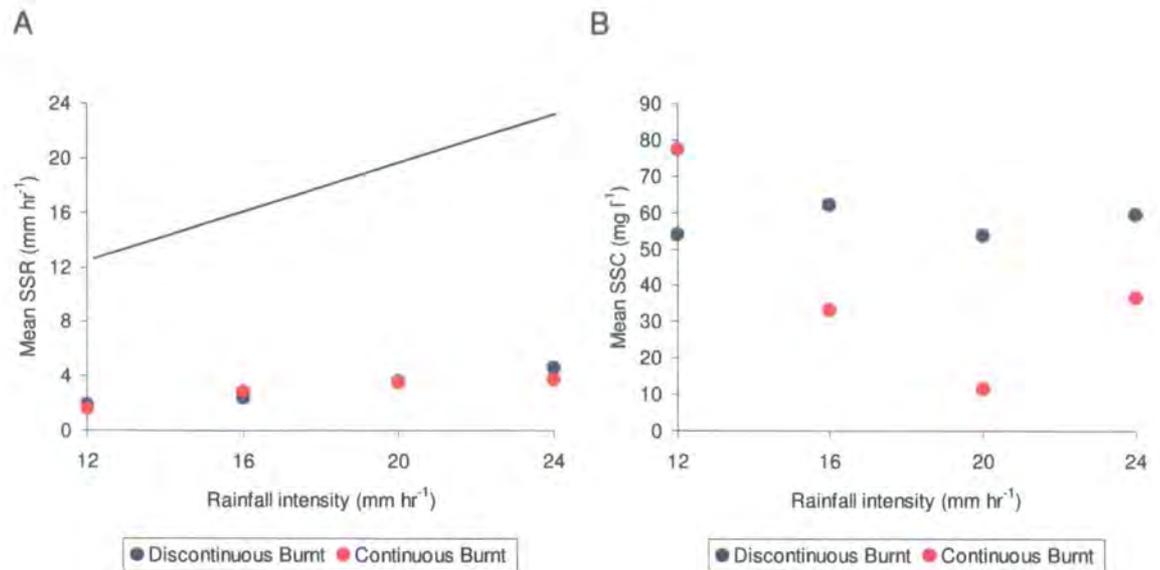
Figure 6.11: Graphs showing the burnt discontinuous and burnt continuous experiments for, A) mean runoff production and B) mean suspended sediment concentration, against rainfall intensities. The 1:1 (O = I) line is shown in 6.11a.

The SSC is greater following burning than following grazing (Figure 6.11b). This is likely to be a result of the increased loose, low-density material (ash and charred vegetation) on the surface that is easily mobilised by surface runoff. The pattern shows a decreasing trend in SSC with increasing rainfall intensity, again indicating sediment exhaustion to be occurring. There is a slight increase in sediment concentration (5 – 25 mg l^{-1}) from 20 mm hr^{-1} to 24 mm hr^{-1} indicating sediment production is occurring at the higher rainfall intensity (Figure 6.7). Similar to the grazed plot, there is a greater SSC once the plot has been left to fully drain rather than only being left for 1 hour. Although greater, the SSCs are still not as high as the first run, reiterating that the block is conditioned for later runs by the first run. This is a significant disadvantage in the laboratory where the same peat block is used in all experiments.

6.3   Field Experiments

6.3.1   The Experimental Set-up

A bounded plot of 1 m × 0.5 m was set up at each study site (Table 6.3). This was constrained on three sides by 20 cm deep aluminium plates inserted into the soil to a

depth of at least 10 cm, with 10 cm above the ground surface (Figure 6.12). The plot was chosen to be representative of the surrounding area. At the front edge of the plot a small trench was excavated and three runoff troughs at 1 cm, 5 cm and 10 cm depths were inserted below the surface into the soil to collect the runoff from the area directly above the trough (Figure 6.12). The plots were bounded to prevent additional water from the adjacent slope entering the plot and to allow all the runoff from the plot to be constrained within the plot until infiltrated below the level of the collecting trays or collected as runoff in tubs beneath the trays. The plot boundary and trough were inserted using a sharp knife in order to ensure the least disturbance to the soil and vegetation. Disturbance can cause break up of crusted surface mats of vegetation and causing preferential percolation pathways.

Figure 6.12: Runoff troughs inserted into the peat to collect the surface (1 cm), 5 cm and 10 cm runoff. This plot was from the Hard Hill Burning Experiment, 20-year burning rotation, inside the exclosure.

The vegetation types and soil types were noted in the field (Table 6.2). The 0 – 1 cm (surface) vegetation and soil was described and density of the root mat noted. Soil samples between 0 – 5 cm and 5 – 10 cm depths together with surface vegetation samples were taken back to the laboratory for further analysis (Table 6.2). The plot was covered at least one hour prior to the experiment to prevent any natural rainfall that may be occurring from falling onto the plot and causing runoff. A 'drip-type' simulator was

used to simulate rainfall at the same intensities as those used in the laboratory experiment (12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1}). The simulator was set up over the plot (Figure 3.15a) and the legs inserted into the ground for stability. The simulator height was set at 2 m for consistency with the laboratory experiments. The water tank and manometer were both connected and the simulator covered with a plastic sheet to prevent the deflection of rainfall outside the plot by wind and any natural rain (if it was raining on the day of the simulation) from being deflected inside the plot.

Plot No.	Location	Dominant Vegetation Type	Altitude (m)	Start date (Year)	Vegetation last recorded (Year)
1	Burnt Hill	Blanket bog pool		1953	
2	Bog Hill	Blanket bog	550	1953	1998
3	Cottage Hill	*Juncus squarrosus* grassland	549	1967	1995
4	Dodgen Pot	Limestone grassland with tree planting	580		
5	Hard Hill Top	*Festuca ovina* grassland	678	1954	1998
6	Hard Hill (Burning and Grazing Experiment)	Blanket bog	600 610 617 632	1954	1982 (in part 2000)
7	Knock Fell	*Agrostis-Festuca* grassland	754	1955	2000
8	Little Dunn Fell	*Festuca ovina* grassland	815	1954	1998
9	Moss Burn	Calcareous Flush	632	1972	1996
10	Silverband	Blanket bog	685	1966	1997
11	River Tees	*Nardus stricta* grassland	488	1967	1995
12	Troutbeck Head	Blanket bog	685	1966	1997
13	Rough Sike	Limestone grassland	548		
14	House Hill	Blanket Bog			

Table 6.3: Long-term enclosure of vegetation change at Moor House and Upper Teesdale NNR.

The experiments were repeated on vegetation types ranging from blanket bog to grassland, which have undergone different management treatments (grazing and burning). At each plot a paired experiment was carried out measuring the runoff and

erosion potential within the exclosure and immediately outside on the grazed moor. The experimental design was duplicated at five of the fourteen exclosure plots (Knock Fell, Hard Hill Burning Plots (multiple runs), Burnt Hill, Cottage Hill, and Silverband) (Figure 3.5 and Table 6.3). The selected plots cover the full range of soil types, vegetation types and slope angles found on the exclosure plots and were the most accessible in the field. The experiments were undertaken in one corner of the exclosure so to minimise disturbance. For example, Figure 6.13, which shows the layout of one of the Hard Hill Burning Exclosures and the location of the experiments in relation to the plots. Simulations took place over two consecutive field days: one inside the plot and the other outside the plot. In addition experiments were carried out on two bare peat surface plots within the Burnt Hill's main gully system. These were on the gully floor and gully wall, where slope angles varied from 5° to 20°, respectively.

The equipment was set up and the first simulation run at 12 mm hr^{-1}. The plot was then left for one hour between each simulation to allow the soil to drain before the next simulation was run (16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1}). This particular sequence was used because the laboratory block experiments showed little variation due to the order of the rainfall intensities used and during large natural rainfall events at Moor House rainfall intensity tends to build up in a series of stages (Figure 3.6). The benefit of carrying out all the simulations on the same plot in the same day is to try and recreate natural rainfall conditions. Choosing simultaneous days for the inside and outside plot experiments reduces the uncertainty associated with changing weather conditions.

Runoff production was measured manually every five minutes during the simulation at the three depths and runoff from the surface was retained for sediment concentration determination. Simulations lasted as long as needed for steady-state runoff to be achieved. The time generally was between 90 and 110 minutes depending on the applied rainfall intensity.
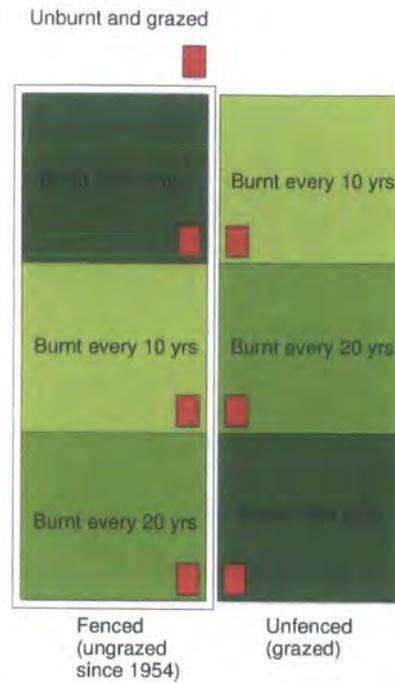
Figure 6.13: The layout of one of the Hard Hill burning exclosures. The red rectangles represent the location of the rainfall simulation experiments. There are four exclosures within the Hard Hill Burning Experiment replicated up the hill as shown on Figure 3.5. Each block has a randomised order of burning treatment.

6.3.2   Results of Experiments on Runoff and Sediment Production

This section presents the results from the field experiments, firstly discussing the results from the moorland grazing exclosures (Knock Fell, Silverband and Cottage Hill), followed by the blanket bog grazing exclosure (Burnt Hill), the Hard Hill Burning Experiment and finally the bare peat experiments.

Moorland Grass Exclosures

Figures 6.14, 6.15 and 6.16 show the results for Knock Fell, Silverband and Cottage Hill grazing exclosures respectively. They were plotted together to allow for comparison. The rainfall simulations were carried out inside and outside the exclosures. The general description of the stratigraphy, slope angles and the bulk and dry bulk densities, moisture content and loss on ignition are shown in Table 6.2. Figures 6.17 and 6.18 show a summary for the results for the runoff production and sediment concentration respectively.
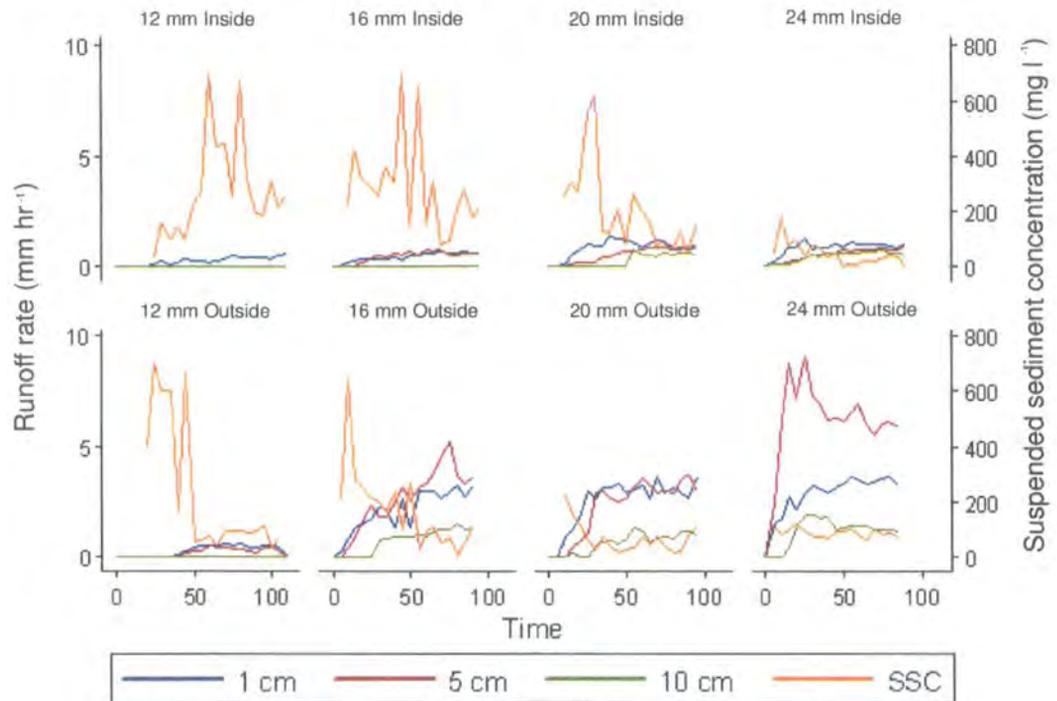
Figure 6.14: Rainfall simulation experiment results for Knock Fell exclosure at rainfall intensities of 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1}.
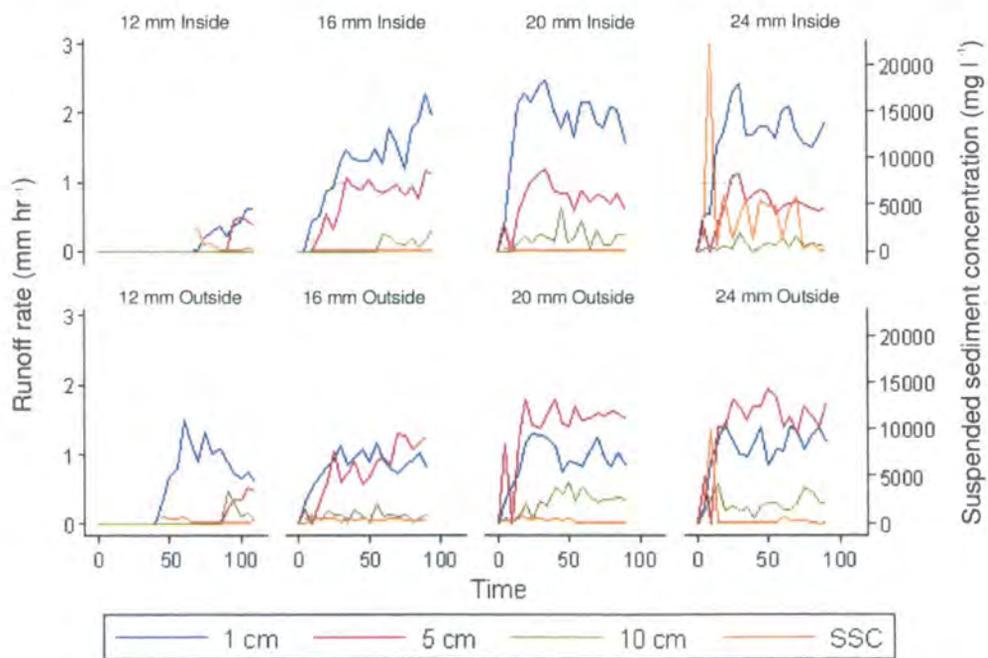
Figure 6.15: The rainfall simulation experiments for Silverband exclosure at rainfall intensities of 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1}.
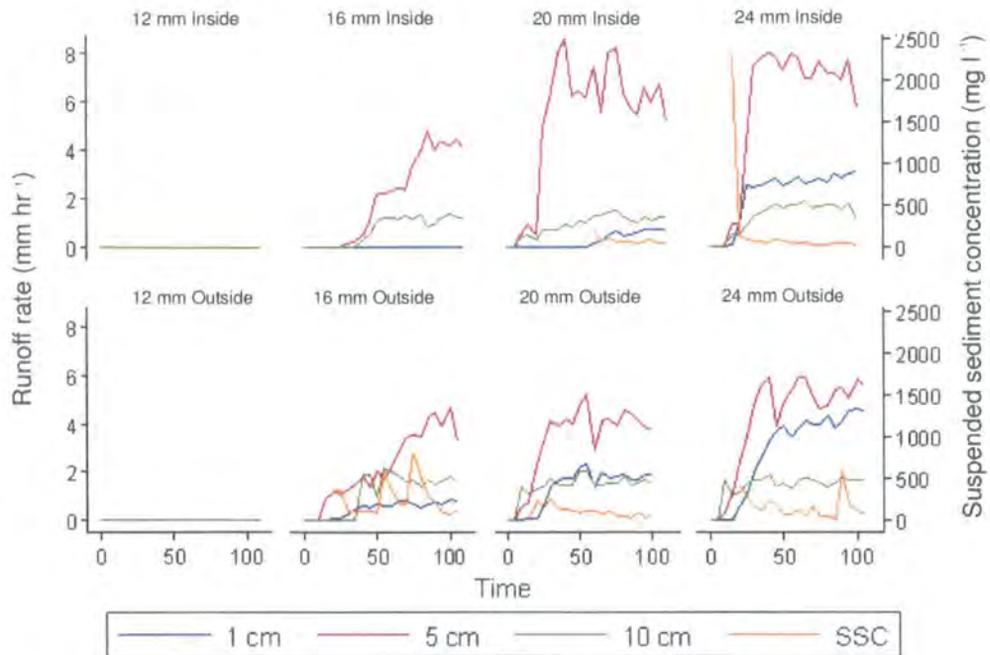
Figure 6.16: The rainfall simulation experiments for Cottage Hill exclosure at rainfall intensities of 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1}.

Figure 6.19 shows a schematic diagram based on the rainfall-runoff simulation water balance equation. The water balance for the field experiments is slightly different from the laboratory peat block experiments. The water balance equation is shown in Equation 6.2 where the output (O) is the dependent on the sum of not only the rainfall input (I), but also storage (S) and throughflow (T), less the loss (L).

$$O = I + T - \Delta S - L \qquad \qquad \text{Equation 6.2}$$
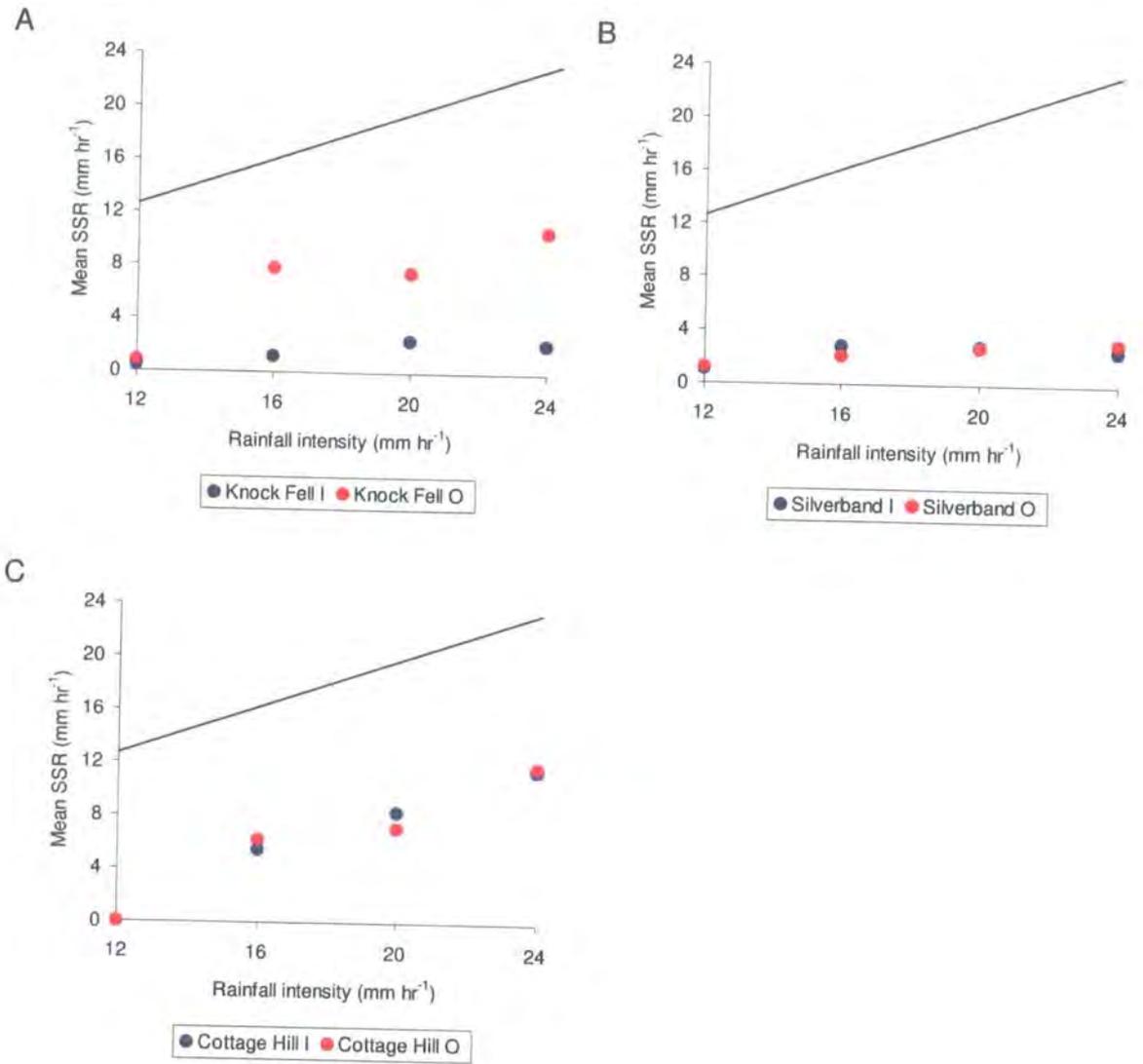
Figure 6.17: Graphs showing the mean steady-state runoff against rainfall intensities for each of the grazing exclosures, A) Knock Fell Inside and Outside, B) Silverband Inside and Outside and C) Cottage Hill Inside and Outside. The 1:1 line is plotted on each diagram (O=I).
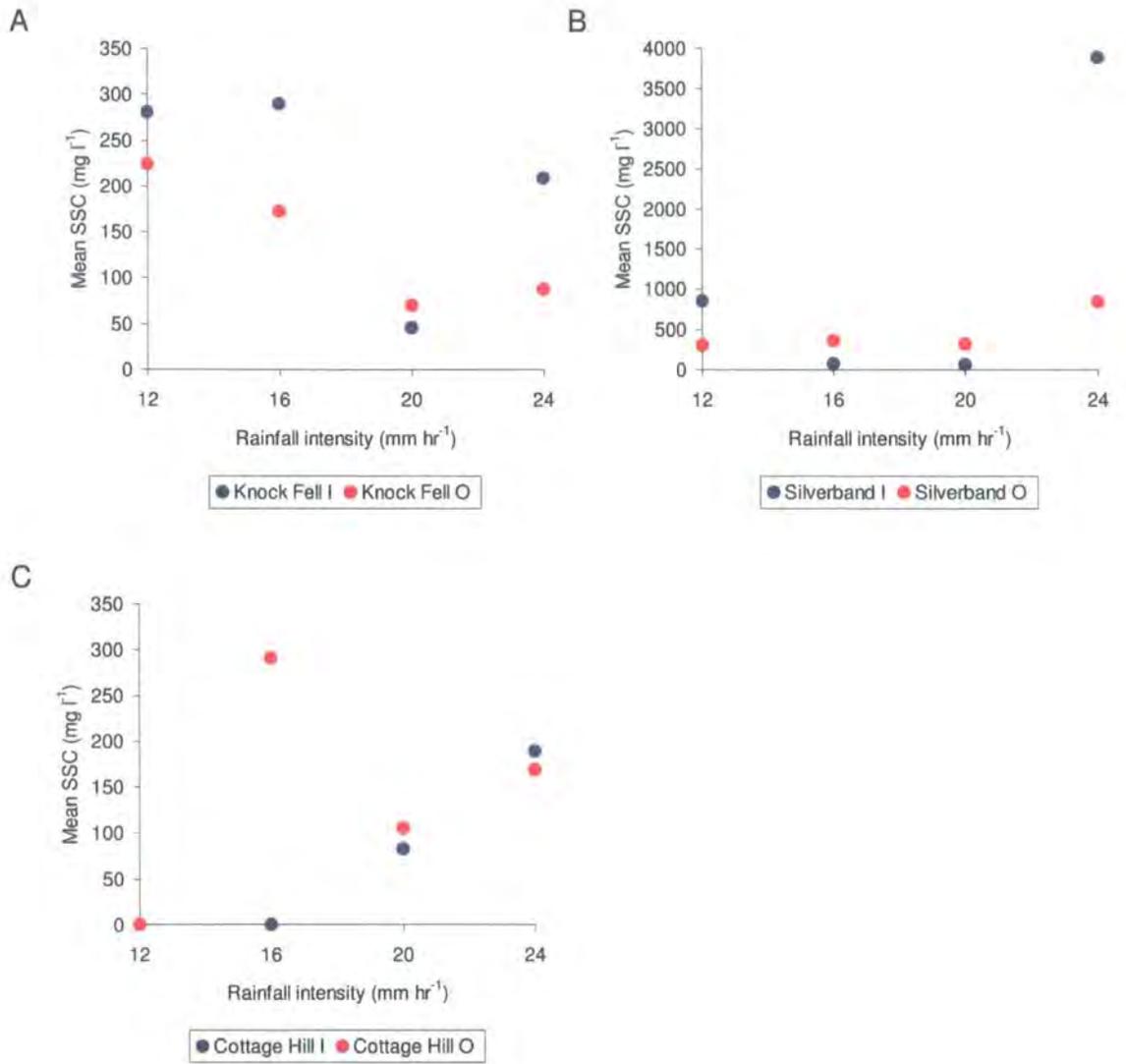
Figure 6.18: Graphs showing the mean suspended sediment concentration against rainfall intensities for each of the grazing exclosures, A) Knock Fell Inside and Outside, B) Silverband Inside and Outside and C) Cottage Hill Inside and Outside.
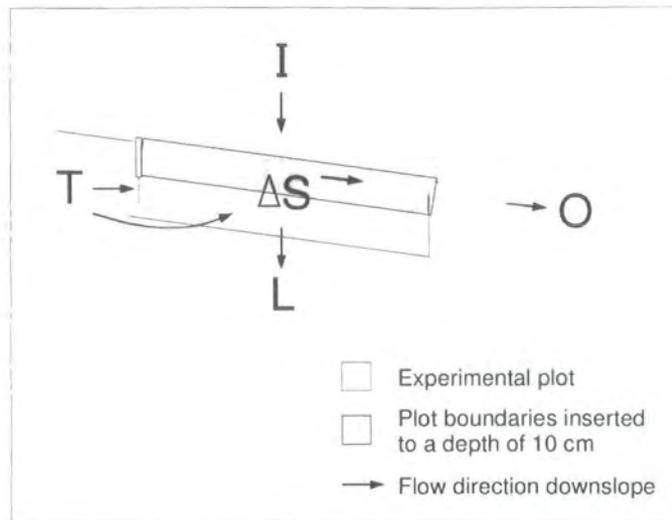
Figure 6.19: Schematic diagram based on the rainfall-runoff simulation water balance equation.

Knock Fell

Figure 6.20: Knock Fell grazing exclosure (altitude – 754 m a.s.l.), showing on the left the enclosed plot and the right the grazed plot (Photograph taken in June 2002).

Figures 6.14 and 6.17a shows the runoff to increase with increasing rainfall intensity. Inside the exclosure the runoff response is less than outside the exclosure. This may well be the result of differences in vegetation and soil type as the slope angle was consistent (2.5°). Figure 6.20 shows the contrast in vegetation cover inside and outside the exclosure. Interestingly outside the exclosure the 5 cm runoff is greater than the 1

cm runoff. This was also observed in the laboratory block experiments and is thought to be a result of the peat being saturated in the lower layers (below 5 cm) and a decreasing hydraulic conductivity in the upper layers (0 – 5 cm).

Figure 6.17a highlights the difference between the runoff production inside and outside the exclosure. At 16 mm hr^{-1} outside the mean infiltration rate is the least (8 mm hr^{-1}). At 20 mm hr^{-1} and 24 mm hr^{-1} the runoff rate is approximately 14 mm hr^{-1} lower than the rainfall intensity.

Inside the exclosure, Figure 6.17a shows the infiltration rate to increase as the rainfall intensity increases. Due to the vegetation density being great inside the exclosure it was hard to observe any evidence of ponding on the surface, unlike in the laboratory peat block experiments; however, this does not mean it may not have been a contributory factor in the increasing the infiltration rates. In addition, the varying topography over the plot surface, deep percolation as shown in Figure 6.19 and the impact of the raindrops on the surface may also have been factors, though due to the dense vegetation the latter is thought to be the least likely.

Figures 6.14 and 6.18a show the SSC to decrease with increasing rainfall intensity. Outside the exclosure there is a peak in SSC at the start of the experiments, indicating sediment exhaustion is occurring during the course of the experiment. Inside the exclosure this is less evident since at rainfall intensities of 12 mm hr^{-1} and 16 mm hr^{-1} the SSC is variable throughout the experiments. Although runoff production is greater outside the exclosure than inside the SSC is less, which is likely to be a result of the differences in soil type inside and outside the exclosure.

Table 6.2 shows clear differences between the plots as well as between soil layers in the same plot. Inside the plot the soil is a Brown Earth whereas outside the plot it is a Peaty Gley; however, despite variations in the moisture content with depth, both inside and outside the plot the moisture content is approximately 86 %. Given moisture contents are similar inside and outside the plot, variations in runoff production and sediment yield are likely to be a result of differences in cover type.

Silverband

Figure 6.15 shows the runoff rates to be low throughout the experiments (no greater than 3 mm hr^{-1}). Outside the plot the surface runoff rate is greater than inside, however the 5 cm runoff rate is higher. Inside the exclosure the greatest runoff rate is at 1 cm depth, which generally increases with increasing rainfall intensity. Figure 6.17b shows runoff rates are similar both inside and outside the plot, which is the result of similar vegetation cover (Figure 6.21). The runoff rates are also low regardless of the rainfall intensity indicating infiltration is increasing as the rainfall intensity increases. For example at a rainfall intensity of 12 mm hr^{-1} the mean infiltration rate was 11 mm hr^{-1}, whereas at 24 mm hr^{-1} the mean infiltration rate was 21 mm hr^{-1}. The runoff rate does however, increase from 12 mm hr^{-1} to 16 mm hr^{-1} before slowing down to 24 mm hr^{-1}. Outside the exclosure the 5 cm runoff is greater than the 1 cm runoff over the range 16 mm hr^{-1} to 24 mm hr^{-1} although differences in rates are small. There are a number of possible reasons for the increases in infiltration. For the Silverband Exclosure plot it is thought to be a result of the uneven topography of the plot surface and ponding occurring on the surface as a result. Table 6.2 and Figure 6.21 show the variations in the surface cover conditions between the two plots. Although there is very little variation in the cover types and extent, Table 6.2 indicates there is more *Sphagnum* spp. outside the exclosure than inside, which may have affected the runoff production between the upper and lower levels.
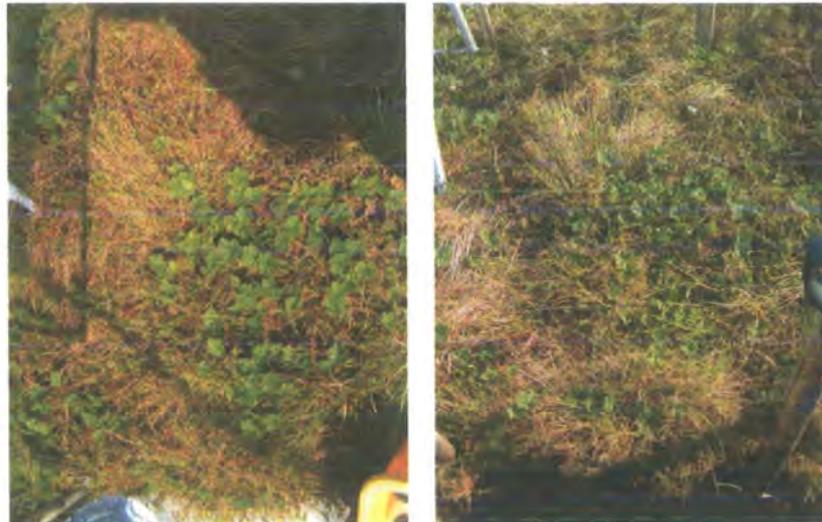
Figure 6.21: Silverband experimental plots (altitude – 685 m a.s.l.), showing on the left the enclosed plot and the right the grazed plot (Photographs taken in June 2003).

The SSC is very low both inside and outside the exclosure (Figure 6.14 and Figure 6.17b). The SSC is particularly low from 12 mm hr^{-1} to 20 mm hr^{-1} but then increases

rapidly at 24 mm hr^{-1} (particularly inside the exclosure), indicating sediment production is occurring at the higher rainfall intensity (Figure 6.7). Similar to the runoff production, such variations inside the exclosure are thought to be the result of more *Sphagnum* spp. outside the exclosure than inside. The presence of *Sphagnum* spp. outside the exclosure increased the moisture content of the upper layers. However the densities of the vegetation and upper soil layers outside the exclosure were less than inside the exclosure so there was more potential for storage within the plot surface layers. The vegetation cover within the exclosure is dense, therefore inhibiting surface runoff. This therefore reiterates the reason for the 5 cm runoff being greater than the surface runoff.

Cottage Hill

The rainfall simulation experiments for the Cottage Hill exclosure plot were carried out (19th April and 20th April 2003) following a long dry period (22 days) (Figure 6.22) and therefore the water table was low and regardless of the wetting up of the plot prior to the experiment it took a run for the plot to fully wet up. Figure 6.22 shows the water table depths in the area of Cottage Hill (Moor House) ranged from 54 to 83 cm. During the time of the rainfall simulation experiments at this site the water table depth was between 54 and 70 cm and therefore the 12 mm hr^{-1} runs may not be directly comparable to other plots. The results of the run is however potentially useful for showing how runoff and sediment productions respond to a storm event following a period of short-term drought.

Figure 6.16 shows the 5 cm runoff is greater than the 1 cm runoff. The 10 cm runoff is also greater than the 1 cm runoff for the 16 mm hr^{-1} and 20 mm hr^{-1} rainfall intensities. This is thought to be the result of the ground being unsaturated and the vegetation cover dense, therefore the rainfall infiltrates into the soil, moves vertically through the upper soil layers to shallow depths. By 24 mm hr^{-1} the surface is likely to have fully re-wetted and rainfall therefore begins to flow over the surface rather than infiltrate and hence the 1 cm runoff rate is greater than the 10 cm runoff rate. The 5 cm runoff rate however, remains dominant, similarly to the other experiments (e.g. the laboratory block experiment). Both inside and outside the plot there was no runoff collected from the 12 mm hr^{-1} rainfall intensities, due to the drought effect. Outside the plot the 5 cm and 10 cm runoff rates are greater than the 1 cm at a rainfall intensity of 16 mm hr^{-1} however, at 20 mm hr^{-1} and 24 mm hr^{-1} the 1 cm runoff is greater.
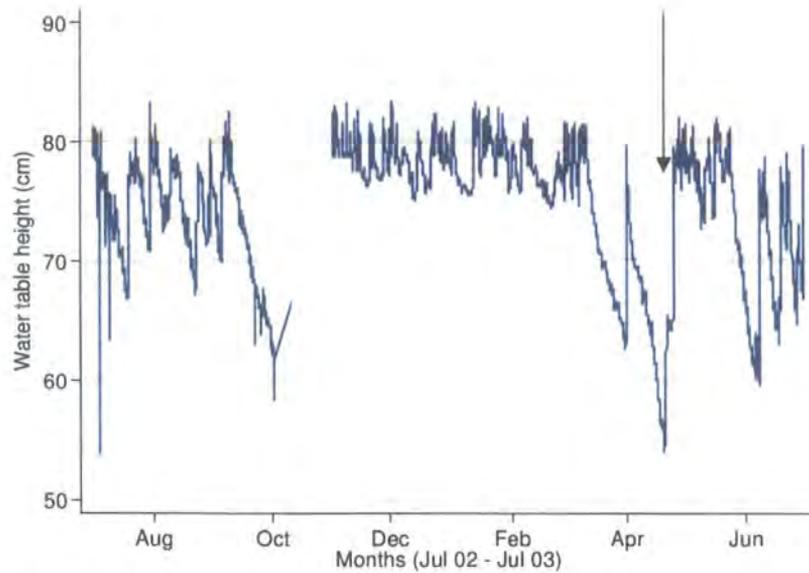
Figure 6.22: Water table height over the rainfall simulation experimental period. The arrow shows the time at which the rainfall simulation experiment was carried out at the Cottage Hill exclosure plot (Source of data: ECN, Lancaster, 2004).

Figure 6.17c shows the mean steady-state runoff rate inside and outside the exclosure to be similar. With the rainfall intensities of 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} both inside and outside the exclosure the runoff rate is very similar to Knock Fell outside, which was interesting given the previous long dry period.

Figure 6.16 and 6.18c shows the SSCs inside the exclosure are low until the 24 mm hr^{-1} rainfall intensity where there is a large peak in concentration at the start of the experiment. This is the result of surface runoff increasing causing the first flush of sediment, whereby there was sufficient surface runoff to detach the sediment and following this sediment exhaustion of the plot occurred (Figure 6.7). Outside the exclosure the SSC is greater than inside. This is likely to be a result of differences in the extent of vegetation cover and greater surface runoff. At the rainfall intensity of 16 mm hr^{-1} an initial flush of sediment occurred (Figure 6.7). The mean SSC rates are also flashier outside the exclosure than inside, indicating that there is more sediment available for transport. The lowest SSC outside the exclosure is at the rainfall intensity of 20 mm hr^{-1}.

Despite the long dry period prior to the rainfall simulation experiments on Cottage Hill, the moisture contents of the upper soil layer both inside and outside the exclosure were approximately 82 %. This is likely to be the result of the presence of *Sphagnum* spp. at

the site. There was a dense vegetation mat inside the exclosure and therefore the densities were low, which are likely to have promoted infiltration into the plot. This is the reason for the surface runoff being low until the rainfall intensity reached 24 mm hr^{-1}. Outside the exclosure the soil is denser, especially in the lower layers (5 – 10 cm) and the moisture content is low. There were more roots deep into the peat and less *Sphagnum* spp., which may have contributed to the 1 cm and 5 cm runoff rates bring similar.

Blanket Bog Exclosures

This section discusses the rainfall simulation results from the blanket bog exclosures (Burnt Hill and the Hard Hill Burning Experiment).

Burnt Hill

Figure 6.23 shows the results for the Burnt Hill Experimental Plot. A summary of the results is presented in Figure 6.24. The general description of the stratigraphy, slope angles and the bulk and dry bulk densities, moisture content and loss on ignition are shown in Table 6.2.

The runoff rate inside the exclosure is less than outside (Figure 6.23 and 6.24a). Surface runoff is the dominant runoff inside the exclosure. Figure 6.24a shows the mean steady state runoff rate inside the exclosure to be virtually constant regardless of increasing rainfall intensity, therefore indicating that infiltration was increasing with increasing rainfall intensity. Due to the dense cover of vegetation inside the exclosure ponding on the surface of the peat was not observed. As infiltration rates are high even where the rainfall intensities are low (at a rainfall intensity of 12 mm hr^{-1} the infiltration rate was approximately 11.5 mm hr^{-1}) it is thought that the soil type and vegetation cover have affected the runoff rates. The 1 cm runoff was higher than the 5 cm and 10 cm runoff depths on all runs (Figure 6.23). This shows that much of the runoff is occurring at the surface. Outside the exclosure the runoff production decreased with depth. Figures 6.23 and 6.24a show the runoff production to increase with increasing rainfall intensity outside the exclosure. This indicates that the rainfall rate is having a direct impact on the runoff rate. At the 20 mm hr^{-1} rainfall intensity outside the exclosure the 5 cm runoff stabilised at the same rate as the 1 cm runoff. This is a common occurrence during rainfall events because the water table depth rises to the surface as the plot wets up.

runoff rate. At the 20 mm hr^{-1} rainfall intensity outside the exclosure the 5 cm runoff stabilised at the same rate as the 1 cm runoff. This is a common occurrence during rainfall events because the water table depth rises to the surface as the plot wets up.
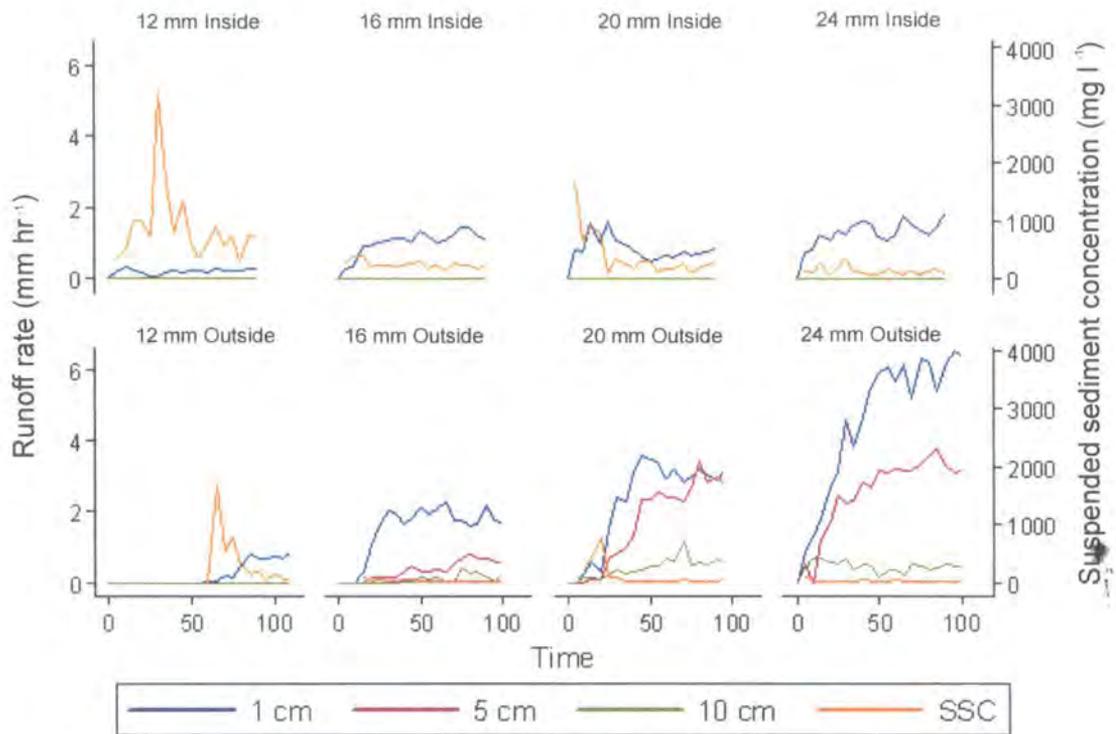
Figure 6.23: The rainfall simulation experiments for the Burnt Hill exclosure at rainfall intensities of 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1}.

Figures 6.23 and 6.24b shows the general trend in SSC decreases with increasing rainfall intensity inside and outside the exclosure. At 12 mm hr^{-1} inside the exclosure SSCs were greatest and most variable. The general trend in decreasing SSC is likely to be a result of sediment exhaustion (Figure 6.7). Both inside and outside the exclosure there is a greater SSC at the start of the runs for the 20 mm hr^{-1} rainfall intensities, which is likely to be the result of some sediment production occurring as the rainfall intensity increased, though this did not occur at the rainfall intensity of 24 mm hr^{-1}, whereby the SSC was lowest both inside and outside the exclosure.

A

B
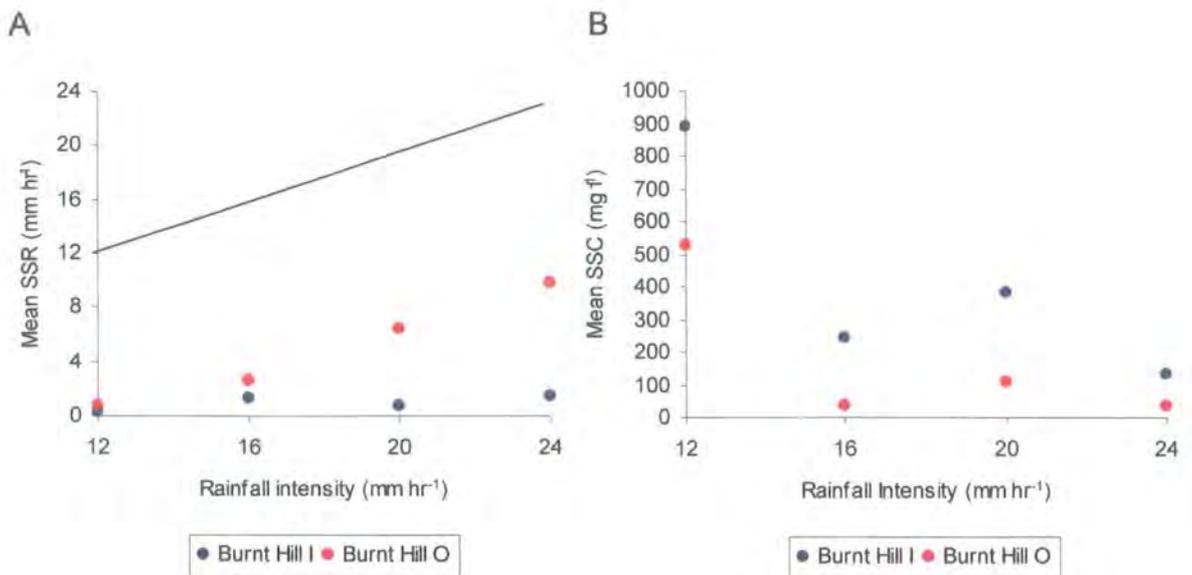
Figure 6.24: Graphs showing the results from the Burnt Hill grazing exclosure (Inside and Outside) for, A) mean runoff production and B) mean suspended sediment concentration, against rainfall intensities. The 1:1 (O = I) line is shown in 6.24a.

Table 6.2 shows the inside of the Burnt Hill exclosure was more saturated than outside, however, from the rainfall simulation results this would not have been expected. The densities of the peat is far less inside the exclosure than outside, which may have led to the water infiltrating to depths greater than 10 cm. The vegetation cover inside the exclosure is predominantly *Sphagnum* spp. and is therefore the reason for the low densities but high moisture content (hydraulic conductivity). Outside the exclosure there are more dense roots and therefore less space for storage within the peat so water would tend to flow as throughflow rather than become stored.

Hard Hill Burning Experiment

This section discusses the rainfall simulation results from the Hard Hill Burning Experiment (10-year burning rotation, 20-year burning rotation, burnt only in 1954 and Unburnt), both inside and outside the plots (seven experiments in all). The set up of the exclosure is shown in Figure 6.13. Figure 6.25 shows the results from the plot burnt on a 10-year burning rotation, Figure 6.26 from the plot burnt on a 20-year burning rotation and Figure 6.27 from the plot burnt in 1954 only and an adjacent unburnt plot. Summary results showing the mean steady-state runoff and mean SSC are shown in Figures 6.28 and 6.29 respectively. The general description of the stratigraphy, slope

angles and the bulk and dry bulk densities, moisture content and loss on ignition are shown in Table 6.2.
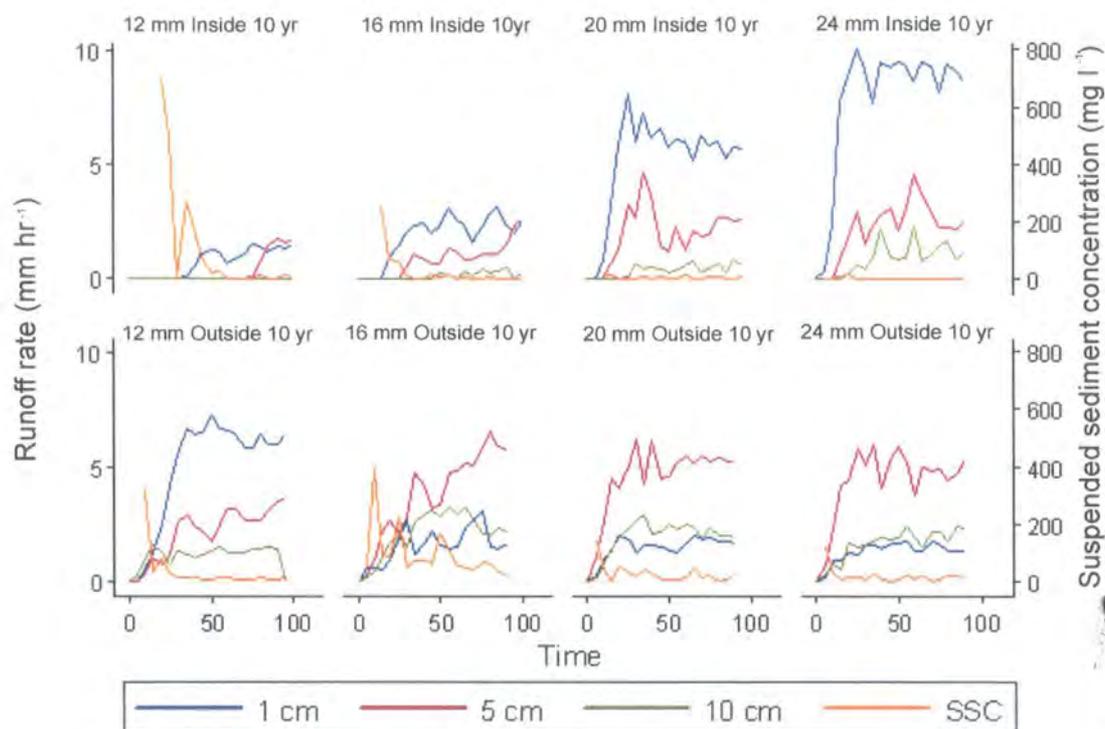
Figure 6.24: Shows the results of the rainfall simulation experiments carried out on the 10-year burning rotation on the Hard Hill Burning Experiment.
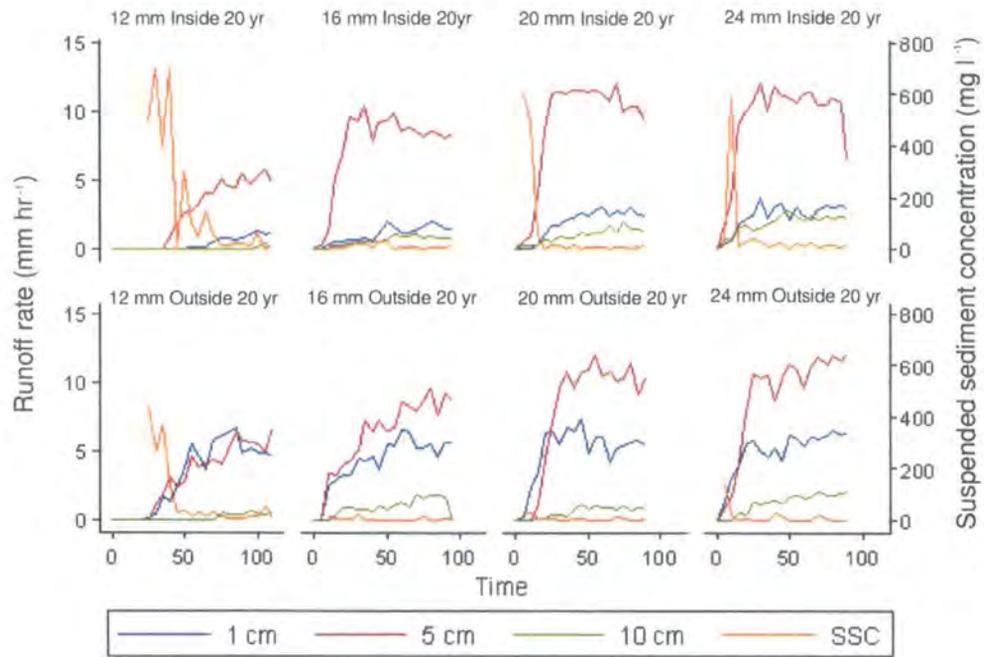
Figure 6.26: Shows the results of the rainfall simulation experiments carried out on the 20-year burning rotation on the Hard Hill Burning Experiment.
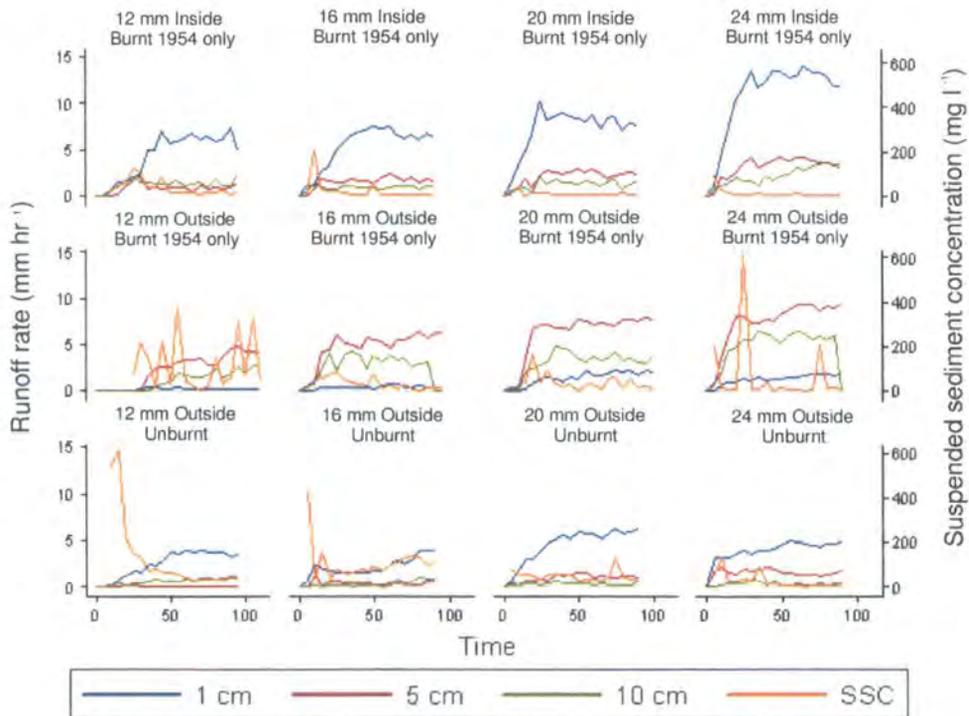
Figure 6.27: Shows the results of the rainfall simulation experiments carried out on the burnt only in 1954 burning rotation on the Hard Hill Burning Experiment and the unburnt and grazed site.
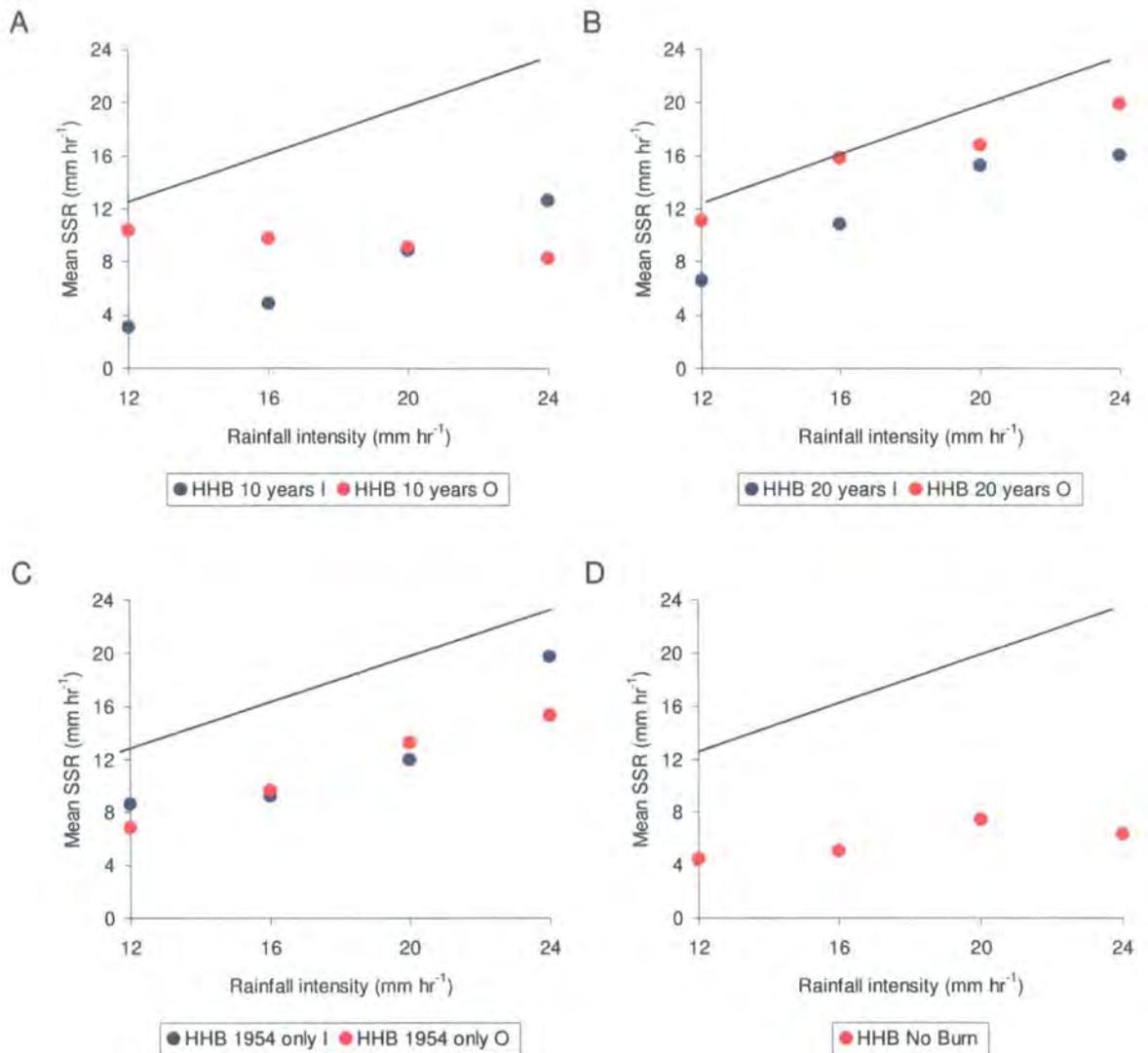
Figure 6.28: Graphs showing the mean steady-state runoff against rainfall intensities for the plots on the Hard Hill Burning Experiment, A) 10-years burning rotation Inside and 10-years burning rotation Outside, B) 20-years burning rotation Inside and 20-years burning rotation Outside, C) Burnt in 1954 only Inside and Burnt in 1954 only Outside and D) Unburnt Outside. The 1:1 line is plotted on each diagram (O = I).
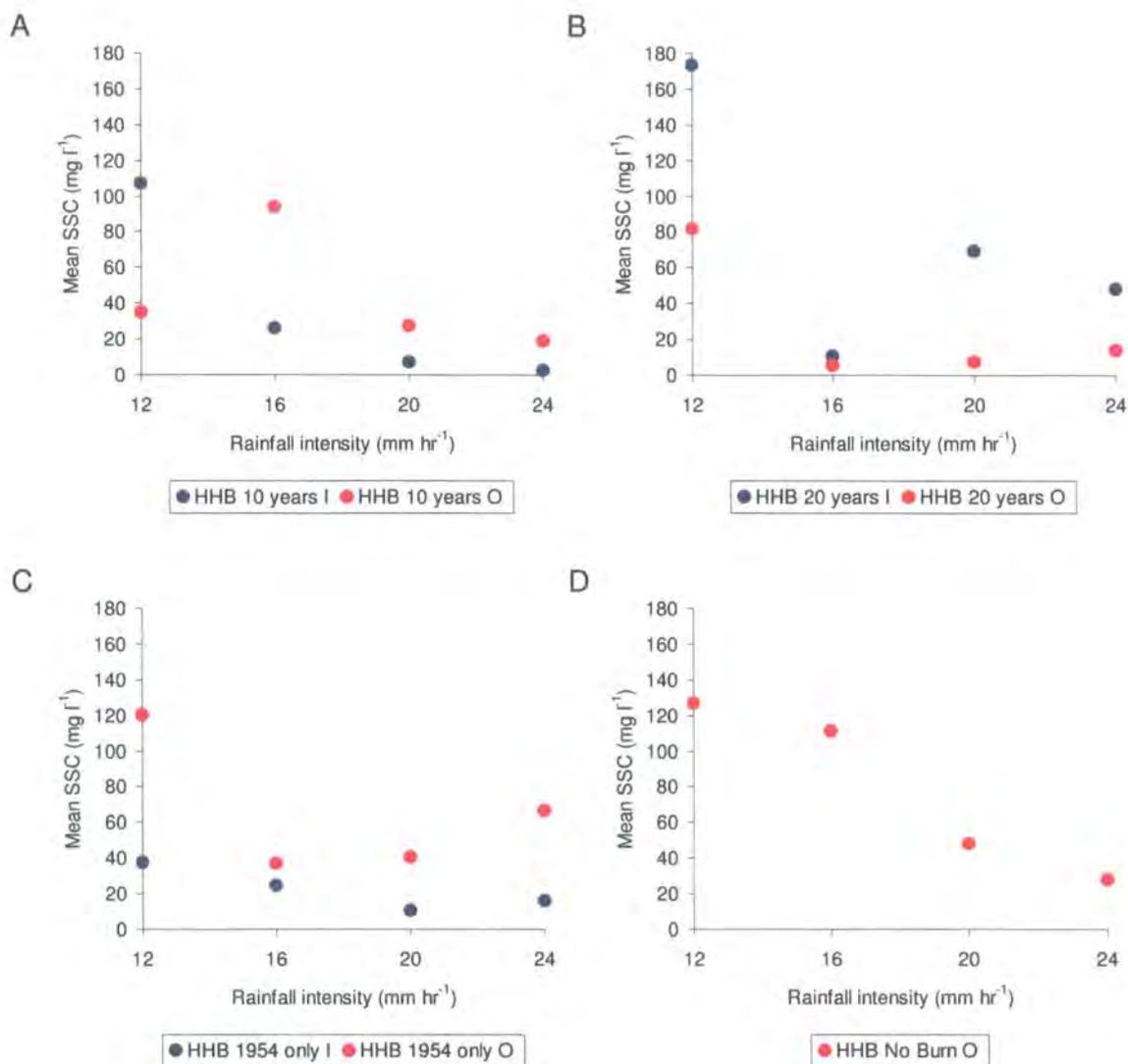
Figure 6.29: Graphs showing the mean suspended sediment concentration against rainfall intensities for the plots on the Hard Hill Burning Experiment, A) 10-years burning rotation Inside and 10-years burning rotation Outside, B) 20-years burning rotation Inside and 20-years burning rotation Outside, C) Burnt in 1954 only Inside and Burnt in 1954 only Outside and D) Unburnt Outside.

Figure 6.25 shows the runoff rates are similar for the two plots; however, in the ungrazed area surface runoff is predominant, whereas, in the grazed area runoff at 5 cm depth dominates. This is thought to be due to the characteristics of the vegetation cover. The vegetation cover inside and outside the exclosure at first sight looks similar (Figure 6.30). The vegetation on the outside plot; however, had *Sphagnum angustifolium* present. This dense mat allows the rainfall to infiltrate and therefore runoff at 5 cm is greater than on the surface. Inside the exclosure the steady-state runoff increases virtually in parallel with the rainfall intensity. Outside the exclosure with the exception of the 12 mm hr^{-1} rainfall intensity the 5 cm and 10 cm depth runoff rates are greater than the 1 cm rate. This may not just be a result of vegetation cover and of soil type. Figure 6.28a shows the mean steady-state runoff rate to be high (approximately 10 mm hr^{-1}) at the rainfall intensity at 12 mm hr^{-1} indicating that plot was nearing saturation (Figure 6.4a). From 16 mm hr^{-1} to 24 mm hr^{-1} the infiltration rate then increases and the runoff production decreases. This may be the result of ponding at the surface, a non-uniform surface topography or the impact of the raindrops at the higher rainfall intensities. It is thought that the natural rainfall which had fell on the plot prior to covering had filled the peat to its field capacity and therefore on the first run there was little capacity for storage within the plot.

The *Calluna vulgaris* is sparse compared to the 20-year burning rotation. This is because fire results in rapid growth of *Eriophorum vaginatum* accompanied by a slower re-growth of *Calluna vulgaris* (Figure 2.16) (Gore and Olsen, 1967; Rawes and Hobbs, 1979; Adamson, 2004).

Figures 6.25 and 6.29a show the SSCs to be relatively low, though comparable to the other Hard Hill Burning exclosure plots. Both inside and outside the exclosure there is a decreasing trend in SSC with increasing rainfall intensity (indicating sediment exhaustion), with the exception of 16 mm hr^{-1} outside where the SSC is very flashy and remains high until after 50 minutes into the experiment. At 12 mm hr^{-1} and 16 mm hr^{-1} both inside and outside the exclosure there are peaks in the SSC at the start of the experiments showing an initial peak in SSC followed by sediment exhaustion occurring during the experiments (Figure 6.6). Despite the differences in vegetation cover and the differing runoff rates the SSCs are similar between plots.
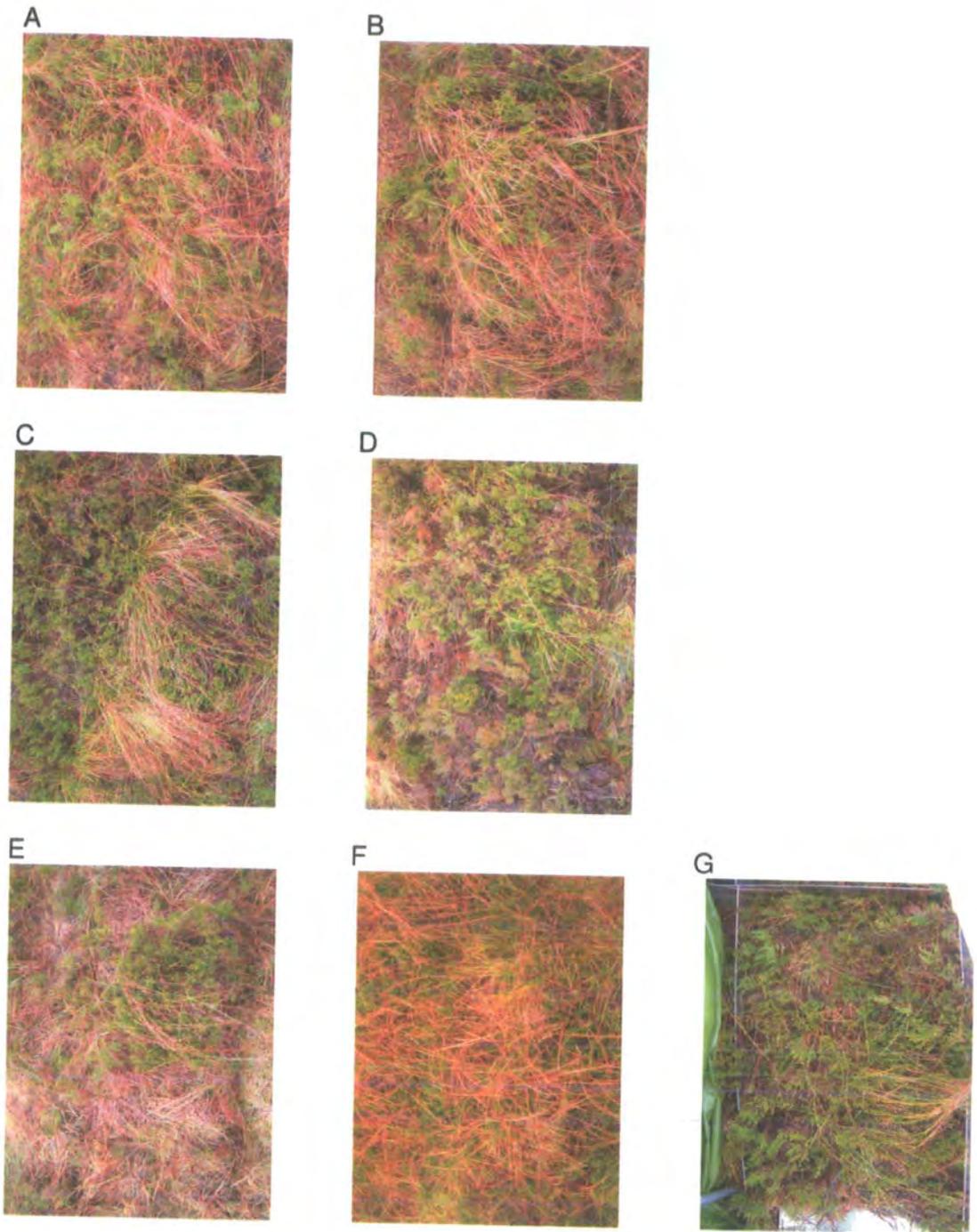
Figure 6.30: Vegetation cover on the plots on the Hard Hill Burning Experiment, A) 10-year rotation inside plot, B) 10-year rotation outside plot, C) 20-year rotation inside plot, D) 20-year rotation outside plot, E) 1954 only inside plot, F) 1954 only outside plot and G) Grazed only (outside plot).

Both inside and outside the exclosure the plots were saturated on the day of the experiment, especially outside the exclosure where the moisture content of the top 10 cm of peat varied from 93 – 95 %. The densities of the peat were greater inside the exclosure than outside (Table 6.2). This may be the reason for the surface runoff being greater inside the exclosure than outside, as less water would be able to infiltrate into the peat.

20-year Burning Rotation

Figure 2.16 showed that with a 20-year burning rotation the *Calluna* vegetation cover was dominant over *Eriophorum*. Figures 6.30c and 6.30d also show this to be the case. The *Calluna* is dense and healthy with some *Eriophorum* amongst it. The results of the rainfall simulation experiment showed the runoff rates to increase with rainfall intensity (Figure 6.28b and Figure 6.30). Figure 6.28b shows the mean steady state runoff rates outside the exclosure to be virtually the same as the rainfall input (O = I). This indicates no storage is occurred during the experiments (Figure 6.20). Inside the exclosure the runoff production is approximately 6 mm hr^{-1} less than the rainfall intensity. Again increased infiltration occurred at the higher runoff rates indicating that the plot was affected by either ponding on the surface, an uneven surface topography or a greater raindrop impact.

The runoff at 5 cm depth dominated both inside and outside the exclosure, which is thought to be the result of vegetation cover, since the dense vegetation mat will allow rainfall to infiltrate into the peat, rather than it flowing over the surface. Surface runoff rates are greater outside the exclosure than inside. Inside the exclosure the 1 cm runoff rate is low, therefore indicating that this vegetation type and cover density may be ideal in preventing surface runoff and possibly erosion. Labadz (1988) discussed how *Eriophorum*-covered peat potentially has a high infiltration capacity and may therefore be the reason for low runoff rates at the surface. The greater surface runoff outside may be due to there being less *Eriophorum vaginatum* outside the exclosure than inside (Figure 6.30): a result of grazing.

In comparison to the 10-year burning rotation the surface runoff is less than half and may indicate that more frequent burning increases surface runoff because the vegetation cover becomes less dense. The *Calluna vulgaris* is sparse in the 10-year burning

rotation, which may be the cause of the greater surface runoff rates and therefore this burning treatment is not only a problem in terms of *Calluna vulgaris* performance but also for surface runoff rates and potential erosion.

Figures 6.26 and 6.29b show the SSC to be greater inside the exclosure than outside. There is a general decreasing trend in SSC with increasing rainfall intensity regardless of exclosure indicating sediment exhaustion is occurring. Figure 6.26 shows that inside the exclosure with the exception of the 16 mm hr^{-1} there is a peak in SSC at the start of each experiment, indicating an initial flush of sediment followed sediment exhaustion is occurred during each experiment (Figure 6.7). Outside the exclosure there is a peak in SSC at the start of the 12 mm hr^{-1} and a smaller peak at the start of the 24 mm hr^{-1} experiment, but at rainfall intensities of 16 mm hr^{-1} and 20 mm hr^{-1} there are no peaks and SSCs are low. This is typical of an initial flush of sediment, followed by sediment exhaustion and sediment production as the rainfall intensity increases. Considering the surface runoff is greater outside the exclosure than inside and the SSC is less, the difference is likely to be a result of vegetation cover.

The main differences between the runoff production inside and outside the exclosure were the amount of surface runoff. As discussed above this was thought to be largely a result of the vegetation cover. Table 6.2 shows the upper 5 cm of the peat to be less saturated (88 %) than the lower layers inside the exclosure and the outside of the exclosure (89 %). This indicates that more water can infiltrate into the peat rather than flow over the surface and may be the reason for the surface runoff being less inside the exclosure. The 5 cm runoff rates are similar and high indicating that the throughflow is predominant at this depth within the peat.

Burnt in 1954 only

The impacts of the 1954 burn (Figures 6.27 and 6.28c) shows that inside the exclosure the surface runoff is greater than the 5 cm and 10 cm runoff and this increases with rainfall intensity. Figure 6.27 shows that outside the exclosure the surface runoff is very low and the 5 cm runoff is the dominant runoff pathway. Both inside and outside the exclosure the 10 cm runoff is relatively high (between 1 mm hr^{-1} and 6 mm hr^{-1}) especially in comparison to the 10- and 20-year burning rotations (where runoff rates are less than 3 mm hr^{-1}). This is thought to be a result of vegetation controls. Inside the

exclosure the vegetation is predominantly *Calluna vulgaris* in a state of degeneration. The grasses and mosses have decreased, e.g. *Eriophorum vaginatum* due to competition for the *Calluna vulgaris* (Figure 6.30) and therefore this could account for the high surface runoff. Outside the plot *Calluna* is also degenerating, however, the ground cover is predominantly covered by *Eriophorum vaginatum*. The vegetation mat is denser and therefore the rainfall will have time to infiltrate into the peat, promoting 5 cm runoff. The vegetation inside and outside the plot is very different (Table 6.2 and Figure 6.30). Runoff production both inside and outside the exclosure from the 1954 burn is less than on the 10- and 20-year burning rotation despite the vegetation being in a state of degeneration, indicating that the more burning the more runoff and potential for erosion. Figure 6.25c shows the runoff production to increase with increasing rainfall intensity. Both inside and outside the exclosure runoff production is approximately 6 mm hr^{-1} less than the rainfall rate.

Figure 6.27 and Figure 6.29c shows a general decrease in SSC with increasing rainfall intensity, with the exception of the 24 mm hr^{-1} outside where there are two peaks in SSC throughout the run. This indicates sediment production is occurring at the higher rainfall intensity. The SSC was greater outside the exclosure than inside. Outside the exclosure there was an initial peak in SSC at 12 mm hr^{-1}, where the SSC was high and flashy throughout the run (with a mean SSC of approximately 120 mg l^{-1}), indicating that sediment was prepared on the surface prior to the simulated rainfall experiments and ready for entrainment (Figures 6.20 and 6.29c).

Figure 6.27 shows the surface runoff to be high inside the exclosure and the 5 cm runoff to be high outside the exclosure. Table 6.2 indicates this to be the result of the lower layers (5 – 10 cm) of the peat being saturated (95 %) therefore little water can infiltrate into the peat and therefore flows over the surface. Outside the exclosure the peat is less saturated at both levels (varying from approximately 86 – 88 %) and the bulk density of the peat is lower than inside the exclosure, therefore more water can infiltrate into the peat and flow was throughflow through the lower layers (5 and 10 cm depths).

Unburnt (Outside only)

The results from outside the plot where only grazing has taken place (no burning) are also presented. The results show that as rainfall intensity increases at a greater rate than

the runoff rate, therefore indicating that the infiltration rate is increasing as the rainfall intensity increases (Figures 6.27 and 6.28d). This is thought to be the result of the increased high intensity rainfall on the peat surface (Bowyer-Bower, 1993). It is not in this case considered the result of ponding on the surface because none was observed and also not thought to be a result of the plot surface because it is thought that it would also have been observed on the other Hard Hill Burning Exclosures. The surface runoff is significantly greater than the 5 cm and 10 cm runoff. The surface runoff increases with increasing rainfall intensity until 24 mm hr^{-1} where it decreases. Overall the runoff rates at all three depths are less than where burning took place (Figure 6.27d). This indicates that burning has a direct effect on runoff rate.

Where there was no burning and only grazing the SSC is initially high and then decreases with increasing rainfall intensity, again indicating sediment exhaustion is occurring (Figures 6.20 and 6.29d). The initial peaks in SSC, particularly at rainfall intensities of 12 mm hr^{-1} and 16 mm hr^{-1} are high followed by a decrease in SSC throughout the runs. No burning indicated the runoff production to be less than where burning had taken place and therefore since the SSC was greater this was unexpected. It was thought that the SSC would have been greater where burning had taken place, since there would be less vegetation to trap the particles and charred vegetation particles on the surface would have been prepared for entrainment. However this did not appear to be the case. It is thought the SSC is high at this site because the *Calluna* and other vegetation is degenerating and particles were on the surface.

Figures 6.28 and 6.29 shows the mean steady state runoff rates from this plot were comparable to 10-year burning rotation inside and 20-year burning rotation inside and the SSCs were also comparable to 20-year burning rotation inside. Table 6.2 shows the moisture contents of the peat in both layers are very similar between the plots. The surface runoff from this plot, although essentially lower was comparable to the burnt plots. The main difference was that the 5 cm and 10 cm runoff rates were less. This may indicate that burning affects runoff production at lower layers. This may be from the break up and cracking of the peat during the burn.

Bare Peat Experiments

This section discusses the results of two individual rainfall simulation experiments, which were carried out on two bare plots of differing slope angles (Figures 6.31 and 6.32).

Figure 6.31 shows the runoff production to be similar from both plots and does not vary greatly with rainfall intensity, indicating that increased infiltration is occurring at the higher rainfall intensities. The runoff production is greatest at the 5 cm depth and least at the 10 cm depth in both plots. It was expected that the 1 cm runoff would be the greatest considering there is no vegetation. On the gully wall despite the 5 cm runoff being the greatest the 1 cm runoff is also high. This can be explained as the slope angle is greater and there is less time for the rainfall to infiltrate into the soil before overland flow occurs. It is considered that the 5 cm runoff rate may be the greatest because water may be flowing down through small cracks on the peat or ponding on the surface and infiltrating into the peat. Figure 6.32a shows the both experiments to follow the same pattern; however, for the bare gully wall the runoff production is approximately 3 mm hr^{-1} greater than for the bare gully floor.

Figures 6.31 and 6.32b shows on both plots a decrease in SSC with increasing rainfall intensity. The initial flush in SSC was removed from Figure 6.32b to allow for better observations of the patterns from other runs. The initial flush of sediment on the bare plot in the gully base was very high followed by a rapid decrease, indicating sediment exhaustion to be occurring from the plot. The ranges of SSC on the bare plot were from 250000 mg l^{-1} to 300 mg l^{-1} and on the gully wall bare plot were from 8000 mg l^{-1} to 400 mg l^{-1} and both appeared flashy. This was thought to be the result of rainfall ponding on the bare peat surface then being released as the ponds filled. Despite the initial flush in sediment from the bare plot the SSC is greater from the gully wall than the bare peat. This is expected as a result of the steepness of the slope angle.
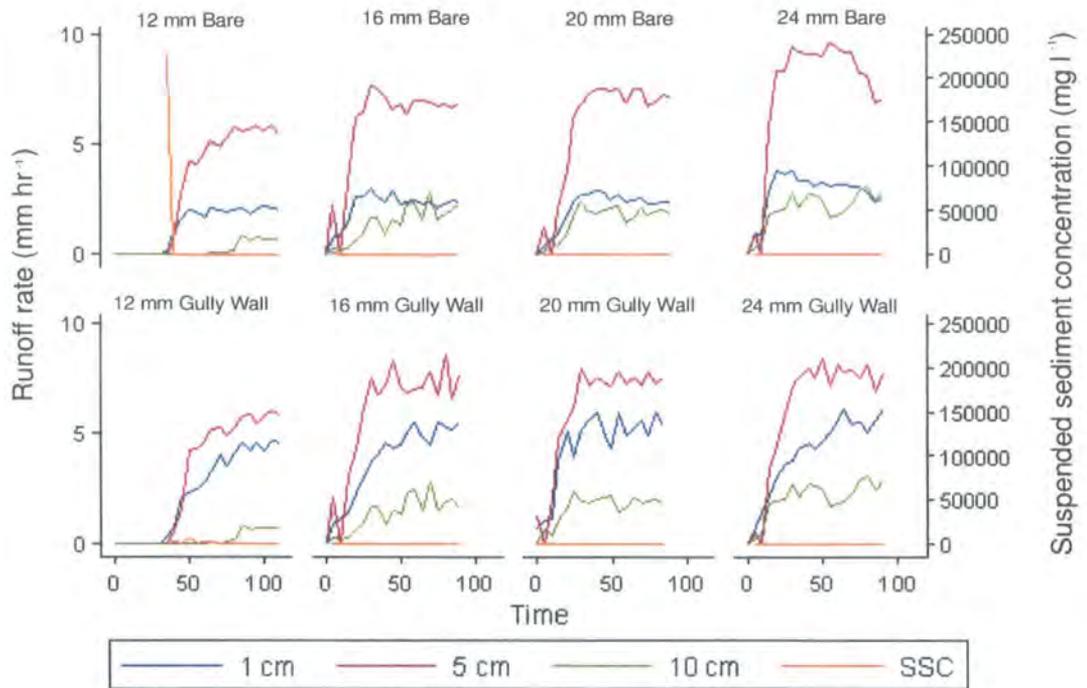
Figure 6.31: The rainfall simulation experiments from Burnt Hill Gully, showing the differences between bare peat in the base of the gully to a bare peat gully wall.
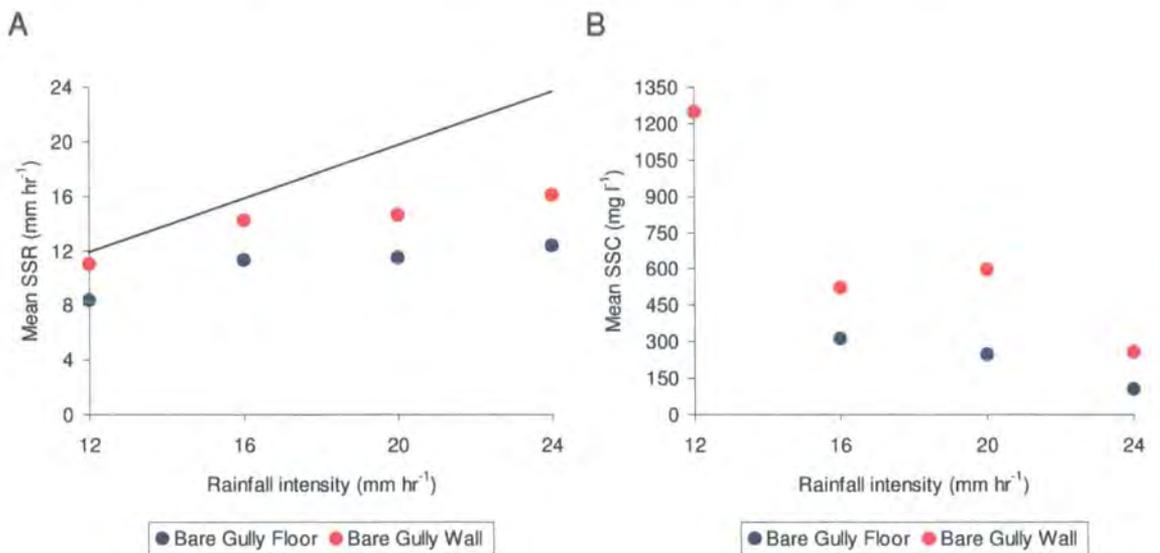
Figure 6.32: Graphs showing the results from the bare gully floor and bare gully wall for, A) mean runoff production and B) mean suspended sediment concentration, against rainfall intensities. The 1:1 (O = I) line is shown in 6.32a.

Table 6.2 indicates the surface peat of both plots was poorly desiccated and therefore it is likely that small cracks in the surface will cause the water to infiltrate rather than flow. Small root structures on the surface of the bare plot would also prohibit overland flow and promote ponding and infiltration. The slope angle of the gully wall plot caused the surface runoff to be greater than the bare plot, however the lower layers (5 – 10 cm) of peat on this plot are clayey and therefore would prevent water infiltrating into the peat, therefore the water would remain in the upper layers affecting the 1 cm and 5 cm runoff production.

6.4   Summary of the laboratory and field experiments

Experiment	Mean SSR (mm hr^{-1})		Mean SSC (mg l^{-1})	
Laboratory Block				
Ungrazed	6.38		49.46	
Grazed	4.47		38.76	
Burnt	3.02		48.48	
Mean	**4.62**		**45.57**	
Field – Grazing Exclosures	**Inside**	**Outside**	**Inside**	**Outside**
Knock Fell	1.56	6.67	206.24	138.74
Silverband	2.34	2.31	1223.63	460.75
Cottage Hill	6.32	6.26	67.99	141.07
Burnt Hill	0.95	4.9	412.64	176.45
Field - Hard Hill Burning Exclosure				
10-year burning rotation	7.38	9.34	35.7	44.08
20-year burning rotation	12.2	15.88	75.38	27.33
Burnt 1954 only	12.4	11.25	22.22	66.05
Unburnt (Grazed only)		5.83		78.63
Mean	**3.70**	**6.65**	**291.97**	**141.64**
Overall Mean	**5.18**		**216.8**	
Gully Plots				
Bare gully floor	10.87		3797.26	
Bare gully wall	14.0		657.33	
Mean	**10.87**		**2227.3**	

Table 6.4: Summary of the mean steady-state runoff rates and mean suspended sediment concentration from the laboratory and field experiments.

The results from the laboratory and field experiments were interesting in terms of the patterns of runoff production and SSC in relation in increasing rainfall intensity. Runoff rates were shown to either increase with increasing rainfall intensity or to stabilise at the

higher rainfall intensities, indicating infiltration rates increased on many plots as rainfall intensity increased. Runoff rates and SSCs were least from the laboratory peat block experiments and greatest from the bare peat experiments (Table 6.4). SSCs generally showed an initial peak in SSC (12 mm hr^{-1}) followed by sediment exhaustion occurring at the rainfall intensities of 16 mm hr^{-1} and 20 mm hr^{-1} and a further peak in SSC at a rainfall intensity of 24 mm hr^{-1}, whereby sediment production occurred (Figure 6.20). Table 6.4 shows runoff production to be greatest outside the grazing exclosures indicating sheep grazing affected runoff production. The SSC was less outside the exclosures however, indicating that sheep grazing had little impact on increasing sediment production, which is interesting in terms of gully erosion. The Hard Hill Burning Experiments showed burning to affect runoff production because the runoff rates were greater than from the grazing exclosures. However burning is shown to reduce the SSC.

6.5   The Throughflow Experiment

6.5.1   The Experimental Set-up

The 'Throughflow Experiment' (Figure 6.33a) was designed to test the assumption that very little lateral flow occurs at depths greater than 5 cm (Holden and Burt, 2002b; 2003a). The motivation for the experiment was that although the results showed a general decrease in runoff production with depth, often (e.g. the grazed laboratory block, Cottage Hill grazing exclosure and the 20-year burning rotation on the Hard Hill Burning Experiment) the 5 cm runoff rate was higher than expected (greater than the surface runoff). Such rates had large impacts on the runoff production (Table 6.4). In addition, the runoff trays were inserted into the peat with the top tray (1 cm depth) inserted the furthest into the peat and the bottom tray (10 cm depth) inserted the least into the peat in all the laboratory and field experiments. The 'Throughflow Experiment' aimed to test if altering the position of the runoff trays inserted in the peat affected the runoff results. For example by inserting the runoff trays at the same distance in the peat or inserting the 10 cm runoff tray the furthest distance into the peat and 1 cm tray the least (Figure 6.33b).

This experiment involved placing a thin (10 cm) intact peat block between two clear glass sheets confined within a box. The peat had a covering of vegetation similar to that

of the laboratory rainfall simulation experiments. Runoff trays were inserted into the peat at 1 cm, 5 cm and 10 cm depths and at differing distances into the peat (Figure 6.33b). 40 litres of rainfall were simulated at an approximate rate of 24 mm hr^{-1} from a water tank in a manner similar to the main field and laboratory experiments. The water was collected from the runoff trays every minute during the experiment (Figure 6.33a). Similar to the laboratory rainfall simulation experiments the slope angle was altered in order to test the differences in runoff between the 2.5°, 5°, and 10° slope angles. The clear glass sides of the experimental tank meant that the path of throughflow could be observed during the experiment. A small drainage hole was located in the bottom corner of the tank to allow the block to drain, therefore representing the throughflow below 10 cm depth. Between the base and peat block there was a thin layer of mineral soil to represent field conditions (Figure 6.33a).
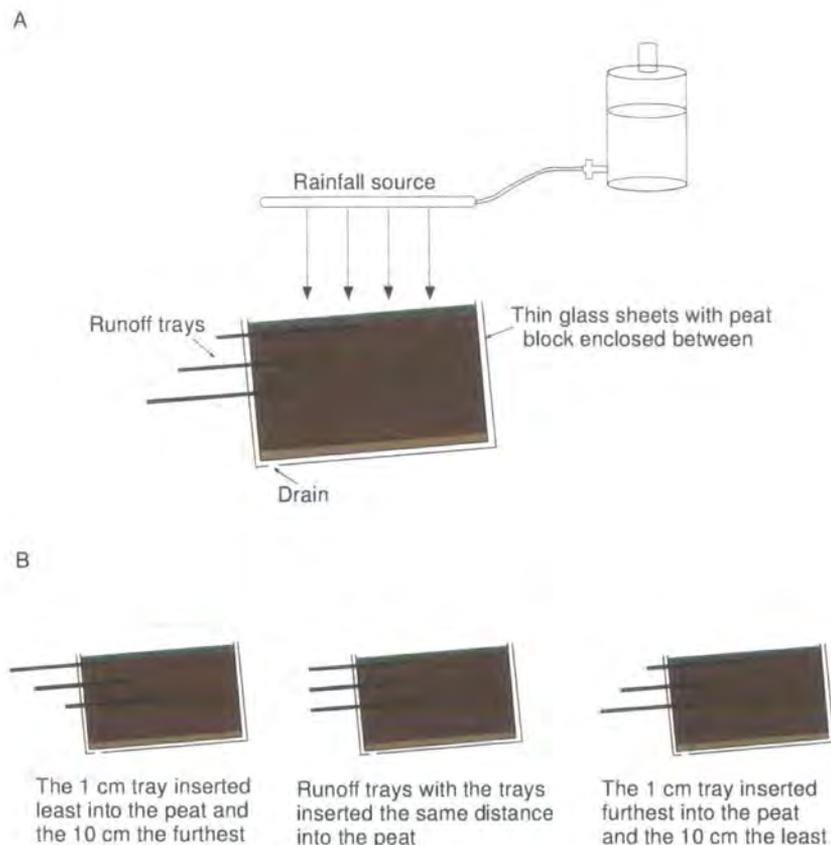
Figure 6.33: Diagram showing: A) the experimental set up of the throughflow experiment, B) the varying positions of the runoff rates.

6.5.2 Results of Experiments on Runoff Production

The results from this experiment showed that both the position of the runoff trays and the slope angle affected the runoff rate (Figure 6.34). The 10 cm depth produced the greatest runoff when the trays were positioned with the 1 cm depth runoff tray inserted the least into the peat and the 10 cm the furthest (Figure 6.34a). The reason for this occurring was that more water was channelled onto the tray by horizontal and vertical throughflow. All the runoff trays inserted into the peat at the same distance gave results expected from peat, whereby the greatest runoff was the surface runoff and least from the 10 cm tray (Figure 6.34b). Figure 6.34c shows the results from the runoff trays positioned the same as they were in the laboratory and field experiments. The 1 cm runoff rate was the greatest, as was expected. The 5 cm depth tray produced the least runoff. The water appeared to by-pass the tray, either by flowing vertically and horizontally so it was caught on the 1 cm tray or the 10 cm tray. This was interesting in comparison to the laboratory and field experiments, whereby this was not often the case. The 1 cm runoff was the highest and followed by the 10 cm. It is thought that the 10 cm depth tray would have produced the least runoff however despite the drain at the bottom the water table appeared to be rising in the peat block affecting this production, therefore affected by the low saturated hydraulic conductivity of the peat.

At a slope angle of 5° the 5 cm runoff again was the lowest and the 10 cm runoff rate the greatest (Figure 6.34d). This again appeared to be a result of a rising water table. The surface runoff rate was greater from the 2.5° slope than the 5° slope indicating that the steeper the slope angle did not cause more overland flow as expected. The 10° slope angle was the only test with the trays positioned as they were in the field and laboratory experiments in which the results followed that of Holden and Burt (2002b; 2003a). The runoff rates at all three depths were small in comparison to the rainfall input indicating that infiltration was occurring. It was also clear that much water infiltrates though the peat below the 10 cm depth and is stored within the peat and released as deep throughflow.

The results from this experiment showed differing results to those in the field. The position of the runoff trays and slope angles affected the results. Runoff rates were generally highest from the 1 cm runoff tray and the 5° slope angle.
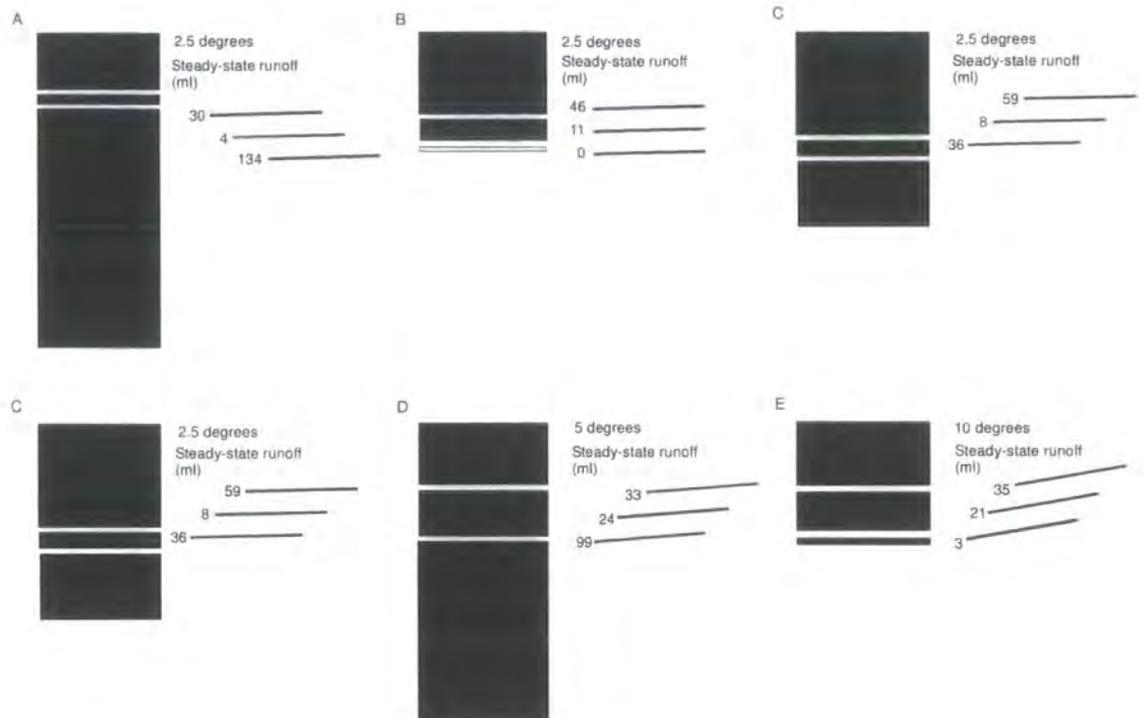
Figure 6.34: The runoff production from the runoff trays inserted into the peat at varying distances and differing degrees of slope. The steady state runoff rates are shown along with their proportions for comparison with the other experiments. Comparable experiments as shown alongside each other, e.g. A – C (varying runoff tray positions) and C – E (varying slope angles).

6.6   Conceptual model of runoff production in upland blanket peat

It is clear from the results that vegetation types in upland UK affect runoff rates (Table 6.4). Figure 6.35 presents a summary of the results. The figures were calculated from the results in Table 6.4, e.g. the burnt and ungrazed heather was determined by calculating the mean steady-state runoff rate from all the runoff trays over the four runs for 10-year burning rotation inside the exclosure, 20-year burning rotation inside the exclosure and burnt in 1954 only inside the exclosure. The results show heather vegetation to yield a greater runoff than grass, but bare peat yielded the greatest runoff.
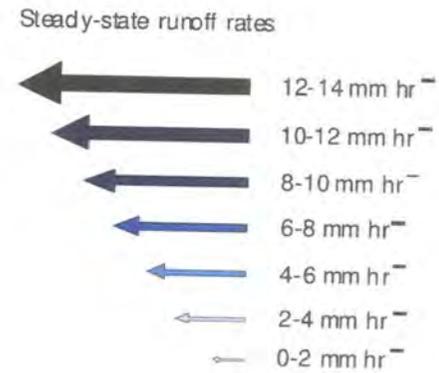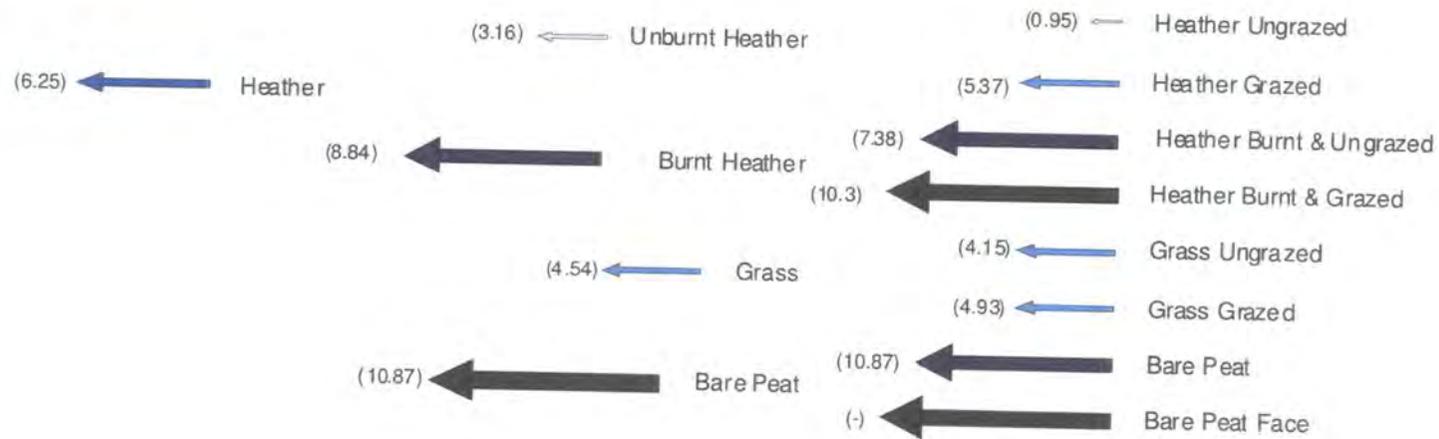
Figure 6.35: Summary of runoff production in upland blanket peat.

The heather and grass vegetation showed to have runoff rates of approximately 7 mm hr^{-1} and 5 mm hr^{-1} respectively. Therefore indicating grasses allow more water to infiltrate into the soil rather than producing overland flow or throughflow. However, the impacts of heather burning affected the results greatly. The runoff production from unburnt heather was approximately 3 mm hr^{-1}, whereas from burnt heather was approximately 11 mm hr^{-1}. This indicates that burning heather caused not only a loss to the vegetation cover but also reduced infiltration and storage causing a dramatic increase in runoff production (8 mm hr^{-1}).

Grazing also showed to affect runoff production as well as reducing vegetation cover. Interestingly sheep grazing on heather vegetation showed to have a greater impact than on the moorland grass. It was expected that moorland grass would show the greatest difference due to preferential grazing. Grazing on unburnt heather vegetation increased runoff production by 4.4 mm hr^{-1}, on burnt heather by 2.3 mm hr^{-1} and on moorland grass by 0.8 mm hr^{-1}. The impacts of both burning and grazing on runoff production is interesting in terms of the future stability of upland blanket peat. Grazing showed to have less of an effect than burning on runoff production and therefore reducing burning by possibly cutting the heather ought to be considered for future management practice.

Bare peat showed runoff rates of 10.9 mm hr^{-1}, indicating runoff production to be great, with little storage occurring within the plot. Encouraging re-vegetation of upland blanket peat is of further importance for the future stability of upland blanket peat in order to reduce runoff production and the percentage cover of bare peat.

6.7   Summary

This chapter has presented the methodologies and results from the laboratory and field rainfall simulation experiments.

The laboratory experiment was carried out using an intact peat block with moorland grass vegetation removed from Moor House and taken back to the laboratory. Rainfall simulation experiments with rainfall intensities of 12 mm hr^{-1}, 16 mm hr^{-1}, 20 mm hr^{-1} and 24 mm hr^{-1} were carried out on the block in an ungrazed, grazed and burnt state. A number of additional experiments were carried out with the block in the ungrazed state to allow comparisons and aid the field results. These including the reversing the order of

the applied rainfall intensities to see if it affected runoff production and sediment yield, altering the time between experiments and the slope angle of the block.

The results showed the runoff production and sediment yield from the ungrazed laboratory peat block was greater than the grazed and burnt block. Varying the time between the runs and the slope angle had little effect on runoff production and sediment concentration from the block. Interestingly the experiments from the burnt block produced the least runoff.

The field experiments took advantage of the Moor House long-term grazing (and burning) exclosures. Paired rainfall simulation experiments were carried out inside and outside of five of the exclosures: Knock Fell, Cottage Hill, Silverband, Burnt Hill and the Hard Hill Burning Experiments. The runoff production and sediment yield was also measured from a bare peat surface on a gully floor and a bare peat gully wall (Burnt Hill's main gully system) in order to compare the results against vegetation surfaces.

The results showed runoff production to be greater from the moorland grass plots than the heather plots, though sediment yields were comparable. Knock Fell exclosure plot demonstrated that the vegetation composition and structure has changed as a result of long-term sheep removal and highlighted the importance of management practices in conditioning runoff. The other plots did not show this as clearly and differences in runoff and sediment production between the inside and outside of the plot were more variable. The vegetation cover and density was generally greater inside the exclosure than outside and therefore it was expected that the results would show greater runoff production outside the exclosures. Sheep grazing increased runoff production and sediment yield.

Burning increased runoff production but had no impact on sediment yield, despite a greater runoff production. Burning had less of an effect on both the runoff rates and sediment production on the 10-year burning rotation than on the 20-year burning rotation or the single 1954 burn. On the 20-year burning rotation or the plot burnt only in 1954 the heather became dominant and had started to degenerate.

Both runoff production and sediment yield was greatest from the bare peat plots. This is the result of there being no vegetation to promote infiltration and trap the sediment.

233

Therefore re-vegetation of upland blanket peat will potentially reduce runoff production and sediment yield and promote future stability.

Generally runoff production was similar from both the laboratory and field experiments. The sediment yield was less from the laboratory experiments (comparable with the Hard Hill Burning Experiments). This is thought to be the result of only using one laboratory peat block, whereby after the early runs the sediment would become exhausted from the plot. This may explain why the sediment yield from the ungrazed experiments was the greatest.

Vegetation cover and upper profile soil properties were shown to be key in determining both the runoff production and sediment yield. An increase in rainfall intensity generally produced either an increase in runoff production or an increase in runoff production followed by an increase in infiltration. The SSC decreased with increasing rainfall intensity during most experiments indicating sediment exhaustion occurring from the plot. Occasional increases in SSCs were observed at a rainfall intensity of 24 mm hr^{-1} indicating that sediment production (particle detachment and entrainment) was occurring at higher rainfall intensities.

The 10 cm runoff tray yielded the least runoff, which agrees with Holden and Burt (2002b; 2003a), however the 5 cm runoff rate was on occasion greater than the 1 cm runoff rate. This was considered to be either the result of through flow entering the plot and dense vegetation cover encouraging infiltration into the upper soil layers. The Throughflow Experiment was then carried out to try and explain this. The Throughflow Experiment was useful in indicating the movement of water through the peat, however did not help the full understanding. The results from The Throughflow Experiment were unlike the results from the laboratory and field experiments in that the 5 cm runoff rates were less than the 1 cm and 10 cm. The 1 cm runoff rate was the greatest, which is expected in upland blanket peat, where the most water movement occurs in the top 5 cm (Holden and Burt, 2002b; 2003a). It was thought that the 10 cm runoff tray was affected by a rising water table during the experiments.

The development of existing gully systems are greatly affected by the runoff production and sediment yield on the interfluve areas, because these areas may input water and sediment into the gully systems or if gully initiation occurs on the interfluves, affect the

drainage of the existing systems. Runoff production and sediment yields are also important in causing local scale movement of sediment in existing gully systems, as shown with the bare peat gully floor and gully wall experiments. The next chapter addresses the local scale changes in gully development at the three study sites.

7.0 GULLY MORPHOLOGY

7.1 Scope of chapter

This chapter presents the results of the gully morphology research from the three study sites, which includes detailed research on a selected number of typical gully systems. The same analysis was carried out on each gully system, although only selected results are presented to avoid repetition. Section 7.2 discusses the results of the morphology of the gully systems at Moor House, while sections 7.3 and 7.4 discuss the results from The Cheviot and Wessenden Head Moss respectively. The final section summarises the research findings (Section 7.5).

7.2 Morphology of gully systems at Moor House

Section 7.2.1 discusses the results from the long profile measurements and Section 7.2.2 discusses the cross profiles from a number of gully systems. This is followed by the variations within the gully systems over the last approximate 50 years using ground-based photographs (Section 7.2.3). Section 7.2.4 then looks at the contemporary vegetation within the bases of the gully systems at Moor House and details of the stratigraphy are discussed in Section 7.2.5. This involved analysis of the cores and monoliths removed from the infilled gully bases. Cores from eroded sites are compared with uneroded cores in order to date the onset of erosion at the site (Section 7.2.6).

7.2.1 Long Profiles

The results from the long profile measurements were previously touched upon in Chapter 4 but are discussed in more detail here. This section presents the long profile results from three representative gully systems at Moor House. Table 7.1 presents a summary of the data with measurements of gully lengths, widths, slopes and peat depths. The long profiles show the variations in slope angle and peat depth within the gully systems. At first glance the gully systems at Moor House appear to be convex in shape; however, Bower's (1960b) classification of dissection was diagrammatically shown on a concave slope, implying that the gully systems in the Pennines formed on concave slopes. The long profile measurements will also allow the determination of the gully shape.

Study Site	Gully System	Gully Length (m)	Mean Gully Width (m)	Mean Peat Depth (m)	Local Gully Height (Fall Height) (m)	Average Gradient	Average angle at break in slope (°)
Moor House	Burnt Hill 1	272	13.5	0.62	16	0.06	2.3
	Burnt Hill 2	290	8.7	0.92	19	0.07	3.5
	Nether Hearth	427.5	8	1.03	18.5	0.04	0.9
	Cottage Hill Main	568	10.6	1.21	12.7	0.02	1.1
	Cottage Hill Top Side	87		1.92	4.3	0.05	4.5
	Cottage Hill Bottom Side	260		1.06	14.5	0.06	3.4
	Rough Sike 1	561	14.95	0.53	11.1	0.02	2.1
							2.4
	Gully A adjacent to Rough Sike	159.3	8.5	0.5	15	0.09	4.6
	Gully B adjacent to Rough Sike	179.2	9	0.56	14	0.08	2.4
	Gully C adjacent to Rough Sike	271.9	9.3	0.55	22	0.08	4.1
	Gully D adjacent to Rough Sike	378.4	8.5	0.67	34	0.09	4.5
	Gully A adjacent to Netherheath	119	13.5	0.68	13.2	0.11	6.2
	Gully B adjacent to Netherheath	138.7	9.9	0.48	15.6	0.11	7.0
	Gully C adjacent to Netherheath	94.7	7	0.34	12.4	0.13	5.9
	Mean	**270.5**	**10.1**	**0.79**	**15.8**	**0.06**	**3.7**
The Cheviot	Gully 1	707.5	6.8	1.13	52.8	0.07	3.4
	Gully 2	282.9	7	0.36	30.8	0.11	4.5
	Gully 3	582.4	10.35	0.45	96.5	0.17	6.8
	Mean	**524.3**	**5.4**	**0.49**	**60.0**	**0.11**	**4.9**
Wessenden Head Moss	Gully 1 Main	346	3.65	3.51	7.1	0.02	1.4
	Gully 1 Side	208			5.3	0.03	2.1
	Gully 2	327.5	5.25	2.9	5.3	0.02	1.1
	Gully 3	503.4	7.4	1.34	11.9	0.02	1.1
	Mean	**346.2**	**8**	**2.58**	**7.4**	**0.02**	**1.4**

Table 7.1: Summary measurements of gully morphology taken from the long profile and cross profile surveys.

Figure 7.1 shows two adjacent long profiles from Burnt Hill. Figure 7.1a is the profile from the intact peat adjacent to the main gully system on Burnt Hill (gully system 1) and the long profile down the gully system is shown in Figure 7.1b. The gully system has a convex profile and a length of 272 m with a fall in height over that profile of approximately 16 m (average gradient of 0.06). From Figures 7.1a and 7.1b the shape of the profiles are shown to be relatively similar and the break in slope is observed at a distance of approximately 150 m from the head of the gully system. The break in slope can be defined as the point along the profiles where the slope angle is observed to steepen. The average angle at the break in slope was measured at 2.3° in the gully (Table 7.1). The gully system profile shows a more gradual profile than the intact profile. The intact profile has a gentler slope than the gully profile over the top 150 m and a much steeper slope in the bottom part of the profile.

Analysis of ground-based and aerial photographs show that the average slope angle at the break in slope is 2.3°, and appears to be the divide between anastomosing and linear dissection. There is no abrupt change in slope and therefore more of a transition of form was observed. Between the anastomosing and linear dissection there was a few metres of dendritic dissection, indicating this transitional zone. It was interesting to note the significance of slope in affecting the dissection type, similarly to the work of Bower (1960a; 1960b), Radley (1962), Mosley (1972) and Wishart and Warburton (2002).

The peat depth also varied down the gully profile. Both Figure 7.1a and 7.1b show that the peat depth is greatest where the slope gradient is least. This occurs on the relatively flat intact peat and the area of anastomosing peat within the upper half of the gully system. From these profiles it is clear that slope has an influence on peat depth.
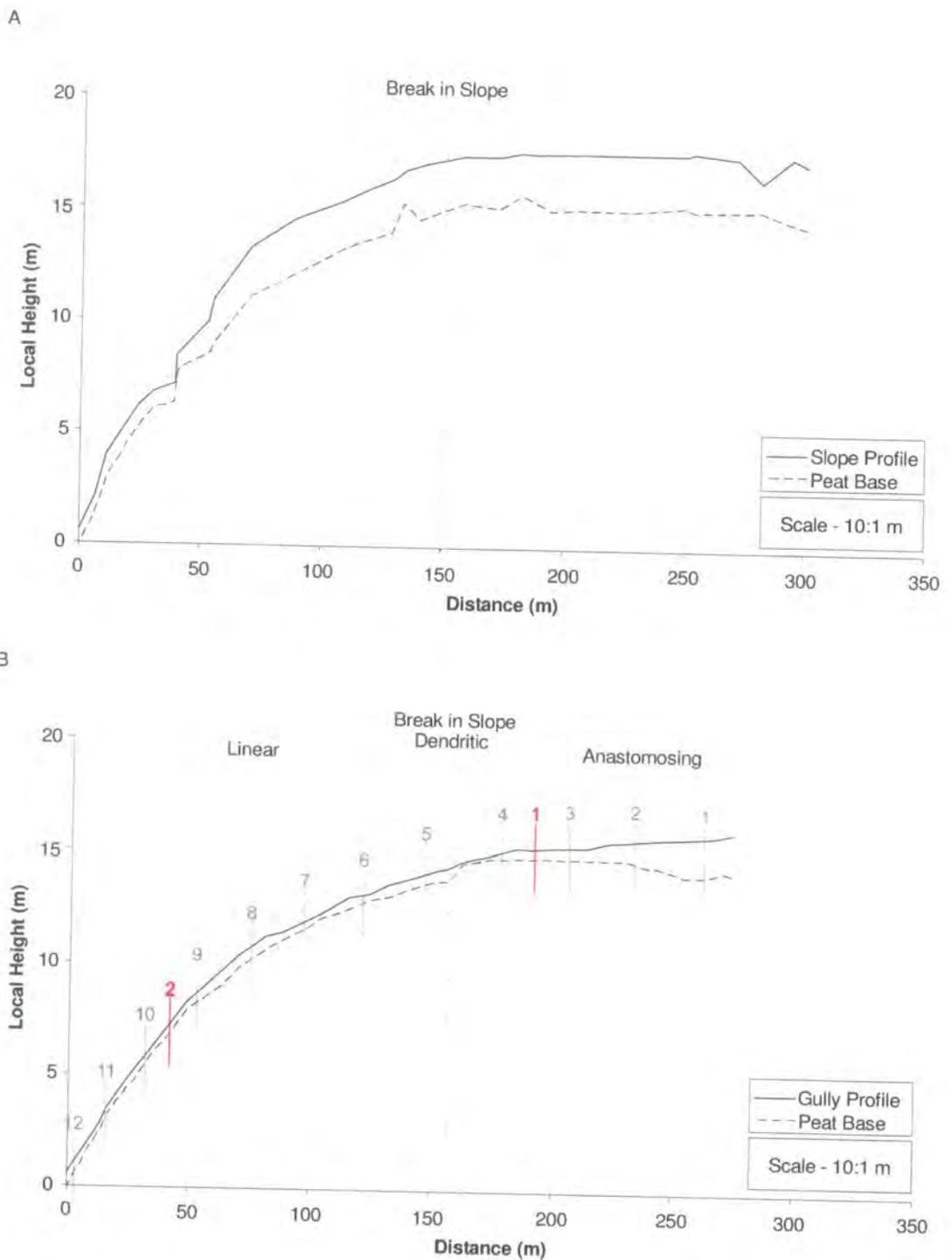
Figure 7.1: Long profiles of a) the slope and peat depth adjacent to Burnt Hill's main gully system and b) the gully profile and peat depth. The break in slope is indicated in the profile as the area between the linear and anastomosing dissection. The location and number of the cross profiles discussed in Section 7.2.2 are shown in grey and the location and number of the cross-sections discussed in Section 7.2.5 are shown in red.

Figure 7.2 shows a long profile from a gully system adjacent to Burnt Hill (Nether Hearth gully system). Selective measurements were carried out at each site. At this site a long profile of the adjacent intact peat was not carried out. This gully system is also generally convex in profile with a gradual change in slope angle of 0.04°. The average angle at the break in slope was 0.9° and therefore was much lower than the main gully system on Burnt Hill (Table 7.1). This break in slope is associated with a change in dissection type: dendritic to linear dissection. Variation in peat depth in Figure 7.2 is less apparent than in Figures 7.1a and 7.1b, however peat thins between 50 to 150 m where the slope angle steepened.
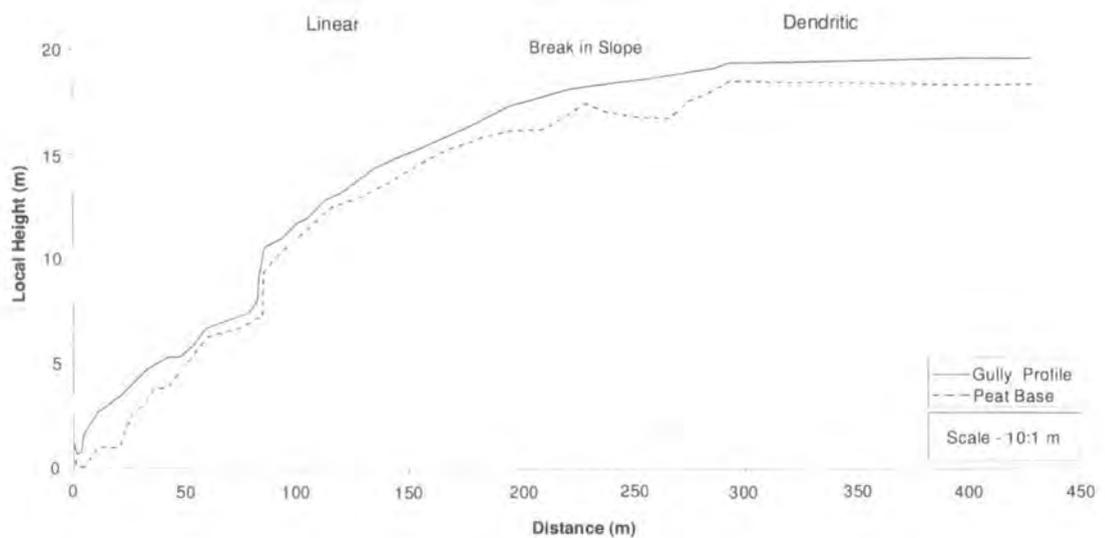
Figure 7.2: Long profile of the Nether Hearth gully system (adjacent to Burnt Hill) and the peat depth. The break in slope divides the area of linear and dendritic dissection.

Burnt Hill 2 gully system long profile and adjacent intact peat profile are shown in Figure 7.3. Figure 7.3a shows a profile similar to that of Figure 7.1a. As with other systems at Moor House the gully profile is generally convex, increasing in slope towards the bottom of the profile. The peat depth is greatest in the area at the top of the slope where the slope angle is the least and thins as the slope increases. Figure 7.3b shows the gully profile, which is 290 m in length with an average gradient of 0.07. The break in slope in this profile is represented by a small step in the profile rather than a gradual slope. The slope angle measured from a few metres above and below the step (5 m above the step and 5 m below) is approximately 3.5° (Table 7.1). Either side of the step in profile the peat depth was significantly different and the step appeared to mark the transition between dendritic and linear dissection.
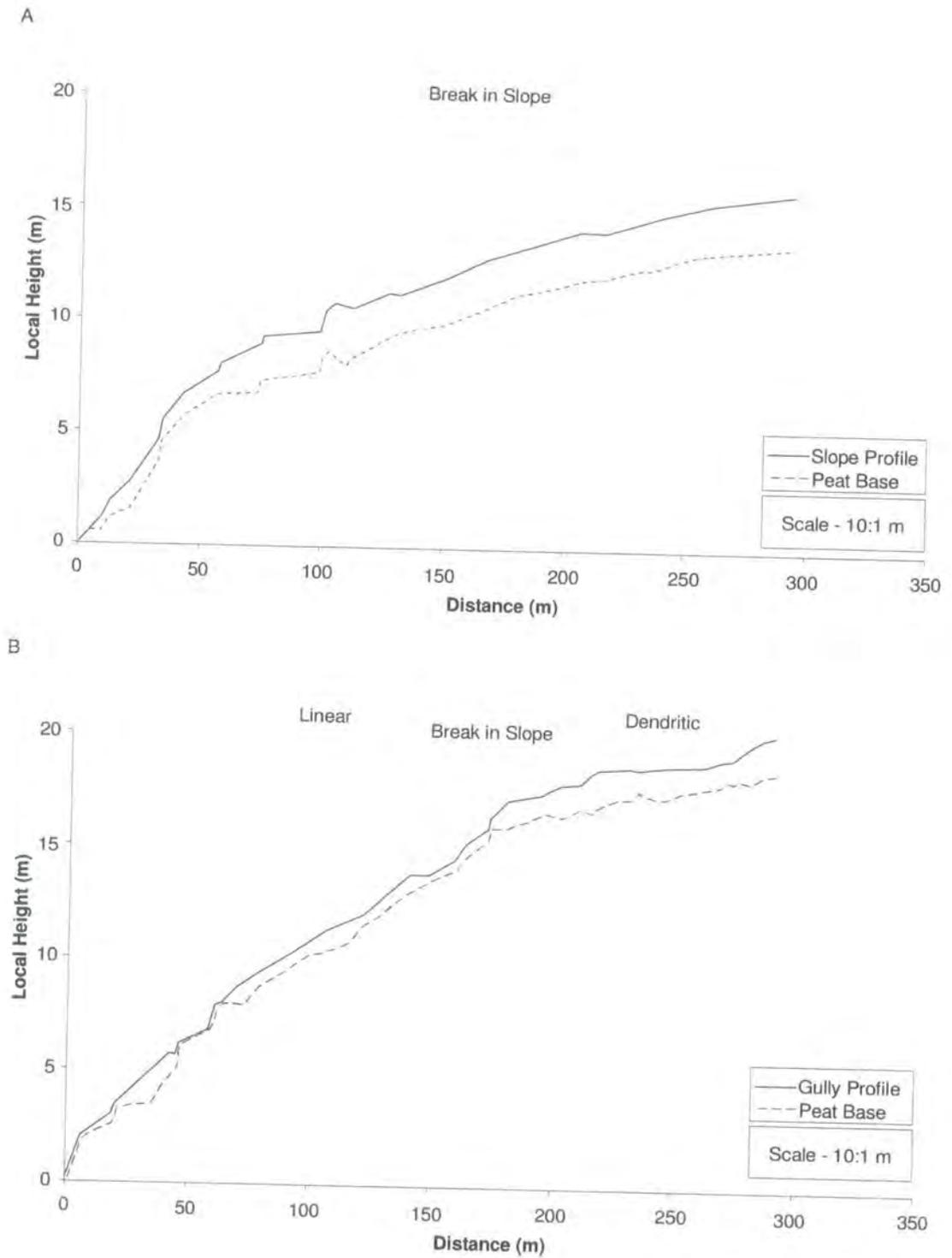
Figure 7.3: Long profiles of a) the slope and peat depth adjacent to Burnt Hill 2 Gully and b) the gully profile and peat depth. The break in slope is indicated in the profile by a step in the gully profile, which divides the areas of linear and dendritic dissection.

Figure 7.4 presents the long profiles for the four linear gully systems adjacent to Rough Sike (Figure 3.17). The four gully systems are similar in profile shape and peat depth. Table 7.1 shows their lengths to vary from 159 m (Gully A) – 378 m (Gully D) with gully length increasing with distance from Rough Sike. Despite their variations in length the average gradients are very similar varying from 0.08 – 0.09. Peat depths within these systems vary from 0.5 m – 0.67 m, which is low compared to other studied gully systems at Moor House (average of 0.79 m).

The long profiles of the remaining eight gully systems surveyed at Moor House are shown in Appendix 3 (Figures A3.1 – A3.5) and Table 7.1 provides summary data for the profiles. Table 7.1 shows the average slope angles at the break in slope from the surveyed long profiles at Moor House vary from 0.9° to 7.0°, with a mean of 3.7°. Gully lengths also vary (Table 7.1) from 87 m to 586 m, with a mean gully length of 270.5 m, which is similar to the Burnt Hill gully systems. Variations in the peat depths within the base of the surveyed gully systems were shown to vary from 0.34 m to 1.92 m, with an overall mean of 0.79 m. These measurements are important in terms of the variations in gully length, gully infill and slope at Moor House.

7.2.2 Cross Profiles

In addition to variations in long profile, variations were observed across the gully systems. Figure 7.5 shows the cross profiles from the Burnt Hill's main gully system and Figure 7.6 presents the means and standard deviations of the peat-mineral interface depths. The orientations of the profiles are shown in Figure 7.5. Cross profiles 1 – 4 are orientated Northwest – Southeast, whereas cross profiles 5 – 12 are from East – West. Figure 7.5 shows variations in gully width and peat depth. Profile 1 (Figure 7.5.1) has the greatest width and peat depth. This profile was from the top of the gully where the dissection type was anastomosing. This is an area of deposition where several smaller channels converge. Profile 2 and 3 are narrow, but with large peat depths. This is also shown in Figure 7.6 where peat depths are shown to above 70 m. This section is more confined than profile 1 and therefore it is thought that erosion is likely to have occurred. There is then a decrease in peat depth from cross profile 4 onwards and peat depths begin to be more variable. Between profile 4 and 5 there is a break in slope in the long profile. This occurs along the transition from anastomosing (observed in profiles 1 – 3), through dendritic dissection (profile 4), to linear dissection (profiles 5 – 12).
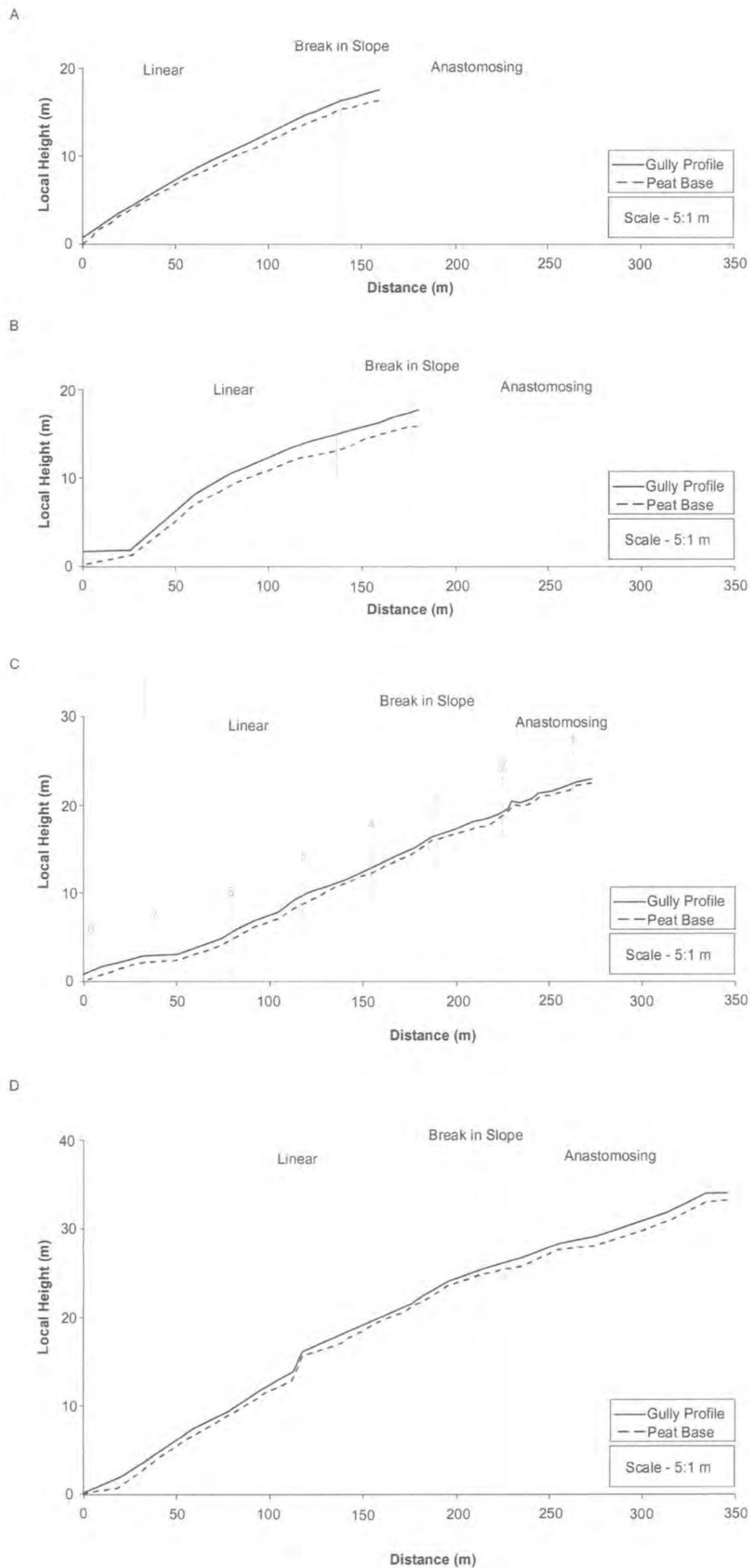
Figure 7.4: Long profiles of: A) the gully profile and peat depth of Gully 1, B) the gully profile and peat depth of Gully 2, C) the gully profile and peat depth of Gully 3 and D) the gully profile and peat depth of Gully 4. The break in slope is indicated on both profiles and the area of Type 1 and Type 2 Dissection. The location and number of the cross profiles discussed in Section 7.2.2 are shown in grey.
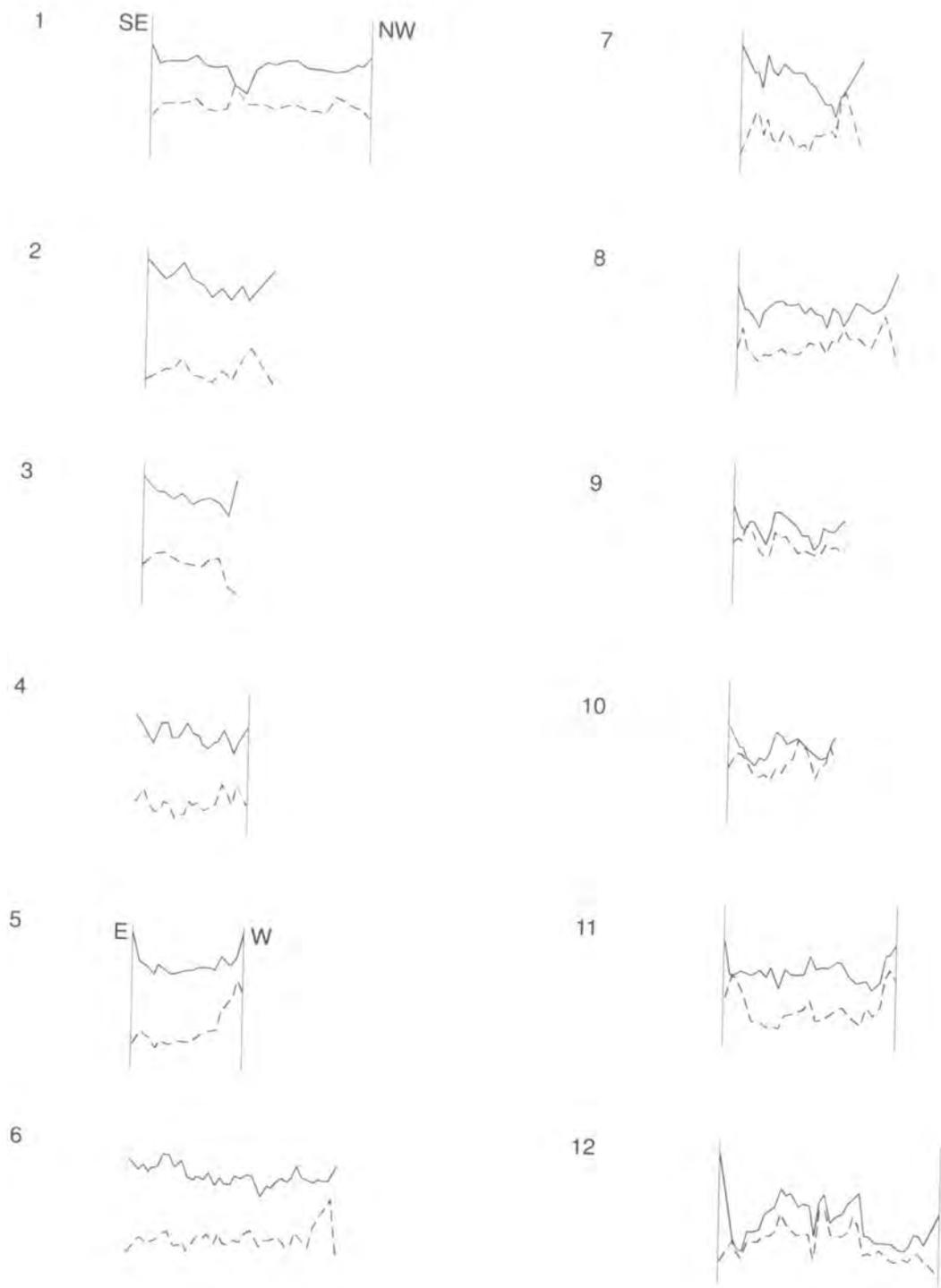
Figure 7.5: Cross profiles from Burnt Hill's main gully system.
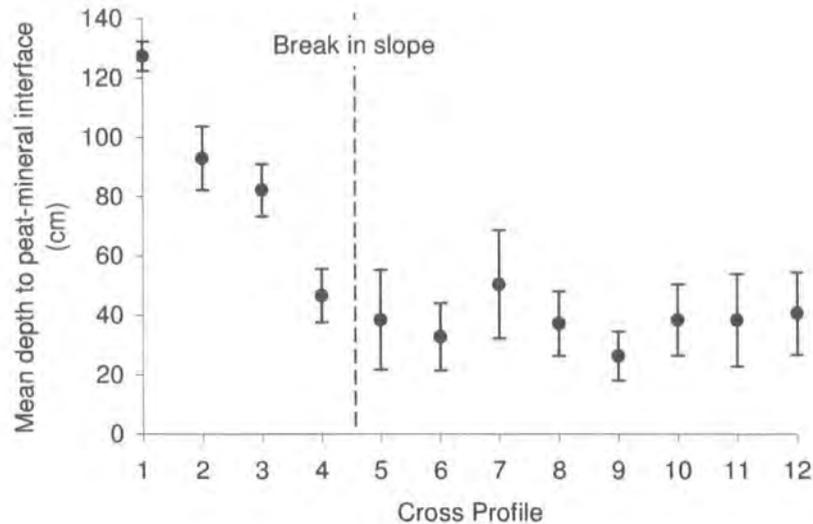
Figure 7.6: Mean and standard deviation of the peat-mineral interface in relation to distance down Burnt Hill's main gully system.

Where linear dissection occurs the peat depth is least and the variation across the gully is greatest (Figure 7.5). This is the area where the slope angle is greatest and therefore incised drainage channels would have transported water, peat and minerals from the gully system. The variations in peat depths are therefore the result of peat deposition occurring in the incised channels and gravels deposited along the gully base once the gully began to infill (profiles 7 – 12 show this clearly, where channel widths have increased).

Figure 7.7 shows the profiles from the four linear gully systems adjacent to Rough Sike. The profiles were from areas of linear dissection approximately half way down the gully long profile. Figure 7.8 presents the means and standard deviations of the peat-mineral interface depth for the profiles shown in Figure 7.7. The shape of the profiles are similar to those in the linear dissected area of Burnt Hill's main gully system (Figures 7.5.5 – 7.5.12), however Figure 7.8 shows that there are variations in their peat depths. The four gully systems show no great variations in gully width, peat depth or slope gradients compared with a gully system such as Burnt Hill's main gully system (Table 7.1, Figures 7.4 and 7.8). The profiles all fit the trend of the main gully system researched (Gully 3), i.e. the variations are similar to profiles 7.8.1 – 7.8.3 (above the break in slope) and 7.8.5 – 7.8.8 (below the break in slope).

The results from the long profiles and cross profiles from the four linear gully systems are interesting because they show that gully systems on the same hillslope were observed to be morphologically similar, for example the Rough Sike gully systems (A-D) (Figure 3.17).
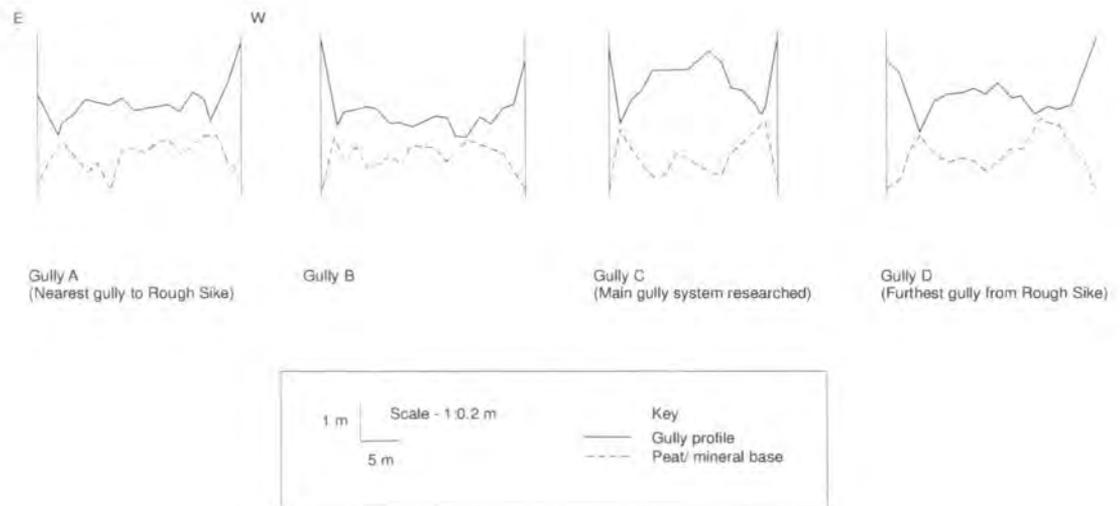
Figure 7.7: Cross profiles of four linear gullies adjacent to Rough Sike.
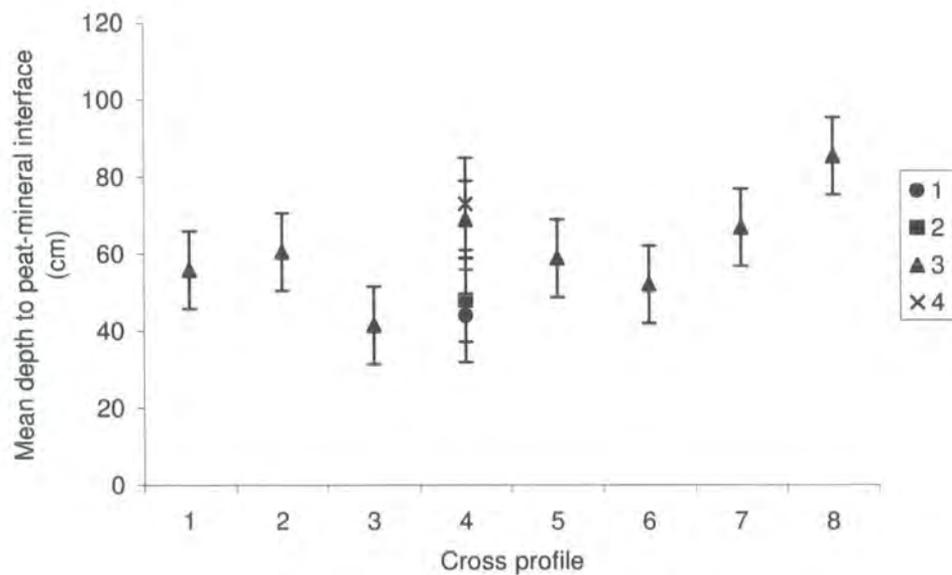
Figure 7.8: Mean and standard deviation of the peat-mineral interface in relation to distance down the four linear gully systems adjacent to Rough Sike.

7.2.3 Ground-based photographs showing changes over time

The long and cross profiles show peat deposits within the bases of the gully systems. This may be uneroded remnants or infilled and re-deposited peat. Ground-based photographs of gully systems at Moor House in conjunction with the aerial photograph analysis explain the development of these systems since 1958. Figure 1.11 showed the historical change within Burnt Hill's main gully system (Higgitt *et al.*, 2001). The photograph was taken at the entrance of the gully and showed significant infill had occurred over a 40-year period. Figures 7.9 and 7.10 are photograph sets also from Burnt Hill's main gully system. These photographs were taken further up the system in the area of anastomosing dissection. Both photographs show change over a 45-year period (1958 – 1998 – 2003). Figures 7.9a and 7.10a show large areas of bare peat and exposed mineral soils with some small patches of vegetation growth. By 1998 both images show that extensive infill within the base of the gully system and re-vegetation had occurred (Figures 7.9b and 7.10b). Over the next 5 years, it appears the vegetation had continued its growth and succession with further local re-colonisation of bare peat e.g. foreground of Figure 7.9c.

In addition to changes over time occurring within the bases of channelised gully systems, changes have also been observed on the interfluves (Figure 7.11) and peat flats (Figure 7.12). Figure 7.11 shows a pool complex on Burnt Hill. Figure 7.11a was taken some 8 years following burning on the moor. The vegetation is shown to have recovered but there are still areas of wetter (lower) ground, which are still bare or in the early stages of re-vegetation (supporting *Eriophorum angustifolium* vegetation). By 1998 the area has fully recovered with no waterlogged pool complexes or bare peat visible.

Figures 7.12 were taken on Moss Flats, an area towards the top of the Rough Sike catchment. Figure 4.13 showed how Moss Flats had begun to re-vegetate since 1950. Figure 7.12b also shows this, whereby the vegetation (particularly of *Eriophorum vaginatum*) is encroaching from the outside to the peat flat towards the centre.
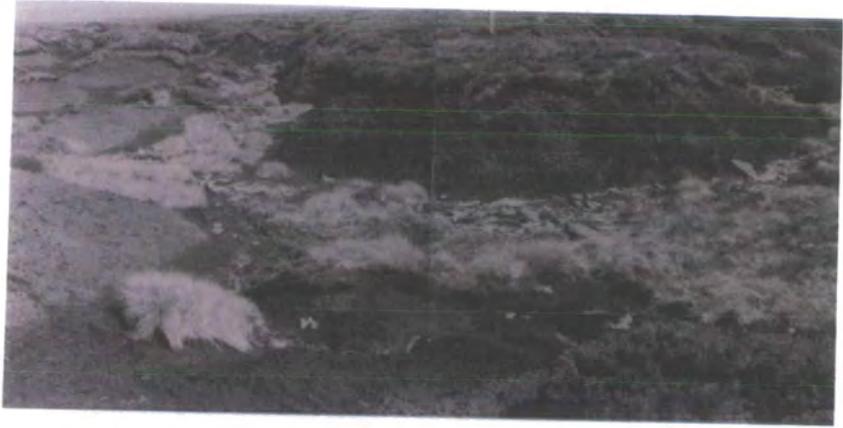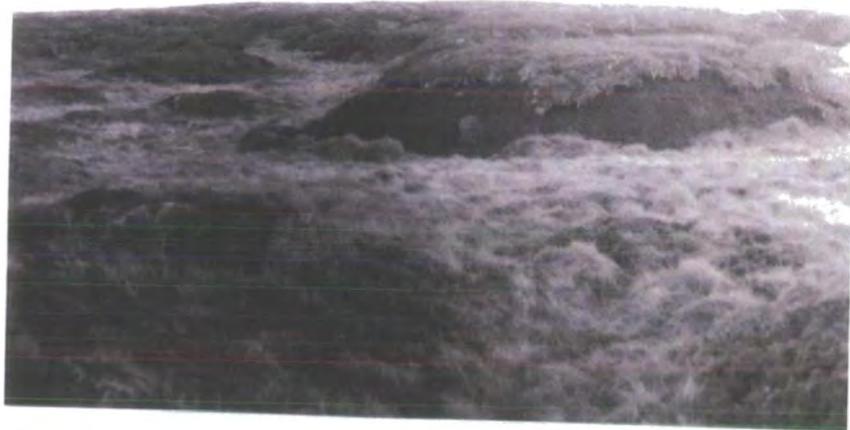
Figure 7.9: Historical change in Burnt Hill's main gully system. A) 1958 (Bower, 1959). B) 1998 (Photographed by Jeff Warburton). C) 2003.

Figure 7.10: Historical change in Burnt Hill's main gully system. A) 1958 (Bower, 1959). B) 1998 (Photographed by Jeff Warburton). C) 2003.

A

B

Figure 7.11: Historical change in a pool complex on Burnt Hill. A) 1958 (Bower, 1959). B) 1998 (Photographed by Jeff Warburton).

A

B
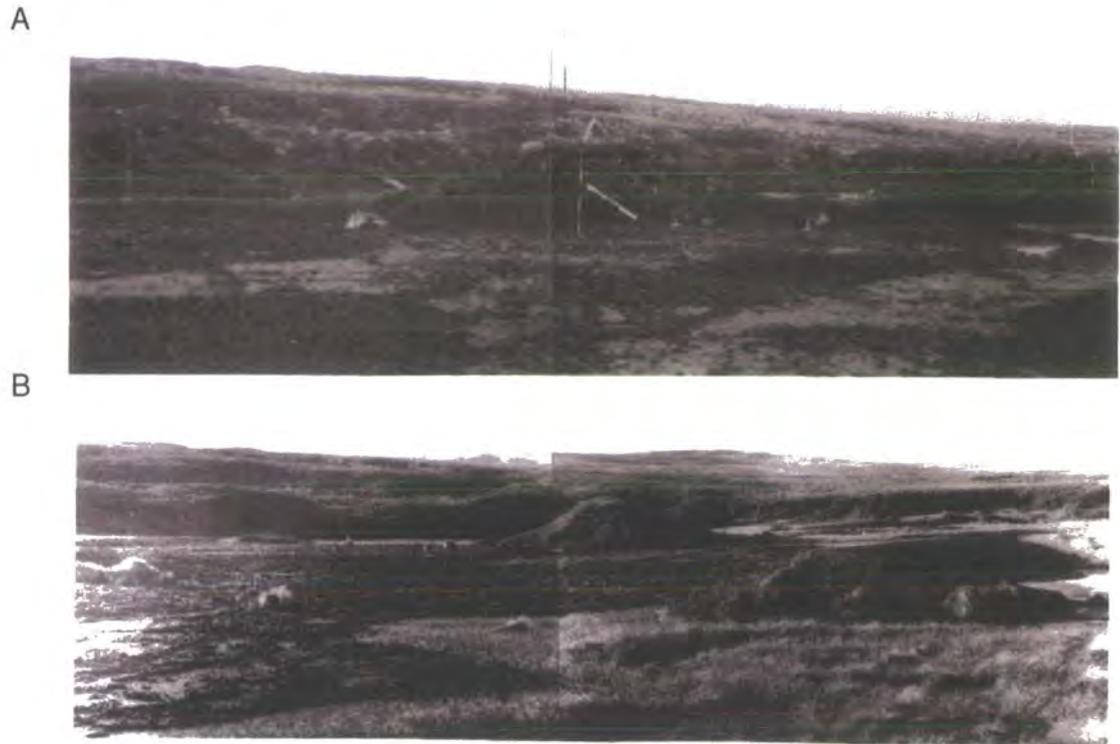
Figure 7.12: Historical change on Moss Flats (looking south-west). A) 1957 (Bower, 1959), B) 1998 (Photographed by Jeff Warburton).

In general ground-based photographs from Moor House show infilling of gully bases and re-vegetation of bare peat areas. Re-vegetation was shown to have occurred on re-deposited peat within gully bottoms, bare peat flats and on interfluve areas. This supports the evidence from the aerial photograph analysis presented in Chapter 4, which showed extensive re-vegetation to have occurred over the last approximate 50-year period. This is therefore interesting in terms of the results from mapping the contemporary vegetation cover within the bases of the gully systems.

7.2.4   Vegetation survey

The main gully system on Burnt Hill was used to diagrammatically show the spatial variation in vegetation cover (Figure 7.13) because a similar pattern follows throughout the Moor House gully systems. Key A relates to the pie charts and shows the vegetation observed in the base of the gully from the ground based survey undertaken in 2003, whilst key B is that from Figure 4.12 showing the vegetation in the gully base taken

from the 2000 aerial photograph. The vegetation in the upper part of the gully system (Area 1 – 2), where the slope angle is lowest (< 2.3°) and much of the surface appears saturated or near saturation, is a mosaic of unvegetated (bare peat), *Eriophorum angustifolium*, *Eriophorum vaginatum*, *Sphagnum cuspidatum*, *Sphagnum recurvum*, *Agrostis tenuis*, *Deschampsia flexuosa* and *Deschampsia cespitosa*. Area 1 has the least vegetation cover and fewest vegetation species indicating that the area is in the early stages of re-vegetation. Area 2 has an increased vegetation cover and diversity; indicative of mid stages of re-vegetation.

The transitional zone (Area 3) between the anastomosing and linear dissection (dendritic dissection) is the area of the break in slope (slope angle of 2.3°) on Figure 7.1. This is where *Calluna vulgaris* was present in the gully base and *Sphagnum cuspidatum* was replaced by *Sphagnum recurvum* and *Polytrichum commune*. There was also a reduction in *Eriophorum angustifolium* and increase in *Eriophorum vaginatum* vegetation. The grasses are found in similar proportions. The loss of *Sphagnum cuspidatum* and *Eriophorum angustifolium* indicates that the ground surface is less saturated and in the mid to late stages of colonisation. This is the result of the increase in slope angle and therefore better drainage.

In the linear dissected area (Area 4) (slope angle > 2.3°) the vegetation shows there are more diverse vegetation types than in Areas 1 – 3. This is an indication that the vegetation is in the late stage of colonisation. The vegetation types are predominantly *Deschampsia flexuosa*, *Calluna vulgaris* and *Juncus effusus*, vegetation more tolerant of drier moors, with the exception of *Juncus effusus*. *Juncus effusus* is present in this area as it tends to be in the area of the active channel and also it is where the peat depth is the least because *Juncus effusus* commonly grows in shallow peat, close to the mineral base. Drainage affects the rate of vegetation growth and given the lower section of the gully system is well drained (more so than Area 3) (Figure 7.5), vegetation growth is more rapid. This then leads to more rapid decomposition and therefore peat accumulation.

Key A: Vegetation Type

- Bare Peat
- Calluna vulgaris
- Sphagnum cuspitadum
- Sphagnum recurvum
- Racomitrium lanuginosum
- Pleurozium schreberi
- Juncus effusus
- Trichophorum cespitosum
- Eriophorum angustifolium
- Eriophorum vaginatum
- Deschampsia cespitosa
- Deschampsia flexuosa
- Vaccinum myrtillus
- Polytrichum commune
- Agrostis tenuis
- Galium saxatile
- Luzula multiflora

Key B: Evolution

- Bare peat
- Early stage of revegetation, i.e. *Sphagnum*
- Mid stage of revegetation, i.e. *Eriophorum*
- Late stage of revegetation, i.e. *Calluna*
- Uneroded vegetation, i.e. *Calluna*

Scale (m)

0   80

N

Figure 7.13: Spatial variation in vegetation and peat within Burnt Hill's main gully system.

Observations from Burnt Hill's main gully system are similar to observation from other gully systems at Moor House. The general pattern of vegetation cover and type suggests that the flat, anastomosing dissected areas are the least vegetated (as discussed in Chapter 4) and more saturated, where early colonising species such as *Sphagnum cuspidatum* and *Eriophorum angustifolium* and *Eriophorum vaginatum* are located. As the slope angle increases the drainage effect or re-colonisation stabilising effect cause increases the extent and types of vegetation. *Calluna vulgaris* and a variety of grasses such as *Deschampsia flexuosa* flourish.

7.2.5 Stratigraphic analysis

This section presents the stratigraphic data from six gully systems at Moor House. The data includes: detailed cross-sections; stratigraphy, bulk density, dry bulk density, moisture content, loss on ignition data; particle shape and form photographs and graphs; and macrofossil assemblages.

Figures 7.14 and 7.15 are stratigraphic cross-sections from Burnt Hill's main gully systems at Moor House. Their locations of the cross-sections within the gully system are shown in Figure 7.1. Figure 7.14 represents an area of anastomosing dissection at the top of the gully (Cross-section 1) and Figure 7.15 an area of linear dissection below the break in slope (Cross-section 2). They were produced either by excavating trenches across the gully systems and exposing the stratigraphy or by taking core samples across the gully from which the stratigraphy was cross-correlated. This enables the patterns of infill within the gully bases to be identified, which is interesting in terms of changes over time. The stratigraphy of each of the monolith and core samples taken from the cross sections is shown in Appendix 3.

In Figure 7.14 a coarse dark brown peat has been re-deposited on the gully floor from the gully sides. On the east side of the gully this process is still occurring where there is bare peat is exposed and *Eriophorum angustifolium* is present. Generally there is little variability across the gully cross-section. The sides of the gully system show evidence of basal 'wildwood' peat and this peat is therefore intact. The middle of the gully shows evidence of erosion to the mineral base. Since then fibrous *Sphagnum* peat has grown, indicating the early stages of re-colonisation.
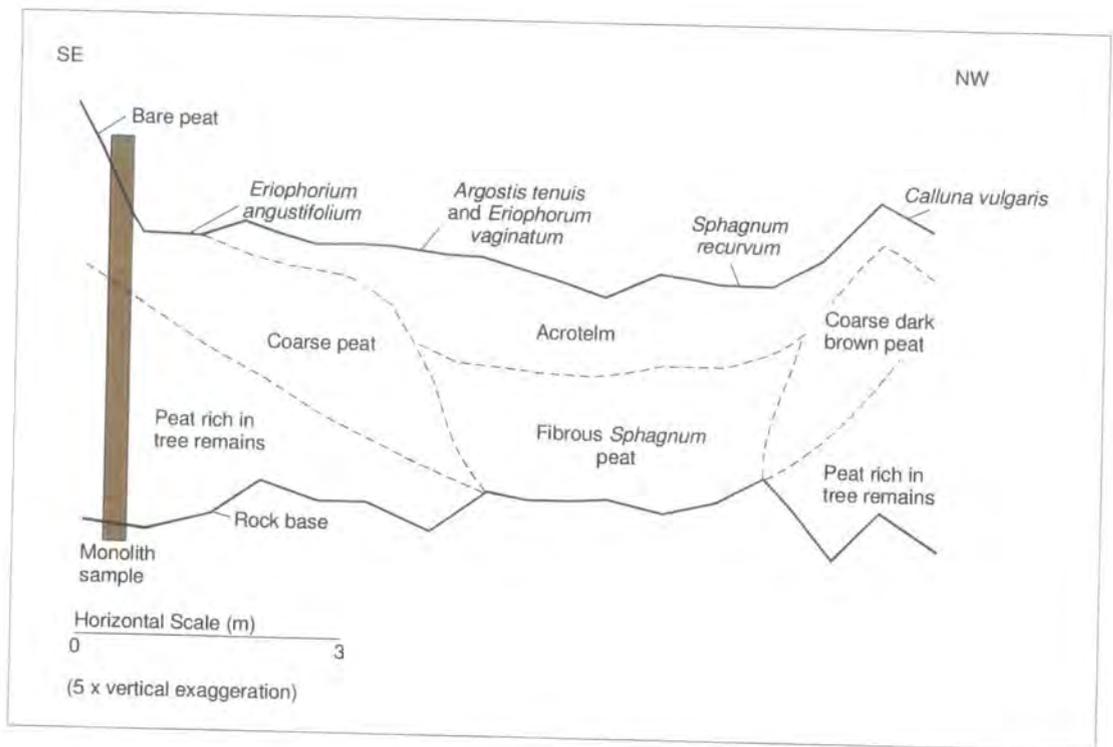
Figure 7.14: Stratigraphic cross-section from an area (Cross-section 1) of anastomosing dissection in Burnt Hill's main gully system.
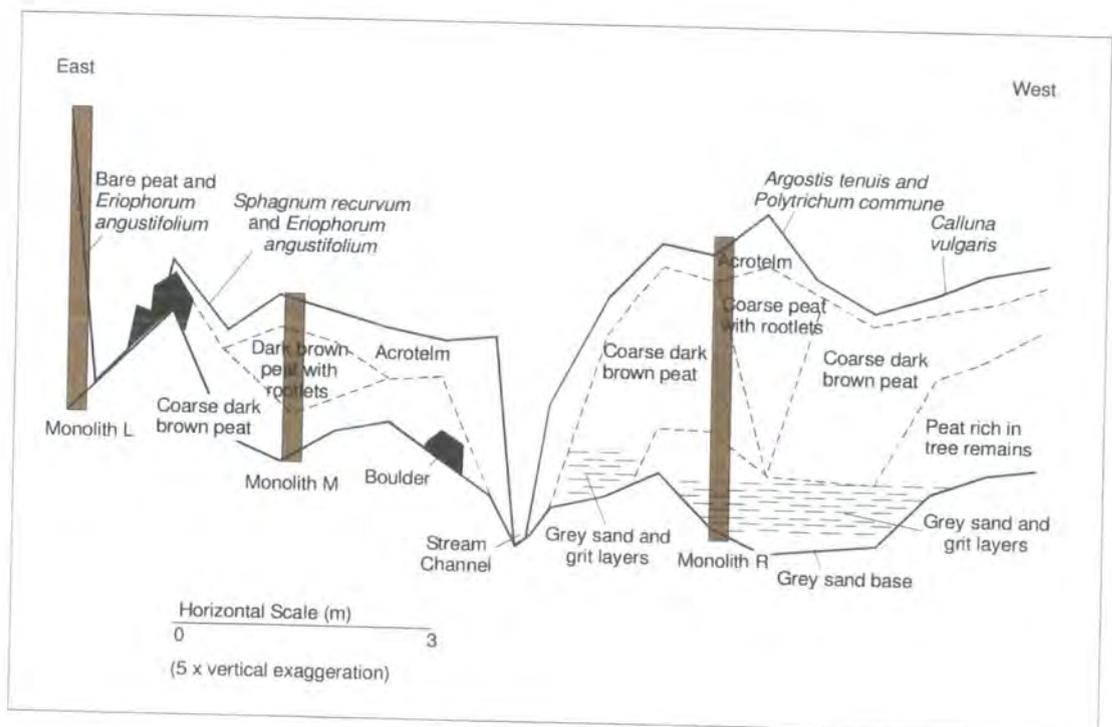
Figure 7.15: Stratigraphic cross-section from an area (Cross-section 2) of linear dissection in Burnt Hill's main gully system.

Figure 7.16 shows the stratigraphy, bulk density, dry bulk density, moisture content and loss on ignition data from the monolith removed from Cross-section 1. Here variations in these parameters are small, with the exception of some abrupt changes between 20 cm and 25 cm, which is a result of the concentration of large remnants of the 'wildwood' (Table A3.1). There is a slight decrease in the loss on ignition with depth, indicating the percentage organics decrease with depth.
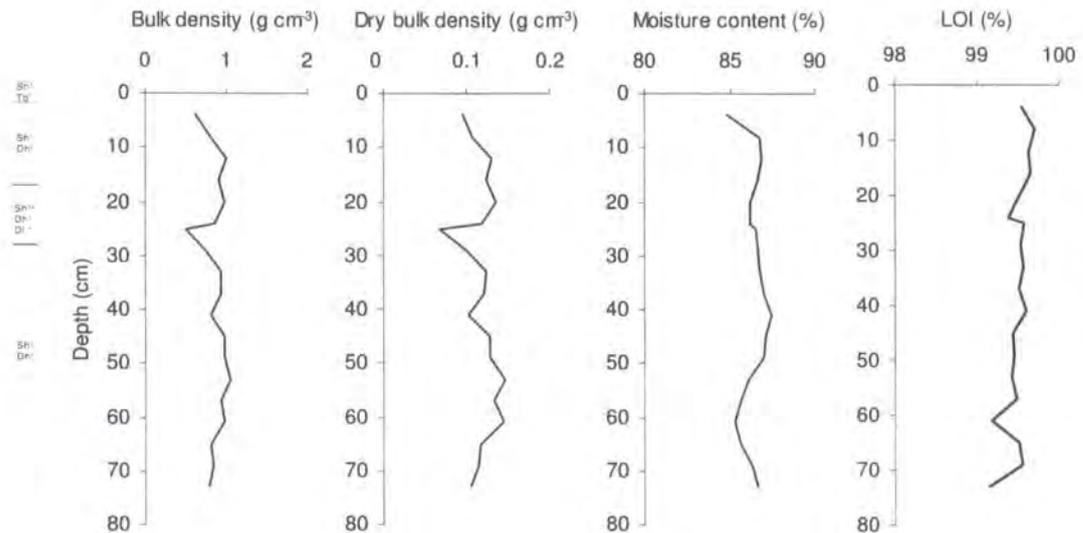
Figure 7.16: Stratigraphy, bulk density, dry bulk density, moisture content and loss on ignition data from the monolith removed from the cross-section shown in Figure 7.14.

Particle shape and form data (Figure 7.17) shows variations with depth in the stratigraphy. Figure 7.17 shows the upper (0 – 4 cm) and lower (30 – 73 cm) to be the most coarse and fibrous, indicating the peat is intact. From 4 – 30 cm the peat is less fibrous with more rounded particles, indicative of re-deposited peat. The stratigraphic analysis of the data also shows the peat below 19 cm contains remnants of 'wildwood' and is therefore reiterating it is intact. Between 0 – 4 cm there is coarser vegetation species within the peat therefore again indicating that the peat has started to re-vegetate and therefore some *in situ* peat is present.

0-4 cm

4-19 cm

19-30 cm

30-73 cm
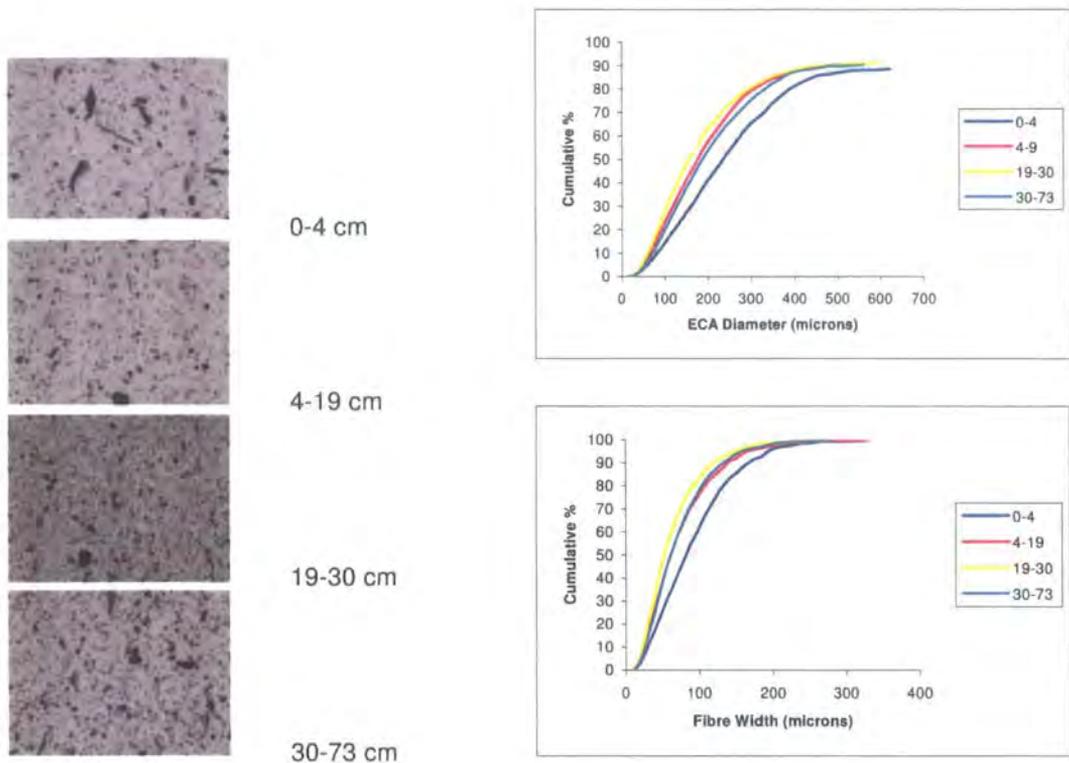
Figure 7.17: Particle shape and form data from the monolith removed from the cross-section shown in Figure 7.14. The size range analysed is from 100 – 1500 microns.

Figure 7.18 shows the vegetation species and their variability over the 73 cm depth of peat. Zone 1 (70 cm to 73 cm) shows there to be various grasses (*Deschampsia* spp. and *Eriophorum* spp.), *Calluna vulgaris* and wood remnants. This is the time when the blanket peat was stabilising and there would be much movement of the colonising vegetation and peat. Between 54 cm and 20 cm (Zones 2 and 3) there was a predominance of *Deschampsia* spp. and *Calluna vulgaris*, species tolerant of drier bog conditions (e.g. hummocks or gully initiation). There was some evidence of wetter conditions (e.g. pool complexes) since *Sphagnum cuspidatum* was also present. At a depth of 20 cm (start of Zone 4) there was a dramatic drop in the number of vegetation types, with the exception of *Calluna vulgaris* and *Sphagnum recurvum*, both species, which tolerate drier bog conditions. This could therefore indicate the onset of severe erosion and gullying.

There was evidence at a depth of 12 cm to 16 cm of charred vegetation. This may coincide with the last major burn on 'Burnt Hill' in 1950. The peat above this would have been re-deposited from the gully sides. There is an abundance of unidentifiable

organic matter in the stratigraphy to a depth of 4 cm, suggesting peat is likely to have been re-deposited from the gully sides. At this depth (Zone 5) the vegetation species begin to increase, indicating that re-vegetation within the gully base is occurring. Throughout the stratigraphy the *Calluna vulgaris* are dominant. There is no current evidence that *Calluna* is growing in the gully floor, therefore this is likely to have fallen from the top of the gully banks into the profile.
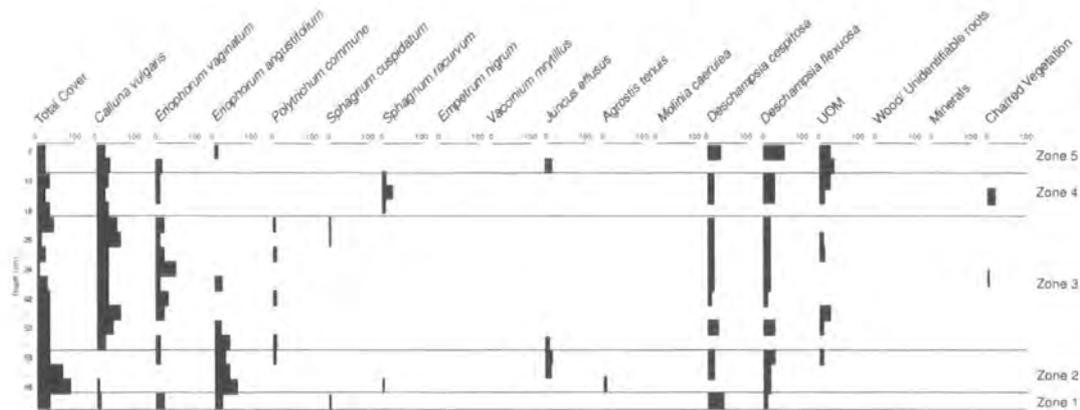
Figure 7.18: Macrofossil assemblage from the monolith removed from the cross-section shown in Figure 7.14.

Unlike Figure 7.14 where the peat appears not to have been fully removed from the gully base (e.g. 'wildwood' peat on either side of the gully), Figure 7.15 shows much more severe erosion. This observation agrees with the results from the GIS and also from the ground-based photographs, whereby the peat was eroded to the mineral base. Figure 7.15 shows considerable variation in peat type across the gully. This is the result of peat being deposited by lateral inputs, gully floor flows and *in situ* development. Towards the west side of the gully most infill has taken place. Since the lower peat layers have lenses of sand and grit, which suggests this peat would have been initially deposited when the gully system was still actively eroding. The sand and grit layers would be deposited over peat layers during high flow.

Once peat had accumulated the flow and erosion potential would have been reduced and the peat would begin to stabilise, re-vegetate and subsequently develop *in situ*. Another reason suggesting the gully floor peat is re-deposited rather than peat grown *in situ* is that the 1958 ground based photograph show the gully base to be bare. Since that time

approximately 50 cm of peat has accumulated and re-vegetated in the base of the system. Therefore over a 50-year time period 50 cm of peat has accumulated. If it were to have grown *in situ* it would have had to accumulate at a rate of 1 cm yr^{-1}. This is too high given that general accumulation rates for peat in this environment are thought to vary from 0.1 to 1.2 mm yr^{-1}.

The coarse dark brown peat with rootlets within the stratigraphy is typical of regenerating peat. Figures 7.14 and 7.15 (east side walls) are both bare with localised re-vegetation occurring. This is a result of the active channel undercutting on the eastern margin. The west side has been less affected by erosion since there is evidence of intact 'wildwood' peat within the stratigraphy. An area of no peat accumulation in the centre of the gully as well as along the east bank indicates there are two active channels within this linear dissected area of the gully system. Given there were few minerals in the base this would indicate that sediment is exhausted.

Figures 7.19 to 7.21 present the results from the stratigraphy, bulk density, dry bulk density, moisture content and loss on ignition for the three monoliths removed from this cross section Figure 7.15. The bulk density, dry bulk density, moisture content and loss on ignition values for the two side monoliths show abrupt changes in the bottom 10 cm of the profiles, which is the result of the grey clay and silt (east bank) and the peat being re-deposited and layers of sand and grit present in the stratigraphy (west bank). The results in Figure 7.20 are highly variable in the middle of the stratigraphy. This is likely to be a result of the peat within this location being inwashed, re-deposited and grown *in situ* in later years.

Figures 7.22 to 7.24 provide particle shape and form data. Unlike Figure 7.17 the particle form data for Figures 7.22 to 7.24 show the peat to be far more fibrous in the upper layers.

Figure 7.22 shows peat typical of that which is re-deposited (2 cm – 13 cm). Above this there is a clear acrotelm, where grass and wood (twigs) can be identified, which in the photograph indicates that the peat is growing *in situ*. The bottom 35 cm to 52 cm has sand layers in the stratigraphy and evidence of wood up to 13 cm.
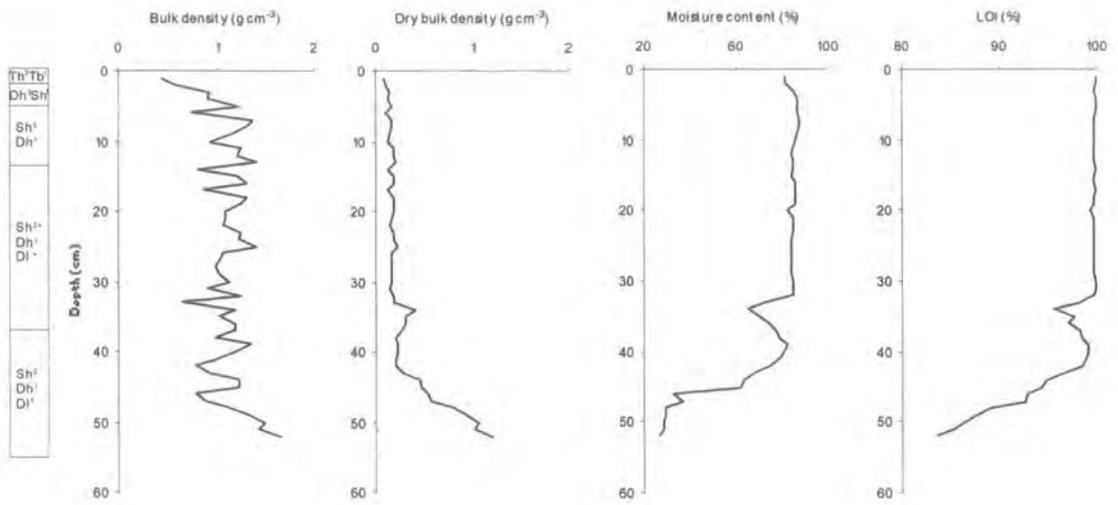
Figure 7.19: Bulk density, dry bulk density, moisture content and loss on ignition data from the right (west) monolith removed from the cross-section shown in Figure 7.15.
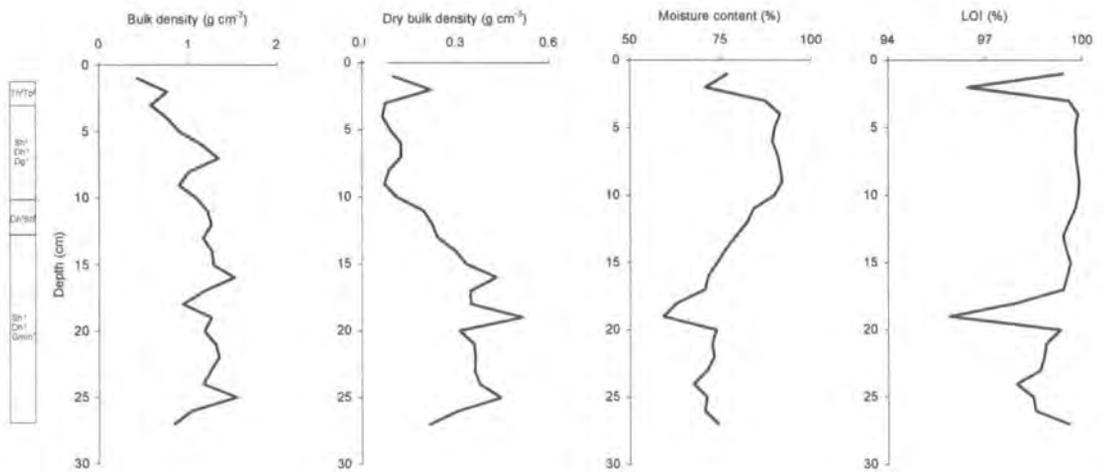
Figure 7.20: Bulk density, dry bulk density, moisture content and loss on ignition data from the middle monolith removed from the cross-section shown in Figure 7.15.
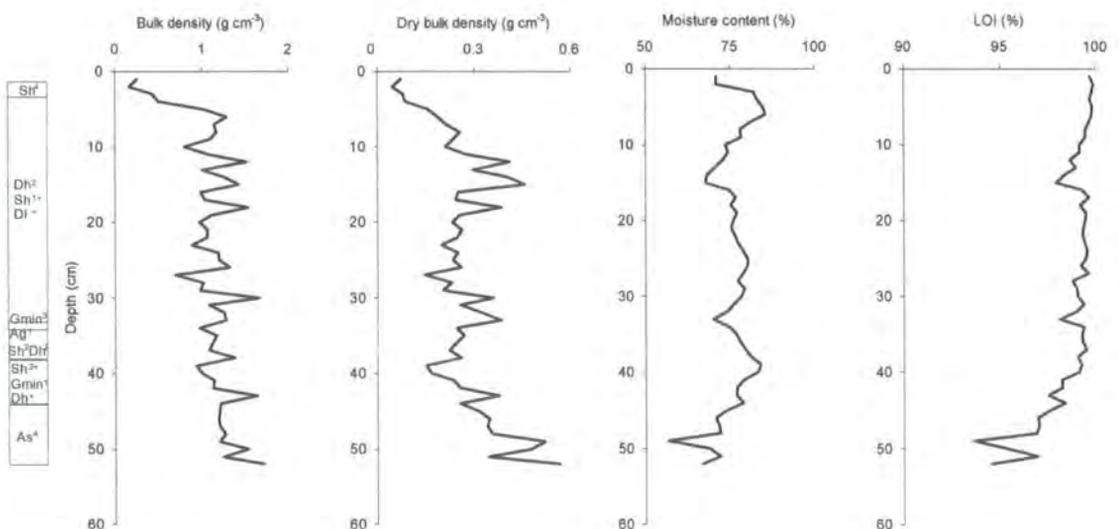
Figure 7.21: Bulk density, dry bulk density, moisture content and loss on ignition data from the left (east) monolith removed from the cross-section shown in Figure 7.15.

260
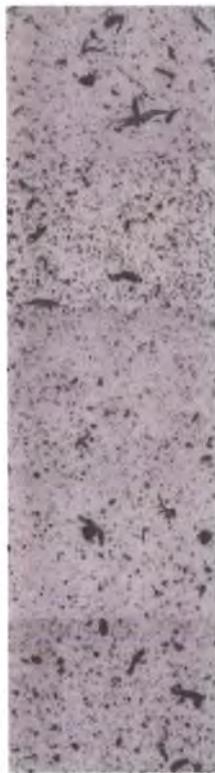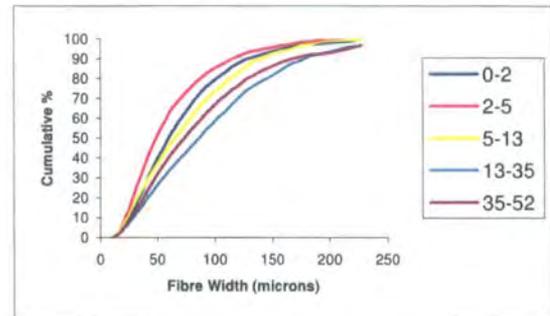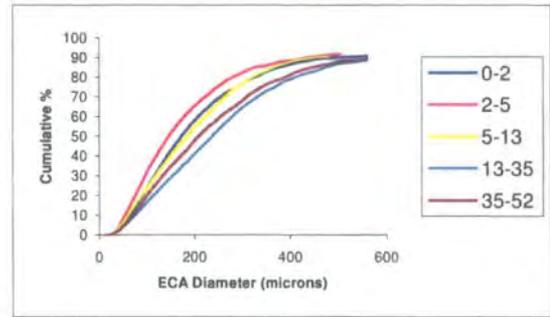
Figure 7.22: Particle shape and form data from the right (west) monolith removed from the cross-section shown in Figure 7.15. The size range analysed is from 100 – 1500 microns.
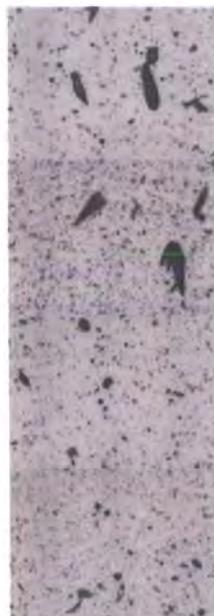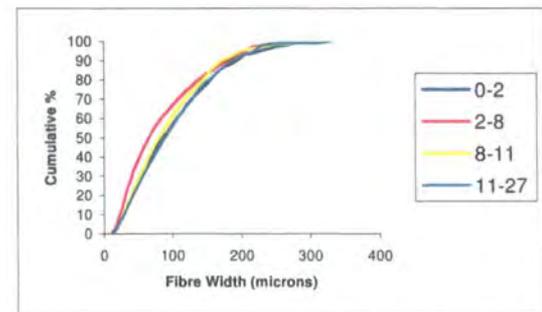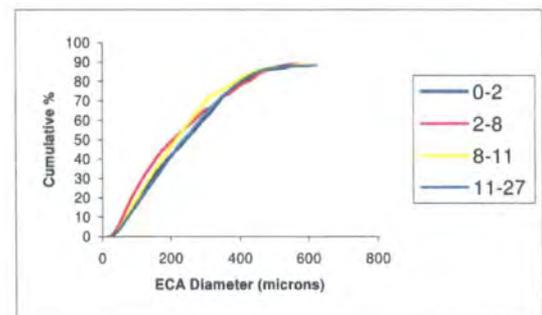
Figure 7.23: Particle shape and form data from the middle monolith removed from the cross-section shown in Figure 7.15. The size range analysed is from 100 – 1500 microns.

0-2 cm

2-32 cm

32-33 cm

33-38 cm

38-46 cm

46-52 cm
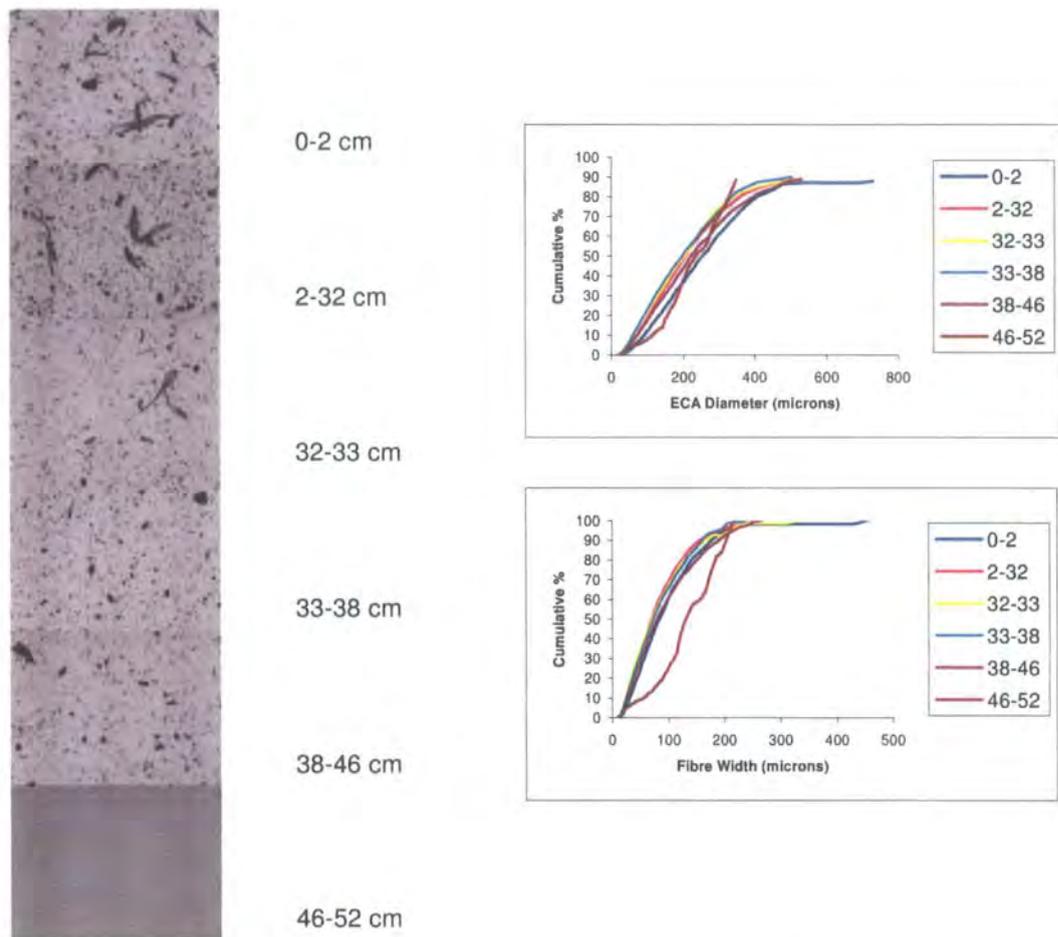
Figure 7.24: Particle shape and form data from the left (east) monolith removed from the cross-section shown in Figure 7.15. The size range analysed is from 100 – 1500 microns.

Figure 7.23 shows little variation in the equivalent circular diameter and the fibre widths of the vegetation throughout the profile. At a depth of 0 cm – 8 cm there is evidence of *Sphagnum* spp. and *Calluna* grown *in situ*. From 8 cm – 27 cm depths however the photographs show there to be little vegetation present in the stratigraphy and therefore the large particles at this depth are likely to be peat and sand re-deposited from further up the gully system.

Figure 7.24 shows the particles to be fine from 32 cm – 52 cm, which is likely to be a result of much clay and sand (Table A3.2). The top 32 cm show more coarse particles, grass fibres and wood within the stratigraphy, typical of peat, which is uneroded with some inwashed peat from the gully sides.

The macrofossil assemblages from the monoliths removed from Figure 7.15 are shown in Figures 7.25 – 7.27. Figure 7.25 shows the bottom 4 cm of the profile has minerals, unidentifiable organic matter and wood remnants (Zone 1). The whole profile shows many wood remnants. The top 8 cm shows a change in vegetation species, which is likely to be linked with the re-vegetation of the base of the gully system (since 1978). Peat depth is greatest on the west side of the gully system and the vegetation cover is in the late stages of development (e.g. grasses and *Calluna vulgaris*) (Figure 7.25). These species are also more typical of those grown on drier areas of peatlands. Due to the depth of the peat and the type of vegetation in this area, it is thought that the flow prior to gully infill ran down the western side of the gully. As deposition of the peat occurred, the gully began to infill. Infill and re-vegetation within the base of the gully is thought to have progressed from the west to the east side (Figure 7.28). This is a result of the channel undercutting the eastern gully side. Given the vegetation in the linear dissected area of the gully system (especially on the western side) is in a later stage of development it is thought that the gully may have back-filled and vegetation encroached from the valley sides below the gully entrance (Figure 7.29). Both Figures 7.28 and 7.29 show schematic diagrams of the infill in the base of Burnt Hill's main gully system.

Figure 7.26 shows the assemblage from the middle of the gully system and is very different from those found on the west and east bank (Figures 7.18 and 7.25). Far less vegetation species were observed. Zone 1 shows there to be a large mineral content, large unidentifiable organic matter content, typical of re-deposited peat, as well as peat rich in *Calluna vulgaris* and *Eriophorum vaginatum* species. This is also likely to have been re-deposited from the eroding peat further up the system, where these species were growing or decomposed on the intact peat surface. Further re-deposition of peat appeared to have taken place until a depth of up to 8 cm. From 0 cm to 8 cm the peat appears to have grown *in situ*, with grasses and some *Calluna*, which increased dramatically in the top 4 cm.

Figure 7.25: Macrofossil assemblage from the right (west) monolith removed from the cross-section shown in Figure 7.15.

Figure 7.26: Macrofossil assemblage from the middle monolith removed from the cross-section shown in Figure 7.15.

Figure 7.27: Macrofossil assemblage from the left (east) monolith removed from the cross-section shown in Figure 7.15.

Stage 1: Typical of 1958. Gully eroded to the peat-mineral base and eroding laterally. The gully banks are starting to be undercut and collapse into the base of the gully.

Stage 2: The re-deposited peat begins to re-vegetate or is eroded away and re-deposited further down the system. A channel has formed on the west side of the gully from which peat and minerals are transported and eroded. The east side of the system beings to stabilise.

Stage 3: Peat and minerals are re-deposited in the channel causing the channel to infill. Lateral erosion occurs and peat and mineral sediments are deposited on the vegetation.

Stage 4: Typical of 1998. Channel has shifted and the main channel is hugging the east bank causing bank collapse. The rest of the gully begins to stabilise and re-vegetate. The west side of the gully is higher and drier bog species are able to grow.

East   West

Prevailing wind direction

Horizontal Scale (m)   Scale - 1 : 0.2 m
0   6

Vegetation
Peat
Mineral

Figure 7.28: Schematic diagram showing the infill of Burnt Hill's gully system based on the data from Figures 1.11 and 7.15.

265

Stage 1: Typical of 1958. Gully eroded to the peat-mineral base especially in the area of linear dissection. The gully slope profile is steep and peat and minerals are flushed out of the system..

Stage 2: Peat and minerals from the top area of the gully are re-deposited further down the system as a result of back-filling headward encroachment. The gully slope angle begins to decrease and the gully begins to stabilise. Re-vegetation occurs.

Stage 3: Typical of 1998. The gully system continues to infill and re-vegetate. Peat is still inputted into the top of the system from Burnt Hill however remains in the system as the vegetation traps the peat and prevents it from leaving the system. During storm events some of this peat and peat from haggs and banks is re-deposited.

South   North   Horizontal scale (m)   Scale - 10: 1 m

                                      0   100

Figure 7.29: Schematic diagram showing the infill of Burnt Hill's main gully system based on Figures 1.7, 2.2, 7.1, 7.9 and 7.10.

Figure 7.27 presents the macrofossil assemblage from the left (east) monolith. The contemporary surface in the vicinity of Figure 7.27 shows the vegetation on the east side of the gully floor to be in the early stages of development. The vegetation is also typical of that grown in wet conditions. The bottom 4 cm shows there to be abundant minerals (silt and clay) within the lower stratigraphy (Zone 1). There is also evidence of unidentifiable organic matter, *Calluna vulgaris* and *Sphagnum recurvum* and *Eriophorum angustifolium*. This is likely to have been re-deposited when the peat was developing. The unidentifiable organic content remains high and vegetation low throughout the stratigraphy up to a depth of 8 cm. This is indicative of uneroded 'wildwood' peat. In addition, following the onset of erosion it is likely that peat would have been inwashed from the gully sides. The top 8 cm shows an increase in vegetation and a decrease in unidentifiable organic matter. The vegetation species are predominantly grasses and *Calluna vulgaris*. Since the surface is largely unvegetated in this location, the vegetation shown within the profile is likely to have been input from the gully bank.

Both the middle monolith and east monoliths show an increase in vegetation species in the top 8 cm of the stratigraphy. It is likely that this is when the peat within the base of the gully system began to stabilise. If a growth rate of the peat of 0.3 mm yr^{-1} is assumed (Figure 1.2) then it would have take 26 years to develop. Therefore the lower peat in the profile must have been re-deposited in this location since 1958 to 1978.

The infill and re-vegetation shown in Burnt Hill's main gully system is not unique. Figure 7.30 shows a stratigraphic cross-section from a second gully system on Burnt Hill in the area of linear dissection in the bottom half of the gully system and shows characteristics of both Figure 7.14 and 7.15. At the margins of the cross section there is evidence of intact 'wildwood' peat. There is also grey clay at the base of this peat, which is the postglacial head deposit in the area. Unlike Burnt Hill's main gully system there is no active channel within this gully and the gully system has infilled to a point almost level with the adjacent intact peat. There are gravels in the base of the gully system on the South side of the cross section indicating that a channel was once active in this location. Also on the South side coarse dark brown peat overlays dark brown peat with rootlets. This is likely to be the result of peat being re-deposited on top of living vegetation (similar to that found in Burnt Hill's main gully system). The vegetation cover within this system (apart from where the bed at its highest) is *Sphagnum* spp.

indicating that the peat is saturated. In the absence of channel, water flowing down the gully system moves as throughflow through the peat.
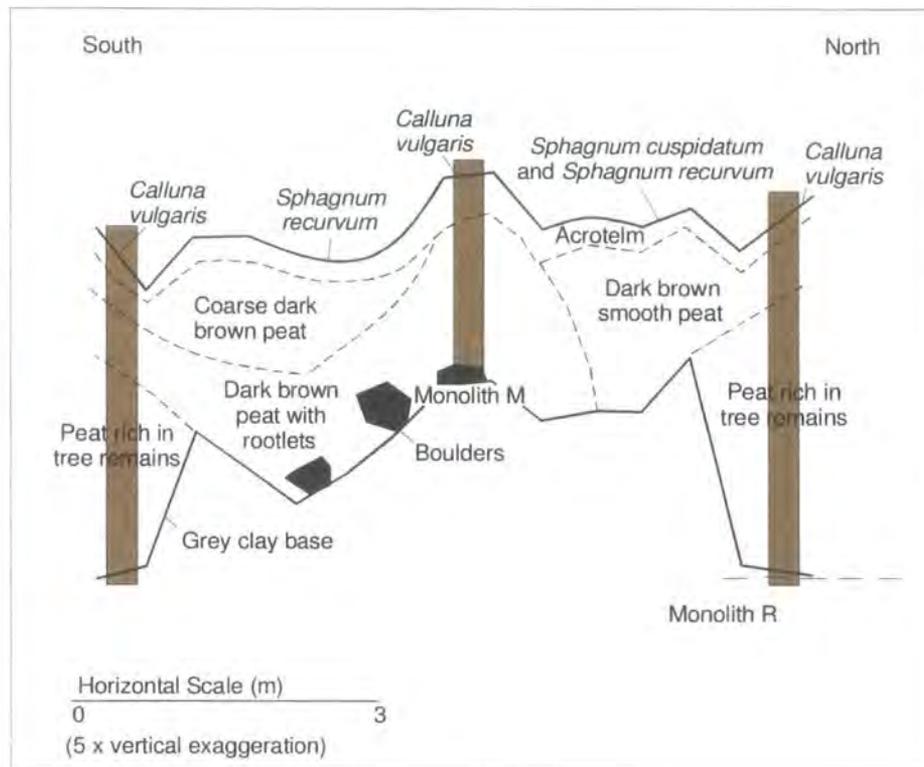
Figure 7.30: Stratigraphic cross-section from an area of linear dissection in Burnt Hill 2 gully system.

Figure 7.31 shows the cross sections from four linear gully systems adjacent to Rough Sike (Figure 7.7). Information on their stratigraphies can be found in Tables A3.5 – A3.15. Despite similarities in overall form, the cross-sections show variations in the stratigraphy between the four gully systems. Gully A and gully B have similar stratigraphies and gully C and gully D are also similar. Gully C and gully D contain more sand and grit layers within the peat indicating that the peat was re-deposited. The sand and grit layers indicate the re-deposition occurred during a time of active erosion within the gully. Due to the depth of the re-deposition it is thought that the flow and peat-mineral sediment load down these two systems must have been relatively high. This is likely to have been flushed from the large peat flat at the head of the linear gullies. The cause for this may be that the gully systems are longer in profile than in gullies A and B, therefore more sediment would be removed and transported during the time of erosion (Table 7.1 and Appendix 3).

Figure 7.31: Stratigraphic cross-section from the four linear gully systems adjacent to Rough Sike.

7.2.6   Estimating the onset of peat erosion and regeneration

The stratigraphic data from the infilled gully systems at Moor House provides information on the depth of peat and the processes involved in erosion of the gully systems and subsequent re-vegetation. Aerial photograph analysis and repeat ground-based photographs have helped to date the onset of regeneration of the gully systems, however, the onset of gully erosion is more difficult to determine. Tallis (1985b) removed cores from intact peat directly adjacent to eroded sites to provide information as to the depth of the peat when erosion onset. This section presents the results from two cores removed from Moss Flats and an adjacent uneroded site. This provides evidence of the onset of moorland erosion (latest phase of erosion), not gully erosion though, both are thought to have occurred simultaneously.

Tables A3.16 and A3.17 show the stratigraphic descriptions from Moss Flats (eroded) and Moss Flats (uneroded) respectively and Figure 7.32 shows a simplified stratigraphy, the bulk density, dry bulk density, moisture content and loss on ignition for the cores removed from Moss Flats (eroded) and an intact peat site adjacent to Moss Flats (uneroded).

Figure 7.32a shows the peat on Moss Flats to be a depth of 198 cm. There is little variation in the profiles until the peat-mineral transition at a depth of 178 cm. There is some variation in the loss on ignition profile at a depth of approximately 40 cm, which coincides with the burnt layer in the stratigraphy. Figure 7.32b shows the peat depth to be 286 cm deep (88 cm greater than the eroded site). However, as with Figure 7.32a there is little variation in the profiles, apart from in the bottom 27 cm. In the top approximate 90 cm there is some variation in the bulk density, moisture content and loss on ignition profiles. Interestingly at this depth the moisture content decreases for an approximate 20 cm depth. This may be indicative of the onset of erosion because of drainage occurring within the peat local to the gully system. Since the peat depth at Moss Flats is 88 cm less than on the intact peat adjacent to Moss Flats, this is likely to be the time of the onset of erosion.
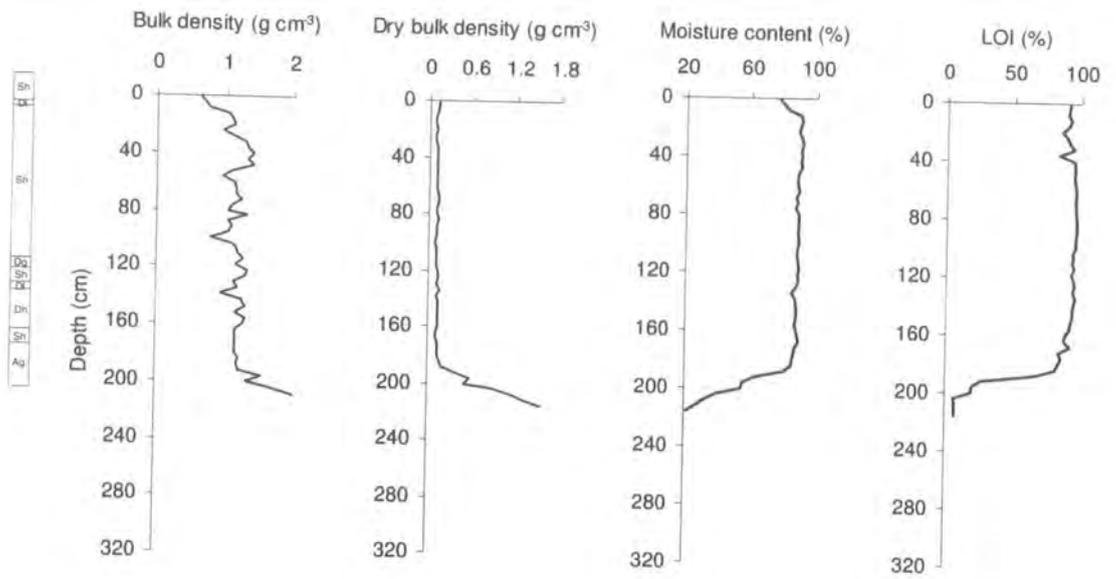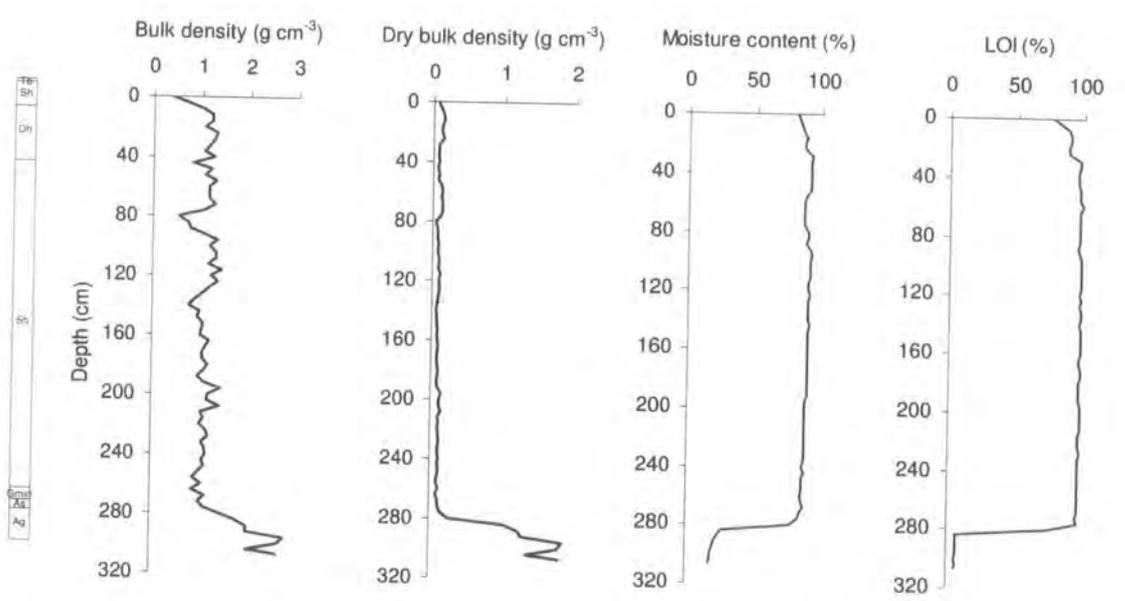
Figure 7.32: Stratigraphy, bulk density, dry bulk density, moisture content and loss on ignition data for A) Moss Flats and B) intact peat directly adjacent to Moss Flats.

Due to the uncertainty of the SCP dating (Chapter 5) an average peat accumulation rate of 0.3 mm yr^{-1} was chosen based on the results by Tallis (1995a) (Figure 1.2). As shown in Figure 1.2 and Chapter 5 there is a great variability in the peat accumulation rate of upland blanket peat both in time and space. The results presented here can therefore only be regarded as estimates of the onset of erosion and a dating technique such as Radiocarbon dating would be required to test the reliability of the rate of peat accumulation.

The intact profile since the onset of erosion and the development of Moss Flats would have continued accumulating peat. Given there has been an approximate 90 cm of peat accumulation since the suggested onset of erosion, at an average peat accumulation rate of 0.3 mm yr^{-1}, the onset of erosion would have been approximately 300 years ago, making Moss Flats 300 years old. In addition on the surface of Moss Flats there is evidence of 'wildwood' indicating that Moss Flats has not eroded fully down the peat profile to the mineral interface but has undergone some erosion, typically by wind, freeze and thaw and desiccation. Radiocarbon dates of the base of Moss Flats (depth of 188 cm) estimated dates from 3100 years to 8000 years. A peat accumulation rate of 0.3 mm yr^{-1} and depth of 188 cm would only be 626 years. Therefore it is likely that the peat accumulation rate is likely to be less than first thought and the onset of erosion may have been some time earlier.

7.3 Morphology of gully systems on The Cheviot

7.3.1 Long Profiles

Figure 7.33 shows the long profiles from three gully systems on The Cheviot and demonstrates that the length of the gully systems and the shape of the profiles vary (Table 7.1). Figure 7.33a shows a break in slope approximately 420 m from the bottom of the gully system. This break in slope did not correspond to a change in gully type but coincided with an increase in peat depth. Gully 2 was the smallest of the three gully systems studied, with a length of 283 m and average gradient of 0.11. The fall in height is low in comparison to Gully 3, with an average gradient of 0.17; however, Gully 3 extends beyond the peat margin where the slope angle steepens (below the break in slope). Generally the steeper profiles of The Cheviot gully system are the result of the general topography of The Cheviot (Figure 4.3). The break in slope in this gully system divides the gully into two types: linear and anastomosing. Figure 7.33c shows the long profile of the largest of the three gully systems (582 m in length). The lower section of the gully was very steep and fed into a stream below the limit of the peat blanket. Below the break in slope at approximately 300 m along the profile the dissection type was linear; however, above this it was dendritic. The top of the gully system was close (approximately 50 m) to the summit of The Cheviot adjacent to the area of anastomosing dissection.
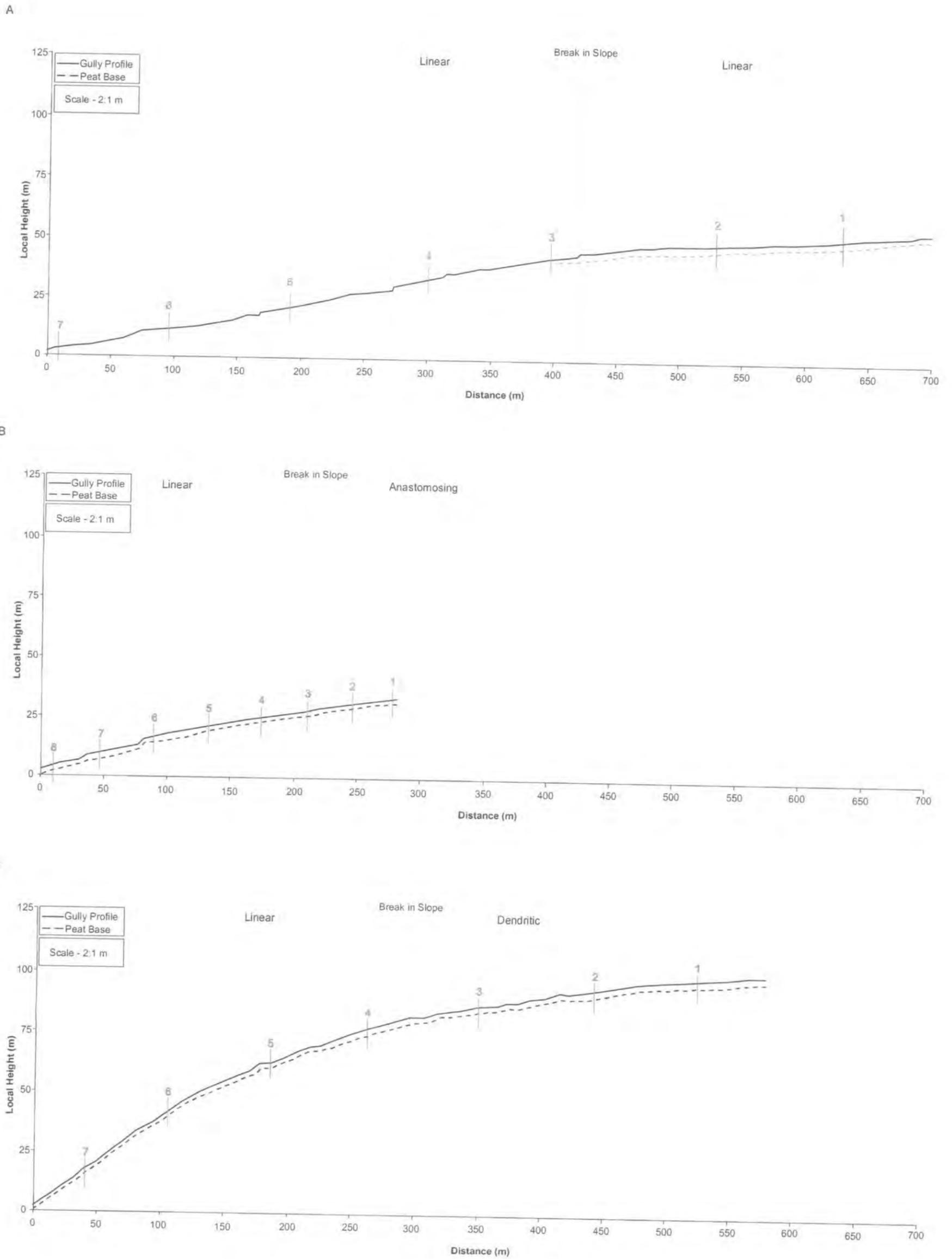
Figure 7.33: Long profiles of (A) Gully 1, (B) Gully 2 and (C) Gully 3. The breaks in slope in each of the profiles represent (A) a transition not in gully type but in peat development, (B) from linear to anastomosing dissection and (C) from linear to dendritic dissection. The peat depths are exaggerated X2 in all the profiles. The location of the cross profiles are shown.

7.3.2 Cross profiles

Figure 7.34 presents the mean and standard deviations of the cross profiles in Gully 1, showing that there is no peat below the break in slope within the gully, where the gully has incised into the mineral base to approximately 1 m (Figure 7.35a). Above the break in slope peat and vegetation are visible within the gully base (Figure 7.35b). Cross profile 7 shows the gully incision to be less than cross profiles 4 – 6. This is the result of the gully widening toward the entrance.
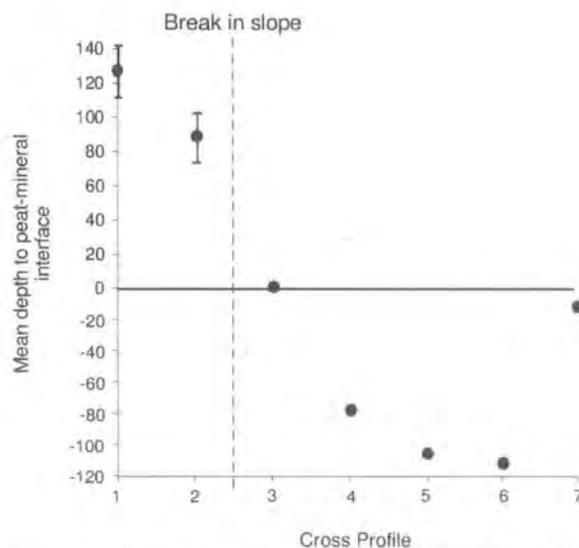
Figure 7.34: Mean and standard deviation of the peat-mineral interface in relation to distance down Gully 1.

Figure 7.36 and Figure 7.37 show the profiles across Gully 2. There is approximately 50 cm of peat within the gully base. The gully system is of similar width to many of the systems at Moor House (e.g. Figure 7.5). Variations in the surface height and peat depth above the gully floor are shown. Figure 7.37 shows the two breaks in slope. The upper break in slope marks a transition in dissection from anastomosing to linear and the lower break in slope represents a step in the profile (Figure 7.33b). The decrease in peat depth from profiles 5 and 6 is a result of the step in profile. Further up the system where there is a gradual change in slope (threshold slope angle of 4.5° between gully types) (Table 7.1) shows little change in peat depth, but the width of the gully system decreases (from profile 2 – 3).

Figure 7.35: Photographs showing the variation within Gully 1. A) The upper section of the gully system (above the break in slope). B) The lower section of the gully system (below the break in slope).
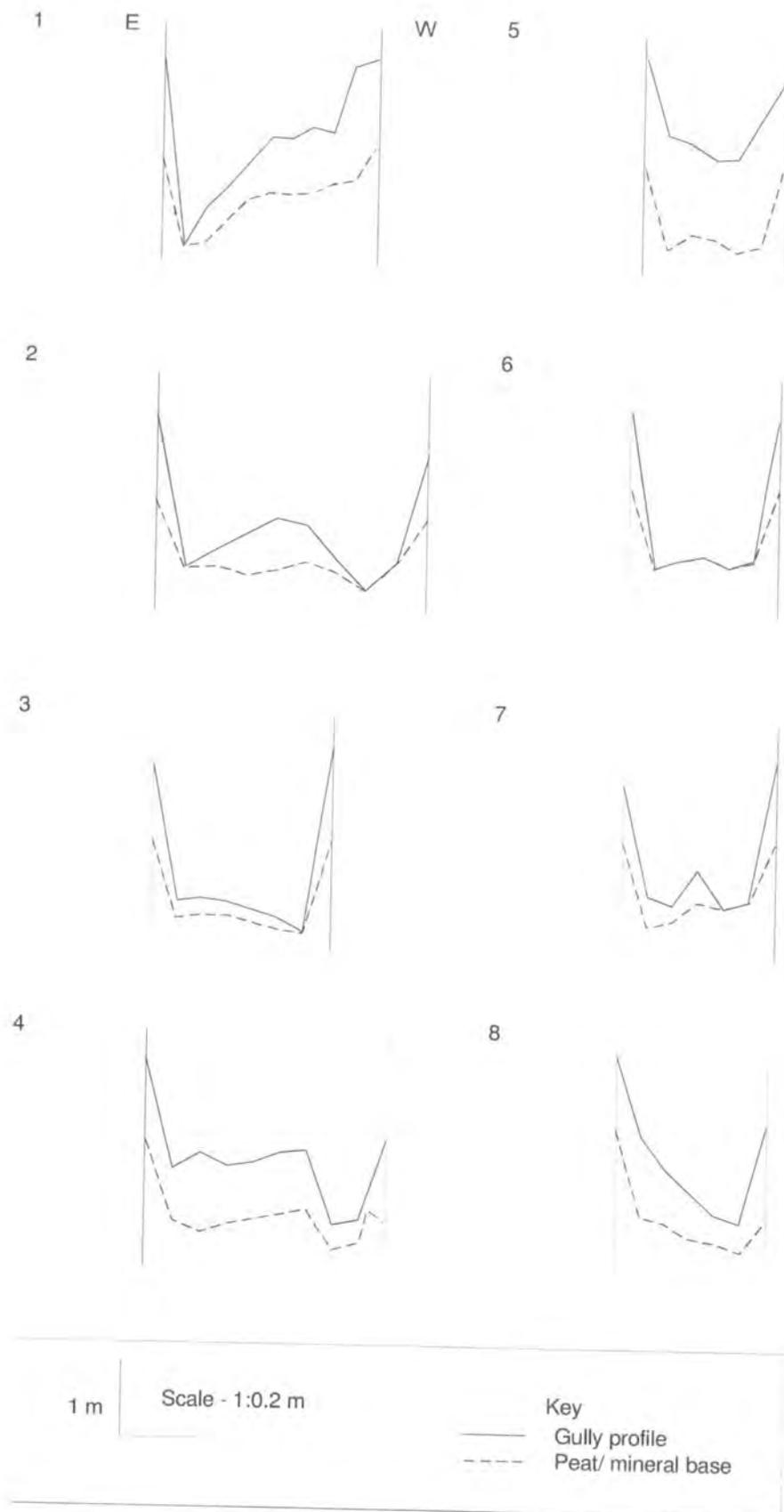
Figure 7.36: Cross profiles of Gully 2. The locations of the profiles are shown in Figure 7.33b.
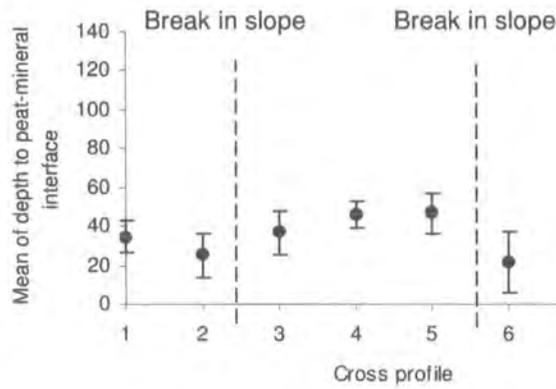
Figure 7.37: Mean and standard deviation of the peat-mineral interface in relation to distance down Gully 2.

Figure 7.38 show the peat depth to decrease with increasing distance down the gully system. The location of cross profile 7 is located beyond the peat margin therefore negative values are shown. This is different to Gully 1 whereby the negative values were a result of the gully incising into the mineral substrate.
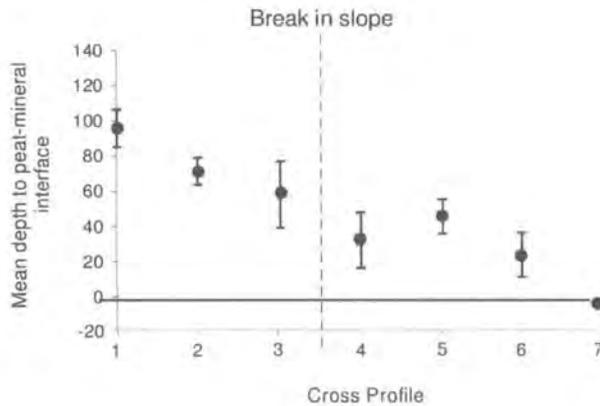
Figure 7.38: Mean and standard deviation of the peat-mineral interface in relation to distance down Gully 3.

7.3.3   Ground based photographs showing changes over time

Figure 7.39 shows two photographs from West Hill on The Cheviot, Figure 7.39a taken in the 1920's and Figure 7.39b taken in 1999. As with the re-photographed images from Moor House it is clear that there has been infill in the base of the gully system and re-vegetation has occurred. The 1920's photograph shows there to be large areas of bare

peat within the gully floor and a small channel flowing through the bare peat. The vegetation in the gully system is sparse with a few small vegetated islands separated by bare peat.

A

B

Figure 7.39: Historical change on The Cheviot plateau. A) West Hill 1920s (photograph IPR/9-6C British Geological Survey. © NERC. All rights reserved). B) West Hill 1999 (Wishart and Warburton). (Source: Wishart and Warburton, 2002).

279

The 1999 photograph shows significant infill in the base of the gully system. The exact scale of the system is unknown, however, assuming it is similar to Gully 2, this infill is likely to be approximately 50 cm to 70 cm. The gully is completely covered with grass, which is similar to many of the contemporary gully systems on The Cheviot (e.g. Gully 2 and Gully 3).

7.3.4   Vegetation survey

Figure 7.40 shows the spatial pattern of vegetation in Gully 2. Gully 1 was largely bare and showed less re-vegetation had occurred over the last approximate 20 years in comparison to Gully 2 and 3 on The Cheviot. Although Gully 3 extended beyond the peat margin the re-vegetation with the gully was similar on Gully 2 and The Cheviot as a whole. As found at Moor House the vegetation in the base of the gully system is in the later stages of re-colonisation towards the bottom of the gully system, than the head.

The top of the gully system (Area 1), where the slope angle is < 4.5° it is typically unvegetated (36 %) and any vegetation is *Sphagnum pulchrum*, *Deschampsia cespitosa*, *Vaccinium myrtillus* and *Molinia caerulea*. Further down the system where the slope angle increases (4.5°) the species of vegetation become more variable (Area 2). There is only 9 % of bare peat exposed in the area and this is on the gully sides or directly adjacent to them. The decrease in bare peat from 36 % - 9 % is expected since the better drainage lower down the system would promote re-colonsiation. The percentage of grasses increases and *Calluna vulgaris* is present. This is indicative of drier peat and in later stages of re-colonisation. In Areas 3 – 4 the extent of bare peat, grasses and *Calluna vulgaris* remains similar. There was a reduction in the *Sphagnum* spp., which is likely to be the result of slope. A number of additional species were found towards the bottom of the gully system (Area 4), these were *Galium saxatile* and *Carex nigra*, of which *Galium saxatile* is often found on dry grassland. A meandering channel was observed running down the gully, associated with vegetation in earlier stages of colonisation. This was not visible in many areas within the gully system in the field (2004) and is though to be a result of the vegetation colonising further over the last 20 years. However, a channel was visible along the east side of the gully floor in much of the system (Figure 7.40).

Key A: Vegetation Type

■ Bare Peat
■ Calluna vulgaris
□ Sphagnum cuspitadum
□ Eriophorum angustifolium
■ Eriophorum vaginatum
■ Deschampsia cespitosa
■ Deschampsia flexuosa
□ Vaccinum myrtillus
■ Polytrichum commune
■ Agrostis tenuis
□ Galium saxatile
□ Sphagnum pulchrum
■ Molinia caerulea
■ Carex nigra

Key B: Evolution

■ Bare peat
■ Early stage of revegetation, i.e. *Sphagnum*
■ Mid stage of revegetation, i.e. *Eriophorum*
■ Late stage of revegetation, i.e. *Calluna*
■ Uneroded vegetation, i.e. *Calluna*

Scale (m)
0 _____ 70

N

Figure 7.40: Spatial variation in vegetation in the base of Gully 2.

7.3.5 Stratigraphic analysis

Gully 2 is used in this section to illustrate the stratigraphy in a gully base on The Cheviot. Figure 7.41 shows a cross-section from a linear dissected area within Gully 2 (cross profile 5) (Figure 7.33). The gully incised the most where the main flow is likely to have occurred within the channel. Following exposure of the mineral substrate peat with layers of silt and sand were deposited. The east side of the cross-section shows a coarse dark brown peat in the lower layers. This is likely to have been washed in from the gully sides. Above this a red-coloured, smooth, fibrous peat appears to have developed *in situ* (*Sphagnum* spp.) or been re-deposited from further up the system. Above this *in situ* peat has grown.
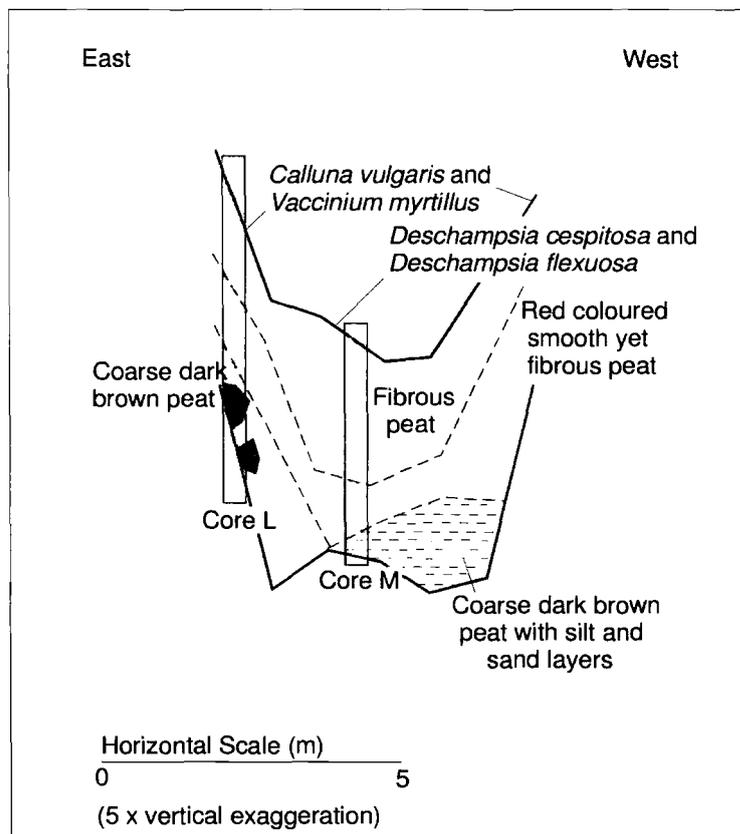
Figure 7.41: Stratigraphic cross-section from an area of linear dissection on Gully 2.

An example of peat that has been re-deposited from the gully sides into the base from the gully bank collapsing is shown in Figure 7.42. This was observed in Gully 2, lower down the system from the location of the cross-section shown in Figure 7.41. Figure 7.43 also shows bank collapse into the base of a gully system. This was observed in

282

Gully 1 and from this photograph it is clear that the collapse of this bank, blocked the gully system, leading to the gully infilling upslope and re-vegetating.

Figure 7.42: Evidence of gully bank collapse towards the top of Gully 2.
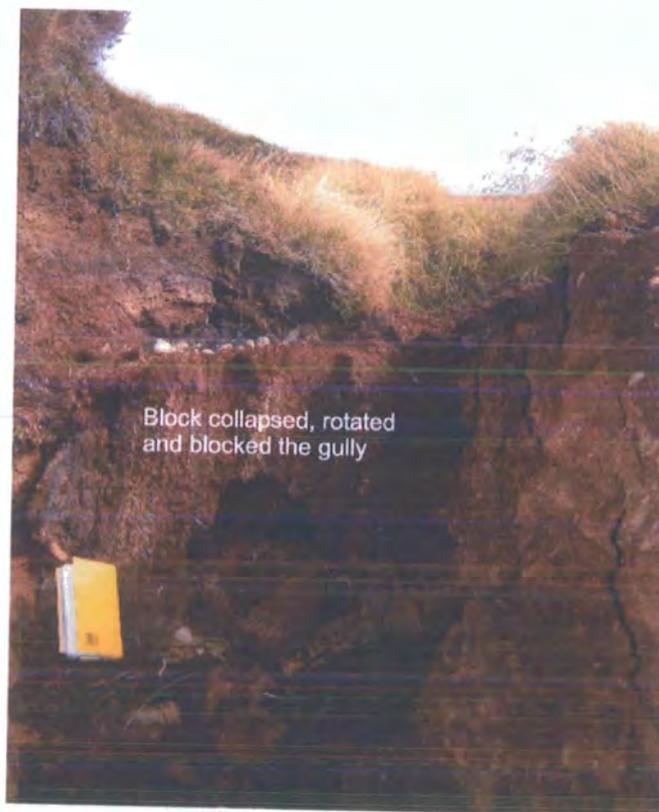
Figure 7.43: Evidence of gully bank collapse in Gully 1, which has caused the gully to block, infill and re-vegetate upslope.
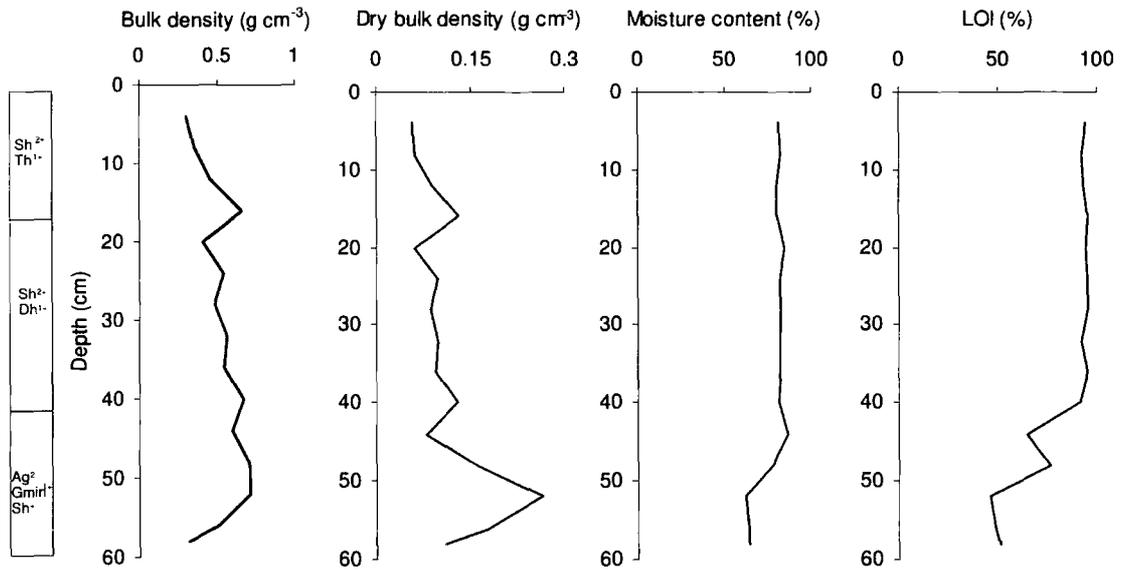
Figure 7.44: Stratigraphy, bulk density, dry bulk density, moisture content and loss on ignition data from the middle core removed from the cross-section shown in Figure 7.41.

Details of the stratigraphy of the two cores in Figure 7.41 are shown in Tables A3.18 and A3.19. Figure 7.44 shows there to be little variation in the profiles until a depth of 44 cm, where the profiles are likely to have been affected by the silt and sand layers within the re-deposited peat. Figure 7.45 shows the particles in the profile to be similar throughout, e.g. the fibre widths are virtually identical. Between 16 cm – 40 cm, in the area of red, fibrous peat, there are large *Sphagnum* particles. This indicates that the peat here is likely to have been in the early stages of colonisation and therefore this peat is *in situ*. The upper fibrous peat layer (0 cm – 16 cm) is also *in situ* peat. From Figure 7.46 it is clear that there is more evidence of grasses within the stratigraphy and therefore is likely to be peat developed in the mid or later stages of colonisation, which fit with the results from Figure 7.40, whereby there are more grasses within the base of the gully system.
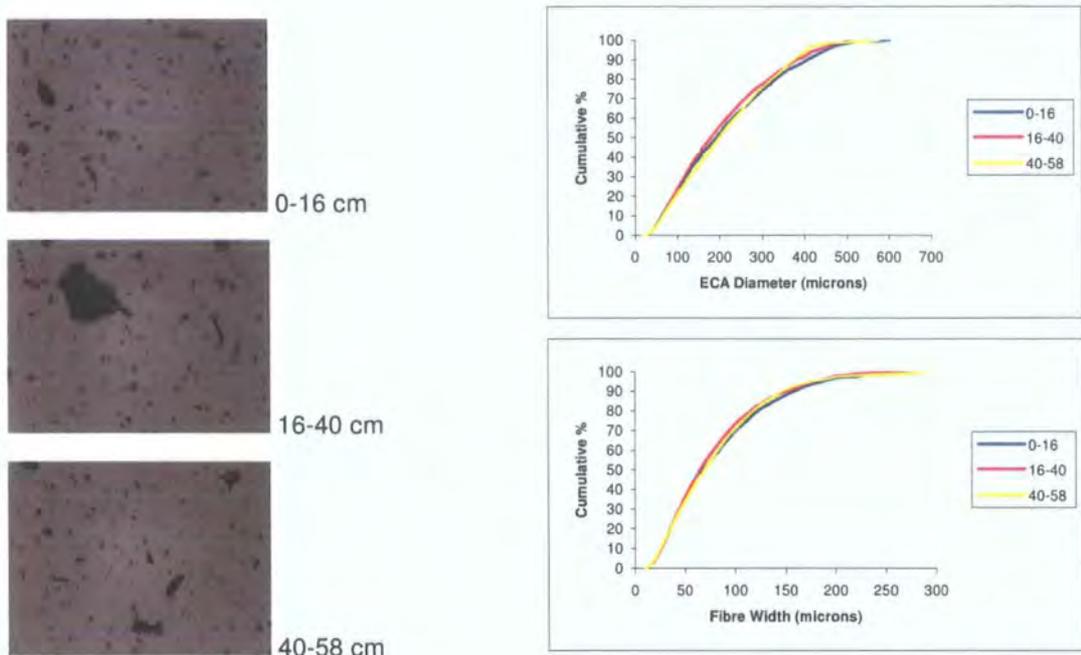
Figure 7.45: Particle shape and form photographs and graphs from the middle core from the cross-section shown in Figure 7.41.
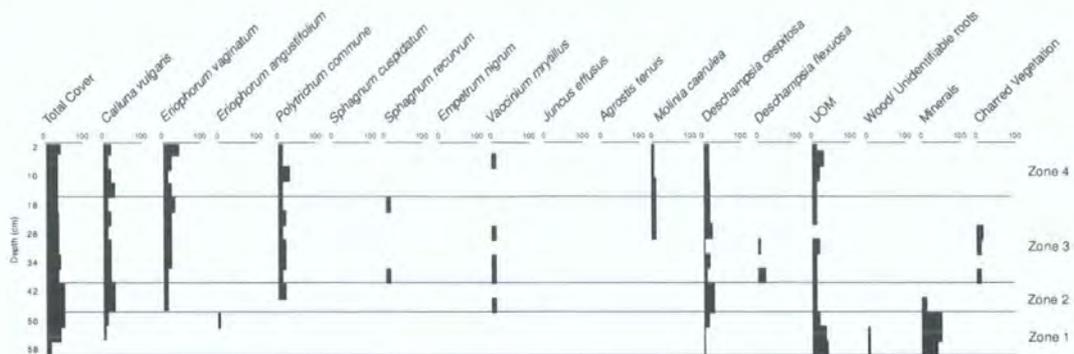
Figure 7.46: Macrofossil assemblage from the middle core removed from the cross-section shown in Figure 7.41.

Figure 7.46 shows the development of the peat stratigraphy in the base of this gully system. Zone 1 is full of minerals within the stratigraphy and unidentifiable organic matter. There is also evidence of some *Calluna vulgaris*, which is likely to have been eroded from the gully banks further up the gully system and re-deposited at this location. This re-deposited peat then began to re-colonise with *Eroiphorum angustifolium* (an early colonising species). Zone 2 shows further re-vegetation occurring in the base of the gully system, with the number of species (particularly grass

285

species) increasing in Zone 3 and 4. There is evidence of charred vegetation in Zone 3. *Calluna vulgaris* remained high in the stratigraphy from 0 cm to 48 cm. This is not extensive in the base of Gully 2 and may be a result of bank collapse and later colonisation. In Zone 4 the vegetation species in the stratigraphy are species typical of drier bog conditions (as shown in Figure 7.40) and therefore further colonisation of *Calluna vulgaris* is likely to follow.

7.3.6   Estimating of the onset of erosion and regeneration

Tables A3.20 and A3.21 show the stratigraphies of an eroded site at the top of Gully 3 (eroded) and an adjacent intact peat profile (uneroded) respectively and Figure 7.47a and 7.47b presents a simplified stratigraphy, the bulk density, dry bulk density, moisture content and loss on ignition data from the eroded and uneroded core respectively.

The uneroded core is 182 cm in length, whereas the eroded core is only 82 cm. The bottom 82 cm of the uneroded core and the full eroded core shows the profiles of both cores to be very similar, especially in bulk density and loss on ignition. Towards the top of the eroded core and at a depth of approximately 110 cm down the uneroded core, both cores show a dramatic decrease in the bulk density. The top 100 cm of the uneroded core are very different and show far more variation, especially in the loss-on-ignition profile. The moisture content of the uneroded core is least at surface, as a result of the 15 cm depth vegetation cover and was relatively low at the bottom of the profile; however, this is likely to be due to the influence of the peat and mineral substrate. There is some evidence of a very slight decrease in moisture content at an approximate depth of 100 cm, which was also observed within other cores in The Cheviot. Based on this, it is thought that the most recent phase of erosion on The Cheviot may have occurred approximately 330 years ago (if the peat accumulation rate since this period was 0.3 mm yr^{-1}). As discussed in Section 7.2.6, due to the variability in peat accumulation rates both in time and space the results presented here can only be regarded as estimates of the onset of erosion and Radiocarbon dating would be required to test the rate of peat accumulation and the estimated date of the onset of erosion. Despite this an estimated date of 330 years is interesting as it virtually coincides with the onset of erosion at Moss Flats, Moor House. These dates are only approximate, as the use of dating techniques, such as radiocarbon dating is required to confirm estimates.

A
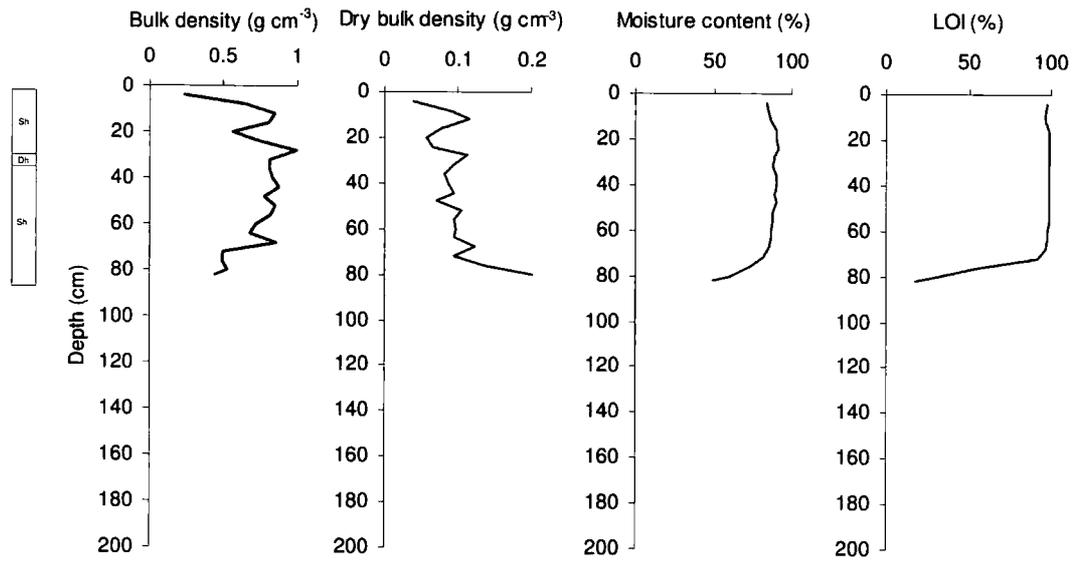
B
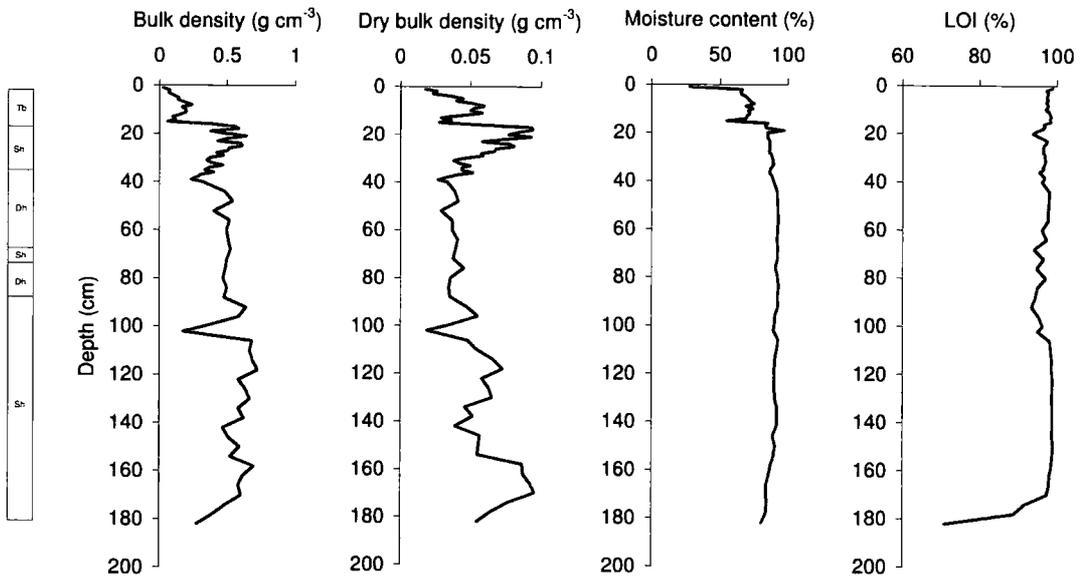
Figure 7.47: Stratigraphy, bulk density, dry bulk density, moisture content and loss on ignition data from: A) The gully bank at the top of Gully 3. B) The Cheviot uneroded.

7.4 Morphology of gully systems on Wessenden Head Moss

7.4.1 Long profiles

Figure 7.48 shows the long profiles from the three main gully systems studied on Wessenden Head Moss. The profiles are straight, slightly concave and convex in comparison to those at Moor House and on The Cheviot, which are convex in shape. Gully 1 has a length of 346 m with an average gradient of 0.02. The critical slope angles for all the profiles do not occur where the slope steepens towards the bottom of the gully systems. The breaks in slope do; however, coincide with changes in gully type, from a single linear channel to a multiple linear channel. The gully type was named multiple linear dissection given that the linear gully divides into five individual systems which are all linear in their own right. An aerial view of the gully system can be seen in Figure 3.19 and Figure 7.49 shows an example of the channels dividing. It is thought that this divide may be related to a cut or hiatus in form. Below the break in slope shown in Figure 7.48a the slope angle decreased. This is unexpected as it is thought that as the channels converge the slope angle would increase. However, it appears that the channel is close to the mineral substrate and therefore the rate of erosion is reduced (this is indicated in Figure 7.48a by the peat-mineral base line). The top of the systems shown in Figures 7.48a and 7.48b lead into the area of peat flats (anastomosing) dissection, which is extensive on the higher ground of Wessenden Head Moss (> 490 m) (Figures 4.6 and 4.7).

Figure 7.48c again shows the net gradient of Gully 2 as 0.02, with a length of 503 m. This gully system is convex in profile with the deepest peat in the middle section of the system. Indicating that before the gully system began to stabilise there was no peat in the gully base and that the profile would have been similar to the other gully systems on Wessenden Head Moss (straight). This is the result of the topography of the area. It may be that this system is older than the other systems, or that the change in slope at approximately 150 m from the bottom of the gully system has acted as a dam in preventing the peat leaving the system and has therefore been deposited within the system causing it to back fill at a faster rate. The latter seems more likely. The break in slope represents the divide between linear and dendritic dissection with no anastomosing dissection.
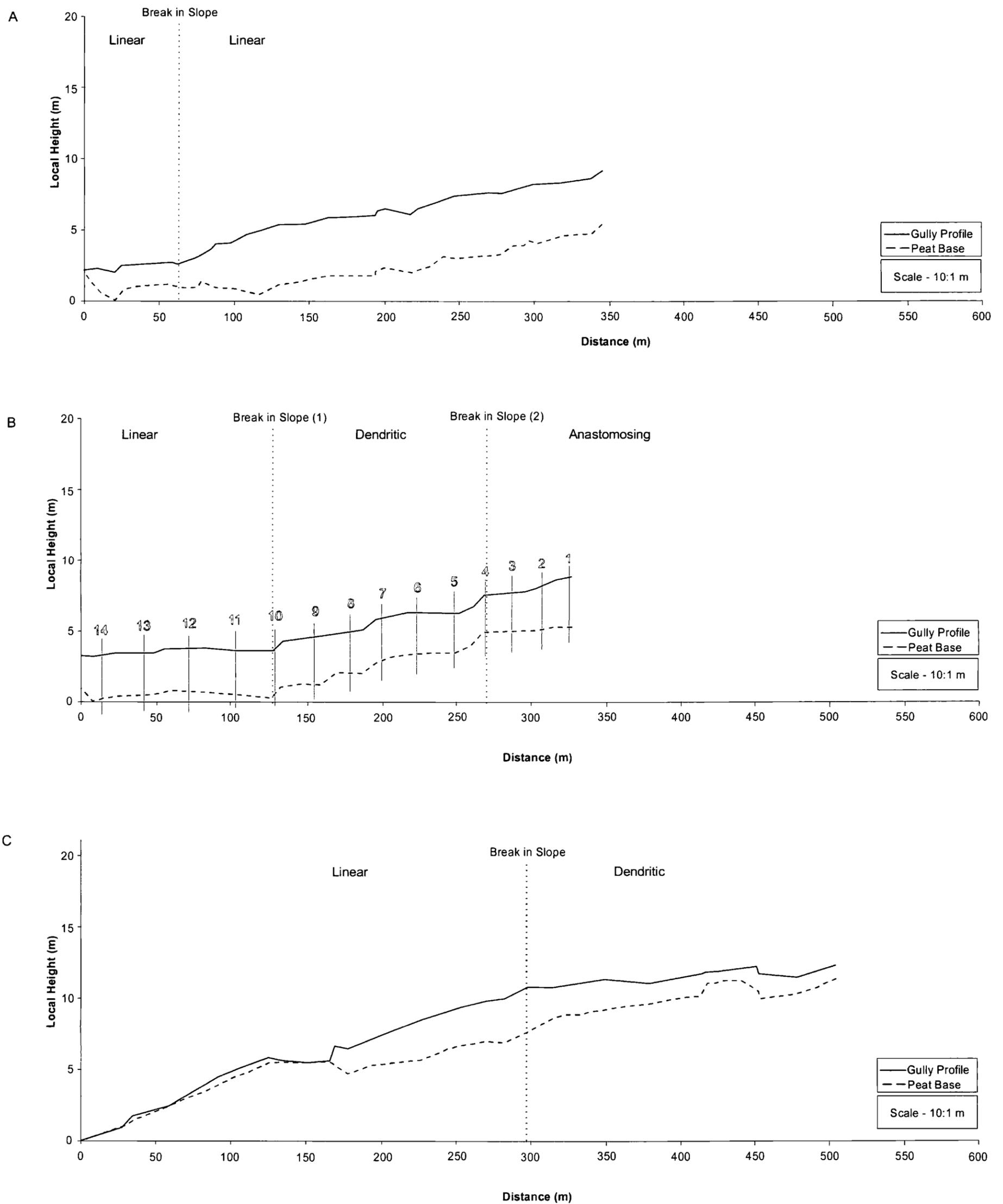
Figure 7.48: Long profiles of (A) Gully 1 main gully. The break in slope indicates a transition from single linear to multiple linear dissection. (B) Gully 2. The breaks in slope represent the transition from linear to dendritic and dendritic to anastomosing dissection. (C) Gully 3. The break in slope represents the transition from linear to dendritic dissection. The location of the cross profiles discussed in Section 7.4.2 is shown on the Gully 2 profile.

Figure 7.49: The main gully system and tributary gully system of Gully 1.

7.4.2 Cross profiles

Gully 2 is used throughout this section to show the variations in the cross profiles. Gully 1 was a narrow system (< 3 m) and Gully 3 extended beyond the peat margin. The bottom of Gully 2 (Figure 7.50c) was wide and discharged into a larger gully system. The sediment delivery from Gully 2 to the larger gully system (in addition to other gullies further up the large system) would therefore impact upon its recovery and the overall sediment budget of this upland area. It was therefore decided that this gully would be the most interesting for this study.

Figure 7.51 shows the peat depth within the Gully 2 system to vary from 2 m – 3 m. The orientation of the cross profiles varies down the gully system. From cross profiles 1 – 8 the orientation is S – N, 9 – 11 is SE – NW and 12 – 14 is E – W (Figure 3.19). Cross profiles 1 and 2 are flat, typical of the peat flats on Wessenden Head Moss (anastomosing dissection) (Figure 7.50a). The peat depth in profile 1 is lower than other profiles in the system, however, in the adjacent eroded flat to Figure 7.48c was approximately 3 m. Profiles 3 to 12 are generally U-shaped with the peat depth generally following a similar pattern to the surface. This is thought to indicate that the gully system had eroded into the mineral substrate forming a U-shape within which infill has occurred. Profiles 13 and 14 are wider than the upper profiles. This is because the gully system in this area is wide (Figure 7.50c) and the peat depth is generally less than other cross profiles within the gully (with the exception of cross profiles 1, 2 and 7).

A
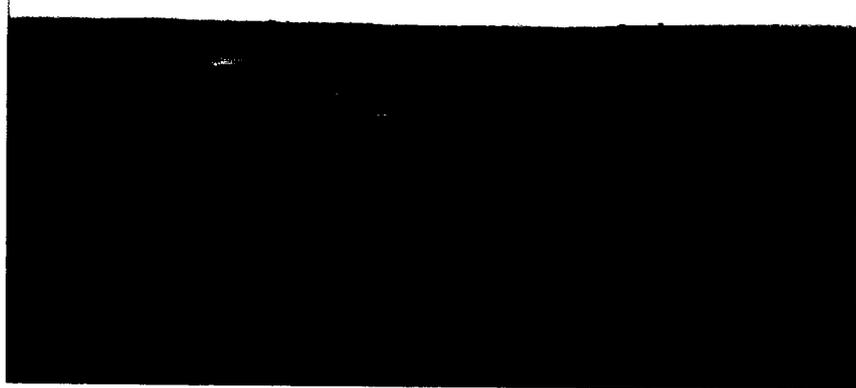
B

C
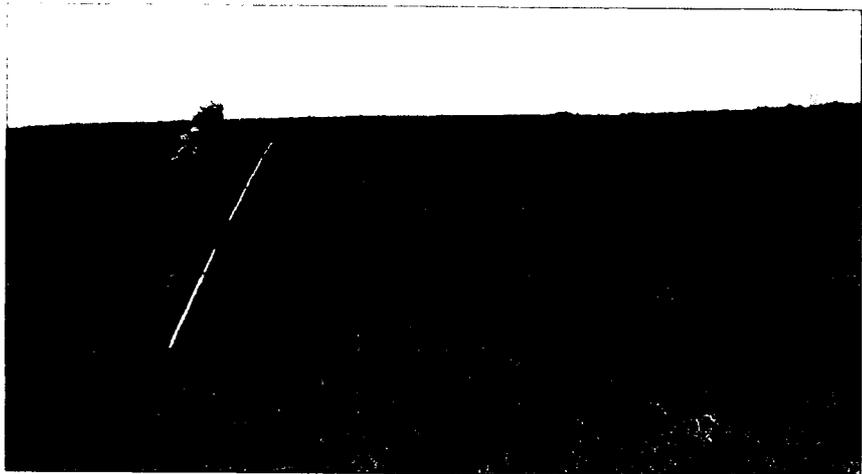
Figure 7.50: Photographs showing the differences in dissection type from the top to the bottom of Gully 2. A) Area of anastomosing dissection, typical of cross profile 1. B) Area of dendritic dissection, typical of cross profile 6. C) Area of linear dissection, typical of cross profile 14.
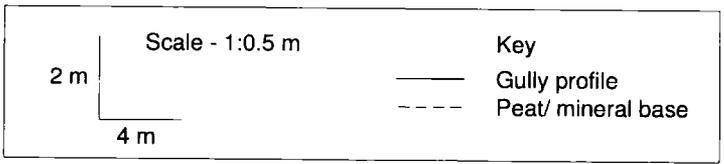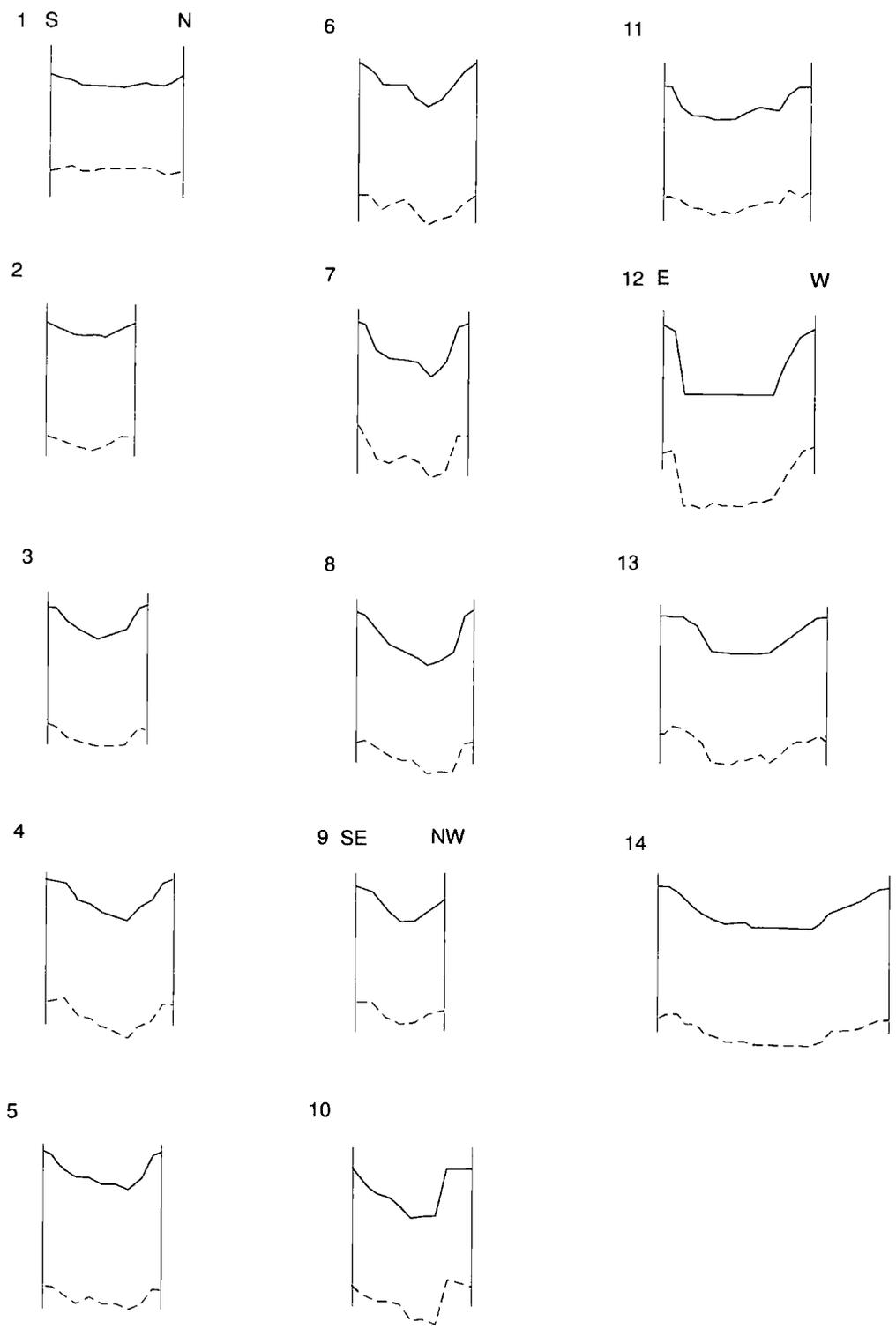
Figure 7.51: Cross profiles of Gully 2.

Figure 7.52 presents the means and standard deviations from the above cross profiles. The locations of the breaks in slope are shown. The variations in gully pattern do not correspond with variations in peat depth and peat depth variability. Figure 7.52 shows an increase peat depth from cross profile 1 – 5 (A), followed a decrease in peat depth from 5 – 11 (B) and an increase from 11 – 14 (C). Profiles 1 – 5 and 11 – 14 show little variation about the mean. Rather than gully pattern the slope angle seems to have a greater influence over peat depth. Profiles 1 – 4 are located where the slope angle is low at the top of the gully system, and the increase in slope angle from profile 4 – 10, coincides with a decrease in peat depth and the greatest variability (resulting from flow pathways forming at the peat-mineral substrate). Profiles 11 – 14 are where the gully gradient is the least and here there is a progressive increase in peat depth to the gully entrance.
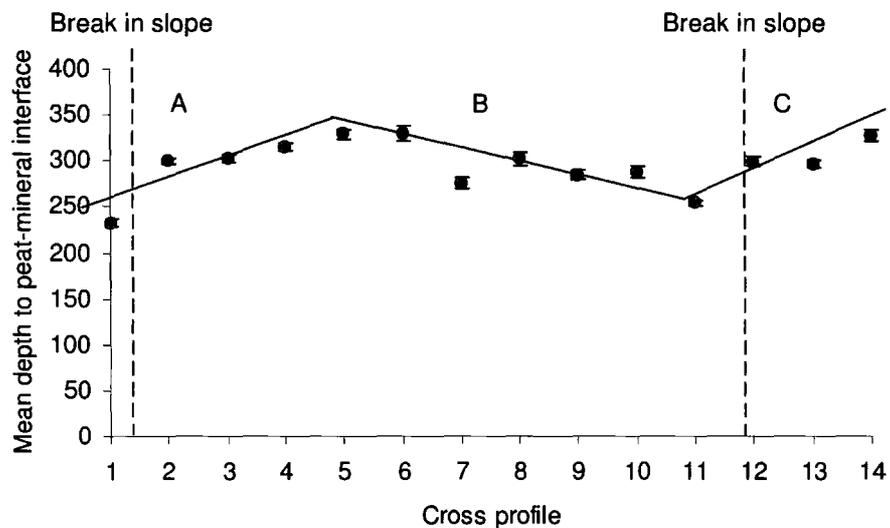
Figure 7.52: Mean and standard deviation of the peat-mineral interface in relation to distance down Gully 2.

7.4.3 Ground-based photographs showing changes over time

A series of photographs were taken on Wessenden Head Moss in 1981 and were re-photographed in 2002 in order to show the historical change approximately over the last 20 years. Figure 7.53 shows the change in Gully 3 in the area of linear dissection, Figure 7.54 shows change within the large gully system draining Gully 2 and Figure 7.55 change on the peat flats above these systems.

A

B

Figure 7.53: Historical change in Gully 3 on Wessenden Head Moss. A) 1981 (Photographed by Tim Burt), B) 2002.

Figure 7.54: Historical change in the gully system, which Gully 2 flows into on Wessenden Head Moss. A) 1981 (Photographed by Tim Burt), B) 2002.

Figure 7.55: Historical change on the peat flats on Wessenden Head Moss. A) 1981 (Photographed by Tim Burt), B) 2002.

Figure 7.53a shows the gully system to be deeply eroded (approximately 2 m) with a saturated gully base. There is gravel in the gully bottom and evidence of re-vegetation occurring in the base of the gully but the gully sides are bare. By 2002 the gully system has infilled by approximately 80 cm and has extensively re-vegetated with grasses. The gully sides have also re-vegetated to some extent. Flow still occurs down the gully (especially during storm conditions) as the grasses are flattened in the downstream direction.

Figure 7.54a shows the gully to be infilling and re-vegetating, however, there is a meandering channel flowing down the gully. The gully system entering this larger gully in the left foreground of the picture (1) shows the vegetation cover to have changes to grasses (from 1981 – 2002) but is still discharging water and sediments into this system. There also appears to have been some infill in the gully base as the gully bank is not as visible (2). The flow appears higher in the Figure 7.54b than in Figure 7.54a. Colonisation of grasses, particularly *Eriophorum* spp. has occurred over this period especially further up the system (3) and towards the gully banks. To the left foreground of Figure 7.54b grasses are flattened as a result of high level flow (4). This channel was not visible in 1981 and the flow channel existed at the bottom of the photograph (5) (along the left bank of the gully system).

Figure 7.55 shows an example of the historical change that has occurred on the peat flats. There is less change than in the gully systems (Figure 7.53). this is thought to be the result of flats being slower to re-vegetate. There has been little change in the height of the peat from 1981 – 2002, which shows that little peat has been gained in these areas. There are a few more gravels on the peat surface indicating some peat loss, however this loss is negligible in comparison to the amount of infill, which has occurred in the gully bases. The intact vegetation in Figure 7.55a is disaggregated but in Figure 7.55b there are more, smaller, isolated patches of vegetation; some in previously bare areas of peat, which indicates that re-vegetation may be slowly occurring. Additional historical photographs from Wessenden Head Moss are shown in Appendix 3. Both Figures A3.6 and A3.7 show infill and re-vegetation within the gully system from 1981 – 2000 and Figure A3.8 shows re-vegetation to have occurred on the footpath. This is therefore interesting in view of the discussion in Chapter 4, whereby it was thought increased

recreation in the area might have increased the erosion from 1976 – 2004. This shows this may not be the case.

7.4.4   Vegetation survey

Figure 7.56 shows the variation in vegetation within Gully 2 (selected for similar reasons as in Section 7.4.3). The upper area (1) of anastomosing dissection shows 72 % of this area to be unvegetated or bare (see Figure 7.50a and 7.56). The remaining area is covered with *Eriophorum* spp., especially *Eriophorum angustifolium* in areas where the gully begins to channelise and the flow becomes concentrated (and therefore ground becomes more saturated).

In Area 2 the channel is narrow and meandering, with separated islands of *Eriophorum vaginatum*. In the wettest areas *Eriophorum latifolium* was evident and bare peat. Further down the system (3) *Eriophorum vaginatum* and *Eriophorum latifolium* and bare peat are still present but there is an increase in the grass species (e.g. *Deschamspia cespitosa* and *Molinia caerulea*). There is also some mineral deposits at the confluence. This is likely to have been re-deposited from the peat flats at the head of the tributary gully system. Towards the bottom of the gully system (4), the system widens and again there is an increase in the number of vegetation species. The bare peat is only found on the gully sides. The peat in this area however is saturated giving a larger number of wet tolerant species (e.g. *Eriophorum latifolium*, *Eriophorum angustifolium* and *Juncus effusus*). The greatest cover type is *Eriophorum vaginatum*, which tends to be in the areas of slightly higher ground within the gully base.

Similar to both Moor House and The Cheviot the number of species increases down profile. An increase in slope angle was suggested to be the cause. However, the gradient does not increase from the head to the exit of the gully system, as it does at both Moor House and The Cheviot, nor did it in Gully 1 on Wessenden Head Moss, where again this same pattern emerged. Another explanation for this therefore may be a result of increased nutrients as a result of wash down the system or vegetation encroachment from below the gully entrance (Figure 7.29). It is therefore likely that the combination of drainage and increasing nutrients promotes species variation.

Key A: Vegetation Type

- Mineral Substrate
- Bare Peat
- Erica tetralix
- Juncus effusus
- Eriophorum latifolium
- Eriophorum angustifolium
- Eriophorum vaginatum
- Deschampsia cespitosa
- Deschampsia flexuosa
- Polytrichum commune
- Molinia caerulea

Key B: Evolution

- Mineral Substrate
- Bare peat
- Early stage of revegetation, i.e. *Sphagnum*
- Mid stage of revegetation, i.e. *Eriophorum*
- Late stage of revegetation, i.e. *Calluna*
- Uneroded vegetation, i.e. *Calluna*

Scale (m)
0   80

Figure 7.56: Spatial pattern of vegetation in the base of Gully 2.

7.4.5 Stratigraphic analysis

Figure 7.57 shows a stratigraphic cross-section from the area of linear dissection towards the bottom of Gully 2 (cross profile 14), where the gully is approximately 12 m wide. The peat in the base of this gully is similar across the profile. In the gully base there is abundant silt, sand and clay. Above this is a thick (2 – 4 m) depth of dark brown/ black peat, which is likely to be re-deposited peat. The sides of the gully show a layer of *Sphagnum* peat overlying the dark brown/ black peat. Above this is a dark brown/ black, coarse peat, typical of that found on exposed gully banks. The gully banks are re-vegetated with early colonising vegetation species, such as *Eriophorum* spp. and *Juncus effusus*. These vegetation species have also re-vegetated the gully base. The gully west side has exposed bare peat, which appears to have been re-deposited from the gully bank.
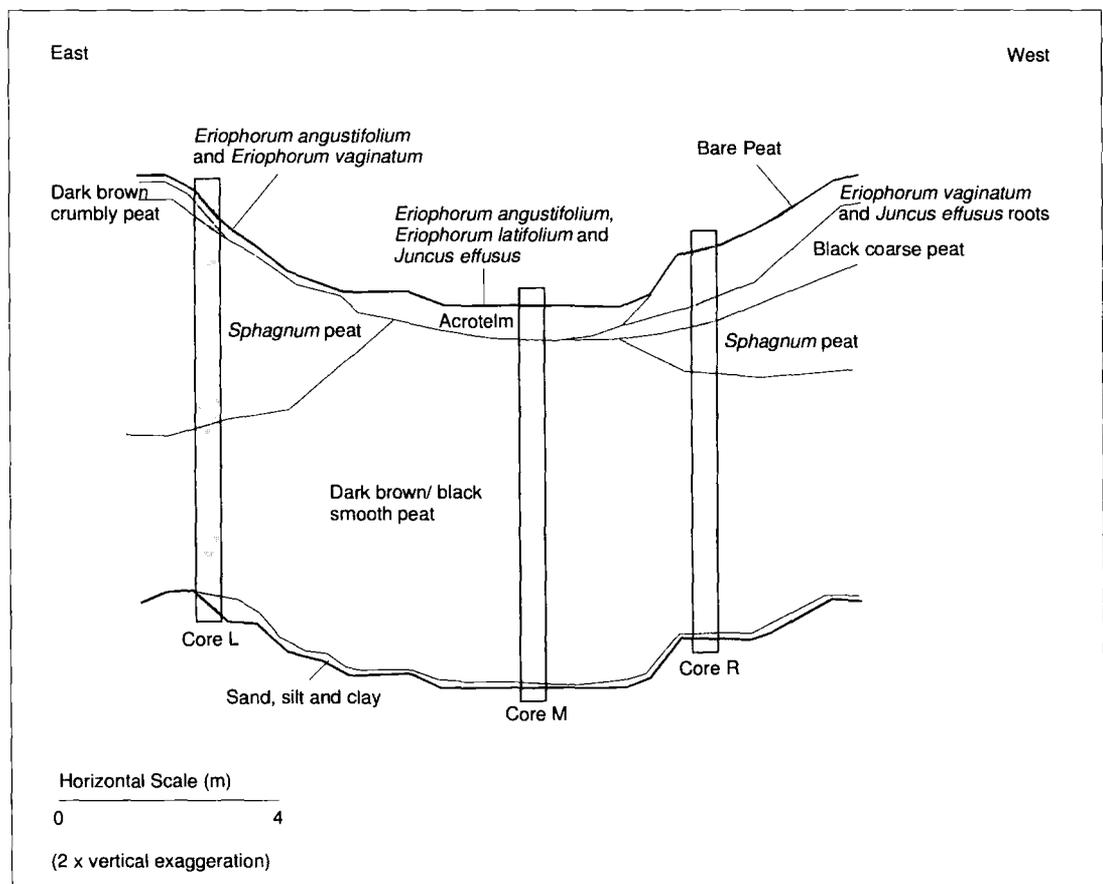
Figure 7.57: Stratigraphic cross section from cross profile 14 an area the area of linear dissection towards the entrance of Gully 2 (Figure 7.50c).

Further information on the stratigraphy of the three cores is presented in Tables A3.22 – A3.24. Figure 7.58 shows the basic stratigraphy, bulk density, dry bulk density, moisture content and loss on ignition from the left (east) core. There are great variations in these properties (these are shown in Table A3.22). The large variations in the loss on ignition profile are a result of the clay content in the core and the high bulk density values tend to be where dense *Sphagnum* leaves and roots are present in the stratigraphy. Figure 7.59 shows the bulk density from the middle core to generally increase with increasing depth. The moisture content and loss on ignition profiles show some abrupt variation, which are likely to be a result of the wood remnants within the peat. Figure 7.60 presents the basic stratigraphy, bulk density, dry bulk density, moisture content and loss on ignition profiles from the right core. All the profiles show very little variation apart from in the lower layers where clay, silt and sand are present.

Figure 7.61 and 7.62 presents the macrofossil assemblages from the east and middle cores respectively. The right core was not looked at in terms of its macrofossil assemblage given there was little variation and it was considered a core from the gully east side and the middle would provide enough evidence of the changes over time.

Figure 7.61 shows Zone 1 contains minerals, which are likely to be the peat-mineral substrate of the gully bed. There is also *Calluna vulgaris* and *Agrostis tenuis* present. This is likely to have been input from the gully banks when the gully bed was exposed. Higher up the core *Juncus effusus* and *Eriophorum angustifolium* are present indicating the early stages of re-colonisation of the gully system. Many of the macrofossils in Zone 2 were unidentifiable, with some *Calluna vulgaris* and grasses. This zone is thought to be the main infill, when little vegetation was growing in the gully base and much of the peat was input from further up the system and from the gully sides. Zone 3 is likely to be where *in situ* peat has grown; however, it is thought that some peat would still be washed through the system at this time. The *Sphagnum* spp. is not evident at this depth. This may be a result of industrial pollution in the area. There is a decrease in *Calluna vulgaris* and an increase in *Eriophorum* spp. in Zone 4, which is visible on the gully floor at present day. *Agrostis tenuis* was evident throughout the stratigraphy, which is not the case in Figure 7.62, where instead *Deschamspia flexuosa* and *Erophorum latifolium* were more dominant.

Figure 7.58: Stratigraphy, bulk density, dry bulk density, moisture content and loss on ignition data from the east core removed from the cross-section shown in Figure 7.57.

Figure 7.59: Stratigraphy, bulk density, dry bulk density, moisture content and loss on ignition data from the middle core removed from the cross-section shown in Figure 7.57.

Figure 7.60: Stratigraphy, bulk density, dry bulk density, moisture content and loss on ignition data from the west core removed from the cross-section shown in Figure 7.57.

Figure 7.61: Macrofossil assemblage from the left core from Cross Profile 14, Gully 2.
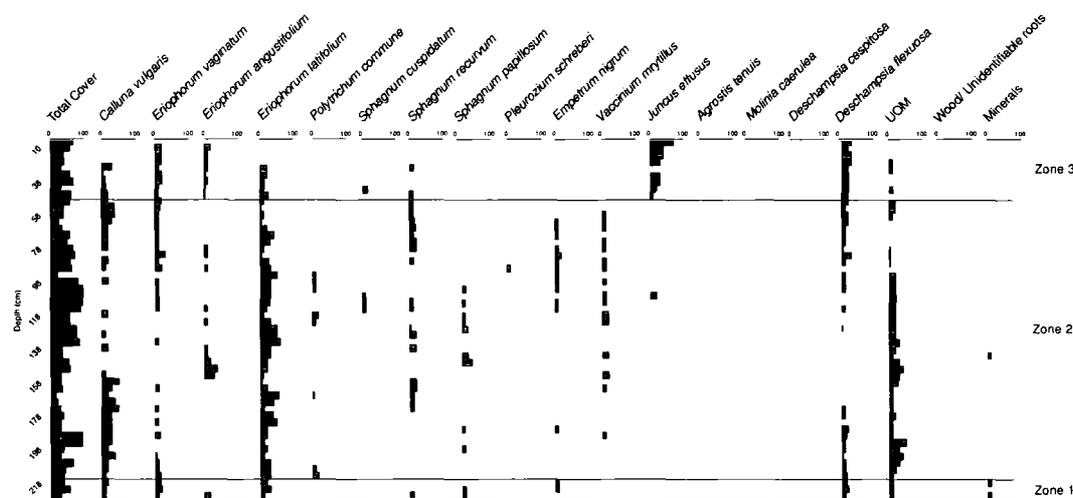
Figure 7.62: Macrofossil assemblage from the middle core from Cross Profile 14, Gully 2.

Figure 7.62 shows a similar pattern to the east bank. Minerals were evident in Zone 1 with *Eriophorum* spp., *Deschamspia flexuosa* and *Calluna vulgaris*. *Eriophorum* may have been colonising at this period but it is likely that given there is a high content of *Deschamspia flexuosa* and *Calluna vulgaris* aswell, that it is re-deposited peat. In Zone 2 there is evidence of minerals to a depth of approximately 100 cm, indicating that the peat is likely to be inwashed. There is a high content of *Erophorum latifolium* throughout the stratigraphy (which is not the case in Figure 7.61), indicating that this may have been colonising on the inwashed peat or was being washed in. Zone 3 shows the *Calluna vulgaris* is reduced, indicating that the peat is no longer inwashed to the same extent and

is beginning to grow *in situ*. *Sphagnum* spp. die out and there is an increase in *Eriophorum vaginatum* and *Eriophorum angustifolium*, whilst *Eriophorum latifolium* declines. This shows the gully system is becoming gradually less saturated as shown in Figure 7.59.

Both Figure 7.61 and 7.62 show evidence of inwashing to have occurred from the gully sides and further up the system. The growth of *in situ* peat within the base of this gully system is thought to have occurred in the last approximate 100 years (based on a 0.3 mm yr^{-1} peat accumulation rate). However, on the gully sides there is dark brown, coarse peat with grass roots to a depth of 9 cm, indicating that the re-vegetation of the gully sides possibly occurred later than the gully bottom (over approximately 30 years) (based on a 0.3 mm yr^{-1} peat accumulation rate, although rates may well have been different).

7.4.6 Estimating the onset of peat erosion and regeneration

The Troel-Smith and von Post classification information can be seen in Tables A3.25 and A3.26 respectively. Figure 7.63 shows the basic stratigraphy, bulk density, dry bulk density, moisture content and loss on ignition for a core from the top of Gully 2 at the edge of the eroded peat flat (eroded) and Figure 7.64 from an intact area of intact peat adjacent to Gully 2 (uneroded).

Figure 7.63 shows a maximum peat depth of 344 cm. The bulk density varies around 1 g cm^{-3} and steadily increases with depth. The dry bulk density, moisture content and loss-on-ignition profiles show little variations apart from the lower layers, which is a result of sand and gravels within the peat. The moisture content is shown to decrease dramatically at a depth of 128 cm and at a depth of 122 cm there is a change in the peat type from a smooth peat with grass roots to a fibrous *Sphagnum* peat. The profiles from the uneroded core (Figure 7.64) show the core depth is 340 cm, which is shorter that the eroded core. The mineral substrate is the same and given the peat depth is approximately the same. This may indicate that peat has been re-worked in the other core. The bulk density of this core is shown to vary about 1.1 g cm^{-3}, becoming increasingly variable in the top 45 cm of the core. The loss on ignition profile varied little down the core, whereas there were a number of abrupt changes in the dry bulk density and moisture content profiles. The main drops in moisture content were observed at a depth of 44 cm and 172 cm. The reason for the decrease at a depth of 44 cm is unknown given the peat at this depth was a

smooth, brown peat with grass roots. At a depth of 172 cm the peat is saturated *Sphagnum* peat with coarse roots.

Given the general stratigraphy, density, moisture content and loss-on-ignition profiles did not suggest a likely hiatus for the onset of erosion on Wessenden Head Moss, particle shape and form and macrofossil assemblages were examined (Figure 7.65 and 7.66 respectively). Figure 7.65 shows a large contrast in fibre widths between Figure 7.65a and 7.65b. Figure 7.65a shows a strong skew with the fibres mainly within a narrow range, whereas Figure 7.65b shows the equivalent circular area diameter and fibre width to vary throughout the core. This therefore indicates that the eroded core is more uniform, which is likely to be a result of the peat being inwashed. The photograph from Figure 7.65b at a depth of 153 cm to 173 cm examined had no *Sphagnum* compared with 173 cm to 200 cm. There appeared to have been a shift from Sphagnum to grass vegetation, before returning back to *Sphagnum* vegetation between 66 cm and 153 cm. This may indicate that the peat was not saturated at this depth and may be a result of the onset of erosion.

The macrofossil assemblage (Figure 7.66) also shows this change at a depth of 172 cm. This is marker by a shift from Zone 2 to Zone 3. This is therefore thought to be the depth of the onset of erosion on Wessenden Head Moss, which indicates the erosion to have occurred approximately 570 years ago. This is based on an average peat accumulation rate of 0.3 mm yr^{-1} and therefore the date of the onset of erosion can only be regarded as an estimate without the use of a dating technique, such as Radiocarbon dating to test the reliability of the rate of peat accumulation. The possible date of the onset of erosion on Wessenden Head Moss is approximately double of the date of the onset of erosion thought to be at Moor House and on The Cheviot. *Racomitrium lanuginosum* has been used by researchers such as Tallis (1985b) to date the onset of erosion in the Southern Pennines. This study identified abundant *Sphagnum* throughout the stratigraphy, whereas *Racomitrium lanuginosum* was very sparse. *Racomitrium lanuginosum* was observed in the uneroded core and not in eroded cores from Wessenden Head Moss at 5 depths within the stratigraphy. These were at depths of 38 cm, 122 cm, 206 cm, 262 cm and 282 cm, which may represent changes in land use, climate or smaller phases of erosion, however from this study this cannot be proven and no *Racomitrium lanuginosum* was observed at a depth of 172 cm. Generally where *Racomitrium lanuginosum* is found, it is

thought to indicate when the moor was in a drier state; however, due to the sparseness of the *Racomitrium lanuginosum* it could not be used for estimating the onset of erosion.
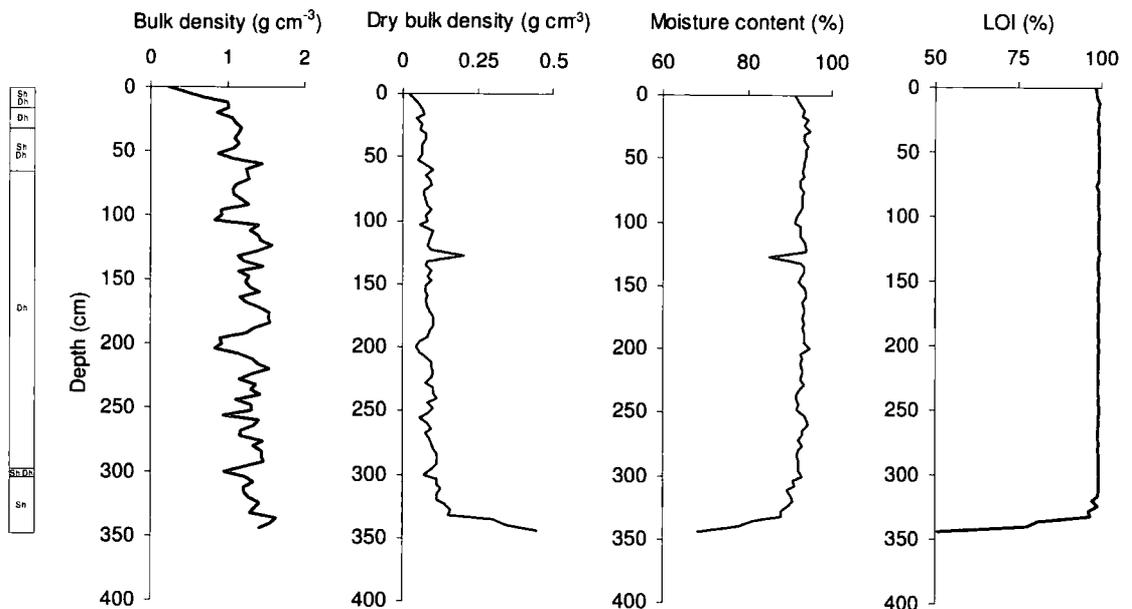
Figure 7.63: Stratigraphy, bulk density, dry bulk density, moisture content and loss on ignition data from the top of Gully 2 (eroded).
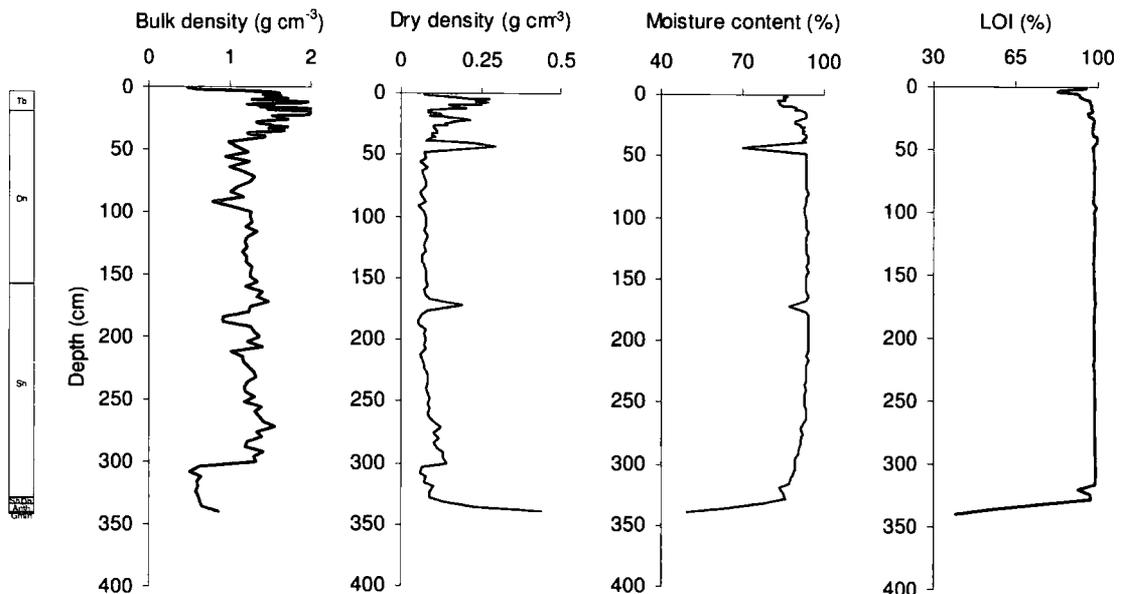
Figure 7.64: Stratigraphy, bulk density, dry bulk density, moisture content and loss on ignition data from the intact peat directly adjacent to Gully 2 (Wessenden Head Moss uneroded).

A

0-3 cm

3-7 cm

7-70 cm

70-83 cm

83-94 cm

94-105 cm

105-161 cm

161-190 cm

190-203 cm

203-223 cm

223-260 cm

260-277 cm

277-287 cm

287-324 cm

324-383 cm

383-390 cm
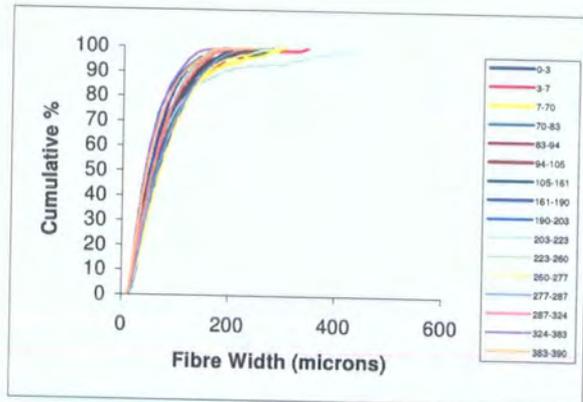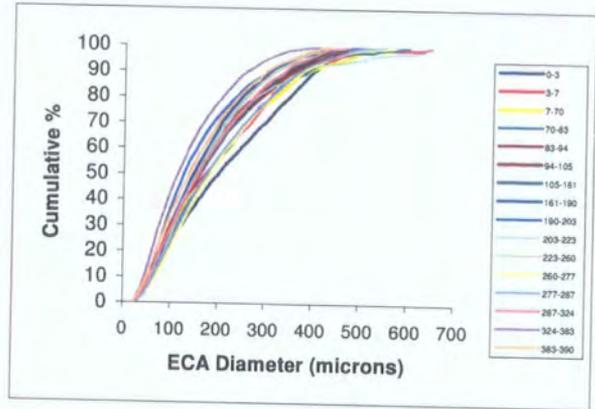
B

0-2 cm

2-6 cm

6-10 cm

10-12 cm

12-20 cm

20-25 cm

25-32 cm

32-66 cm

66-153 cm

153-173 cm

173-200 cm

200-226 cm

226-267 cm

267-287 cm

287-327 cm

327-331 cm

331-332 cm

332-339 cm

339-340 cm
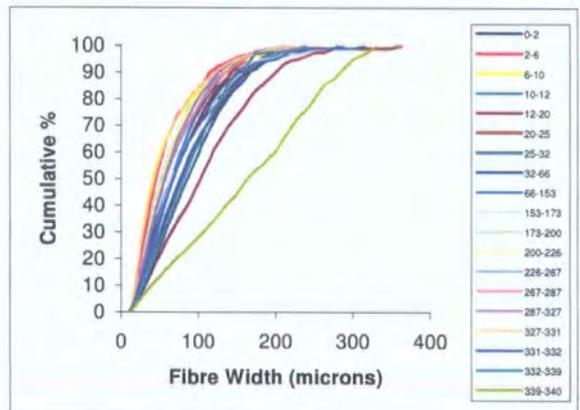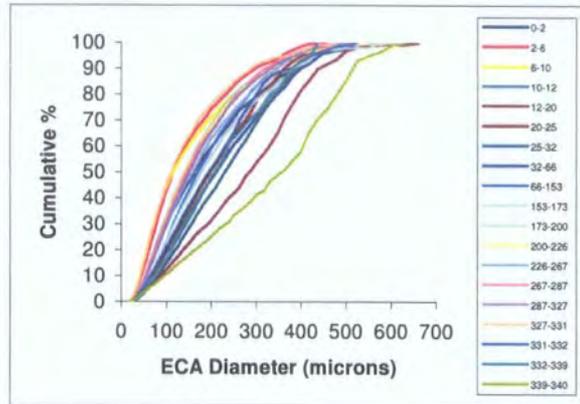
Figure 7.65: Particle shape graphs for: A) Wessenden Head Moss eroded peat flat - Gully 2. B) Site adjacent to Gully 2 (Wessenden Head Moss uneroded). The analysable size range varies from 100 – 1500 microns.

A

B
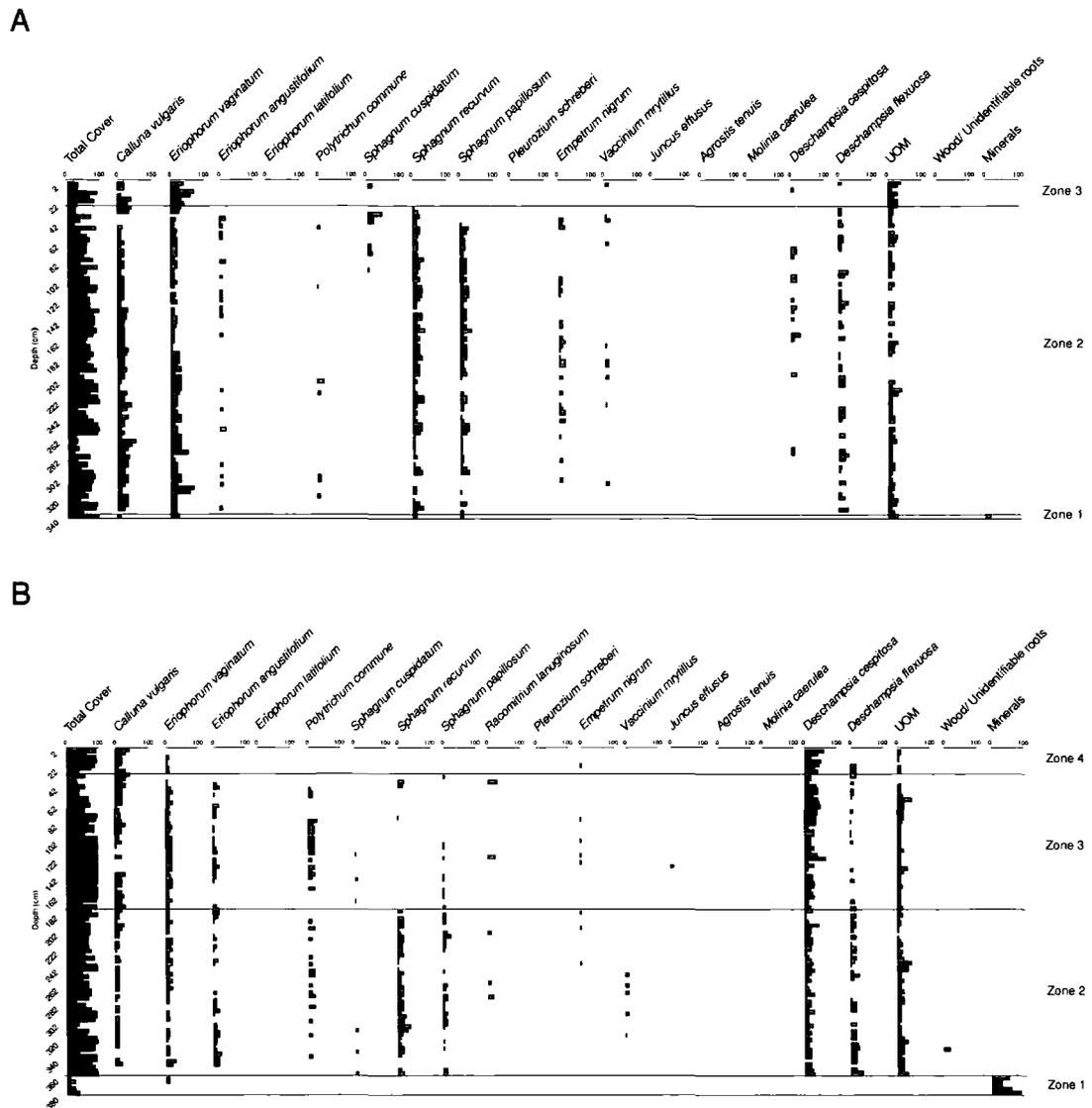
Figure 7.66: Macrofossil assemblage from the core removed from: A) Top of Gully 2 (eroded). B) Intact peat directly adjacent to Gully 2 (Wessenden Head Moss uneroded).

7.5 Summary

This chapter has addressed the morphostratigraphic study in a number of gully systems at the three study sites. The field research involved ground-based surveying, sampling and repeat photography. The laboratory analysis was conducted on the cores and monoliths removed from the field.

The long profiles showed gully lengths at the three study sites to be comparable. The fall heights varied with the steepest systems being on The Cheviot and the least steep on

Wessenden Head Moss. A link was made between the break slope angle and the dissection type, however this varied with study area as a result of local topography. Approximate mean slope angles for the dentritic transitional zone for the three study sites were 3.7° at Moor House, 4.9° on The Cheviot and 1.4° on Wessenden Head Moss. A continuum of form was observed. Peat depth increased at Moor House and The Cheviot with a decrease in slope, however this was less evident on Wessenden Head Moss. This increase in slope was coupled with increased variability across the gully systems therefore indicating flow pathways were formed. This was most evident at Moor House and least noticeable on Wessenden Head Moss and was thought to be the result the gully systems on Wessenden Head Moss generally starting in the peat flats, then becoming very narrow. Runoff from the peat flats is thought to have caused large quantities of peat to be removed from the gully systems or re-deposited lower down the system, where the gully widened (towards the gully entrance). In addition, the gully systems studied on Wessenden Head Moss had no single channel running down the gully; the whole gully was saturated with the vegetation flattened in the direction of flow.

The repeat ground-based photographs provided important evidence of changes over the last few decades at the three sites and each showed infill and re-vegetation to have occurred. Based on the stratigraphy and on the ground-based photographs, the changes seemed most rapid at Moor House and least on Wessenden Head Moss. However, given the timescale of observation was only 20 years on Wessenden Head Moss, it would have been interesting to see the changes prior to this (e.g. Figure 7.53 – 7.55).

The vegetation surveys showed the number of species increase with distance down gully, indicating that the vegetation is in the later stages of re-colonisation towards the bottom of the system. Moor House and The Cheviot showed an increase in slope towards the bottom of the gully systems and therefore increased drainage was thought to be the reason for this. The slope angle decreased at the bottom of the gully systems on Wessenden Head Moss and therefore it was thought that increased nutrient supply or vegetation encroachment was also important. However, increased drainage, nutrient supply and vegetation encroachment all cause stabilisation.

Stratigraphic changes were observed down the gully profile and across the gully. The peat within the gully stratigraphy appeared eroded, re-deposited or grown *in situ*. The

processes operating on the gully sides and in the gully bottom varied. The gully banks played an important role in sediment supply to the gully floor (e.g. Figures 7.42 and 7.43). Re-deposition occurred within the system, particularly where the gully system widened toward the entrance. The re-deposited peat was thought to be peat being reworked because little peat was lost from the areas of sediment supply (e.g. Figure 7.55).

Comparing eroded and adjacent uneroded cores at the three study sites provided an estimate of the onset of peat erosion. It is thought the most recent phase of erosion resulted from climatic change and land management and occurred some 300 years ago at Moor House, 330 years ago on The Cheviot and 570 years ago on Wessenden Head Moss, based on a peat accumulation rate of 0.3 mm yr^{-1} (Tallis, 1995a). Peat accumulation rates vary both in time and space and without the use of an accurate dating technique such as Radiocarbon dating the results can only be regarded as estimates of the onset of erosion.

8.0 DISCUSSION

8.1 Scope of Chapter

The previous four chapters have presented the results of this study along with preliminary interpretations and discussion. This chapter discusses the results in detail forming linkages between regional and local-scale variations in gully development and erosion potential, in light of a current understanding of upland peat erosion. The sections presented below relate to the aim and objectives specified in Chapter 1.

8.2 Regional scale variations in gully development (Objectives 1, 2, 3)

This study has highlighted regional variations in gully development across the Pennines (NE – SW). An evaluation of past research on the extent of blanket peat erosion in upland Britain and its basic causes was carried out in Chapters 1 and 2. Bower's (1959; 1960a; 1960b; 1961; 1962) research is recognised as the pioneering study into blanket peat erosion and her Type 1 and Type 2 classification of dissection types is still widely used. Her research has been criticised by Radley (1963) and Mosley (1972) for its broad generalisations. Mosley (1972) emphasised the limitations of for the qualitative nature of Bower's study and suggested the Type 1 and Type 2 classification scheme be quantified. Mosley documented examples of end members in Bower's classification scheme observing a continuum of form between Type 1 and Type 2 dissection. Wishart and Warburton (2002) stated that a linear, dendritic and anastomosing dissection classification scheme better described the gully systems in The Cheviot Hills.

This study critically assessed the usefulness of Bower's (1960b) classification in comparison to quantitative measures of gully form derived using a GIS framework. The quantitative nature of this research (the first undertaken since Mosley (1972)) has highlighted variations in form of gully patterns and identified end-members associated with Bower's gully classification. These features were observed at both the regional scale and local scale (e.g. Figure 4.1 and 7.1). Type 1 and Type 2 dissection are suitable general classes for describing peatland gully systems and are easily observed from maps and aerial photography. However, with GIS and remote sensing, detailed ground-based research and statistical analysis the old Bower classification could be improved (Bower, 1960). Linear, dendritic and anastomosing dissection was used to classify the gully

systems at the three study sites and proved useful for quantitative measurements. Dendritic dissection was observed to represent a middle position between continuum between Type 1 (typically anastomosing dissection) and Type 2 (typically linear dissection) (Figure 4.1).

Each study site showed the number of gully systems decreased with increasing gully order and gully length to increase with order along a trendline, again showing a continuum of forms, whereby there was a greater number of low order, short gully systems (< 50 m), typical of anastomosing and dendritic dissection and less high order, long gully systems (> 200 m), typical of linear dissection. The drainage density of the gully systems was found to be least at Moor House (2.88 km km^{-2}) and greatest on Wessenden Head Moss (9.81 km km^{-2}). This was expected given the patterns of dissection at the three study sites, e.g. Wessenden Head Moss is more dissected than Moor House (Figures 3.17 and 3.19), and given the calculations of drainage densities by other researchers in the Southern Pennines, e.g. Burt and Oldman (1986) and Yeloff *et al.* (2005).

Bower's (1960b) classification of dissection types was diagrammatically shown on a concave slope, implying that the gully systems in the Pennines formed on concave slopes. Mosley's (1972) quantitative research into gully systems observed gully networks on concave slopes to be typically Type 1 dissected and on convex slopes, Type 2. This research has shown that linear, dendritic and anastomosing dissection on Wessenden Head Moss to occur on convex, straight and concave slopes. The general pattern however, and of particular importance at Moor House and on The Cheviot, is that the gully systems (all dissection types) across Northern England have typically developed on convex slopes (e.g. Figure 7.1) (Tallis, 1998). This is therefore important in terms of the topography of these areas and the development of gully systems.

The revised classification scheme was used to examine regional variations in gully systems at the three study sites and compare the different extent and patterns of erosion and regeneration that are present. The total cover of blanket peat was found to be greatest on Wessenden Head Moss (75 %), followed by Moor House (69 %) and then The Cheviot (48 %). The most extensive of erosion was on The Cheviot (80 %), followed by Wessenden Head Moss (64 %) and then Moor House (48 %). Despite this, the re-vegetation of these eroded areas was found to be greatest at Moor House (80 %),

followed by The Cheviot (61 %) and then Wessenden Head Moss (45 %). In terms of the types of dissection, Moor House showed the greatest linear dissection (58 %). Linear dissection was also found to be extensive on Wessenden Head Moss (37.5 %) and not so important on The Cheviot (21 %). The greatest extent of re-vegetation within the dissection types was found to be within the linear dissected gully systems (73 %), followed by dendritic (70 %) and then anastomosing (44 %). This is thought to be the result of: drainage, since colonisation of vegetation occur seems to in drained rather than saturated soils; increased nutrient supply down gully from re-deposited peat; and encroachment of vegetation up gully from below the gully entrance.

Tallis (1985a) mapped the extent of erosion in the Peak District (Figure 2.5), the extent of erosion at Moor House was mapped by Garnett and Adamson (1997) and in The Cheviot Hills by Wishart and Warburton (2002). Results imply The Cheviot was eroded more severely than Wessenden Head Moss and Moor House. The aerial photograph data from Wessenden Head Moss (1888) was taken at a similar time to the investigations of Tallis (1985a); however, the extent of peat cover was very different. The results from this study showed 64 % of the peat to be eroded, mainly bare peat erosion to the peat-mineral base. Of the eroded peat 43 % was observed to be re-vegetating. Tallis (1985a) observed that of the peat 85 % was eroded. The reason for the differences in the extent of erosion is thought to be the result of other areas in the Southern Pennines being more eroded than Wessenden Head Moss (e.g. Bleaklow and Kinder Plateaux). Therefore the results from this study are thought to be accurate for Wessenden Head Moss, but slightly underestimated in terms of the erosion of the Southern Pennines as a whole, where it is well known that the Southern Pennines is more severely eroded than other blanket peatlands, such as the North Pennines (Conway, 1954).

This study also observed linear dissection to occur at the lower altitudinal areas at the three study sites and anastomosing dissection to be more concentrated at higher altitudes (Figures 4.6 and 4.7). The differences in the relative importance of the different dissection types at different altitudes tend to be the result of the general topography of the study areas (Figure 4.3). In the Peak District, Bower (1960a) found that Type 2 erosion was more typical in lower altitudinal bands affecting approximately 50 % of the moorlands at 400 m and Anderson and Tallis (1981) suggested that 95 % of the erosion at an altitude of 600 m was affected by Type 1 dissection. On The Cheviot Hills Wishart and Warburton (2002) observed gully erosion to be concentrated in the

upper altitudinal bands, accounting for 86 % of the mire between 650 – 699 m and the lower altitudinal bands erosion was less common.

Using sequential air photographs and historical ground-based photographs the rates and patterns of erosion and/or regeneration were assessed within the three study areas over the last 50 years. Change had occurred in particular within the gully systems in terms of infilling and re-vegetating and on the peat flats in terms of some re-vegetation. Small-scale channel re-adjustments of the gully systems were observed, however this study also observed little large-scale changes in gully form. This was evident at the three study sites. The main changes were in gully infill and re-vegetation of bare peat. At Moor House the main Burnt Hill gully system was used as an example to show patterns and extents of infill and re-vegetation, which has occurred in the bases of the gully systems (Figure 4.12). The infill of this gully system was extensive over the last 40-years (Figure 1.11, 7.9 and 7.10). Re-vegetation was more extensive and in the later stages of re-colonising at the bottom of the gully system for the same reasons as suggested above, whereby drainage, increase nutrient supply and vegetation encroachment promoted re-vegetation. The Cheviot and Wessenden Head Moss also showed the same patterns of infill and re-vegetation, however to less a degree than at Moor House. Unlike Moor House (Figures 4.13) the peat flats on Wessenden Head Moss showed little change over the same timescales (last approximate 20 years) (Figure 7.55). Within the gully systems re-vegetation occurred most extensively in wide channels because the flow was less concentrated.

Author(s)	Peat Cover (%)	Peat Erosion (%)	Re-vegetation (%)
This Study	69	48	82
Garnett and Adamson (1997)	80.1	22	54
Crisp (1966)	80 – 85	11 – 20	0

Table 8.1: Summary table of the extent of peat cover, peat erosion and re-vegetation calculated for Moor House and Upper Teesdale NNR.

Table 8.1 shows a summary table of the extent of peat cover, peat erosion and re-vegetation. The results from this research showed 69 % of the area of 40.3 km^2 observed to be peat covered, of which 48 % of the peat is eroded and of the eroded peat, 82 % is re-vegetated. Within the Moor House NNR Garnett and Adamson (1997) observed the total area of peat cover to be 80.1 %, 7.8 % was suffering from erosion, 9.4

315

% was re-vegetating and 62.8 % was uneroded. Therefore of the 80.1 % peat, 22 % was eroded, and of that eroded peat, 54 % was re-vegetated. There are two possible reasons for the differences between the results from this study and Adamson and Garnett's (1997) study. Firstly, the boundaries of the study area were extended to the far side of the River Tees after 1997. The far side of the River Tees is a large area with less peat cover. Secondly this study covered less of an area than Adamson and Garnett (1997) but carried out a detailed assessment of the area studied (Figure 3.5 and 3.17). The general area studied for this research was the Rough Sike catchment and slightly beyond. The Rough Sike catchment was previously studied by Crisp (1966) who found 11 – 20 % of the 80 – 85 % peat in the Rough Sike catchment to be eroding, with no peat re-vegetating. This is also much lower than that observed in this research and given it is unlikely that much further erosion has occurred since 1966 the percentage variations are likely to be a result of differences in methods of calculation. The 2000 aerial photograph used in this research showed a clear picture of the peat surface from which this research was carried out and due to the use of new technologies, such as GIS this research is considered at the most accurate and most rigorous. In addition the time of observation may have been different.

Within this research 48 % of The Cheviot (between 690 m and 815 m) was shown to be peat covered and of that 80 % was eroded but much of this eroded peat is re-vegetating (69 %). The results obtained by Wishart and Warburton (2002) in The Cheviot Hills were comparable with this research. Wishart and Warburton (2002) found that between 650 m and 815 m, 81 % was eroded. The main variations between this research and that of Wishart and Warburton (2002) were in the extent of each dissection type. This research observed there to be 21 % linear dissection, 63 % anastomosing dissection and 16 % dendritic dissection. Wishart and Warburton (2002) however, observed linear dissection was the most common dissection type, covering 51 % of the eroded peat, followed by 26 % of anastomosing dissection and 23 % dendritic dissection. The differences are thought to be a result of Wishart and Warburton's (2002) research covered a larger area than The Cheviot alone, whereby linear dissection was observed to be greater at Comb Fell and Hedgehope Hill than on The Cheviot itself and therefore would have influenced the extent of the dissection types.

8.3 Rates of peat accumulation (Objective 6)

Based on the depth of the SCP 'take-off', the rates of peat accumulation at the three study sites were estimated. Peat accumulation rates varied with vegetation type and regional area. The initial 'take-off' in SCPs is estimated to be an 1850 'take-off' rather than 1950 given the rates of peat accumulation. Since the 'take-off' in SCPs was lower on the heather than the moorland grass at Moor House the peat accumulation rate was higher. Rates of peat accumulation based on an estimated 1850 'take-off' were 1.2 mm yr^{-1} for the heather and 0.6 mm yr^{-1} for the moorland grass at Moor House. Local variations in the SCP profiles were observed from the Moor House samples implying there is a significant potential error in the SCP methodology when assessing recent peat accumulation at the local scale and independent dating is needed to verify such rates.

The regional scale variations in the SCP concentrations showed the greatest concentration on Wessenden Head Moss and the lowest on The Cheviot. This was expected since Wessenden Head Moss is located in an area adjacent to fossil fuel power stations. The rates of peat accumulation on The Cheviot and Wessenden Head Moss were comparable to Moor House with estimates of 0.4 mm yr^{-1} and 0.5 mm yr^{-1}, respectively.

8.4 Rainfall simulation experiments (Objective 7)

A rainfall-runoff simulator was used to assess erosion potential on intact vegetation surfaces within the interfluve areas of the blanket peat catchment. The results clearly demonstrate vegetation and surface properties are the key factor in determining both the runoff production and sediment yield. Runoff rates from moorland grass (4.54 mm hr^{-1}) were less than from heather moorland (6.25 mm hr^{-1}). Bare peat gave the highest rates of runoff (10.87 mm hr^{-1}).

Figures 6.35 and 8.1 show the variations in mean steady-state runoff from different cover types. Figure 8.1 shows the results of the bare, grass and heather experiments from this research and the bare, grass, heather and *Sphagnum* experiments from Holden and Burt's (2002b) experiments. The results from this study show bare peat to produce the highest runoff rates, followed by heather and moorland grass. Holden and Burt (2002b) found *Sphagnum* to produce the highest runoff rate followed by bare peat;

heather and moorland grass were very similar. The runoff rates from the heather for this research are thought to be greatest due to burning, since burning increased the runoff production on the heather by 5.24 mm hr^{-1} (Figure 6.35). The runoff rates follow a continuum with increasing rainfall intensity for the heather experiments from the rainfall intensities used by Holden and Burt (2002b) to the rainfall intensities used in this study, therefore indicating that the results from this study were comparable with Holden and Burt (2002b). For the moorland grass experiments the mean steady-state runoff rate by Holden and Burt (2002b) at a rainfall intensity of 12 mm hr^{-1} is similar to the mean steady-state runoff rate for a rainfall intensity of 16 mm hr^{-1} in this study. This indicates that although the results are similar the mean steady-state runoff rates for Holden and Burt (2002b) were approximately 4 mm hr^{-1} higher for a given rainfall intensity than for this experiment. This study showed the mean steady-state runoff rate to be greater for the bare peat experiments than observed by Holden and Burt (2002b). Therefore indicating that for a given rainfall intensity the mean steady state runoff rate is approximately 4 mm hr^{-1} greater for this experiment than for Holden and Burt (2002b).
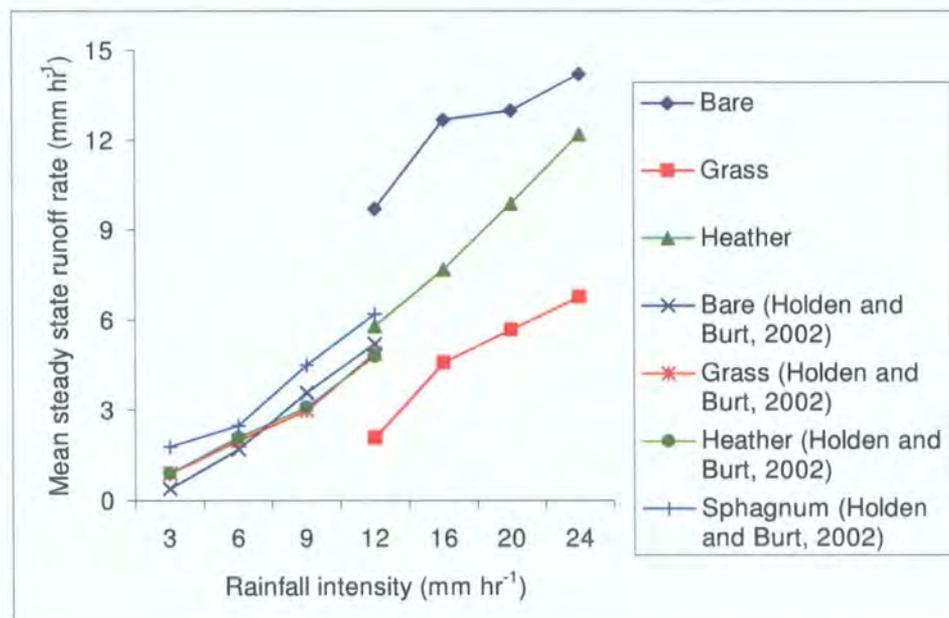
Figure 8.1: Mean steady state runoff against rainfall intensity for surface cover types on field plots exposed to rainfall simulation.

Table 8.2 shows the mean steady-state runoff rate and percentage of applied rainfall to runoff rate for the field and laboratory experiments from this research and the field

318

research by Holden and Burt (2002b). The results from the field experiments from this research showed that 38.2 % of the applied rainfall was runoff, 28.7 % for the laboratory experiments and 36.8 % for the research carried out by Holden and Burt (2002b). This therefore indicates that the percentages of the runoff and infiltration rates from this study were similar than those by Holden and Burt (2002b). The results from both the laboratory peat block experiments and the field experimental plot experiments were also comparable; however, the results from the field experiments were approximately 9.5 % greater than the laboratory peat block experiments.

Mean steady state runoff rate (mm hr^{-1}) (% of applied rainfall that is runoff)			
Rainfall Intensity (mm hr^{-1})	Field Experiments	Laboratory Experiments	Holden and Burt (2002b)
3	-	-	1.0 (33.0)
6	-	-	2.0 (33.0)
9	-	-	3.5 (39.0)
12	3.7 (30.8)	3.1 (25.8)	5.0 (42.0)
16	6.3 (39.4)	4.9 (30.6)	-
20	8.1 (40.5)	6.0 (30.0)	-
24	10.1 (42.0)	6.8 (28.3)	-
Mean	7.1 (38.2)	5.2 (28.7)	2.9 (36.8)

Table 8.2: Mean steady state runoff rate (mm hr^{-1}) and percentage of the applied rainfall that is runoff from the field and laboratory rainfall simulation experiments from this research and field research from Holden and Burt (2002b).

Runoff rates in this study generally decreased with increasing depth, showing the majority of the runoff production in the upper 5 cm of the profile, therefore agreeing with the suggestion by Holden and Burt (2002b; 2002c, 2003a) that very little runoff occurs below 5 cm in peat. Holden and Burt (2002b) showed that the blanket peats in the North Pennines were dominated by flow within the top 10 cm of the peat mass. This was the result of the very low hydraulic conductivity of the peat below this depth.

However, in the upper few centimetres of the peat the hydraulic conductivities are sufficiently high to allow rapid throughflow generation. This does not say however that no water is produced from the peat profile below a depth of 5 cm, because there is still a significant contribution to runoff from the macropores and pipe flow pathways from deeper within the peat (Holden and Burt, 2003a).

Rates of sediment production were generally low in this study. Sediment became exhausted from the plot throughout the experiments, given that the 12 mm hr^{-1} rainfall intensity generally produced the greatest SSC. From some plots (e.g. Silverband and Cottage Hill) the SSC increased again following signs of exhaustion. This was the result of particle detachment occurring at higher rainfall intensities (Figure 6.7). However, Holden and Burt (2002b) found the sediment concentration increased with increasing rainfall intensity.

It is thought that the sediment supply from an open hillslope or gully wall would be greater as more sediment would be available; however, in blanket peatlands there are generally not continuous bare slopes especially since the remaining bare peat areas are re-vegetating and are becoming enclosed with vegetation, therefore sediment becomes entrapped (e.g. Figure 2.14 and 2.15). Therefore it is not expected that the rates of sediment production from blanket peat areas would be great. This agreed with Burt and Gardiner (1984) who noted that surface runoff from an uneroded site where vegetation was present there was little sediment supplied. Burt and Gardiner (1984) did observe that on a bare, eroded surface the sediment supply was more abundant. Rainsplash was an important agent in disturbing the bare peat surface and entrainment of peat occurred as particles were noticed splashed up to the top to 15 cm in height (Holden and Burt, 2002b). This study demonstrated the importance of rain splash in eroding bare peat. The sediment concentration during the simulation experiments varied greatly due to small pools forming in the depressions in the microtopography of the peat surface and water being released as the pools filled. Surface wash was observed on the collecting trays with individual particles and fibres in transport. Seepage from small cracks from under the peat, above the trays was also observed. This appeared to be an important erosion processes. Surface wash did not move in sheets but as small rills across the surface of the collecting trays. This was also noted by Holden and Burt (2002b), as well as sediment supply to the runoff troughs oscillated in relation to micropool and mircorill, cut and fill processes.

Figure 6.35 showed variations in runoff rates from the different land management practices. Figures 6.17 and 6.24a showed the mean steady-state runoff against rainfall intensity for all the grazing exclosures studied in this research and Figure 6.28 for all the Hard Hill Burning Experiments. As stated above burning was shown to have the greatest influence on increasing the runoff production. Despite this, burning had no impact on sediment yield (Table 6.4). The 10-year burning rotation and the unburnt vegetation cover were shown to have the lowest runoff rates in comparison to the 20-year burning rotation and the single 1954 burn. This was unexpected because it was thought that the reduced vegetation cover on the 10-year burning rotation and on the no burn plot (since the heather would be degenerating) would have yielded the greatest runoff rates. However, the extent of *Eriophorum* vegetation cover was considered a possible reason for this since Labadz (1988) discussed how *Eriophorum* has a high infiltration capacity.

The latest burning on the Hard Hill Burning Experiment took place 8 – 9 years ago and therefore the results do not provide direct evidence of how runoff rates are affected by burning. Research carried out on peat hydrology directly after burning has shown runoff rates to reduce as a result of burning. This is either by fibrous remains of burnt heather forming a dense ground surface litter (Imeson, 1971) or from a more intense burn (or a burn after a drought period), which has more of an effect on the vegetation cover and the peat surface. The peat may dry and crust, from which increased overland flow would occur, or it may crust and crack, from which the rainwater can infiltrate into the peat. The increased rate and intensity of infiltration and throughflow produced accelerates the formation and growth of shallow gully networks and seepage faces (Imeson, 1971).

Reduced grazing pressure benefited the extent and diversity vegetation cover. Knock Fell exclosure plot demonstrated that the vegetation composition and structure has changed as a result of long-term sheep removal. At the Burnt Hill exclosure (Figure 6.24a) and Knock Fell exclosure (Figure 6.17a) the runoff rate was greater outside the exclosure than inside. Figure 6.35 shows that generally grazing has an effect on runoff production. Similarly to burning, reduced grazing pressure is shown to have no effect on the sediment yield, though the concentrations were higher than from the Hard Hill Burning Experiments. This may indicate that burning reduces sediment yield.

Both runoff production and sediment yield were greatest from the bare peat plots (Table 6.4 and Figure 6.35). This is because the there is no vegetation to reduce runoff rates and promote infiltration and no vegetation trap the sediment. The irregularly of the peat surfaces did aid in preventing erosion of the whole peat surface by channelling the runoff, promoting infiltration and trapping sediment.

Not only do cover type and land use factors affect the runoff production and sediment yield during a rainfall event, but so also does the antecedent rainfall conditions prior to the rainfall simulation experiment. For example, the rainfall event follows a drought or snow cover, a series of rainfall events would be required for the ground to wet-up. With an increasing number of hot dry summers being predicted for many upland blanket peatlands (Marsh and Sanderson, 1997), peat desiccation may increase and there is a need to assess its effects on both bare and vegetated peat surfaces. It is known that as peat dries the structure is permanently altered such that it becomes hydrophobic (Egglesmann et al., 1993). Holden and Burt (2002b) carried out rainfall simulation experiments following drought conditions to see the effect on runoff production and sediment concentration. They found that following dry, warm weather the rainfall tends to infiltrate into the blanket peat, reducing the rates of steady-state surface runoff and more flow takes place within the peat. Summer desiccation of the peat is thought to prepare the peat for removal and therefore peat erosion was greatest in the autumn and winter. As the winter then progressed sediment exhaustion occurred and frost action was of minimal importance (Francis, 1990). Tallis (1973) showed that substantial peat erosion occurred during snowmelt and during heavy rain. Both the effects of desiccation having a greater effect than freeze-thaw and frost and snow melt being a major cause of erosion were observed by Burt and Gardiner (1984). This is therefore interesting in terms of the future stability of upland blanket peat, given that if climatic change occurs, runoff production and sediment yield may be affected, impacting on erosion and re-vegetation.

8.5   Local Scale Gully Development (Objective 4)

As discussed in Section 8.2, the topography of the three study sites had a major impact on the extent of peat cover, extent of erosion and gully patterns (Figure 4.3). The local scale research (Chapter 7) showed that topography also had a major influence on peat depth. As slope angles increased peat depth decreased and vice versa, e.g. peat depths

were least on The Cheviot and greatest on Wessenden Head Moss. Tallis (1987) showed that in the Southern Pennines as slope angle increases peat depth decreases. This study has therefore shown that this occurs over the whole Pennines, not just in the Southern Pennines. Hobbs (1986) noted that in peatland areas the greater the altitude and the steeper the slope, the thinner the peat. This study therefore agrees with this statement, given that the altitude of The Cheviot is also the greatest of the three study sites (Figure 4.3 and Table 7.1).

Gully lengths at the three study sites were comparable; however, the overall gradients and the average gradient over the break in slope varied, with the steepest gully systems being on The Cheviot (0.17) and the least on Wessenden Head Moss (0.02). A link was made between the slope angle and the dissection type, but no one slope could be assigned to one dissection type because this varied with study site. Cross-sectional form of the gully systems varied with position in the gully system and between regions. For example, gully widths tended to be greatest at the head of the gully, in the area of dendritic or anastomosing dissection. Where slope angles steepened within a gully profile flow paths were observed at the peat-mineral interface, whereas on flatter slopes the gully floor was more uniform.

Detailed ground-based research of a number of gully systems allowed a better understanding of the development of gully systems over time (Figure 7.28 and 7.29). This research concurred with that of Bower (1961) who suggested that the early stages of gully development occur when the gully systems are shallow and contained within the peat. Developing gully systems then erode headward and laterally and eventually incise to the peat base. In the advanced stages the gully systems have incised to the peat-mineral base but remain narrow with a V-shaped cross-profile. They then, in the late stages, widen by stream channel migrating across the gully floor. The stream power decreases and it is from then that the gully system moves into the recovery stage whereby the gully begins to infill and re-vegetate (Figure 7.29). When vegetation begins to take control and the gully begins to stabilise the stability is dependent on the nature of the peat and gully bank processes and the discharge in the gully (Figure 1.9) (Wishart and Warburton, 2002).

The stratigraphic infill within the bases of the gully systems varied in cross-section as a result of the different processes acting on the gully sides and gully floor. At the start of

323

the recovery phase movement of bare peat and loose minerals continues the gully floor and during rainfall events sediment is mobilised and re-deposited further down the system. Figure 7.29 shows infilling and re-vegetation of the gully systems to occur at a faster rate down gully. Eventually in the late recovery stages little peat is mobilised other than from collapsing gully banks and some movement within the narrow channel hugging one side of the gully system. This side generally appears to be the windward side because vegetation tends to recover on the leeward side at a much faster rate where it is sheltered from the prevailing weather conditions (Figure 7.28). In less re-vegetated systems there will be periods of cut and fill within the gully floor before full recovery occurs. As Gardiner (1984) observed in the Southern Pennines, sediment exhaustion would occur during storm events and *Eriophorum* spp. provides efficient protection against erosion. In gully systems such as Burnt Hill it is likely that re-vegetation will continue, increasing the infill within the gully base.

Both at Moor House and on The Cheviot similar patterns of infilling and re-vegetation were observed as shown in Figures 7.28 and 7.29. On Wessenden Head Moss the bases of the gully systems were far more saturated. Rather than one channel meandering along the gully floor, the whole of the gully floor was saturated and acting as the channel. This is thought to be the result of the topography of Wessenden Head Moss (Figure 4.3), with low slope angles and therefore much of the water is stagnant rather than it draining away. Labadz (1988); however, noted a lack of water storage in Shiny Brook, Wessenden Head Moss.

In early stages of re-vegetation the growth rate is slow but as the vegetation increases the growth rate becomes more rapid. The general curve describing the slow early growth, the latter rapid rise and the final slowing down is called the logistic curve and was discussed by Thornes (1985). The theory behind the curve is that as the vegetation increases, more nutrients built up in the soil allowing for further and more widespread vegetation growth. There is, however, the possibility there will be re-working of the infilling peat and secondary erosion. This is likely where water is flowing down the system, through pipes underneath the peat on the intact peat surfaces. The lack of mineral load in water flowing over a peat mass gives recovering gully systems a low erosive capability (Radley, 1962), particularly where intact vegetation cover is present (Tallis, 1985a). Interestingly, Thornes (1985) discussed that if re-working and re-

deposition were to occur in the gully base, nutrients and seeds would also be transported and would promote further vegetation growth.

8.7   Onset of Erosion

A chronology of estimated dates of the onset of erosion and re-vegetation were produced from detail stratigraphic cross-sections from adjacent eroded and uneroded cores. Given the assumptions of the estimated 1850 'take-off' in SCP concentration a 0.3 mm yr^{-1} rate of peat accumulation suggested by Tallis (1995a) was used in the calculations. Chapter 5 discussed that peat accumulation rates can vary both in time and space and therefore these results can only be regarded as estimates for the onset of erosion without the use of a dating technique, such as Radiocarbon dating to result the results. Estimates of the onset of erosion varied with regional study area. Results from Wessenden Head Moss were comparable to previous authors research such as Tallis (1994; 1995b; 1997a; 1997b) in the Southern Pennines (570 years) (Table 8.3). Erosion appeared to have started on Wessenden Head Moss (570 years) some three centuries before Moor House (300 years) and The Cheviot (330 years); yet the Southern Pennines are still in a more eroded state than much of the North Pennines is today. This therefore highlights the importance of the duration of erosion in affecting the intensity of erosion and time for recovery.

Table 8.3 shows the timescales of the onset of peat erosion vary. Nevertheless there is a clear consensus that point towards peat erosion at a range of sites around 300 – 600 years ago (AD 1400 – 1700). Wetter and harsher conditions of the Little Ice Age (ca. AD 1500 – 1850) have been suggested to be responsible for the erosion (Rhodes and Stevenson, 1997); however, anthropogenic activity cannot be ruled out over this period since intensification of the land use occurred after about AD 1550. For those earlier estimates the irreversible desiccation of the blanket peat during the Early Mediaeval Warm Period (ca. AD 1100 – 1250) appears to be a significant factor (Tallis, 1995b, 1997). The variable times of the onset of erosion were discussed by Tallis (1998) as phases of erosion. The results from this study therefore show the gully erosion at the three study sites as the result of the latest phase of erosion.

Timescale →

	500	250	0	250	500	750	1000	1250	1500	1750	2000

B.C. | A.D.

MOORLAND EROSION

Scotland, Ireland and Wales
Peat erosion (Rhodes and Stevenson, 1997)

North Pennines and LakeDistrict
Peat Erosion (Higgitt et al., 2001)

Wessenden Head Moss
Peat erosion (Burt and Labadz, 1990)

GULLY EROSION

Wessenden Head Moss
Hagged areas (Tallis, 1981a)

Featherbed Moss
Gullying (Tallis, 1981a)

Featherbed Moss
Gullying (Tallis, 1981b)

Wessenden Head Moss
Gullying (Burt et al., 1990)

Southern Pennines
Gullying (Tallis, 1965, 1973 and Labadz et al., 1991)

Southern Pennines
Gullying (Tallis, 1994, 1995b, 1997a, 1997b)

The Cheviot
Gullying (Wishart and Warburton, 2002)

Wessenden Head Moss
Gullying (This Study)

Moor House
Gullying (This Study)

The Cheviot
Gullying (This Study)

RE-VEGETATION

Wessenden Head Moss
Re-vegetation (This Study)

North Pennines and LakeDistrict
Re-vegetation (Higgitt et al., 2001)

Moor House
Re-vegetation (This Study)

The Cheviot
Re-vegetation (This Study)

Table 8.3: Summary of estimates of the onset of peat erosion in different regions of upland Britain. The dates obtained from this research are included in red. The dashed lines represent possible erosion and solid lines, definite.

Peat erosion in the Shiny Brook catchment, Wessenden Head Moss, was estimated from long-term average organic sediment yield to the Wessenden Head Reservoir and surveying of the volume of peat drainage network to the Shiny Brook catchment. Estimates of erosion were around AD 1800 (Burt et al., 1990); however, they suggested that very rapid extension of gullying occurred since AD 1770 and the initial extension began around AD 1300. Labadz (1988) found peat erosion in the Shiny Brook catchment was variable in both time and space.

A date of AD 1450 for the development of Type 1 and Type 2 dissection from the Southern Pennines (Tallis, 1994; 1995b; 1997a; 1997b) corresponds with the estimate

of AD 1430 from this research (Table 8.3). The general dates for the onset of erosion in this research for Moor House, The Cheviot and Wessenden Head Moss, are AD 1700, 1670 and 1430, respectively. These dates correspond broadly to the Little Ice Age and appear to be reasonable estimates of the onset of erosion at the three sites. However, due to the local variability in peat accumulation rates these dates must only be treated as estimates.

Evans (1993) discussed variations between the North and Southern Pennines in the dates of the onset of erosion when he presented data from other researchers observations (Defoe, 1724 – 1726; Farey, 1811; Rhodes, 1824). He noted that Defoe (1724-1726) observed a smooth and pleasant Plain on the summit of The Cheviot in the early 18th Century, whereas now the peat is severely eroded. This may therefore indicate that the erosion on The Cheviot summit may have occurred after 1726, which is slightly later than the estimates from this research (AD 1670). In 1811 Farey discussed the lead and sulphur mills in the Peak District and the surrounding industrial towns. The *Sphagnum* spp. at this time (early 19th Century) was noted to be 'a dead and slowly decaying mass, thinly sprinkled with heaths, [and] aquatic grasses', and the peat was 'crossed in all directions by gullies'. The North Peak in 1824 was observed to have healthy *Eriophorum* spp. vegetation and had therefore changed from *Sphagnum* covered to *Eriophorum* covered, as it still is today (Rhodes, 1824).

Evans (1993) suggested that *Eriophorum* and *Calluna*, which covers much of the blanket peat moorland today, is resistant to erosion and even during a rare large storm peat headcuts in gully systems would retreat by less than 0.3 m. He therefore suggested that for gully systems to have extended rapidly the vegetation at the time of the onset of erosion probably comprised of *Sphagnum* spp., which can easily be stripped away during high flows. He suggested that incision must have taken place rapidly, capturing pools to further speed up erosion.

Evidence of the stabilisation of erosion and dates of the onset of re-vegetation in the Pennines has been discussed by Johnson and Dunham (1963), Mayfield and Pearson (1972) and Wishart and Warburton (2002). Johnson and Dunham (1963) observed re-colonisation of the blanket bog between Swath Beck and Crooked Back on the north side of Hard Hill, Moor House and Upper Teesdale NNR, as a result of a stable and waterlogged surface developing. Mayfield and Pearson (1972) observed natural

vegetation re-colonisation in the base of a number of gully systems in the Peak District and Wishart and Warburton (2002) who produced the most extensive study discussing re-vegetation within the gully systems on The Cheviot, showed re-vegetation to have occurred since the 1920s on The Cheviot through repeat photography.

This study examined re-vegetation and re-colonisation across Northern England and has shown all three study sites have evidence of re-vegetation. Based on evidence from repeat aerial photography, ground based photographs and stratigraphic sequences, it is likely that much of the infilling and re-vegetation has occurred since the early 1960s. The Cheviot and Moor House had re-vegetated the most and Wessenden Head Moss the least. On The Cheviot 61 % of the once eroded peat had re-vegetated, 80 % at Moor House and 45 % on Wessenden Head Moss. This is interesting considering the onset of erosion on Wessenden Head Moss was earlier than on The Cheviot and at Moor House. This has important implications on the causes of erosion and rates of recovery, and as stated above, is interesting in terms of the duration and intensity of erosion. In addition to the duration of erosion, it is likely that the Southern Pennines are more eroded than the North Pennines because of management practice, climate and location of the Southern Pennines (limit of peat growth).

8.8   A model of peatland gully development (Objective 8)

Figure 8.2 presents a conceptual erosion model of historical peatland gully development, interfluve stability and peat erosion in the Pennines.

The development of peatland gully systems and interfluves can be represented in a conceptual erosion model (Figure 8.2). The model was produced based on the results calculated for the onset of erosion; the known climatic and anthropogenic influences; and from aerial and ground-based photographic evidence. On the interfluve areas entrainment and re-deposition of sediment occurs during storm events but unless vegetation destruction occurs, no significant changes occur. Following vegetation destruction, gully initiation, extension, through to infilling and re-vegetation is shown. The extension of the gully (headward erosion) is thought to take place over a relatively short time period followed by a longer period of expansion in cross-sectional form (widening of the gully system through erosion of the gully walls).

TIMESCALE
(years)

PROCESSES

CAUSES

200 - 600

Undisturbed Blanket Peat Moorland

Onset of Erosion following Vegetation Destruction

Gully Initiation

Headward Recession into the Intact Peat

Gully Extension

Vertical Erosion

Erosion to the Peat Base or Stable Peat

Lateral Erosion

Gully Expansion and Reduction in Stream Power

Infilling of the Gully Base by Wash,
Redeposition and Vegetation Recolonisation

Continued Re-vegetation
Stability?

Localised Erosion, Re-Working
and Re-deposition

Recovery of the Gully System
Loss of channel
System Resembles a Flush

Undisturbed Blanket Peat Moorland

Localised re-deposition of peat

Undisturbed Blanket Peat Moorland

Gully Expansion

Change in the hydrological balance
of the blanket peat and erosion continues

Climate Change
(Little Ice Age)

Land management
(Intensification of Agriculture)

Climate Change
(Improved)

Industrial Pollution

Climate Change
(Minor Optimum)

Land Management
(Concern for Moorlands - Restoration)

Climate Change
(Warming)

50 - 100

Present

Future

Figure 8.2: Conceptual erosion model of historical peatland gully development, interfluve stability and peat erosion in the Pennines.

Where infilling of the system by sediment and initial re-colonisation of vegetation occurs the process is thought to be rapid (20 years) and is likely to occur over relatively short time scales with temporary stability followed by re-working during storm events or as the active channel shifts (Wishart and Warburton, 2002). The later re-vegetation (after the gully system has infilled substantially and is no longer being re-worked) is likely to take place over a longer timescale. The timescale of erosion and re-vegetation has been estimated from the data obtained in this study. The variation in timing is a result of the variability in the dates of the onset of erosion and possible re-vegetation between the three study sites.

The three study sites in this study showed recovery by infilling and re-vegetation occurring in the bases of the gully systems. In gully systems such as those on Burnt Hill, Moor House, the gully system is in the later stages of recovery and re-deposition only occurs locally within the gully system. Infilling therefore is now occurring due to decaying vegetation and peat accumulation and therefore rates of infill are slower than they may have been some 40-years ago. The estimated time of recovery for such gully systems therefore is thought to be over the next 300 – 600 years. The gully systems present today will never completely disappear, but are likely to become less active, increasingly decoupled from the upland streams and resemble a flush. In the Southern Pennines, however, areas of erosion (e.g. Bleaklow and Kinder Plateau) are more advanced than on Wessenden Head Moss. The hydrological balance of these areas has been completely altered due to continued expansion of the gully systems; the peat has been totally stripped and the peatland will never recover.

Where recovery of the gully systems is occurring there are large implications for the sediment budget. It is expected that there will be a continued de-coupling of the gully systems from the streams, which will lead to a decrease in the amount of organic matter in streams and channels, affecting water colour and reservoir sedimentation.

This study has shown that natural re-vegetation of the gully systems in Northern England has occurred over the last approximate 50 years and seem likely to continue to do so in the future under similar a similar climate and land management practices. Whether recovery of the upland blanket peatlands occurs through natural re-vegetation or is enhanced through conservation management, the future stability of upland blanket peat is important.

Present research in upland UK has indicated that the climate is warming (Holden and Adamson, 2001; Holden, 2002). There is a growing consensus that increasing amounts of carbon dioxide and other greenhouse gases (e.g. methane and nitrous oxide) in the atmosphere will lead to an incremental increase in average temperature of 3° C by the year 2100 (Parry *et al.*, 1988). Along with this there may be in increase in extreme events, such as that on 30th July 2002 where erosion tends to take place rapidly and over a short time period and an increase in the risk of fire. Heathwaite (1993) and Evans *et al.* (1999) both discuss how climate change scenarios predicting increases in winter precipitation and increased seasonality could lead to increased erosion and de-stabilisation of blanket peat.

This study has shown the position within the gully system to be important in terms of the growth of vegetation; locally, the most re-vegetation occurred towards the gully entrance and regionally at Moor House and on The Cheviot. Great increases in temperature may have dramatic effects on vegetation cover type and density, especially in those areas that are already well drained, e.g. in areas of linear dissection where re-vegetation is generally greatest. Blanket bog may be replaced by grassland species, which can cope in drier weather conditions, e.g. blanket peat typically grows in upland areas with rainfall > 1200 mm yr^{-1}, whereas grassland species can be found in lowland, drier regions of Britain. This study has shown that, although vegetation type had an impact on runoff production and sediment yield, further erosion seemed unlikely because detachment and re-deposition occurred locally, therefore further re-vegetation will continue will occur in those areas already showing signs of recovery. Areas of greatest concern for the future are those such as Bleaklow and Kinder Plateau, which are stripped of peat or have large areas of exposed bare peat.

8.9   Historical Sediment Budget

Figure 8.3 presents a conceptual historical sediment budget for Pennine peatlands. The historical sediment budget is interesting in terms of the linkages between the erosional processes and storage elements linked to the wider peatland system, e.g. peat loss from the interfluve areas, infill in the gully bases and the output to upland streams and reservoirs.

1958

2004

☐ Processes   ◯ Storage elements
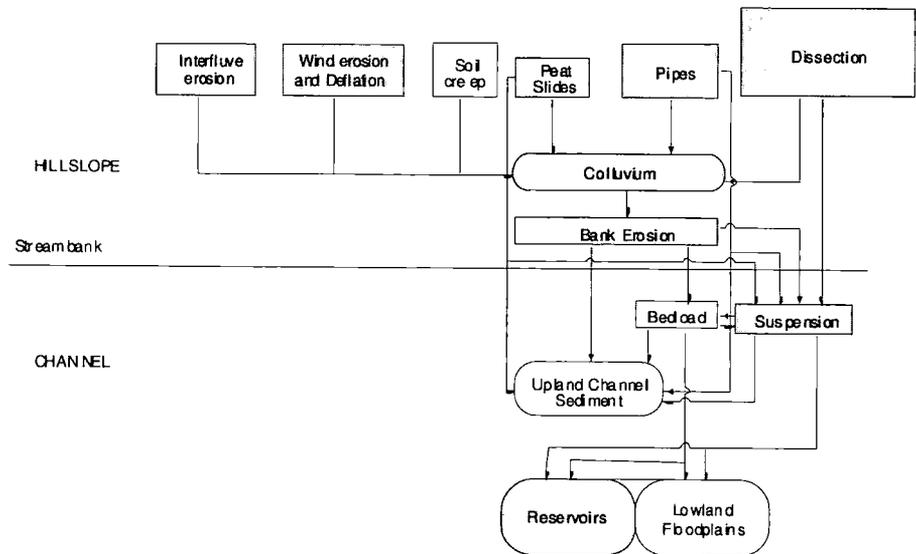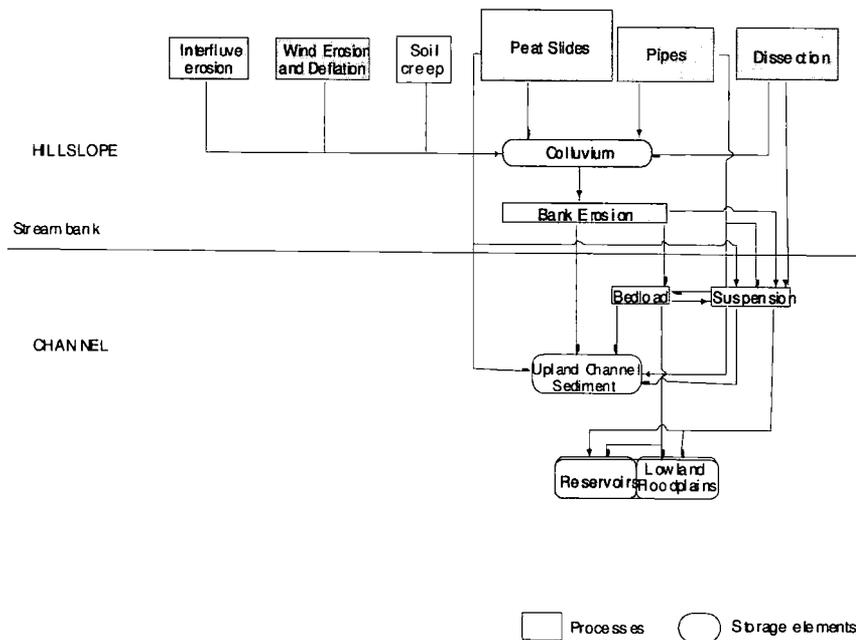
Figure 8.3: Conceptual historical sediment budget for the Pennines. The shaded boxes highlight the components of the sediment budget, which tend to dominated by organic detritus or peat (Adapted from Figure 2.1 and Warburton, 1998).

The sizes of the boxes represent the volume of sediment removed and therefore Figure 8.3 generally shows an overall reduction in the amount of sediment removed from the hillslopes between 1958 and 2004; resulting in a decline in material entering the stream channels and being deposited in the reservoirs and on lowland floodplains. There is a demonstrable reduction in the amount of sediment lost from gully systems from 1958 – 2004, which is thought to be the result of infilling and re-vegetation of gully floors. The establishment of vegetation traps further sediment and results in local movement and re-deposition of sediment within the gully rather than removal from the system. The same principles relate to interfluve erosion because the intact vegetation cover traps the sediment preventing it from being removed from the hillslope. In addition the observed reduction in bare peat area has led to a reduction in sediment supply from wind deflation and splash.

However, there has been an increase in the number of reported peat mass movements over the last approximate 50 years (Mills *et al.*, 2002) an trend which has continued with several recent events such as the Dooncarton landslides, Co. Mayo, Ireland; Peatslides on the Shetland Isles; and landslides/ peatslides in the Lake District and North Yorkshire Moors, in the last 3 years. Despite this contribution over the last approximate 50 years there has been a net overall decrease in the amount of sediment entering the stream channels (sediment is remaining on the hillslopes). Increases in the extent of vegetation cover and the de-coupling of gully systems from stream channels over this time period have been directly observed (Table 4.5). The reduction of sediment entering the stream channels has important implications for bank erosion, a reduction in bedload, and of particular importance in upland areas, a reduction in suspended sediment concentration. The effects of this is reduced sediment supply downstream and lower amounts of sediment entering storage in reservoirs and lowland floodplains and a reduction in water colour, which is problematic in eroding peatland areas. Therefore the increase in vegetation cover in the uplands, which prevents sediment entering channels is of great importance to water managers lower down the catchment.

As suggested above climatic change adds to the uncertainty of the upland peatland sediment budget. Fluctuations in temperature and rainfall will induce dramatic changes in vegetation cover. This will be interesting in terms of the future impacts on peatland sediment supply (the prognosis is falling yields). However, potentially more frequent

storm events brought about by climatic change may cause the mass mobilisation of the sediment that remains on the hillslopes, greatly enhancing sediment delivery to stream channels (at least on a local scale).

9.0 CONCLUSION

9.1 Major Findings

The major findings of this research can be divided into two main categories: upland blanket peat gully development and interfluve erosion potential.

(1) The Revised Classification Scheme

Past literature on peatland gully patterns has been dominated by the research of Bower (1959; 1960a; 1960b; 1961; 1962). The Type 1 and Type 2 classification scheme of dissection has been widely used. Mosely (1972) carried out quantitative study to assess the usefulness of Bower's classification scheme and concluded whilst end members could be observed a continuum of forms was more representative. The present study agrees with Mosley (1972) and adopted a revised classification of gully types used by Wishart and Warburton (2002) in The Cheviot Hills. This classification scheme covered a greater range of types (Linear, Dendritic and Anastomosing Dissection). Dendritic dissection appeared represent the continuum of form between both anastomosing (typically Type 1) and linear (typically Type 2) dissection (Figure 4.1).

(2) The Extent and Patterns of Erosion

The extent and patterns of erosion were assessed at three regional study sites. The total cover of blanket peat was found to be greatest on Wessenden Head Moss (75 %), followed by Moor House (69 %) and then The Cheviot (48 %) and the greatest extent of erosion was observed on The Cheviot (80 %), followed by Wessenden Head Moss (64 %) and then Moor House (48 %). The local topography of the study areas was important in conditioning the extent and patterns of erosion (Figure 4.3). Linear dissection was also found to be most extensive at Moor House (58 %), followed by Wessenden Head Moss (37.5 %) and not so important on The Cheviot (21 %).

(3) Infilling and Re-vegetation

Infilling of the gully systems and re-vegetation was shown to have occurred at all three study sites over the last approximate 50-year time period, though at different rates.

335

Gully systems were most re-vegetated towards the gully entrance. This is thought to be the result in increased drainage, nutrient supply and vegetation encroachment. The least re-vegetation had occurred on Wessenden Head Moss and was thought to be because of a number of factors: topography; the climate-pollution gradient across the British Isles and loss of *Sphagnum* (an early colonising species) in the Southern Pennines; greater peat depth leading to inherent instability; greater grazing intensities; and increased visitor pressures. Infilling and re-vegetation of the gully systems is likely to continue, with the exception of severely eroded areas where the peat is totally stripped and surface hydrological regime destroyed, the peat will not recover, e.g. Bleaklow and Kinder Plateau.

(4)   Rates of Peat Accumulation

SCP deposition varied both locally (small plot) and regionally. The SCP deposition was greatest on Wessenden Head Moss and least on The Cheviot, fitting nearly with the pollution gradient across the Pennines. Rates of peat accumulation varied from 0.4 – 1.2 mm yr^{-1} based on an assumed 1850 'take-off' in SCP deposition. This was argued on the basis of peat accumulation rate being too high for upland blanket peat based on a 1950 'take-off' (1.1 – 3.3 mm yr^{-1}).

(5)   Runoff Production

Rainfall simulation experiments showed runoff production and sediment yield varied with vegetation cover type and management practice. Runoff rates from moorland grass (4.54 mm hr^{-1}) were less than from heather moorland (6.25 mm hr^{-1}). Bare peat gave the highest rates of runoff (10.87 mm hr^{-1}). Results tended to show the percentages of the runoff and infiltration rates to be comparable with Holden and Burt (2002b). Grazing pressure showed to affect the vegetation cover, soil type and runoff production (e.g. Knock Fell). Runoff decreased rapidly with depth and most the runoff production was observed within the top 5 cm of the peat stratigraphy.

(6)   Sediment Yield

Sediment yield decreased during the experiments due to sediment exhaustion occurring from the plot; however, sediment production occurred at high rainfall intensities (e.g. 24

mm hr^{-1}). Comparing the sediment loss on managed land, the results showed both grazing and burning little effect on sediment yield. The sediment loss from moorland grass was greater than the heather though these results may have been influenced by burning, where sediment concentrations were relatively low (45.6 mg l^{-1}) (Table 6.4). Although the loss of peat from the interfluves is generally relatively high, it is not likely that the peat is removed from the area; it is re-deposited further downslope (e.g. Figure 2.14).

(7)   Estimates of the Onset of Erosion

Local scale variations in gully development again demonstrated topography was an important factor determining gully patterns. Infilling and re-vegetation had occurred within the gully systems at the three study sites, though at varying rates. The estimated onset of erosion occurred earliest on Wessenden Head Moss (570 years ago), though the recovery is lowest. Despite there being no dating techniques used to test the estimate of the onset of erosion from this study the results were found to be comparable with other estimates (Table 8.3). Figures 4.11, 7.28 and 7.29 showed the patterns of infilling within the gully bases and Figures 4.12 and 4.13 showed patterns of re-vegetation. These patterns were replicated throughout the study areas.

(8)   The Conceptual Model of Gully Development

A conceptual erosion model of gully development and interfluves was presented in Figure 8.2 based on the findings from this study. Over time, vegetation destruction leads to gully initiation, followed by extension, through to eventual infilling and re-vegetation. The extension of the gully (headward erosion) is thought to take place over a relatively short time period followed by a longer period of expansion (widening of the gully system through erosion of the gully walls). This was observed to be the pattern for the three study areas in this study; however, as also shown in Figure 8.3 recovery of the gully systems is not always the endpoint. For example areas such as Bleaklow and Kinder are severely eroded areas and irrecoverable. Over the same time period the interfluves show some entrainment and re-deposition of sediment during storm events or by wind action but no significant erosion occurs.

(9) Conceptual Historical Sediment Budget

A conceptual historical sediment budget was presented in Figure 8.3 based on the findings from this study. An overall reduction in the amount of sediment removed from the hillslopes between 1958 and 2004 was observed; resulting in a net decrease in the amount of sediment entering the stream channels and being deposited in the reservoirs and on lowland floodplains. Climatic change; however, adds uncertainty to the future of upland blanket peatland sediment budgets; and may result in changes in vegetation cover and storm frequency.

9.2   Methodological Critique

In any field-based study there is always a limitation of the number of sites which can be studied in the time frame of the investigation. Inevitably this results in incomplete sampling of the full range of erosion types and in response a nested sampling strategy was adopted in this study. While this yielded useful results there are some methodological improvements, which can be suggested for future studies.

To assess the regional scale variations in gully development digital elevation models from the three study sites at an accuracy of 2 m would have allowed a more sophisticated analysis of the linkages between gully patterns and slope. The accuracy of the DEM is important for this study (Table 7.1), where the average angle over significant breaks in slope varied from $0.9°$ – $7.0°$ and therefore with a 10 m DEM such variations could be missed. With the LiDAR data for the Southern Pennines, where a 2 m DEM is now available, the opportunities for this research in the future is increasing and would be interesting for developing this study.

Objective 2 of this study examined regional variations in extending gully systems across the Pennines from SW to NE (The Cheviot Hills, North Pennines and Southern Pennines) and compared the different patterns of erosion and regeneration that were present. Regional comparisons were made from the three study sites; however, the area of Wessenden Head Moss is an area that is less eroded than other areas in the Southern Pennines, e.g. Bleaklow and Kinder. This area is an area recovering from erosion (although it is at a slower rate than The Cheviot and Moor House) and is suggested to be at the natural end point of recovery for gully systems. Bleaklow and Kinder for

338

example, where the peat has been totally stripped and the hydrological balance of the landscape changed completely, are areas that are likely to be unrecoverable.

The number of gully systems sampled for the detailed assessment of the local scale variations in gully development were twelve at Moor House, three on The Cheviot and three on Wessenden Head Moss. The risk of choosing only three gully systems on The Cheviot and Wessenden Head Moss raises the possibility of failing to investigate the full range of systems; however, the GIS was used to allow the most representative gully systems from each study area to be selected. A nested approach was chosen for this study because time is the most limiting factor to sampling. Following the analysis of the twelve systems at Moor House similar patterns were emerging. For example, gully lengths, widths and slope angles (Table 7.1) and patterns of gully infill (Figure 7.28 and 7.29) although some local variations needed to be accounted for (Figure 7.4).

The use of SCPs in this study showed significant variations in the 'take-off' over the micro-plot scale. The major finding from this was that due to the rates of peat accumulation, an assumed 1850 'take-off' is thought to be more appropriate than the 1950 'take-off'. SCPs are time markers and therefore obtaining dates from a chronology such as bomb carbon would have enabled this to be tested.

In terms of the rainfall simulation experiments, replication of the results under different antecedent conditions and spatial replicates within the plots would have tested the significance of the runoff rates under different natural conditions.

9.3   Suggestions for Future Research

The scope for future work on peatland gully systems and on the interfluve areas is still considerable:

(1)   There is scope for looking at other regions, for example the Shetlands, Ireland, Bleaklow and Kinder. It would be interesting to investigate the changes, which have occurred on areas such as Bleaklow and Kinder over the similar period of this study and assess the hydrological balance of landscape change, which would be possible to state a natural endpoint.

339

(2)   A detailed DEM would allow the slope and erosion type theory to be tested. This would be an important extension to this research. In addition, there is scope for undertaking a simple laboratory model to establish the threshold in gully patterns. This would require the testing of slope angles and peat depths in relation to gully patterns.

(3)   There is scope for modelling the development of gully systems. A model would be used to predict the future stability of upland blanket peat and in particular the timescales of recovery. Looking at the three study sites there is an obvious sequence in space as a substitute for time (ergodic hypothesis). Wessenden Head Moss is currently in a stage of recovery, which Moor House was in the 1960s and 1970s. The Cheviot is likely to be only some 10 years behind Moor House and therefore in 40 years and 10 years, Wessenden Head Moss and The Cheviot may be in the same recovery stages as Moor House. This is, however, dependent on the local controls, future land management practices and climatic influences of the areas. This could be tested.

(4)   There is the scope for further development of a sediment budget framework using measured rates of erosion from the 1950s to present. Contemporary sediment budgets are well developed (Evans and Warburton, 2005); however, historical budgets are not. Historical sediment budgets are interesting in terms of the peat loss from the interfluve areas, infill in the gully bases and the output to upland streams and reservoirs. This study has started this and has highlighted that little change would be shown to occur on the interfluves, re-adjustment and re-deposition of peat followed by re-vegetation in the gully systems will show a gradual decrease in sediment loss from the uplands from the 1950s to present (Figure 8.3).

(5)   This study requires clarification of 'take-off' in SCP deposition at 1850, in order to do this a dating control is required. This requires the dating for more recent peats (last hundred or so years). Examples of possible chronologies can be gained from ^{210}Pb or other radionucliedes (^{241}Am and ^{137}Cs) to date peat up to 200 years and the last 50 years, respectively, ^{241}Am and ^{137}Cs are from post-1954 weapons testing and have increased atmospheric levels of ^{14}C dramatically, therefore can be used to date peats in the last 50 years, and also bomb carbon

dating from the last 50 years. This would therefore show up in the SCP profiles with the 1950 'take-off' (Charman, 2002).

(6)   Dates for the onset of erosion have been suggested for many years (Tallis, 1985b) and speculations made of the onset of re-vegetation (Wishart and Warburton, 2002). In order to confirm the dates of the onset of erosion and re-vegetation the use of a reliable chronology is needed alongside these results. There are a number of dating techniques that could be potentially used and would provide exact dates from which further sedimentation rates could be studied in detail and from which we could build upon given today's technology. Radiocarbon dating (^{14}C) is the most common technique used in peat and is suggested for dating the onset of erosion from these cores.

(7)   The gully systems on upland blanket peat are continually developing. In years to come (20 – 50 years) it would be interesting to see whether infill and re-vegetation continue. This will include re-photographing those photographs from this work. This would be an important and ongoing study given the changes in legislation (e.g. CAP Reform), importance or conservation of these areas at this time and predicted climatic changes. Over a shorter timescale the changes in vegetation type and extent should be mapped 5 years in order to observe such changes, for example, the changes in the extent of vegetation cover has proved interesting on Moss Flats over that last few years since the outbreak of Foot and Mouth Disease in 2001.

(8)   Replicates of the rainfall simulation experiments ought to be conducted at similar and different times of the year to see how the natural rainfall affects the results. This would provide invaluable data as to how runoff and sediment production will be affected on upland blanket peatlands if future climatic predictions are true. In addition, it would be interesting using a number of different blocks with varying degrees of grazing pressure and burn intensities would provide invaluable data for land management practice in the future. By combining a hydrological model (e.g. TOPMODEL) and a sediment transport model this would improve the findings of this research and allow the prediction of runoff and sediment production to be gained for other sites.

REFERENCES

Aaby, B. (1976). "Cyclic climatic variations in climate over the past 5500 years reflected in raised bogs." Nature 265: 281-284.

Aaby, B. (1986). Sampling techniques for lakes and bogs. Handbook of Holocene Palaeoecology and Palaeohydrology. Berglund, B. E. (ed.), John Wiley and Sons Ltd.: 181-194.

Adamson, J. K. (2002). "ECN Terrestrial Sites: Moor House and Upper Teesdale, Cumbria and Durham." [Online], Available: http://www.ecn.ac.uk/sites/moorh.html, [19th April 2002].

Adamson, J. K. (2004). Research at Moor House - Upper Teesdale National Nature Reserve. ESRC Seminar Series - Sustaining Mountain Landscapes: conflict and compromise in the British Uplands, Northern Pennines landscape instability and environmental change. University of Durham.

Adamson, J. K. and Karl, J. (2003). Changes in vegetation at Moor House within sheep exclosure plots established between 1953 and 1972, Environmenal Change Network Report to English Nature.

Adamson, J. K., Rowland, A. P., Scott, W. A. and Hornung, M. (1996). "Changes in soil acidity and related variables over 25 years in the North Pennine Uplands, UK." Soil Use and Management 12: 55-61.

Allaby, M. (1983). The Changing Uplands. Cheltenham, Countryside Commission.
Anderson, P. and Radford, E. (1994). "Changes in vegetation following reduction in grazing pressure on the National Trust's Kinder Estate, Peak District, Derbyshire, England." Biological Conservation 69: 55-63.

Anderson, P. and Tallis, J. H. (1981). The nature and extent of soil and peat erosion in the Peak District. Peak District Moorland Erosion Study, Phase 1 Report. Phillips, J. Yalden, D. and Tallis, J. H. (eds.), Derbyshire, Peak District Joint Planning Board, Bakewell: 52-64.

Anderson, P., Tallis, J. H. and Yalden, D.W. (1996). Restoring Moorland: Peak District National Park Management Project, Phase III Report. Derbyshire, Peak District Joint Planning Board, Bakewell.

Archer, D. and D. Stewart (1995). "The installation and use of a snow pillow to monitoer snow water equivalent." Journal of the Chartered Institution of Water and Environmental Management 9: 221-230.

Atherden, M. (1992). Upland Britain: A natural history. Manchester, Manchester University Press.

Averis, A., Averis, B., Birks, J., Horsfield, D., Thompson, D. and Yeo, M. (2004). An Illustrated Guide to British Upland Vegetation, Joint Nature Conservation Committee.

Ball, D. F., Dale, J., Sheail, J. and Heal, O. W. (1982). Vegetation change in upland landscapes. Cambridge, Natural Environment Research Council, Institute of Terrestrial Ecology: 1-45.

Ballantyne, C. K. (1991). "Late Holocene erosion in upland Britain: climatic deterioration or human influence?" Holocene 1: 81-85.

Barber, K. E. (1981). Peat stratigraphy and climatic change: a palaeoecological test of the theory of cyclic peat bog regeneration. Rotterdam, A. A. Balkema.

Barber, K. E., Battarbee, R. W., Brooks, S. J., Eglinton, G., Stevenson, A. C., Thompsom, R., Appleby, P. G., Austin, W. E. N., Cameron, N. G., Ficken, K. J., Golding, P., Harkness, D. D., Holmes, J. A., Hutchinson, R., Lishman, J. P., Maddy, D., Pinder, L. C. V., Rose, N. L. and Stoneman, R. E. (1999). "Proxy records of climate change in the UK over the last two millennia: documented

change and sedimentary records from lakes and bogs." Journal of the Geological Society 156: 369-380.

Bardgett, R. D., Marsden, J. H., Howard, D. C. and Hossell, J. E. (1995). The Extent and Condition of Heather in Moorland, and the Potential Impact of Climate Change. Heaths and Moorland: Cultural Landscapes. Thompson, D. B. A., Hester, A. L. and Usher, M. B. (eds.), Edinburgh: 43-50.

Barnes, F. A. (1963). "Peat Erosion in the southern Pennies: problems of interpretation." East Midland Geographer 3(4): 215-222.

Batterbee, R. (2004). The Future of Britain's Upland Waters: Introduction. Delegates of 'The Future of Britain's Upland Waters'. London.

Berglund, B. E. (1986). Handbook of Holocene Palaeoecology and Palaeohydrology, John Wiley & Sons Ltd.

Birnie, R. V. (1993). "Erosion rates on bare peat surfaces in Shetland." Scottish Geographical Magazine 109(1): 12-17.

Blackford, J. J. and Chambers, F. M. (1995). "Proxy records for climate from blanket mires: evidence for a Dark Age (1400 BP) climatic deterioration in the British Isles." The Holocene 1: 63-67.

Boelter, D. H. (1965). "Hydraulic conductivity of peats." Soil Science 100(4): 227-231.

Bol, R. A., Harkness, D. D., Huang, Y. and Howard, D. M. (1999). "The influence of soil processes on carbon isotope distribution and turnover in the British uplands." European Journal of Soil Science 50: 41-51.

Bower, M. M. (1959). A summary of available evidence and a further investigation of the causes, methods and results of erosion in blanket peat, Unpublished M.Sc. Thesis.

Bower, M. M. (1960a). "Peat erosion in the Pennines." Advancement of Science 64: 323-331.

Bower, M. M. (1960b). "The erosion of blanket peat in the southern Pennines." East Midland Geographer 2(13): 22-33.

Bower, M. (1961). "The distribution of erosion in blanket peat bogs in the Pennines." Transactions of the Institute of British Geographers 29: 17-30.

Bower, M. M. (1962). "The cause of erosion in blanket peat bogs: A review of evidence in light of recent work in the Pennines." Scottish Geographical Magazine 78: 33-43.

Bowyer- Bower, T. A. S. and Burt, T. P. (1989). "Rainfall simulators for investigating soil response to rainfall." Soil Technology 2: 1-16.

Bragg, O. M. (1982). The Acrotelm of Dun Moss: Plants, Water and Their Relationships. Dundee, University of Dundee.

Bragg, O. M. (1995). Towards the ecohydrological basis for raised mire restoration. Restoration of Temperate Wetlands. Wheeler, B. D., Shaw, S. C., Fojten, W. J. and Robertson, R. A. (eds.), Chichester, John Wiley & Sons: 305-314.

Bragg, O. M. and Tallis, J. H. (2001). "The sensitivity of peat-covered upland landscapes." Catena 42(2-4): 345-360.

Brand, E. W. and Premchitt, J. (1982). "Response times of cylindrical piezometers." Geotechnique 32: 203-216.

Buckham, A. F. and Cockfield, W. F. (1950). "Gullies formed by sinking of the ground." American Journal of Science 278: 137-141.

Burt, T. P. (1996). The hydrology of headwater catchments. River Flows and Channel Forms. Petts, G. E. and Calow, P. (eds.), Oxford, Blackwell: 6-31.

Burt, T. P. and Gardiner, A. T. (1984). Runoff and sediment production in a small peat-covered catchment: some preliminary results. Catchment experiments in fluvial geomorphology. Proc. IGU Commission meeting, Exeter and Huddersfield, 1981. Burt, T. P. (ed.), Norwich, Geo Books: 133-151.

Burt, T. P. and Labadz, J. (1990). "Blanket peat erosion in the southern Pennines." Geography Review 3(4): 31-35.

Burt, T. P. and Oldman, J. C. (1986). "The performance of stream networks in Britain: Further comments." Earth Surface Processes and Landforms 11: 111-113.

Burt, T. P. and Slattery, M. C. (1996). Time-Dependent Changes in Soil Properties and Surface Runoff Generation. Advances in Hillslope Processes: Volume 1. Anderson, M. G. and Brooks, S. M. (eds.), Chichester, John Wiley and Sons Ltd.:79-95.

Burt, T. P., Evans, M. G. and Warburton, J. (1998). Contemporary runoff and erosion in blanket peat catchments on the Moor House National Nature Reserve. Geomorphological Studies in the North Pennines: Field Guide. Warburton, J. (ed.), British Geomorphological Research Group.

Burt, T. P., Heathwaite, A. L. and Labadz, J. C. (1990). Runoff production in peat covered catchments. Process studies in hillslope hydrology. Anderson, M. G. and Burt, T. P. (eds.), Chichester, Wiley: 463-500.

Carling, P. A. (1986a). "The Noon Hill flash floods; July 17th 1983. Hydrological and geomorphological aspects of a major formative event in an upland landscape." Transactions of the Institute of British Geographers 11: 105-118.

Carling, P. A. (1986b). "Peat slides in Teesdale and Weardale, Northern Pennines, July 1983: description and failure mechanisms." Earth Surface Processes & Landforms 11: 193-206.

Carruthers, D. J., Burnett, G. A. and Anderson, W. (1932). The geology of the Cheviot Hills (3 and 5). Memoirs of the Geological Survey. London, His Majesty's Stationery Office.

Chambers, C. (1978). "A radiocarbon-dated pollen diagram from valley bog, on the Moor House National Nature Reserve." New Phytologist 80: 273-280.

Charman, D. (2002). Peatlands and Environmental Change. Chichester, John Wiley and Sons Ltd.

Clement, S. (2001a). Recent history and regeneration of an upland gully system at Moor House National Nature Reserve, North Pennines. Unpublished M.Sc. Thesis, Department of Geography, University of Durham, Durham: 104.

Clement, S. (2001b). GPS mapping of an eroded peat flat, Moor House National Nature Reserve, North Pennines. Unpublished Module Report, Department of Geography, University of Durham, Durham: 31.

Clymo, R. S. (1983). Peat. Mires: Swamp, Bog Fen and Moor. Gore, A. J. P. (ed.), Amsterdam, Elsevier: 159-224.

Clymo, R. S. (1984). "The limits of peat bog growth." Philosophical Transactions of the Royal Society of London Series B303: 605-654.

Clymo, R. S. (1991). Peat Growth. Quaternary Landscapes. Shane, L. K. C. and Cushing, E. J. (eds.), London, Belhaven Press: 76-112.

Clymo, R. S. and Mackay, A. W. (1987) "Upwash and downwash of pollen and spores in the unsaturated surface layer of Sphagnum-dominated peat." New Phytologist 105: 175

Common, R. (1954). "The Geomorphology of the East Cheviot Area." The Scottish Geographical Magazine 70(3): 124-138.

Conway, V. M. (1954). "The stratigraphy and pollen analysis of southern Pennine blanket peats." Journal of Ecology 42: 117-147.

Conway, V. M. and Millar, A. (1960). "The hydrology of small peat-covered catchments in the northern Pennines." Journal of the Institute of Water Engineers 14: 415-424.

Crisp, D. T. (1966). "Input and output of minerals for an area of Pennine moorland: The importance of precipitation, drainage, peat erosion and animals." Journal of Applied Ecology 3: 327-347.

Crisp, D. T. and Robson, S. (1979). "Some effects of discharge upon the transport of animals and peat in a North Pennine headstream." Journal of Applied Ecology 16: 721-736.

Davies, P., Loxham, J. and Huggon, G. (1996). Repairing upland path erosion: A best practice guide, Lake District National Park Authority, The National Trust and English Nature (supported by the Countryside Commission and the British Upland Footpath Trust).

Dean, C. (2004). Restoring moorlands in the Peak District National Park, Moor For The Future Partnership. 2004.

Defoe, D. (1724-26; repr 1927). A Tour Thro' the Whole Island of Great Britain, Volumes 1 and 2. London, Davies.

Dixon, D. D. (1903). Upper Coguetdale, Northumberland: Its History, Traditions, Folklore and Scenery. Newcastle, Graham, F.

Duley, F. L. and Hayes, O. E. (1932). "The effect of the degree of slope on runoff and soil erosion." Journal of Agricultural Research 45: 349.

Dunne, T. and Black, R. D. (1970). "An experimental investigation of runoff predication in permeable soils." Water Resources Research 6(2): 478-490.

Egglesmann, R., Heathwaite, A. L., Grosse-Braukmann, G., Kuster, E., Naucke, W., Schuch, M. and Schweickle, V. (1993). Physical processes and properties of mires. Mires: Process, Exploitation and Conservation. Heathwaite, A. L. and Gottlich, Kh. (eds.), Chichester, Wiley: 171-262.

Ellis, C. J. and Tallis, J. H. (2001). "Climatic control of peat erosion in a North Wales blanket mire." New Phytologist 152(2): 313-324.

Emmett, B. and Ferrier, B. (2004). Land-use changes in upland catchments and effects of upland waters. Presentation to delegates of 'The Future of Britain's Upland Waters' Conference, 21st April 2004, London.

English Nature (2001a). State of Nature: The upland challenge. Peterborough, External Relations Team, English Nature.

English Nature (2001b). Time for a new way forward? English Nature Magazine. The Upland Challenge, 55, May.

English Nature (2003). Tremendous response received in the North East. The Northern Echo: Ecological. Darlington: 12.

English Nature (2004). Farmers get more money for sheep grazing scheme. Darlington and Stockton Times: 19.

Environment Agency (1998). The Impact of Grazing and Upland Management on Erosion and Runoff: Additional Information. Research and Development Record P2/035/9, Environment Agency Publishing Organisation.

Evans, M. G. and Burt, T. P. (1998). Contemporary erosion in the Rough Sike Catchment, Moor House National Nature Reserve, North Pennines. Geomorphological studies in the North Pennines: Field Guide. Warburton, J. (ed.), British Geomorphological Research Group.

Evans, M. G. and Burt, T. P. (In Press) Erosional processes and sediment transport in upland rivers. Sediment Cascades.

Evans, M. G. and Warburton, J. (2001). "Transport and dispersal of organic debris (Peat blocks) in upland fluvial systems." Earth Surface Processes and Landforms 26(10): 1087-1102.

Evans, M. G. and Warburton, J. (2005). "Sediment budget for an eroding peat-moorland catchment in northern England." Earth Surface Processes & Landforms 30(5): 557-577

Evans, M. G., Burt, T. P., Holden, J. and Adamson, J. K. (1999). "Runoff generation and water table fluctuations in blanket peat: evidence from UK data spanning the dry summer of 1995." Journal of Hydrology 221(3-4): 141-160.

Evans, R. (1993). Sensitivity of the British landscape to erosion. Landscape sensitivity. Thomas, D. S. G. and Allison, R. J., Chichester, John Wiley and Sons Ltd.

Evans, R. (1997a). "Accelerated soil erosion in Britain." Geography 82(2): 149-162.

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

Farey, J. (1811). A General View of the Agriculture and Minerals of Derbyshire. London, MacMillan.

Ferguson, P. and Lee, J. A. (1983). "Past and present sulphur pollution in the southern Pennines." Atmospheric Environment 17: 1131-1137.

Fielding, A. H. and Haworth, P. F. (1999). Upland Habitats. London, Routledge.

Foster, D. R., Wright, H. E. Jr., Thelaus, M. and King, D. A. (1988). "Bog development and landform dynamics in central Sweden and south-eastern Labrador, Canada." Journal of Ecology 76: 1164-1185.

Foster, I. D. L., Fullen, M. A., Brandsma, R. T. and Chapman, A. S. (2000). "Drip-screen rainfall simulators for hydo- and pedo-geomorhological research: The coventry experience." Earth Surface Processes and Landforms 25(Special Issue): 691-707.

Francis, I. S. (1990). "Blanket peat erosion in a mid-Wales catchment during two drought years." Earth Surface Processes and Landforms 15: 445-456.

Fullen, M. A. (1983). "Some changes in air temperature and wind velocity after buring of heather (*Calluna vulgaris*) moorland and their relation to moorland surface processes." Naturalist 108: 17-24.

Gardiner, A. T. (1983). Runoff and erosional processes in a peat-moorland catchment. Unpublished Thesis, Department of Geography. Huddersfield, Huddersfield Polytechnic.

Gardner, S. M., Liepert, C. and Rees, S. (1993). "Managing Heather Moorland: Impacts of Burning and Cutting on Calluna Regeneration." Journal of Environmental Planning and Management 36(3): 283-293.

Garnett, M. H. (1998). Carbon storage in Pennine moorland and response to change. Geography. Newcastle, University of Newcastle.

Garnett, M. H. and Adamson, J. K. (1997). Blanket mire monitoring and research at Moor House National Nature Reserve (Poster display). Blanket Mire Degradation: Causes, consequences and challenges, University of Manchester, Mires Research Group.

Garnett, M. H. and Stephenson, A. C. (2004) "Testing the use of bomb radiocarbon to date the surface layers of blanket peat. " Radiocarbon 46 (2): 841-851.

Garnett, M. H., Ineson, P. and Adamson, J. K. (1997). "A long-term upland temperature record: No evidence for recent warming." Weather 52: 342-351.

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

Gerits, J. J. P., De Lima, J. L. M. P. and Van den Broek, T. M. W. (1990). Overland flow and erosion. Process Studies in Hillslope Hydrology. Anderson, M. G. and Burt, T. P., Chichester, John Wiley and Sons Ltd.: 173-113.

Gilman, K. and Newson, M. D. (1980). Soil Pipes and Pipeflow; a Hydrological Study in Upland Wales. Norwich, Geobooks.

Gimingham, C. H. (1960). "Biological Flora: *Calluna vulgaris* (L.) Hull." Journal of Ecology 48: 455-483.

Gimingham, C. H. (1972). Ecology of Heathlands. London, Chapman and Hall.

Godwin, H. (1981). The Archives of Peat Bogs. Cambridge, Cambridge University Press.

Gordon, J. E., Brazier, V., Thompson, Des B. A. and Horsfield, D. (2001). "Geoecology and the conservation management of sensitive upland landscapes in Scotland." Catena 42: 323-332.

Gordon, J. E., Thompson, Des B. A., Haynes, V. M., MacDonald, R. and Brazier, V. (1998). "Environmental sensitivity and conservation management in the Cairngorn Mountains, Scotland." Ambio 27: 335-344.

Gore, A. J. P. (1965). "Water, peat and erosion in the Northern Pennines." Proceedings of the North of England Soils Discussion Group 1: 41-44.

Gore, A. J. P. (1968). Reclamation of eroded peat areas, 9th Annual Progress Report, Moor House.

Gore, A. J. P. and Godfrey, M. (1981). "Reclamation of eroded peat in the Pennines." Journal of Ecology 69: 85-96.

Gore, A. J. P. and Olsen, J. S. (1967). "Preliminary models for accumulation of organic matter in an Eriophorum-Calluna ecosystem." Series Botanical 6: 297-313.

Goudie, A. S. and Brunsden, D. (1994). The Environment of the British Isles: An Atlas. Oxford, Oxford University Press.

Goudie, A. (1998). Geomorphological Techniques. Cambridge, University Press.

Grieve, I.C., Davidson, D.A. and Gordon, J.E. (1995) Nature, extent and severity of soil erosion in upland Scotland. Land Degradation and Rehabilitation, 6, 41-55.

Gregory, K. J. and Walling, B. (1973). Drainage Basin Form and Process: A Geomorphological Approach. London, Arnold, pp. 38-58.

Haggett, P. and Chorley, R. J. (1969). Network Analysis in Geography. London, Edward Arnold.

Haigh, M. J. and J. Krecek (1991). "Headwater management: problems and policies." Land Use Policy 8: 171-176.

Heathwaite, A. L. (1992). "Disappearing peat." Geography Review 5(3): 26-31.

Heathwaite, A. L. (1993). "Disappearing peat - regenerating peat? The impact of climate change on British peatlands." The Geographical Journal 159(2): 203-208.

Heathwaite, A. L., R. Egglesmann, Gottlich, Kh. and Kaule, G. (1993). Ecohydrology, mire drainage and mire conservation. Mires: Processes, Exploitation and Conservation. Heathwaite, A. L. and Gottlich, Kh. (eds.), Chichester, Wiley: 417-484.

Higgins, C. G. (1990). Gully development. Groundwater Geomorphology; the Role of Subsurface Water in Earth-surface Processes and Landforms. Higgins, C. G. and Coates, D. R. (eds.), Geology Society of America Special Paper 252: 139-155.

Higgitt, D. L., Warburton, J. and Evans, M. G. (2001). Sediment Transfer in Upland Environments. Geomorphological Processes and Landscape Environments. Higgitt, D. L. and Lee, E. M. (eds.), Oxford, Blackwell Publishers Ltd.: 190-214.

Hobbs, R. J. (1984). "Length of burning rotation and community composition in high-level Calluna-Eriophorum bog in N England." Vegetatio 57: 129-136.

Hobbs, R. J. (1986). "Mire morphology and the properties and behaviour of some British and foreign peats." Quarterly Journal of Engineering Geology, London 19: 7-80.

Hobbs, R. J. and Gimingham, C. H. (1987). "Vegetation, fire and herbivore interactions in heathland." Journal of Environmental Management 16: 87-173.

Holden, J. (2000) Runoff production in blanket peat covered catchments. Unpublished PhD Thesis, Department of Geography, University of Durham, Durham.

Holden, J. (2001). "Recent reduction of frost in the North Pennines." Journal of Meteorology 26(264): 369-374.

Holden, J. and Adamson, J. K. (2001) "Gordon Manley and the North Pennines." Journal of Meteorology 26(263): 329-333.

Holden, J. and Adamson, J. K. (2002). "The Moor House long-term upland temperature record - new evidence of recent warming." Weather 57: 119-127.

Holden, J. and Burt, T. P. (2002a). "Piping and pipeflow in a deep peat catchment." Catena 48(3): 163-199.

Holden, J. and Burt, T. P. (2002b). "Infiltration, runoff and sediment production in blanket peat catchments: Implications of field rainfall simulation experiments." Hydrological Processes 16(13): 2537-2557.

Holden, J. and Burt, T. P. (2003a). "Hydrological studies on blanket peat: the significance of the acrotelm-catotelm model." Journal of Ecology 91: 86-102.

Holden, J. and Burt, T. P. (2003b). "Hydraulic conductivity in upland blanket peat: measurement and variability." Hydrological Processes 17: 1227-1237.

Holden, J., Burt, T. P. and Vilas, M. (2002). "Application of ground-penetrating radar to the identification of subsurface piping in blanket peat." Earth Surface Processes and Landforms 27(3): 235-249.

Holden, J., Chapman, P. J. and Labadz, J. C. (2004). "Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration." Progress in Physical Geography 28(1): 95-123.

Holden, N. M. (1998). "By-pass of water through laboratory columns of milled peat." International Peat Journal 8: 13-22.

Holy, M. (1980). Erosion and Environment. Environment Sciences and Applications, Vol. 9. Oxford, Pergamon Press.

Horngung, M. and Langan, S. J. (1999). Nitrogen deposition: sources, impacts and responses in natural and semi-natural ecosystems. The Impact of Nitrogen Deposition on Natural and Semi-Natural Ecosystems. Langan, S. J. (ed.) Dordrecht, Kluwer Academic Publishing: 1-14.

Horton, R. E. (1933). "The role of infiltration in the hydrological cycle." Transactions of the American Geophysical Union 14: 446-460.

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

Ingram, H. A. P. (1967). "Problems of hydrology and plant distribution in mires." Journal of Ecology 55: 711-724.

Ingram, H. A. P. (1978). "Soil layers in mires: function and terminology." Journal of Soil Science 29: 224-227.

Ingram, H. A. P. (1983). Hydrology. Mires: swamp, bog, fen and moor, Ecosystems of the world 4A. Gore, A. J. P. (ed.), Amsterdam, Elsevier: 67-158.

Johnson, R. H. (1957). "Observations on the stream patterns of some peat moorlands in the southern Pennines." Mem. Manchester Lit. Phil. Society 99: 1-18.

Johnson, G. A. and Dunham, K. C. (1963). The Geology of Moor House. London, H.M.S.O.

Jones, J. A. A. (1982). Experimental studies of pipe hydrology. Badland Geomorphology. Bryan, R. B. and Yair, A. (eds.), Norwich, Geobooks: 355-371.

Jones, J. A. A. (1997). Hydrological processes within the river basin. Global Hydrology: Processes, resources and environmental management. Jones, J. A. A. (ed.), London, Longman Ltd.: 58-95.

Jones, J. A. A., Wathern, P., Connelly, L. J., Richardson, J. M. (1991). Modelling flow in natural soil pipes and its impact on plant ecology in mountain wetlands. Hydrological Basis of Ecologically Sound Management of Soil and

Groundwater: Proceedings of the Vienna Symposium, August 1991, IAHS Publication 202: 131-142.

King, C. A. M. (1976). The Geomorphology of the British Isles, Northern England. London, Methuen and Co.

Kirkby, M. J. (1988). "Hillslope runoff processes and models." Journal of Hydrology 100: 315-339.

Kirkby, M. J. and Chorley, R. J. (1967). "Throughflow, overland flow and erosion." Bulletin of the International Association of Scientific Hydrology 12: 5-21.

Labadz, J. C. (1988). Runoff and sediment production in blanket peat moorland: studies in the Southern Pennines. Unpublished PhD Thesis, Huddersfield Polytechnic.

Labadz, J. C., Burt, T. P. and 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.

Lappalainen, E. (1998). Global Peat Resources, International Peat Society.

Lamb, H. H. (1985). Climate and landscape in the British Isles. The English Landscape: Past, Present and Future. Woodell, S. R. J. (ed.), Oxford, Oxford University Press: 148-167.

Laws, J. O. (1941). "Measurements of the fall-velocity of water-drops and raindrops." Transactions of the American Geophysical Union 22(3): 709-721.

Lee, J. A., Tallis, J. H. and Woodin, S. J. (1988). Acidic deposition and British vegetation. Ecological change in the uplands. Usher, M. B. and Thompson, D. B. A. (ed.), Oxford, UK, Blackwell Scientific Publications: 151-162.

Lewis, F. J. (1906). "The plant remains in the Scottish peat mosses. Part II. The Scottish Highlands." Transactions. Royal Society of Edinburgh 47: 793-833.

Luk, S.-H. and Morgan, C. (1981). "Spatial variations of rainwash and runoff within apparently homogeneous areas." Catena 8: 383-402.

Mackay, A. W. (1997). Peat erosion: some implications for conservation and management of blanket mires and heather moorland in the UK. Conserving Peatlands. Parklyn, L., Stoneman, R. E. and Ingram, H. A. P. (ed.), Wallingford, CAB International: 82-87.

Mackay, A. W. and 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(1): 31-44.

Mallik, A. U., Gimingham, C. H. and Rahman, A. A. (1984). "Ecological effects of heather burning, I. Water infiltration, moisture retention and porosity of surface soil." Journal of Ecology 72: 767-776.

Maltby, E., Legg, C. J. and Proctor, M. C. F. (1990). "The ecology of severe moorland fire on the North York Moors: effects of the 1976 fire, and subsequent surface and vegetation development." Journal of Ecology 78: 490-518.

Manley, G. (1936). "The climate of the northern Pennines: the coldest part of England." Quarterly Journal of the Royal Meteorological Society 62: 103-115.

Manley, G. (1942). "Meteorological observations on Great Dunn Fell, a mountain station in northern England." Quarterly Journal of the Royal Meteorological Society 68: 151-165.

Manley, G. (1943). "Further climatological averages from the northern Pennines, with a note on topographical effects." Quarterly Journal of the Royal Meteorological Society 69: 251-261.

Marrs, R. H., Rizard, A. and Harrison, A. F. (1989). "The effects of removing sheep grazing on soil chemistry, above-ground nutrient distribution, and selected aspects of soil fertility in long-term experiments at Moor House National Nature Reserve." Journal of Applied Ecology 26: 647-661.

349

Marsh, T. J. and Sanderson, F. J. (1997). "A review of hydrological conditions throughout the period of the LOIS monitoring programme-considered within the context of the recent UK climatic volatility." Science of the Total Environment 194: 56-69.

Mather, A. S. (1983). "Land deterioration in upland Britain." Progress in Physical Geography 7(2): 210-228.

Mayfield, B. and Pearson, M. C. (1972). "Human interference with the north Derbyshire blanket peat." East Midland Geographer 12: 245-251.

McCohan, C. P., Carling, P. A. and Pascoe, D. (1987). "Chemical and ecological effects of a Pennine peat slide." Environmental Pollution 45: 275-289.

McTernan, M. (1993). "The Heather Moorland Ecosystem." Geography Review, November: 2-6.

Meyer, L. D. (1994). Rainfall Simulators for Soil Erosion Research. Soil Erosion Research Methods. Lal, R., Soil and Water Conservation Society and St. Lucie Press.

Milne, J. A. and Hartley, S. E. (2001). "Upland plant communities- sensitivity to change." Catena 42: 333-343.

Mills, A., Warburton, J. and Higgitt, D. L. (2002) Peat mass movements: a World and regional database. The British Uplands: Dynamics of Change. Burt, T. P., Thompson, D. B. A. and Warburton, J. (eds.), Report No. 319. Peterborough, JNCC: 166-167.

Moore, P. D. (1973). "The influence of prehistoric cultures upon the initiation and spread of blanket bog in upland Wales." Nature 241: 350-353.

Mosley, M. P. (1972). "Gully systems in blanket peat, Bleaklow, North Derbyshire." East Midland Geographer 5(5): 235-244.

Muschamp-Perry, J. J. (1893). The waterspout (or cloud burst) on the Cheviots. British Rainfall 1983: on the distribution of rain over the British Isles during the year of 1893. Symons, G. J. and Sowervy Wallsi, H. (eds.), London, Edward Stanford: 14-15.

National Trust (2004). Work on Wessenden Head Moss, Humpidge, R.

Nicholson, E. M. (1957). Moor House, Westmorland. Britain's Nature Reserves. Nicholson, E. M., London, Country Life Limited: 115-119.

Northumberland National Park Authority (1998). Northumberland National Park Education Service Update [Online], Available: http://www.northumberland-national- TheNational/VisitorGuide/ park.org.ukPark/TheCheviots/default.html, [16th June 2004], Northumberland National Park Authority, Hexham.

Osvald, H. (1923). "Die vegetation des Hochmoores Komosse." Svenska Vaxtsociologiska Sallskapets Handlingar 1: 1-436.

Osvald, H. (1949). "Notes on the vegetation of British and Irish mosses." Acta Phytogeographica Suecica 26: 1-62.

Parry, M. L., Carter, T. R. and Konijn, N. T. (1988). The impact of climatic variations on agriculture: vol. 1: assessments in cool temperate and cold regions. Dordrecht, Kluwer Academic Press.

Pears, N. (1975). "The growth rate of hill peats in Scotland." Geografiska Foreningens i Stockholm Forhandlingar 97: 265-270.

Pearsall, W. H. (1941). The 'Mosses' of the Stainmore District. The Journal of Ecology. T. B. E. Society. Cambridge, Cambridge University Press: 161-203.

Pearsall, W. H. (1950). Moorlands and Bogs. Mountains and Moorlands. Pearsall, W. H. (ed.), London, Collins: 188-217.

Penning-Rowsell, E. C. (1969) The Morphometric Analysis of Drainage Basins from Maps. Occasional Papers No. 1, Department of Geography, University College London.

Pepin, N. C. (1997). "Scenarios of future climate change: effects on frost occurrence and severity in the Maritime Uplands of Northern England." Geografiska Annaler 79A(1-2): 121-137.

Phillips, J. R. (1981). Moor Burning. Peak District Moorland Erosion Study Phase 1 Report. Phillips, J., Yalden, D. and Tallis, J. H. Derbyshire, Peak District Joint Planning Board, Bakewell: 171-175.

Phillips, J. R., Yalden, D., Tallis, J. H. (1981). Peak District Moorland Erosion Study: Phase 1 Report. Derbyshire, Bakewell.

Phillips, R. (1994) Grasses, Ferns, Mosses and Lichens of Great Britain and Ireland. London, Macmillan Publishers Ltd.

Philip, J. R. (1957). "The theory of infiltration 1. The infiltration equation and its solution." Soil Science 83: 345-357.

Poesen, J., Nachtergaele, J., Verstraeten, G. and Valentin, C. (2003). "Gully erosion and environmental change: importance and research needs." Catena (Special issue on Gully erosion and global change) 50: 91-133.

Poesen, J., Vandekerckhove, L, Nachtergaele, J., Oostwoud Wijdenes, D. J., Verstraeten, G. and Van Wesmael, B. (2001). Gully erosion in Dryland Environments. Dryland Rivers: Hydrology and geomorphology of semi-arid channels. Bull, L. J. and Kirkby, M. J., Chichester, John Wiley and Sons Ltd.: Chapter 8.

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

Radley, J. (1962). "Peat Erosion on the High Moors of Derbyshire and West Yorkshire." East Midland Geographer 5(17): 40-50.

Radley, J. (1965). "Significance of major moorland fires." Nature 205: 1254-1259.

Ramsar (2004). The Ramsar Convention on Wetlands [Online], Available: http://www.ramsar.org/key_brochure_2004_e.htm, [28th November 2004].

Ratcliffe, D. A. (1977). A Nature Conservation Review: the selection of biological sites of national importance. Cambridge, Cambridge University press (for the Nature Conservancy Council).

Ratcliffe, D. A. and Thompson. D. B. A. (1988). The British uplands: their ecological character and international significance. Ecological change in the uplands. Usher, M. B. and Thompson, D. B. A., Oxford, Blackwell Scientific Publications: 9-36.

Rawes, M. (1981). "Further effects of excluding sheep from high-level grasslands in the North Pennines." Journal of Ecology 69: 651-669.

Rawes, M. (1983). "Changes in two high altitude blanket bogs after the cessation of sheep grazing." Journal of Ecology 71: 219-235.

Rawes, M. and Hobbs, R. (1979). "Management of semi-natural blanket bog in the Northern Pennines." Journal of Ecology 67: 789-807.

Rawes, M. and Welch, D. (1964). "Studies on sheep grazing in the Northern Pennines." Journal of British Grassland Society 19: 403-411.

Reid, L. M. and Dunne, T. (1996). Rapid Evaluation of Sediment Budgets. Reislirchen, Catena.

Renberg, I. and Wik, M. (1985). "Carbonaceous particles in lake sediments - pollutants from fossil fuel combustion." Ambio 14: 161-163.

Rhodes, A. N. (1998). "A method for the preparation and quantification of microscopic charcoal from terrestrial and lacustrine sediment cores." Holocene 8(1): 113-117.

Rickson, R. J. (2004). "Experimental techniques for erosion studies: Rainfall Simulation." [Online], Available: http://www.silsoe.cranfield.ac.uk/staff/cv/j_rickson.htm, [14th April 2004]

River Swale Regeneration Project (2002). "Moorland Gripping." [Online], Available: http://www.riverswale.org.uk/project09.htm, [19th August 2002].

Roberston, R. A., Nicholson, I. A. and Hughes, R. (1968). Runoff studies on peat a catchment. Transactions of the second international peat congress, Leningrad, USSR, 1963. Roberston, R. A. (ed.), London, HMSO.

Romkens, M. J. M., Prasad, S. N.and Whisler, F. D. (1990). Surface sealing and infiltration. Process Studies in Hillslope Hydrology. Anderson, M. G. and Burt, T. P. (eds.),Chichester, John Wiley and Sons Ltd.: 127-171.

Rose, N. L. (1995). "Carbonaceous particle record in lake sediments from the Arctic and other remote areas of the Northern Hemisphere." Science of the Total Environment 160-161: 487-496.

Rose, N. L. and Harlock, S. (1998). "The spatial distribution of characterised fly-ash particles and trace metals in lake sediments and catchment mosses in the United Kingdom." Water, Air, and Soil Pollution 106(3-4): 287-308.

Rose, N. L., Harlock, S. and Appleby, P. G. (1999). "The spatial and temporal distributions of spheroidal carbonaceous fly- ash particles (SCP) in the sediment records of European Mountain Lakes." Water, Air, and Soil Pollution 113(1-4): 1-32.

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." Holocene 5(3): 328-335.

Rose, N. L, Juggins, S., Watt, J. and Battarbee, R. (1994). "Fuel-type characterization of spheroidal carbonaceous particles using surface chemistry." Ambio 23(4-5): 296-299.

Rosen, D. and Dumayne-Peaty, L. (2001). "Human impact on the vegetation of South Wales during late historical times: palynological and palaeoenvironmental results from Crymlyn Bog NNR, West Glamorgan, Wales, UK." The Holocene 11(1): 11-23.

Rycroft, D. W., Williams, J. A. and Ingram, H. A. P. (1975). "Transmission of water through peat I. Review." Journal of Ecology 63: 535-556.

Sansom, A. (1996). "Floods and sheep - Is there a link?" Bulletin of the British Ecological Society 27: 27-32.

Selby, M. J. (2000). Hillslope Materials and Processes. Oxford, Oxford University Press.

Shimwell, D. (1974). "Sheep grazing intensity in Edlae. 1692-1747, and its effects on blanket peat erosion." Derbyshire Archaeological Journal 94: 35-40.

Simmons, I. (1990). "Upland Peats: Human impact on an ecosystem." Geography Review: 27-30.

Skeffington, R., Wilson, E., Maltby, E., Immirzi, P. and Putwain, P. (1997). Acid deposition and blanket mire degradation and restoration. Blanket Mire Degradation: Causes, consequences and challenges, University of Manchester, Mires Research Group.

Smithson, P. A. (1985). The present climate of the Northern Pennines. Field Guide to the Periglacial Landforms of Northern England. Boardman, J. (ed.), Cambridge, Research Association: 1-3.

Stevenson, A. C. and Thompson, D.B.A. (1993). "Long-term changes in the extent of heather moorland in upland Britain and Ireland: palaeoecological evidence for the importance of grazing." Holocene 3: 70–76.

Stevenson, A. C., Jones, V. J. and Battarbee, R. W. (1990). "The cause of peat erosion: a palaeolimnological approach." New Phytologist 114: 727-735.

Stewart, A. J. A. and Lance, A. N. (1991). "Effects of moor-draining on the hydrology and vegetation of Northern Pennine blanket bog." Journal of Applied Ecology 28: 1105-1117.

Strahler, A. N. (1952). "Hypsometric (area-altitude) analysis of erosional topography." Bulletin of the Geological Society of America 63: 1117-42.

Svensson, G. (1988). "Fossil plant communities and regeneration patterns on a raised bog in south Sweden." Journal of Ecology 76: 41-59.

Tallis, G. M. (1994). "Compartmental models and competing risk." Mathematical Biosciences 121(1): 111-122.

Tallis, J. H. (1964). "Studies on Southern Pennine Peats. II. The pattern of erosion." Journal of Ecology 47: 333-344.

Tallis, J. H. (1965). "Studies on the Southern Pennine Peats. IV. Evidence of recent erosion." Journal of Ecology 53: 509-520.

Tallis, J. H. (1973). "Studies on Southern Pennine Peats. V. Direct observations on peat erosion and peat hydrology at Featherbed Moss, Derbyshire." Journal of Ecology 61: 1-22.

Tallis, J. H. (1981a). The nature and extent of soil and peat erosion in the Peak District - literature survey. Peak District Moorland Erosion Study Phase 1 Report. Phillips, J., Yalden, D. and Tallis, J. H. (eds.), Derbyshire, Peak District Joint Planning Board, Bakewell: 65-73.

Tallis, J. H. (1981b). 'Rates of erosion'. Peak District Moorland Erosion Study Phase 1 Report. Phillips, J., Yalden, D. and Tallis, J. H. (eds.), Bakewell, Peak Park Joint Planning Board: 74-83.

Tallis, J. H. (1981c). Sedimentation in the reservoirs of the Peak District. Peak District Moorland Erosion Study Phase 1 Report. Phillips, J., Yalden, D. and Tallis, J. H. (eds.), Derbyshire, Peak District Joint Planning Board, Bakewell: 190-197.

Tallis, J. H. (1981d). Uncontrolled fires. Peak District Moorland Erosion Study Phase 1 Report. Phillips, J., Yalden, D. and Tallis, J. H. (eds.), Derbyshire, Peak Park Joint Planning Board, Bakewell, Derbyshire: 176-182.

Tallis, J. H. (1985a). Erosion of blanket peat in the southern Pennines: new light on an old problem. The geomorphology of north-west England. Johnson, R. H. (eds.), Manchester University Press: 313-336, refs.

Tallis, J. H. (1985b). "Mass movement and erosion of a southern Pennine blanket peat." Journal of Ecology 73(1): 283-315.

Tallis, J. H. (1987). "Fire and flood at Holme Moss: erosion processes in an upland blanket mire." Journal of Ecology 75(4): 1099-1129.

Tallis, J. H. (1989). "Aspects of blanket peat erosion." Proceedings of the North of England Soils Discussion Group 24: 27-38.

Tallis, J. H. (1994). "Pool-and-hummock patterning in a southern Pennine blanket mire II.

Tallis, J. H. (1995a). Blanket mires in the upland landscape. Restoration of temperate wetlands. Wheeler, B. D., Shaw, S. C., Fojten, W. J. and Robertson, R. A. (eds.), Chichester, John Wiley and Sons: 495-508.

Tallis, J. H. (1995b). "Climate and erosion signals in British blanket peats: the significance of Racomitrium lanuginosum remains." Journal of Ecology 83(6): 1021-1030.

Tallis, J. H. (1997a). "Peat erosion in the Pennines: the badlands of Britain. The Macauley Land Use Research Institute, Aberdeen, UK." Biologist 44: 277-279.

Tallis, J. H. (1997b). The Southern Pennine experience: an overview of blanket mire degradation. Blanket Mire Degradation: Causes, Consequences and Challenges: Proceedings of the Mire Research Group of the British Ecological Society. J. H.

Tallis, Meade, R. E. and Hulme, P. D. (eds.), Aberdeen, Macaulay Land Use Research Institute: 7-15.

Tallis, J. H. (1997c). "The pollen record of *Empetrum nigrum* in southern Pennine peats: Implications for erosion and climate change." Journal of Ecology 85(4): 455-465.

Tallis, J. H. (1998). "Growth and Degradation of British and Irish blanket mires." Environmental Review 6: 81-122.

Tallis, J. H. and Livett, E. A. (1994). "Pool-and-hummock patterning in a southern Pennine blanket mire I. Stratigraphic profiles for the last 2800 years." Journal of Ecology 82(4): 775-788.

Tallis, J. H. and Yalden, D. W. (1983). Peak District Moorland Management Project, Phase II Report. Bakewell, Peak Park Joint Planning Board.

Tallis, J. H., Meade, R. and Hulme, P.D. (1997). Blanket Mire Degradation: Causes, Consequences and Challenges. The Blanket Mire Degradation Conference, University of Manchester, Mires Research Group.

Taylor, J. A. and Tucker, R. B. (1970). The peat deposits of Wales: an inventory and interpretation. Proceedings of the 3rd International Peat Congress 1968, Quebec. Lafleur, C. and Butler, J., Ottawa, Department of Energy, Mines and Resources: 163-173.

The Countryside Agency (2004) "The Cheviots." [Online], Available: http://www.countryside.gov.uk/LAR/Landscape/CC/north-east/cheviots.asp, [26th September 2004].

Thompson, D. B. A., Hester, A. J. and Usher, M. B. (1995). Heaths and Moorlands, Cultural Landscapes. Edinburgh, MHSO.

Thornes, J. B. (1980). Erosional Processes of Running Water and their Spatial and Temporal Contorls: A Theoretical Viewpoint. Soil Erosion. Kirkby, M. J. and Morgan, R. P. C. (eds.), Chichester, John Wiley and Sons: 129-182.

Thornes, J. B. (1985). "The Ecology of Erosion." Geography: 222-235.

Tomlinson, R. W. (1979). Water levels in peatlands and some implications for runoff and erosional processes. Geographical approaches to fluvial processes. Pitty, A. F. (eds.), Norwich, Geobooks: 149-162.

Tomlinson, R. W. (1981). "The erosion of peat in the uplands of Northern Ireland." Irish Geography 14: 51-64.

Walker, D. and Walker, P. M. (1961). "Stratigraphic evidence of regeneration in some Irish bogs." Journal of Ecology 49: 169-185.

Warburton, J. (1998). A contemporary sediment budget for the North Pennines. Geomorphological Studies in the North Pennines: Field Guide. Warburton, J. (ed.), Durham, British Geomorphological Research Group (BGRG): 16-23.

Warburton, J. (2003). "Wind-splash erosion of bare peat on UK upland moorlands." Catena 52: 191-207.

Warburton, J., Higgitt, D. and Mills, A. (2003). "Anatomy of a Pennine Peat Slide, Northern Pennines." Earth Surface Processes & Landforms 28: 457-473.

Warburton, J., Holden, J. and Mills, A. J. (2004). "Hydrological controls of surficial mass movements in peat." Earth-Science Reviews in press.

Wasylikowa, K. (1986). Analysis of fossil fruits and seeds. Handbook of Holocene Palaeoecology and Palaeohydrology. Berglund, B. E. (ed.), Chichester, John Wiley and Sons Ltd.: 571-590.

Watt, J. (1998). "Automated characterisation of individual carbonaceous fly-ash particles by computer controlled scanning electron microscopy: analytical methods and critcal review of alternative techniques." Water, Air and Soil Pollution 106(309-327).

Weber, S. (2004). How a grouse moor pays its way. Darlington and Stockton Times. Darlington: 21.

Welch, D. and Rawes, M. (1964). "The early effects of excluding sheep from high-level grasslands in the North Pennines." Journal of Applied Ecology 1: 281-300.

Wein, R. W. (1973). "Biological flora of the British Isles Eriophrum vaginatum L." Journal of Ecology 61: 601-615.

Wishart, D. and Warburton, J. (2002). "An assessment of Blanket Mire Degradation and Peatland Gully Development in the Cheviot Hills, Northumberland." Scottish Geographical Journal 117(3): 185-206.

Worrall, F., Reed, M., Warburton, J. and Burt, T. P. (2003). "Carbon budget for a British upland peat catchment." The Science of the Total Environment 312: 133-146.

Yalden, D. (1981). Practical interpretation. Peak District Moorland Erosion Study Phase 1 Report. Phillips, J., Yalden, D. and Tallis, J. H. (eds.), Derbyshire, Peak District Joint Planning Board, Bakewell: 235-239.

Yang, H., Battarbee, R. W., Rose, N. L. and Boyle, J. F. (2001a). "Storage and distribution of trace metals and spheroidal carbonaceous particles (SCPs) from atmospheric deposition in the catchment peats of Lochnagar, Scotland." Environmental Pollution 115(2): 231-238.

Yang, H., Rose, N. L. and Battarbee, R. W. (2001b). "Dating of recent catchment peats using spheroidal carbonaceous particle (SCP) concentration profiles with particular reference to Lochnagar, Scotland." Holocene 11(5): 593-597.

Yeloff, D. E., Labadz, J. C., Hunt, C. O., Higgitt, D. L. and Foster, I. D. L. (2005). "Blanket peat erosion and sediment yield in an upland reservoir catchment in the southern Pennines, UK." Earth Surface Processes and Landforms 30: 717-733.

APPENDICIES

APPENDIX 1: Accompanies Study Sites and Methodology (Chapter 3)

Time (mins)	5 minute run Intensity (mm hr^{-1})				15 minute run Intensity (mm hr^{-1})			
	12	16	20	24	12	16	20	24
5	500	730	830	1040				
10	500	700	860	1090				
15	480	690	860	1040	1450	2050	2550	2700
20	460	700	850	1020				
25	475	690	860	1050				
30	470	630	845	1040	1460	2070	2540	2990
35	475	690	830	1040				
40	480	690	870	1040				
45	460	700	860	1030	1455	1970	2550	2960
50	480	690	860	1055				
55	480	690	850	1050				
60	480	690	860	1040	1440	2070	2540	2960
Total	5740	8290	10235	12353	5805	8210	10180	11610

Table A1.1: Showing the results from the calibration of the rainfall simulator for the four different rainfall intensities.

| Area | Site | Field Research | | | | | | Laboratory Analysis | | | |
| | | Long Profile | Cross-profiles | Cross-sections | | Veg Survey | Cores | Troel Smith and von Post Classification | BD, BDB, LOI, % moisture | Particle Shape and Form | Macrofossil Analysis |
				Exposed	Undisturbed						
Moor House	Burnt Hill 1	*	*	*		*	*	*	*	*	*
	Burnt Hill 2	*	*	*		*	*	*	*	*	
	Burnt Hill Uneroded					*	*	*	*	*	*
	Neather Hearth	*	*	*		*	*	*	*	*	
	Cottage Hill	*	*		*	*		*	*	*	
	Rough Sike 1	*	*		*	*		*	*	*	
	3 Linear Gullies - Rough Sike	*	*		*	*		*	*		
	3 Linear Gullies - Netherheath Sike	*	*		*	*		*	*		
	Moss Flats Eroded					*	*	*	*	*	
	Moss Flats Uneroded					*	*	*	*	*	
The Cheviot	Gully 1	*	*		*	*		*	*	*	
	Gully 2	*	*		*	*		*	*	*	*
	Gully 3	*	*		*	*		*	*		
	Uneroded					*	*	*		*	*
Wessenden Head Moss	Gully 1	*	*		*	*		*	*		
	Gully 2	*	*		*	*		*	*	*	*
	Gully 3 (West Grain)	*	*		*	*		*	*		
	Uneroded					*	*	*	*	*	*

Table A1.2: Field and laboratory research conducted at the selected locations within the three study sites.

Site	Monolith Sample	Core Sample	Stratigraphy	BD	DBD	LOI	% Moisture	Particle Shape and Form	SCP Anlaysis	Macrofossil Analysis
Moor House										
Uneroded Moor House										
Core from Uneroded Burnt Hill		*	*	*	*	*	*	*		*
Grass Block		*	*	*	*	*	*		*	
Heather Block		*	*	*	*	*	*		*	
Burnt Hill 1 Gully										
Core from Pool Complex		*	*	*	*	*	*	*		
Trench 1 Right	*		*	*	*	*	*	*		
Trench 2 Right	*		*	*	*	*	*	*	*	*
Trench 3 Left	*		*	*	*	*	*			
Trench 4 Left	*		*	*	*	*	*			
Trench 4 Middle	*		*	*	*	*	*			
Trench 4 Right	*		*	*	*	*	*			
Trench 5 Left	*		*	*	*	*	*			
Trench 5 Middle	*		*	*	*	*	*			
Trench 5 Right	*		*	*	*	*	*			
Trench 6 Left	*		*	*	*	*	*	*		*
Trench 6 Middle	*		*	*	*	*	*	*		*
Trench 6 Right	*		*	*	*	*	*	*		*
Burnt Hill 2 Gully										
Core from Top 1		*	*	*	*	*	*	*		
Core from Top 2		*	*	*	*	*	*			
Core from Top (step)		*	*	*	*	*	*			
Trench 1 Left		*	*	*	*	*	*	*		
Trench 1 Middle		*	*	*	*	*	*	*		
Trench 1 Right		*	*	*	*	*	*	*		
Trench 2 Left	*		*	*	*	*	*			
Trench 2 Middle	*		*	*	*	*	*			
Trench 2 Right	*		*	*	*	*	*			
Trench 3 Left	*		*	*	*	*	*			
Trench 3 Middle	*		*	*	*	*	*			
Trench 3 Right	*		*	*	*	*	*			
Trench 4 Left	*		*	*	*	*	*			
Trench 4 Middle	*		*	*	*	*	*			
Trench 4 Right	*		*	*	*	*	*			
Trench 5 Left	*		*	*	*	*	*			
Trench 5 Middle	*		*	*	*	*	*			
Trench 5 Right	*		*	*	*	*	*			
Trench 6 Left	*		*	*	*	*	*	*		
Trench 6 Middle	*		*	*	*	*	*	*		
Trench 6 Right	*		*	*	*	*	*	*		
Netherheath										
Core from Top 1		*	*	*	*	*	*	*		
Core from Top 2		*	*	*	*	*	*			
Core from Top 3		*	*	*	*	*	*			
Trench 1 Left	*		*	*	*	*	*	*		
Trench 1 Middle	*		*	*	*	*	*	*		
Trench 1 Right	*		*	*	*	*	*	*		
Trench 2 Left	*		*	*	*	*	*			
Trench 2 Middle	*		*	*	*	*	*			
Trench 2 Right	*		*	*	*	*	*			
Trench 3 Left	*		*	*	*	*	*			
Trench 3 Middle	*		*	*	*	*	*			
Trench 3 Right	*		*	*	*	*	*			
Trench 4 Left	*		*	*	*	*	*			
Trench 4 Middle	*		*	*	*	*	*			
Trench 4 Right	*		*	*	*	*	*			
Pool adjacent to T5 L	*	*	*	*	*	*	*			
Trench 5 Left	*		*	*	*	*	*			
Trench 5 Middle	*		*	*	*	*	*			
Trench 5 Right	*		*	*	*	*	*			
Trench 6 Left	*		*	*	*	*	*	*		
Trench 6 Middle	*		*	*	*	*	*	*		
Trench 6 Right	*		*	*	*	*	*	*		
Cottage Hill Gully										
Cross section 1 Core Left		*	*	*	*	*	*			
Cross section 1 Core Middle		*	*	*	*	*	*			
Core from Drop		*	*	*	*	*	*	*		
Cross section 2 Core Left		*	*	*	*	*	*	*		
Cross section 2 Core Middle		*	*	*	*	*	*	*		
Cross section 2 Core Middle to Right		*	*	*	*	*	*	*		
Cross section 3 Core Left		*	*	*	*	*	*			
Cross section 3 Core Right		*	*	*	*	*	*			
Rough Sike Gully										
Core from top Left Bank		*	*	*	*	*	*	*		
Core from top Left		*	*	*	*	*	*	*		
Core from top Right		*	*	*	*	*	*	*		
Cross section 2 Core Left		*	*	*	*	*	*	*		
Cross section 2 Core Left (L2)		*	*	*	*	*	*	*		
Cross section 2 Core Middle		*	*	*	*	*	*	*		
4 Linear Gullies adjacent to Rough Sike										
Main Middle Gully										
Cross section 1 Core Left		*	*	*	*	*	*			
Cross section 1 Core Middle		*	*	*	*	*	*			
Cross section 1 Core Right		*	*	*	*	*	*			
Cross section 2 Core Left		*	*	*	*	*	*			
Cross section 2 Core Middle		*	*	*	*	*	*			
Cross section 2 Core Right		*	*	*	*	*	*			
Cross section 3 Core Left		*	*	*	*	*	*			
Cross section 3 Core Middle		*	*	*	*	*	*			

	1	2	3	4	5	6	7	8	9
Cross section 3 Core Right	*	*	*	*	*	*			
Other middle Gully									
Cross section 2 Core Left	*	*	*	*	*	*			
Cross section 2 Core Middle	*	*	*	*	*	*			
Cross section 2 Core Right	*	*	*	*	*	*			
Nearest to Rough Sike									
Cross section 2 Core Left	*	*	*	*	*	*			
Cross section 2 Core Right	*	*	*	*	*	*			
Furthest from Rough Sike									
Cross section 2 Core Left	*	*	*	*	*	*			
Cross section 2 Core Middle	*	*	*	*	*	*			
Cross section 2 Core Right	*	*	*	*	*	*			
3 Linear Gullies adjacent to Netherheath Sike									
Main Gully									
Cross section 1 Core Left	*	*	*	*	*	*			
Cross section 1 Core Middle	*	*	*	*	*	*			
Cross section 1 Core Right	*	*	*	*	*	*			
Cross section 2 Core Left	*	*	*	*	*	*			
Cross section 2 Core Middle	*	*	*	*	*	*			
Cross section 2 Core Right	*	*	*	*	*	*			
Cross section 3 Core Left	*	*	*	*	*	*			
Cross section 3 Core Middle	*	*	*	*	*	*			
Cross section 3 Core Right	*	*	*	*	*	*			
Adjacent Gully									
Cross section 2 Core Left	*	*	*	*	*	*			
Cross section 2 Core Middle	*	*	*	*	*	*			
Cross section 2 Core Right	*	*	*	*	*	*			
Furthest from Netherheath Sike									
Cross section 2 Core Left	*	*	*	*	*	*			
Cross section 2 Core Middle	*	*	*	*	*	*			
Cross section 2 Core Right	*	*	*	*	*	*			
Core from Moss Flats (Type 1)	*	*	*	*	*	*	*		
Core from adjacent to Moss Flats (Uneroded)	*	*	*	*	*	*	*		
The Cheviot									
Uneroded Cheviot									
Core	*	*	*	*	*	*	*	*	*
Gully 1									
Extra Sphagnum peat	*	*	*	*	*	*	*		
Extra Smooth peat	*	*	*	*	*	*	*		
Extra Mineral	*	*	*	*	*	*	*		
Extra Black peat	*	*	*	*	*	*	*		
Cross section 1 Core Left	*	*	*	*	*	*			
Cross section 1 Core Middle	*	*	*	*	*	*			
Cross section 1 Core Right	*	*	*	*	*	*			
Cross section 2 Core Left	*	*	*	*	*	*			
Cross section 2 Core Middle	*	*	*	*	*	*			
Cross section 2 Core Right	*	*	*	*	*	*			
Cross section 3 Core Left	*	*	*	*	*	*			
Cross section 3 Core Middle	*	*	*	*	*	*			
Cross section 3 Core Right	*	*	*	*	*	*			
Gully 2									
Cross section 1 Core Middle (XP1)	*	*	*	*	*	*	*		*
Cross section 2 Core Middle (XP5)	*	*	*	*	*	*	*		*
Core from top above XP8	*	*	*	*	*	*	*		*
Gully 3									
Cross section 1 Core Left (XP3)	*	*	*	*	*	*			
Cross section 1 Core Middle (XP3)	*	*	*	*	*	*			
Cross section 1 Core Right (XP3)	*	*	*	*	*	*			
Cross section 2 Core Left (XP6)	*	*	*	*	*	*			
Cross section 2 Core Middle (XP6)	*	*	*	*	*	*			
Cross section 2 Core Right (XP6)	*	*	*	*	*	*			
Cross section 3 Core (XP7)	*	*	*	*	*	*			
Wessenden Head Moss									
Uneroded Southern Pennines									
Core 1	*	*	*	*	*	*	*	*	*
Core 2	*	*							
Core 3	*	*							
Core 4	*	*							
Core 5	*	*							
Core 5 - Medieval Ditch (Gully 3 XS2 R)	*	*	*	*	*	*			
Gully 1									
Cross section 1 Core Middle	*	*	*	*	*	*			
Cross section 2 Core Middle	*	*	*	*	*	*			
Cross section 3 Core Left	*	*	*	*	*	*			
Cross section 3 Core Middle	*	*	*	*	*	*			
Cross section 3 Core Right	*	*	*	*	*	*			
Gully 2									
Cross section 1 Core Middle	*	*	*	*	*	*	*		*
Cross section 2 Core Middle	*	*	*	*	*	*			
Sample from top of drop just below XS2	*	*	*	*	*	*	*		
Cross section 3 Core Left	*	*	*	*	*	*	*		*
Cross section 3 Core Middle	*	*	*	*	*	*	*		*
Cross section 3 Core Right	*	*	*	*	*	*	*		*
Gully 3 - West Grain									
Cross section 1 Core Left	*	*	*	*	*	*			
Cross section 1 Core Middle	*	*	*	*	*	*			
Cross section 1 Core Right	*	*	*	*	*	*			
Cross section 2 Core Middle	*	*	*	*	*	*			
Cross section 3 Core Right	*	*	*	*	*	*	*		

Table A1.3: The field sampling of the monolith and core samples and the laboratory analysis conducted on each sample.

APPENDIX 2: Accompanies Interfluve Peat Accumulation (Chapter 5)

Depth (cm)	Moor House Heather A Counts	gDM⁻¹	Moor House Heather B Counts	gDM⁻¹	Moor House Heather C Counts	gDM⁻¹	Moor House Heather D Counts	gDM⁻¹	Moor House Grass A Counts	gDM⁻¹	Moor House Grass B Counts	gDM⁻¹	Moor House Grass C Counts	gDM⁻¹	Moor House Grass D Counts	gDM⁻¹	The Cheviot Grass Counts	gDM⁻¹	Wessenden Head Moss Grass Counts	gDM⁻¹
1	0	0	64	320	69	345	71	355	59	295	27	135	45	225	22	110	0	0	317	1585
2	27	135	93	465	116	580	126	630	83	415	355	1775	242	1210	237	1185	46	230	568	2840
3	93	465	107	535	279	1395	61	305	151	755	277	1385	298	1490	634	3170	43	215	1121	5605
4	68	340	142	710	436	2180	111	555	191	955	315	1575	321	1605	379	1895	158	790	1390	6950
5	103	515	129	645	214	1070	93	465	516	2580	109	545	281	1405	743	3715	161	805	959	4795
6	274	1370	396	1980	328	1640	133	665	1256	6280	65	325	385	1925	528	2640	374	1870	2013	10065
7	356	1780	821	4105	483	2415	170	850	418	2090	76	380	376	1880	662	3310	347	1735	1836	9180
8	414	2070	495	2475	1022	5110	150	750	593	2965	68	340	147	735	941	4705	388	1940	1744	8720
9	476	2380	616	3080	963	4815	655	3275	646	3230	95	475	276	1380	473	2365	437	2185	361	1805
10	401	2005	1053	5265	1187	5935	788	3940	993	4965	103	515	192	960	609	3045	369	1845	477	2385
11	381	1905	1344	6720	1096	5480	875	4375	766	3830	52	260	41	205	228	1140	528	2640	645	3225
12	664	3320	822	4110	834	4170	1140	5700	836	4180	17	85	18	90	74	370	492	2460	146	730
13	890	4450	964	4820	656	3280	1170	5850	488	2440	64	320	21	105	98	490	408	2040	56	280
14	1269	6345	782	3910	442	2210	1180	5900	70	350	16	80	10	50	87	435	360	1800	68	340
15	1033	5165	415	2075	385	1925	1095	5475	247	1235	20	100	7	35	96	480	329	1645	74	370
16	976	4880	189	945	383	1915	1205	6025	125	625					42	210	318	1590	80	400
17	1341	6705	105	525	319	1595	1250	6250	203	1015					88	440	756	3780	49	245
18	846	4230	136	680	324	1620	870	4350	57	285					58	290	433	2165	36	180
19	187	935	42	210	596	2980	900	4500	14	70					78	390	126	630	21	105
20	133	665	27	135	406	2030	930	4650	18	90					34	170	37	185	116	580
21	41	205	93	465	350	1750	815	4075	50	250					11	55	48	240	247	1235
22	106	530	32	160	382	1910	785	3925	13	65					19	95	68	340	87	435
23	50	250	31	155	59	295	480	2400									39	195	124	620
24	24	120	36	180	108	540	150	750									40	200	161	805
25	38	190	9	45	64	320	180	900									27	135	150	750
26	39	195	47	235	98	490	105	525									52	260	129	645
27	31	155	84	420	76	380	135	675									32	160	60	300
28	67	335	14	70	62	310	80	400									26	130	29	145
29																	10	50	17	85
30																	6	30	15	75
31																	34	170	23	115
32																	17	85	9	45
33																	23	115	11	55
34																	19	95	9	45
35																	43	215	9	45
36																	15	75	21	105
37																	7	35	6	30
38																	12	60	16	80
39																	8	40	44	220
40																	6	30	7	35
Total	10328	51640	9088	45440	11737	58685	15703	78515	7793	38965	1659	8295	2660	13300	6141	30705	6642	33210	13251	66255

Table A2.1: The SCP concentration in: no. of SCPs and no. of gDM⁻¹. The calculation for the 'no. of SCPs per gram dry mass of sediment' was based on the 0.2 g of air-dried peat used in the preparation. Figures in red represent samples with plant debris remaining on the petri dishes restricting vision for counting.

A3.1 Long profiles of gully systems at Moor House

Figure A3.1: Long profile of the gully system leading into Rough Sike and the peat depth. The breaks in slope represent the transition from linear to dendritic and dendritic to linear dissection.
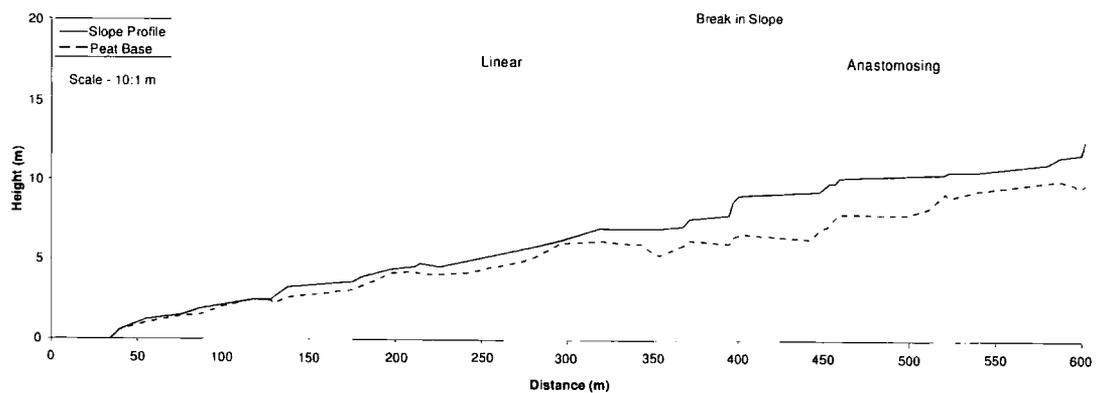
Figure A3.2: Long profile of the main gully system on Cottage Hill and peat depth. The break in slope represents the transition from linear to anastomosing dissection.
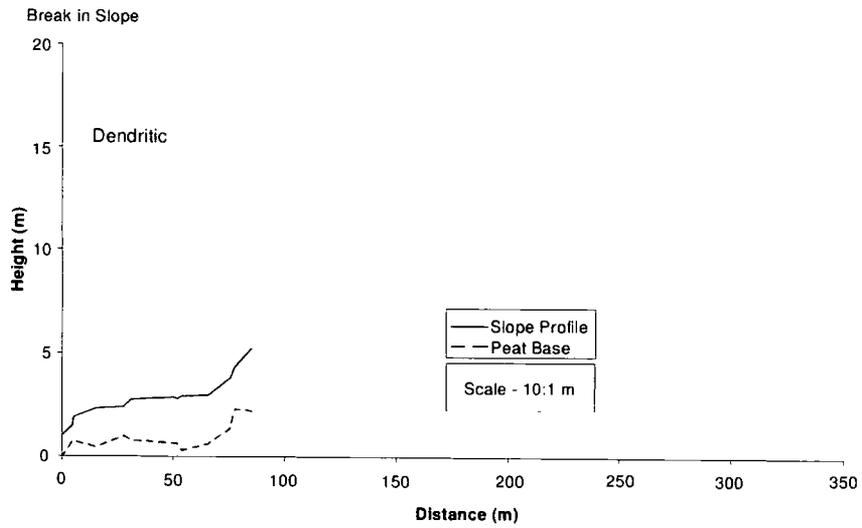
Figure A3.3: Long profile of the top side gully system leading into Cottage Hill's main gully system and peat depth. The break in slope represents the transition from linear to dendritic dissection.
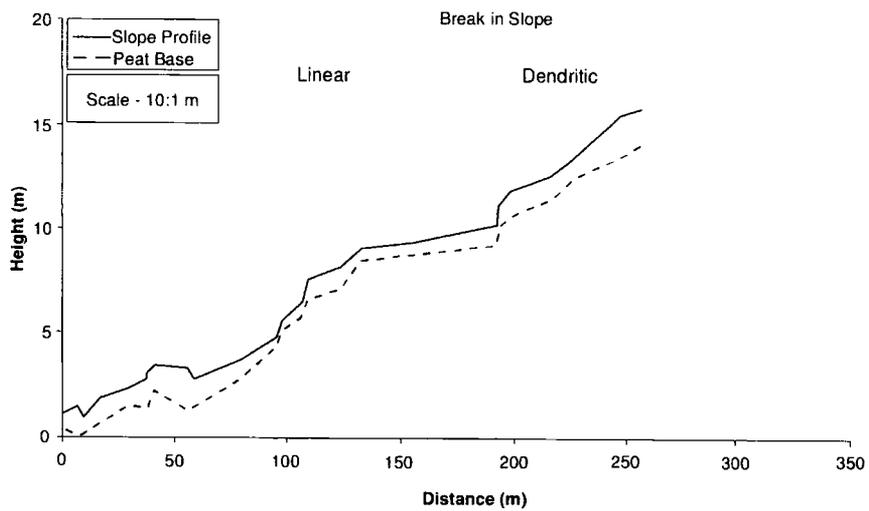
Figure A3.4: Long profile of the bottom side gully system leading into Cottage Hill's main gully system and peat depth. The break in slope represents the transition from linear to dendritic dissection.
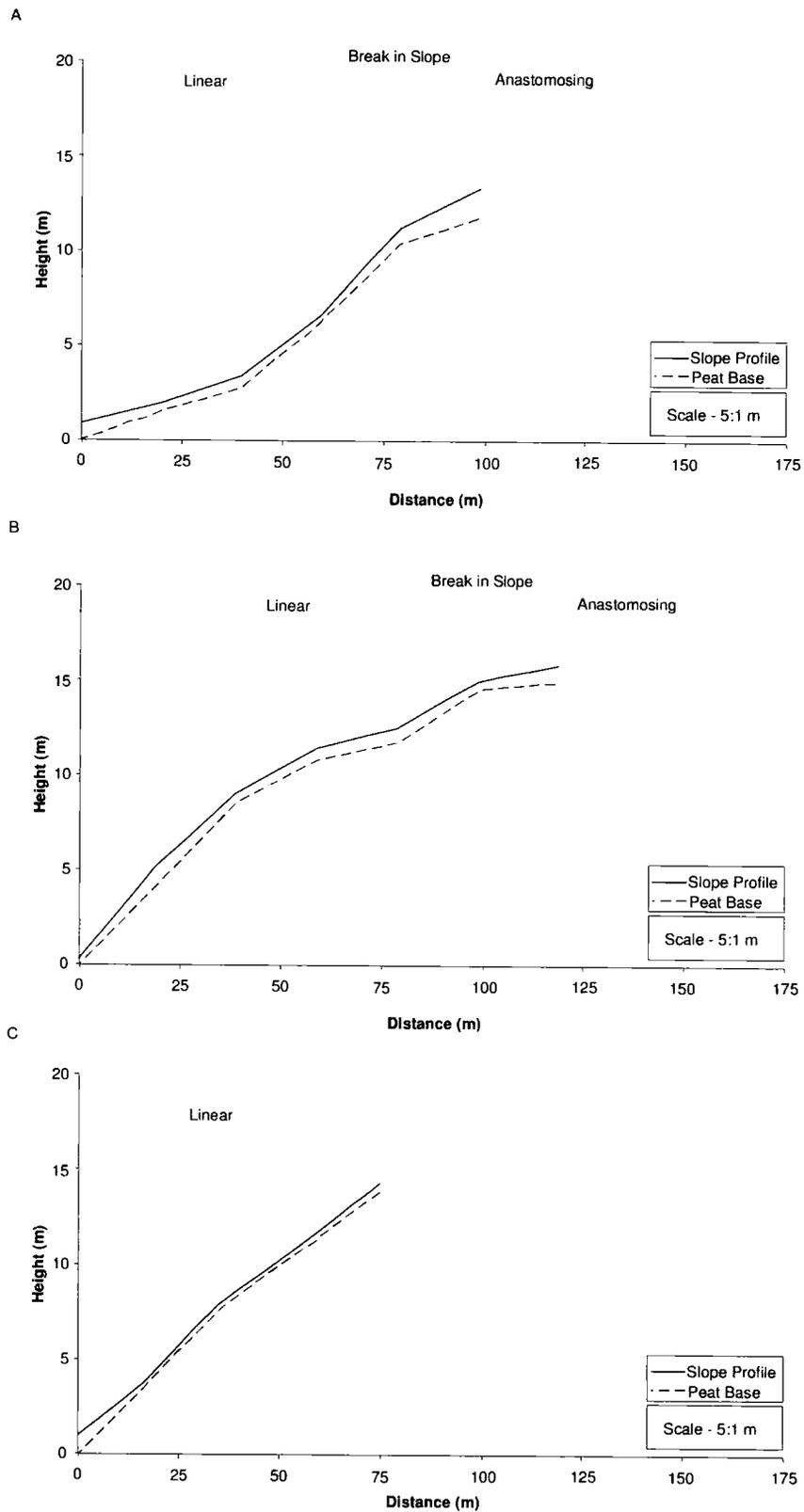
Figure A3.5: Long profiles of A) The gully profile and peat depth of Gully 1. B) The gully profile and peat depth of Gully 2. C) The gully profile and peat depth of Gully 3. The break in slope indicated on the profiles represents the transition between linear and anastomosing dissection.

A3.2 Stratigraphy from the monolith and core samples removed from the three main study sites

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-4	$Sh^3 Tb^1$	Nig^4	$Sicc^4$	H^9	1	2	1	0	Dark brown air-dried peat with *E..angustifolium*
4-19	$Sh^2 Dh^2$	Nig^{3+}	$Sicc^{3+}$	H^7	2	2	0	0	Decomposing, fibrous, red/ brown peat
19-30	$Sh^{2+} Dh^1$ Dl^+	Nig^3	$Sicc^{3+}$	H^8	3	1	0	0	Light brown/ red peat with wood remains
30-73	$Sh^2 Dh^2$	Nig^{3+}	$Sicc^3$	H^7	3	0	0	0	Brown/ red, fibrous, saturated peat

Table A3.1: Stratigraphy of Cross-section 1 (SE), Burnt Hill's main gully system, Moor House.

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-2	$Th^3 Tb^1$	Nig^3	$Sicc^4$	H^3	1	2	1	1	Decomposing vegetation – *Calluna* and *Pleurozium schreberi*
2-5	$Dh^3 Sh^1$	Nig^3	$Sicc^4$	H^5	2	2	0	0	Decomposing, fibrous, red/ brown peat
5-13	$Sh^3 Dh^1$	Nig^{3+}	$Sicc^4$	H^9	3	0	0	0	Dark brown, smooth peat
13-35	$Sh^{2+} Dh^1$ Dl^+	Nig^{3+}	$Sicc^4$	H^8	1	2	1	0	Dark brown, coarse peat with wood remains
35-52	$Sh^2 Dh^1$ Dl^1	Nig^3	$Sicc^4$	H^8	2	2	0	0	Smooth brown, clay peat with coarse and fine fibres and sand layers

Table A3.2: Stratigraphy of Cross-section 2 Right (West), Burnt Hill's main gully system, Moor House.

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-2	$Tb^2 Th^2$	Nig^3	$Sicc^4$	H^4	1	3	1	1	Decomposing grasses, *Calluna* and *Sphagnum* vegetation
2-8	$Sh^2 Dh^1 Dg^1$	Nig^3	$Sicc^{3+}$	H^6	2	2	0	0	Decomposing, fibrous, dark brown peat
8-11	$Sh^3 Dh^1$	Nig^{3+}	$Sicc^{3+}$	H^8	1	3	0	0	Dark brown, smooth, clay peat with dense roots
11-27	$Sh^2 Dh^1 Gmin^1$	Nig^{3+}	$Sicc^{3+}$	H^7	1	3	0	0	Dark brown, fibrous peat with sand layers

Table A3.3: Stratigraphy of Cross-section 2 Middle, Burnt Hill's main gully system, Moor House.

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-2	Sh^4	Nig^{3+}	$Sicc^4$	H^9	1	1	0	0	Dark brown air-dried desiccated peat
2-32	$Dh^2 Sh^{1+} Dl^+$	Nig^3	$Sicc^{3+}$	H^8	2	2	2	0	Fibrous, red/ brown peat with wood remnants
32-33	$Gmin^3 Ag^1$	Nig^2	$Sicc^4$	H^0	0	0	0	0	Sand/ mineral layer
33-38	$Sh^2 Dh^2$	Nig^3	$Sicc^{3+}$	H^8	3	3	0	0	Brown/ red, fibrous, clay peat
38-46	$Sh^{2+} Gmin^1 Dh^+$	Nig^{2+}	$Sicc^{3+}$	H^6	1	0	0	0	Clay peat with sand
46-52	As^4	Nig^2	$Sicc^3$	H^0	0	0	0	0	Grey clay

Table A3.4: Stratigraphy of Cross-section 2 Left (East), Burnt Hill's main gully system, Moor House.

Troel-Smith Classification			Von Post Classification						
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-12	$Th^{2+}Sh^{1+}$	Nig^4	$Sicc^3$	H^5	1	3	0	0	Dark brown/ black saturated peat with grass roots and *Juncus*
12-30	$Sh^2 Dh^1 Dg^1$	Nig^4	$Sicc^3$	H^7	2	2	0	0	Dark brown/ black, saturated peat with coarse and fine fibres and leafy remains
30-40	$Sh^3 Dh^1$	Nig^4	$Sicc^3$	H^8	1	3	0	0	Dark brown/ black, saturated, smooth peat with leafy remains
40-48	$Sh^{2+} Dh^{1+}$	Nig^4	$Sicc^3$	H^7	2	2	0	0	Dark brown/ black, saturated, smooth peat, fibrous with leafy remains
48-64	$Gmin^3 Sh^1 Dh^+$	Nig^4	$Sicc^3$	H^6	0	3	0	0	Saturated peat with sand and coarse roots
64-76	$Gmin^2 As^+ Ag^+ Sh^+ Dh^+$	Nig^3	$Sicc^3$	H^6	0	3	0	0	Saturated peat with sand and coarse roots, grey silt and clay

Table A3.5: Stratigraphy of Gully 1 Left, 4 linear gully systems adjacent to Rough Sike, Moor House.

Troel-Smith Classification			Von Post Classification						
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-9	$Th^2 Sh^2$	Nig^4	$Sicc^4$	H^3	1	3	0	0	Dark brown smooth peat with coarse and fine fibres, grass and small black roots
9-18	$Sh^3 Dh^1$	Nig^4	$Sicc^3$	H^7	2	2	0	0	Dark brown/ black, smooth, saturated peat with coarse and fine fibres
18-26	$Dh^3 Sh^1$	Nig^3	$Sicc^{3+}$	H^7	1	3	0	0	Dark brown, coarse peat with lots of *Sphagnum* roots
26-60	$Sh^{2+} Dh^1 Ag^+$	Nig^3	$Sicc^3$	H^8	2	2	0	0	Dark brown, saturated, smooth, greasy peat with coarse and fine fibres
60-65	$Sh^2 As^{1+} Dh^+$	Nig^4	$Sicc^4$	H^8	2	0	0	0	Dark brown/ black peat with fine fibres and silt
65-73	$As^{1+} Ag^1 Gmaj^1 Gmin^+$	Nig^2	$Sicc^4$	H^0	0	0	0	0	Grey silt/ clay/ sand mix

Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
73-75	$Sh^{1+}As^1$ Dl^+Dh^+ $Gmin^+$	Nig^2	$Sicc^4$	H^3	0	0	2	0	Peat/ silt mix with some wood and sand
75-80	$Ag^2 Gmin^1$ As^1	Nig^2	$Sicc^4$	H^3	0	0	2	0	Peat/ silt/ clay mix with some wood and sand

Table A3.6: Stratigraphy of Gully 1 Right, 4 linear gully systems adjacent to Rough Sike, Moor House.

Troel-Smith Classification				Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-5	$Sh^2 Tb^2$	Nig^3	$Sicc^3$	H^5	1	3	0	0	Decomposing vegetation – dark brown saturated peat with leafy roots
5-21	$Sh^2 Dh^1$ Tb^1	Nig^3	$Sicc^3$	H^5	1	3	0	0	Dark brown smooth saturated peat with grass and leafy roots
21-42	$Sh^3 Dh^1$	Nig^3	$Sicc^3$	H^7	2	2	0	0	Smooth, greasy brown peat with grass roots and coarse and fine fibres
42-56	$Sh^{2+} Dh^1$ Dg^+	Nig^3	$Sicc^3$	H^7	1	2	1	0	Smooth, greasy brown peat with grass roots and coarse and fine fibres, wood and twigs
56-74	$Dh^{2+} Sh^{1+}$	Nig^3	$Sicc^3$	H^6	2	2	0	0	*Sphagnum* peat
74-82	$Sh^{1+} Dh^{1+}$ $Dg^+ Gmin^+$	Nig^{3+}	$Sicc^3$	H^7	2	2	0	0	*Sphagnum* peat. Transition to heather peat. Some twigs and sand layers
82-86	$Sh^2 Ag^{1+}$ Dh^+	Nig^{3+}	$Sicc^{3+}$	H^7	3	1	0	0	Peat/ clay transition. Smooth dark brown/ black peat with fine fibres
86-92	$As^{1+} Ag^{1+}$ $Sh^+ Dl^+$	Nig^{2+}	$Sicc^4$	H^0	0	0	2	0	Brown silt and clay mix with wood

Table A3.7: Stratigraphy of Gully 2 Left, 4 linear gully systems adjacent to Rough Sike, Moor House.

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-39	$Th^2Sh^1Tb^1$	Nig^4	$Sicc^3$	H^3	1	3	0	0	Saturated, very fibrous *Sphagnum* peat with small black roots
39-47	$As^{1+}Dl^1$ Sh^+Dh^+	Nig^3	$Sicc^3$	H^7	3	0	1	0	Light brown saturated silty peat with wood and fine fibres
47-51	$Gmin^2As^{1+}$ Ag^+	Nig^2	$Sicc^4$	H^0	0	0	0	0	Sand/ silt/ clay mix
51-64	Ag^2Gmin^1 As^1	Nig^2	$Sicc^4$	H^0	0	0	0	0	Sand/ silt/ clay mix

Table A3.8: Stratigraphy of Gully 2 Middle, 4 linear gully systems adjacent to Rough Sike, Moor House.

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-2	Tb^4	Nig^3	$Sicc^2$	H^5	1	3	0	0	Living *Sphagnum cuspidatum* vegetation
2-10	$Dh^{2+}Sh^{1+}$	Nig^4	$Sicc^2$	H^6	1	3	0	0	Saturated dark brown peat and *Sphagnum* remains
10-16	Dh^3Sh^1	Nig^4	$Sicc^3$	H^7	1	3	0	0	Saturated dark brown peat and *Sphagnum* remains with grass roots
16-20	$Sh^{2+}Dg^1$ As^+	Nig^4	$Sicc^3$	H^8	1	3	0	0	Transition to dark coarse saturated peat
20-31	Sh^3Dg^1	Nig^4	$Sicc^4$	H^8	2	2	0	0	Dark brown/ black peat with coarse and fine fibres
31-46	Sh^2Dl^1 Dg^+	Nig^3	$Sicc^4$	H^8	2	1	1	0	Brown/ red smooth peat with fine fibres and wood

Table A3.9: Stratigraphy of Gully 2 Right, 4 linear gully systems adjacent to Rough Sike, Moor House.

Troel-Smith Classification				Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-8	$Sh^3 Tb^+$ Th^+	Nig^4	$Sicc^4$	H^6	1	3	0	1	Dark brown/ black, smooth peat with *Calluna*, *Polytrichum commune*, leaves and coarse and fine roots
8-12	$Sh^{2+} Dh^1$ Dl^+	Nig^4	$Sicc^4$	H^8	2	2	1	0	Dark brown/ black peat with coarse and fine fibres and some wood
12-30	$Sh^{2+} Ag^1$ Dl^+	Nig^4	$Sicc^3$	H^9	1	1	1	0	Dark brown/ black, saturated, greasy peat with wood and clay
30-53	$Dh^{2+} Sh^1$ Ag^+	Nig^3	$Sicc^3$	H^7	1	3	0	0	Brown, saturated, greasy, *Sphagnum* peat with leafy remains
53-65	$Sh^2 Dg^+$ $Ag^+ Dl^+$	Nig^4	$Sicc^{3+}$	H^8	2	0	1	0	Dark brown/ black, greasy peat with fine fibres and wood
65-82	$As^2 Gmin^{1+}$ Ag^+	Nig^2	$Sicc^4$	H^0	0	0	0	0	Silt/ sand/ clay mix. Grey
8294	$Ag^2 Gmin^1$ $Gmaj^1$	Nig^2	$Sicc^4$	H^0	0	0	0	0	Sand, grey clay and cobble

Table A3.10: Stratigraphy of Gully 3 Left, 4 linear gully systems adjacent to Rough Sike, Moor House.

Troel-Smith Classification				Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-6	$Sh^{2+} Tb^{1+}$	Nig^4	$Sicc^3$	H^6	1	3	0	0	Dark brown/ black, smooth, saturated peat with grass roots
6-16	$Sh^2 Dh^1$ $Dg^+ As^+$	Nig^{3+}	$Sicc^4$	H^7	2	2	0	0	Dark brown/ black, smooth peat with coarse and fine fibres and silt
16-24	$Sh^{1+} Dh^{1+}$ $As^+ Gmin^+$	Nig^{3+}	$Sicc^4$	H^7	2	3	0	0	Dark brown peat with lots of roots and sand
24-39	$Sh^1 Dh^1$ $As^1 Gmin^1$	Nig^{3+}	$Sicc^4$	H^7	2	3	0	0	Dark brown peat with lots of roots and sand and silt lenses

Depth (cm)	Class type	Darkness	Dryness	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
39-46	$Sh^{1+}As^1$ $Gmin^1 Dh^+$	Nig^{3+}	$Sicc^4$	H^8	1	2	0	0	Dark brown peat with some of roots and sand and silt lenses

Table A3.11: Stratigraphy of Gully 3 Middle, 4 linear gully systems adjacent to Rough Sike, Moor House.

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-7	$Sh^2 Th^1 Dg^+$	Nig^3	$Sicc^4$	H^5	1	2	0	1	Dark brown/ black fibrous peat – *Calluna* and grass roots
7-9	Dl^4	Nig^2	$Sicc^4$	H^5	0	0	3	0	Wood
9-18	$As^2 Sh^1 Ag^+ Dh^+$	Nig^2	$Sicc^4$	H^6	1	2	0	0	Smooth peaty/clay/ silt mix. Light brown with some coarse fibres
18-19	$As^{2+} Amin^1 Dh^+$	Nig^2	$Sicc^3$	H^0	1	1	0	0	Silt and sand, saturated with fibres
19-24	$As^{2+} Ag^1 Dh^+$	Nig^2	$Sicc^3$	H^0	0	0	0	0	Silt and sand, saturated

Table A3.12: Stratigraphy of Gully 3 Right, 4 linear gully systems adjacent to Rough Sike, Moor House.

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-5	Tb^2Th^2	Nig^3	$Sicc^4$	H^4	1	1	0	2	Living *Calluna* and *Pleurozium schreberi* vegetation
5-9	$Dh^{2+}Sh^{1+}$	Nig^3	$Sicc^4$	H^6	3	1	0	0	Very smooth brown/ red peat with lots of coarse and fine fibres
9-12	Dh^2Sh^2	Nig^4	$Sicc^4$	H^8	2	2	0	0	Dark brown peat with few fibres and leafy remains
12-21	$Sh^{3+}Dh^+$	Nig^3	$Sicc^4$	H^9	1	0	0	0	Dark brown/ black smooth peat with few fibres
21-32	Sh^2Dh^1 Ag^1	Nig^3	$Sicc^3$	H^8	1	3	0	0	Smooth, saturated, greasy peat with leafy remains
32-48	$Sh^{2+}Dh^1$ Ag^+	Nig^3	$Sicc^4$	H^8	1	3	0	0	Smooth, greasy peat with leafy remains
48-55	Sh^2Dh^1 Ag^1	Nig^3	$Sicc^4$	H^6	1	3	0	0	Smooth, greasy peat, very fibrous with leafy remains
55-62	$Ag^{1+}Sh^1$ Dh^1Dl^+	Nig^3	$Sicc^4$	H^7	1	2	1	0	Clay, brown peat with some wood and leafy remains
62-72	$Ag^{1+}Sh^1$ As^+Dl^+ Dh^+	Nig^{2+}	$Sicc^4$	H^5	2	0	1	0	Clay/ silt/ peat mix with wood and fine fibres

Table A3.13: Stratigraphy of Gully 4 Left, 4 linear gully systems adjacent to Rough Sike, Moor House.

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-4	Tb^2Th^2	Nig^3	$Sicc^4$	H^4	1	2	0	2	Living *Calluna* and grasses
4-12	Sh^2Th^1 Tb^+Gmin^+	Nig^{3+}	$Sicc^3$	H^6	1	3	0	0	Dark brown saturated smooth peat with sand, wood and leafy roots
12-24	$Sh^{2+}Tb^+$ Dh^+Gmin^+	Nig^4	$Sicc^4$	H^8	2	2	0	0	Dark brown/ black coarse peat with sand, coarse and fine fibres
24-40	$Gmin^2As^1$ Sh^+Dh^+	Nig^3	$Sicc^4$	H^7	2	2	0	0	Peat/ silt/ sand mix with coarse and fine fibres

Table A3.14: Stratigraphy of Gully 4 Middle, 4 linear gully systems adjacent to Rough Sike, Moor House.

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-1	$Tb^2 Th^2$	Nig^3	$Sicc^4$	H^4	1	2	0	2	Living *Calluna*, grasses and *Pleurozium schreberi* vegetation
1-5	$Dg^2 Sh^{1+} Th^+$	Nig^3	$Sicc^3$	H^5	1	3	0	0	Brown/ red saturated fibrous peat
5-12	$Sh^{2+} Dg^1 Dh^+$	Nig^4	$Sicc^4$	H^7	2	2	0	0	Dark brown/ black coarse peat with roots, coarse and fine fibres
12-40	$Sh^{1+} Dh^1 Ag^+ Dl^+$	Nig^3	$Sicc^3$	H^7	1	3	0	0	Brown, smooth, greasy, saturated peat with leafy roots and twigs
40-46	$Dl^{1+} Sh^1 Ag^1 Dg^+$	Nig^4	$Sicc^3$	H^7	0	2	2	0	Dark brown, greasy peat with wood and coarse fibres
46-82	$Ag^2 As^{1+} Gmin^+$	Nig^2	$Sicc^4$	H^0	1	0	0	0	Light brown clay/ sand/ silt mix. Very few fine fibres
82-86	$Ag^2 Gmin^{1+} As^+$	Nig^2	$Sicc^4$	H^0	1	0	0	0	Light brown clay/ sand/ silt mix. Very few fine fibres – less silt

Table A3.15: Stratigraphy of Gully 4 Right, 4 linear gully systems adjacent to Rough Sike, Moor House.

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-3	Sh^4	Nig^4	$Sicc^4$	H^9	1	0	0	0	Dark brown/ black, air-dried desiccated peat with very fine fibres
3-7	$Sh^2 Dg^1 Dl^1$	Nig^4	$Sicc^3$	H^8	2	2	1	0	Dark brown/ black, saturated desiccated peat with coarse and fine fibres and wood
7-19	$Sh^{2+} Dg^{1+}$	Nig^3	$Sicc^3$	H^8	2	2	0	0	Dark brown, saturated, peat with coarse and fine fibres
19-23	$Dl^{2+} Sh^{1+}$	Nig^3	$Sicc^4$	H^8	1	1	3	0	Wood layer and peat
23-35	$Sh^2 Dg^1 Dh^+$	Nig^3	$Sicc^3$	H^7	1	3	0	0	Dark brown, saturated, fibrous peat with twigs

Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
35-49	Sh^2Dh^{1+} Dg^+	Nig^2	$Sicc^3$	H^7	1	3	0	0	Brown, saturated, fibrous, *Sphagnum* peat with a burnt type layer
49-66	$Sh^{2+}Dh^{1+}$	Nig^4	$Sicc^3$	H^8	2	2	0	0	Dark brown/ black, smooth, saturated peat with coarse and fine fibres
66-77	$Sh^{3+}Dh^+$	Nig^4	$Sicc^4$	H^9	2	0	0	0	Dark brown/ black, smooth peat with fine fibres
77-88	$Sh^{2+}Dh^{1+}$	Nig^4	$Sicc^4$	H^8	1	3	0	0	Dark brown/ black, smooth peat with leafy remains
88-129	Sh^2Dg^2	Nig^4	$Sicc^4$	H^9	2	2	0	0	Dark brown/ black, smooth peat with coarse and fine fibres and wood
129-136	Dg^3Sh^1	Nig^4	$Sicc^4$	H^7	1	3	0	0	Very fibrous coarse peat
138-146	Sh^2Dg^2	Nig^4	$Sicc^4$	H^9	2	2	0	0	Dark brown/ black, smooth peat with coarse and fine fibres and wood
146-151	Dl^3Sh^1	Nig^3	$Sicc^4$	H^8	2	2	2	0	Peat with wood layer
151-178	Dh^2Sh^{1+} Dg^+	Nig^3	$Sicc^3$	H^8	1	2	1	0	Brown, saturated, *Sphagnum* peat with leafy remains and wood
178-188	$Sh^{1+}Dh^1$ Ag^1Dg^+	Nig^3	$Sicc^3$	H^8	1	2	1	0	Brown, saturated, *Sphagnum* peat with leafy remains, wood and clay
188-198	Ag^2Sh^1 Dh^+As^+	Nig^2	$Sicc^4$	H^0	1	3	0	0	Grey clay with some silt, peat and leafy remains
198-204	$Ag^{2+}As^1$ Dh^+	Nig^2	$Sicc^4$	H^0	2	0	0	0	Grey clay with some silt and very fine fibres
204-218	As^4	Nig^2	$Sicc^4$	H^0	0	0	0	0	Grey silt

Table A3.16: Stratigraphy of Moss Flats, Moor House (Eroded).

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-2	Tb^4	Nig^2	$Sicc^4$	H^6	1	3	0	1	Decomposing *Calluna*, *Pleurozium schreberi* and *Polytrichum commune* vegetation

									Description
2-6	$Sh^2 Th^{1+} Dg^+$	Nig^{3+}	$Sicc^3$	H^8	2	2	0	0	Dark brown/ black, saturated, smooth peat with coarse and fine fibres
6-18	$Sh^2 Dh^{1+} Dg^+$	Nig^{3+}	$Sicc^3$	H^8	2	2	0	0	Dark brown, saturated, smooth peat with coarse and fine fibres and leafy remains
18-22	$Dh^{2+} Sh^1 Dg^+$	Nig^3	$Sicc^3$	H^7	1	3	0	0	Very fibrous peat layer
22-36	$Dh^2 Sh^{1+} Dg^+$	Nig^3	$Sicc^3$	H^8	1	2	0	0	Brown *Sphagnum* peat, saturated with some thin coarse fibres
36-54	$Dh^{2+} Sh^{1+}$	Nig^3	$Sicc^3$	H^7	1	3	0	0	Brown, saturated, smooth, sphagnum peat with lots of leafy remains
54-94	$Sh^{2+} Dh^{1+}$	Nig^{3+}	$Sicc^4$	H^9	2	2	0	0	Dark brown, smooth peat with leafy remains and coarse and fine fibres
94-110	$Sh^3 Dh^1$	Nig^{3+}	$Sicc^3$	H^8	2	2	0	0	Dark brown/ red, smooth, saturated peat with leafy remains, coarse and fine fibres
110-138	$Sh^3 Dh^1$	Nig^3	$Sicc^3$	H^9	2	2	1	0	Brown, smooth, saturated peat with coarse and fine fibres and wood
138-221	$Sh^3 Dh^1$	Nig^{3+}	$Sicc^3$	H^9	2	2	0	0	Dark brown/ red, smooth, saturated peat with leafy remains, coarse and fine fibres
221-246	$Sh^{2+} Dh^1 Dg^+$	Nig^3	$Sicc^3$	H^9	2	2	0	0	Brown/ red, smooth, saturated peat with leafy remains, coarse and fine fibres
246-272	$Sh^3 Dl^1 Dh^+$	Nig^3	$Sicc^3$	H^9	2	2	1	0	Brown/ red, smooth, very saturated peat with leafy remains, coarse and fine fibres and wood
272-280	$Gmin^1 Ag^1 Dh^1 Dg^+ Sh^+$	Nig^{3+}	$Sicc^{3+}$	H^8	2	2	1	0	Dark brown, very fibrous peat with clay, sand, leafy remains, coarse and fine fibres and twigs
280-286	$As^2 Gmin^{1+} Sh^+$	Nig^{2+}	$Sicc^4$	H^3	0	0	0	0	Silt/ sand/ peat. Dark grey
286-295	$Ag^{2+} Gmaj^1 Gmin^+$	Nig^2	$Sicc^4$	H^0	0	0	0	0	Clay/ sand and cobbles
295-307	Ag^4	Nig^2	$Sicc^4$	H^0	0	0	0	0	Grey clay

Table A3.17: Stratigraphy of the intact peat adjacent to Moss Flats, Moor House (uneroded).

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humific	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-27	$Th^3\ Tb^1$	Nig^3	$Sicc^3$	H^3	1	3	0	0	Living vegetation – *Calluna* and *Vaccinium mrytillus*
27-54	$Sh^{2+}\ Dh^{1+}$	Nig^3	$Sicc^1$	H^6	2	2	0	0	Brown dry peat with coarse and fine *Sphagnum* fibres
54-68	$Sh^{3+}\ Dh^+$	Nig^2	$Sicc^3$	H^7	2	2	0	0	Light brown peat with coarse and fine *Sphagnum* fibres
68-98	Sh^4	Nig^4	$Sicc^3$	H^8	3	1	0	0	Dark brown peat with fine fibres
98-99	$Sh^3\ Gmaj^1$	Nig^3	$Sicc^2$	H^8	2	2	0	0	Bare with large mineral clasts

Table A3.18: Stratigraphy of Gully 2, The Cheviot, Cross Profile 5 left.

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humific	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-16	$Sh^{2+}\ Th^{1+}$	Nig^2	$Sicc^2$	H^5	1	3	0	0	Smooth dark brown peat with numerous grassy roots
16-40	$Sh^{2+}\ Dh^{1+}$	Nig^3	$Sicc^3$	H^7	1	3	0	0	Red/ dark brown peat with sphagnum
40-58	$Ag^2\ Gmin^{1+}\ Sh^+$	Nig^2	$Sicc^1$	H^6	2	2	0	0	Dark brown/ black peat with some sand and silt layers

Table A3.19: Stratigraphy of Gully 2, The Cheviot, Cross Profile 5 middle.

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humific	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-18	$Sh^2 Th^1 Tb^1$	Nig^3	$Sicc^3$	H^5	2	2	0	0	Smooth dark brown peat with coarse and fine fibres
18-27	$Sh^{2+} Dg^{1+}$	Nig^4	$Sicc^2$	H^6	2	2	0	0	Dark brown peat with coarse and fine fibres
27-32	$Dh^3 Sh^1$	Nig^4	$Sicc^2$	H^6	1	3	0	0	Dark brown *Sphagnum* peat
32-61	$Sh^{2+} Dg^1 Dh^+$	Nig^4	$Sicc^2$	H^6	2	2	0	0	Dark brown peat with coarse and fine fibres
61-82	$Sh^{2+} Dh^{1+}$	Nig^3	$Sicc^1$	H^8	2	2	0	0	Smooth dark brown/ red peat with some coarse leafy fibres and fine fibres

Table A3.20: Stratigraphy from the top of Gully 3, The Cheviot (Eroded).

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-13	$Th^2 Tb^2$	Nig^2	$Sicc^2$	H^3	1	2	0	1	Vegetation - Grasses
13-15	Tb^4	Nig^2	$Sicc^2$	H^4	3	3	0	0	Decomposing grasses
15-24	$Sh^{2+} Th^1 Dg^+$	Nig^4	$Sicc^3$	H^6	2	2	0	0	Dark brown/ black smooth peat with coarse and fine roots
24-30	$Sh^3 Dh^1$	Nig^{3+}	$Sicc^3$	H^7	2	2	0	0	Dark brown/ black smooth peat with some coarse and fine roots
30-38	$Sh^{2+} Dh^{1+}$	Nig^{3+}	$Sicc^{3+}$	H^7	2	2	0	0	Transition to *Sphagnum*/ less humified peat, saturated
38-70	Dh^4	Nig^3	$Sicc^{3+}$	H^5	2	2	0	0	Saturated *Sphagnum* peat, fibrous
70-76	$Sh^2 Dh^1 Dg^1$	Nig^{3+}	$Sicc^{3+}$	H^5	2	2	0	0	Saturated *Sphagnum* peat, less fibrous
76-90	$Dh^2 Sh^1 Dg^1$	Nig^3	$Sicc^{3+}$	H^6	2	1	1	0	Mixture of *Sphagnum* peat and woody fragments
90-102	$Sh^3 Dg^+ Dh^+$	Nig^3	$Sicc^3$	H^7	2	2	0	0	Less fibrous, smooth dark brown peat with coarse and fine fibres
102-106	$Sh^{2+} Dg^{1+}$	Nig^{3+}	$Sicc^2$	H^7	2	2	0	0	Dark brown saturated peat with coarse and fine fibres. Not smooth
106-118	$Sh^{2+} Dg^{1+}$	Nig^{3+}	$Sicc^{3+}$	H^6	2	2	0	0	Saturated *Sphagnum* peat, fibrous

Depth	Class type	Darkness	Dryness	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
118-130	$Sh^{2+}Dg^1Dh^+$	Nig^3	$Sicc^{3+}$	H^6	2	2	0	0	Saturated *Sphagnum* peat, fibrous. Not as smooth
130-142	$Sh^{2+}Dg^{1+}$	Nig^{3+}	$Sicc^{3+}$	H^7	2	2	0	0	Dark brown saturated peat with coarse fibres. Not smooth
142-159	$Sh^{2+}Dh^{1+}$	Nig^3	$Sicc^4$	H^6	2	2	0	0	Light brown *Sphagnum* peat
159-178	$Sh^{1+}Dh^{1+}Ag^1$	Nig^3	$Sicc^3$	H^9	3	1	0	0	Very smooth clay peat with fine fibres
178-182	$Sh^1Dh^1Ag^1Gmin^1$	Nig^{2+}	$Sicc^3$	H^9	3	1	0	0	Very smooth clay peat with fine fibres but with some sand grains

Table A3.21: Stratigraphy of the intact peat adjacent to Gully 3, The Cheviot (Uneroded).

	Troel-Smith Classification			Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-2	Tb^4	Nig^2	$Sicc^4$	H^2	1	3	0	0	Living vegetation – *E. angustifolium* and *E. vaginatum*
2-9	Sh^2Tb^2	Nig^3	$Sicc^4$	H^8	2	2	0	0	Air-dried crumbly dark brown peat with grassy roots, coarse and fine fibres
9-31	$Dh^{2+}Sh^{1+}$	Nig^3	$Sicc^3$	H^7	2	2	0	0	Dark brown/ red brown peat with coarse and fine fibres and *Sphagnum*
31-38	Dh^3Sh^1	Nig^3	$Sicc^3$	H^6	1	3	0	0	Fibrous *Sphagnum* peat
38-109	$Dh^{2+}Sh^1Dg^+$	Nig^3	$Sicc^3$	H^7	1	3	0	0	Dark brown/ red brown *Sphagnum* peat, saturated with small black roots
109-116	$Dh^{2+}Sh^{1+}$	Nig^3	$Sicc^3$	H^6	1	3	0	0	Dark brown/ red *Sphagnum* peat with lots of leafy roots
116-171	$Dh^{2+}Sh^1Dg^+$	Nig^3	$Sicc^3$	H^7	1	1	0	0	Dark brown/ red saturated *Sphagnum* peat with lots of grassy roots and small black roots
171-202	$Sh^2Dh^{1+}Dg^+$	Nig^4	$Sicc^{3+}$	H^8	2	2	0	0	Dark brown/ black saturated peat with coarse and fine fibres. Transition from *Sphagnum* peat to coarse black peat
202-214	Sh^2Dh^2	Nig^4	$Sicc^3$	H^7	1	3	0	0	Dark brown/ black peat, saturated with leafy roots
214-255	$Sh^{3+}Dh^+$	Nig^4	$Sicc^{2+}$	H^9	3	1	0	0	Black, greasy, very smooth peat with few fine fibres

Depth	Class type	Darkness	Dryness	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
255-273	$Sh^{2+}Ag^1$ Dh^+	Nig^4	$Sicc^4$	H^9	3	1	0	0	Dark brown/ black smooth, peat with clay and fine fibres
273-279	$Gmin^{1+}$ As^1Sh^1 Ag^+	Nig^3	$Sicc^4$	H^8	3	1	1	0	Dark brown peat with silt, sand and clay mix
279-294	Sh^2Ag^1 Dh^+Dg^+	Nig^4	$Sicc^4$	H^7	2	2	0	0	Dark brown/ black peat with leafy roots, small black roots and clay

Table A3.22: Stratigraphy from Gully 2, Wessenden Head Moss, Cross Profile 14 left.

Troel-Smith Classification				Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-20	Tb^4	Nig^2	$Sicc^4$	H^2	1	3	0	0	Saturated – water and living vegetation – *Sphagnum* spp., *E. angustifolium* and *E. vaginatum*, *Juncus effusus*
20-36	Sh^2Tb^2	Nig^4	$Sicc^3$	H^4	1	3	0	0	Dark brown/ black smooth peat, saturated with grassy and *Juncus* roots
36-53	$Sh^{2+}Dh^1$ Tb^+	Nig^4	$Sicc^3$	H^7	1	3	0	0	Dark brown/ black smooth peat, saturated with grassy and leafy roots
53-77	$Sh^{2+}Dh^{1+}$	Nig^4	$Sicc^3$	H^6	1	2	1	0	Dark brown/ black smooth peat, saturated with grassy leafy roots and wood (twigs)
77-87	Dh^4	Nig^4	$Sicc^3$	H^7	1	3	0	0	Dark brown/ black smooth peat, saturated with grassy roots
87-93	Sh^2Dh^1 Dg^1	Nig^4	$Sicc^3$	H^8	2	2	0	0	Smooth dark brown/ black peat with coarse and fine fibres
93-100	Sh^2Dh^2	Nig^4	$Sicc^3$	H^8	2	2	0	0	Dark brown/ black saturated, smooth peat with grassy roots, coarse and fine fibres
100-115	$Dh^{2+}Sh^1$ Dg^+	Nig^3	$Sicc^{2+}$	H^8	2	2	0	0	Dark brown/ black saturated, greasy peat with red coloured roots
115-130	Sh^2Dh^2	Nig^3	$Sicc^{2+}$	H^7	1	3	0	0	Dark brown smooth peat with leafy roots
130-146	Sh^2Dh^2	Nig^3	$Sicc^{2+}$	H^7	1	3	0	0	Dark brown smooth peat with lots of leafy roots

Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
146-176	$Sh^3 Dh^+ Ag^+$	Nig^4	$Sicc^3$	H^6	2	2	0	0	Dark brown/ black smooth, greasy peat with lots of leafy roots
176-183	$Dl^{2+} Sh^1 Ag^+$	Nig^4	$Sicc^3$	H^6	1	2	1	0	Dark brown/ black smooth, greasy peat with lots of leafy roots and wood
183-188	$Sh^{2+} Ag^1 Dh^+$	Nig^4	$Sicc^3$	H^6	1	2	1	0	Dark brown/ black smooth, greasy peat with lots of leafy roots, wood and clay

Table A3.23: Stratigraphy from Gully 2, Wessenden Head Moss, Cross Profile 14 middle.

Troel-Smith Classification				Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-18	$Sh^2 Tb^{1+} Dh^+$	Nig^3	$Sicc^3$	H^4	1	3	0	0	Red/ brown air-dried peat with *E. vaginatum*, *Juncus effusus* and coarse and fine fibres
18-33	$Sh^2 Dh^2$	Nig^3	$Sicc^3$	H^6	1	3	0	0	Dark brown/ red sphagnum peat with *Juncus* roots and leaves
33-53	$Sh^2 Dh^2$	Nig^3	$Sicc^3$	H^7	1	3	0	0	Dark brown/ red brown sphagnum peat with *Juncus* roots
53-63	$Dh^{3+} Sh^+$	Nig^3	$Sicc^{3+}$	H^7	1	3	0	0	Dark brown/ red peat with leafy fibres
63-88	$Sh^3 Dh^1$	Nig^4	$Sicc^3$	H^8	2	2	0	0	Black saturated coarse peat with coarse and fine fibres
88-101	$Dh^{2+} Sh^{1+}$	Nig^3	$Sicc^4$	H^8	2	2	0	0	Dark brown/ red peat with coarse and fine fibres
101-119	$Dh^3 Sh^+ Dg^+$	Nig^3	$Sicc^4$	H^8	1	3	0	0	Dark brown/ red peat with leafy fibres
119-142	$Sh^2 Dh^2$	Nig^4	$Sicc^3$	H^8	1	2	1	0	Dark brown/ black smooth saturated peat with lots of leafy fibres and wood
142-153	$Sh^2 Dh^2$	Nig^{3+}	$Sicc^3$	H^7	1	3	0	0	Dark brown peat, saturated with leafy roots
153-167	$Sh^2 Dh^2$	Nig^{3+}	$Sicc^3$	H^7	1	3	0	0	Dark brown peat, very saturated with leafy roots
167-181	$Dh^2 Sh^1 Dg^1$	Nig^4	$Sicc^4$	H^6	1	3	0	0	Dark brown/ black peat with coarse and fine fibres, leafy fibres and small black roots
181-192	$Sh^2 Dh^2$	Nig^4	$Sicc^4$	H^8	2	2	0	0	Dark brown/ black peat with coarse and fine fibres
192-	$Sh^2 Dh^2$	Nig^{3+}	$Sicc^3$	H^7	2	2	0	0	Dark brown smooth saturated peat with coarse and

Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
220									fine fibres, leafy roots
220-244	$Sh^{2+}Dh^{1+}$	Nig^4	$Sicc^3$	H^8	2	0	0	0	Very saturated smooth dark brown/ black peat with few fibres
244-262	$Sh^2 Dh^2$	Nig^4	$Sicc^2$	H^8	2	2	0	0	Very saturated smooth dark brown/ black peat with coarse and fine fibres
262-274	$Sh^2 Dl^1 Ag^1$	Nig^3	$Sicc^3$	H^9	3		1	0	Smooth clay/ dark brown peat with wood
274-284	$As^3 Ag^+$ $Gmin^+$	Nig^2	$Sicc^4$	H^0	0	0	0	0	Silt and sand (brown/ tan)

Table A3.24: Stratigraphy from Gully 2, Wessenden Head Moss, Cross Profile 14 right.

Troel-Smith Classification				Von Post Classification					
Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
0-12	$Sh^2 Dh^2$	Nig^{3+}	$Sicc^4$	H^9	2	2	0	0	Fibrous dark brown peat with grass roots (bare)
12-15	$Dh^3 Sh^1$	Nig^{3+}	$Sicc^4$	H^7	2	2	0	0	Grassy roots
15-24	$Dh^{2+} Sh^{1+}$	Nig^{3+}	$Sicc^3$	H^7	2	2	0	0	Fibrous dark brown peat, saturated with *Sphagnum* and leaves
24-33	$Sh^2 Dh^2$	Nig^{3+}	$Sicc^3$	H^6	2	3	0	0	Very fibrous dark brown peat, saturated with *Sphagnum* and leaves
33-58	$Sh^2 Dh^2$	Nig^{3+}	$Sicc^3$	H^6	2	3	0	0	Very fibrous dark brown peat, saturated with *Sphagnum* and grass roots
58-110	$Dh^{2+} Sh^{1+}$	Nig^{3+}	$Sicc^3$	H^7	2	2	0	0	Dark brown smooth saturated peat with grass roots
110-122	$Dh^{1+} Sh^{1+}$ Dg^1	Nig^{3+}	$Sicc^3$	H^7	2	2	0	0	Dark brown smooth saturated peat with grass roots and small black roots
122-146	$Dh^{2+} Sh^{1+}$	Nig^3	$Sicc^3$	H^8	2	2	0	0	Brown, saturated, smooth peat with *Sphagnum* fibres and grass roots
146-163	$Dh^{1+} Dg^{1+}$ Sh^1	Nig^{3+}	$Sicc^4$	H^7	2	2	0	0	Dark brown peat with lots of grass roots and small black roots
163-206	$Dh^2 Sh^1$ Dg^1	Nig^{3+}	$Sicc^3$	H^7	2	2	0	0	Dark brown peat, saturated with small black roots, *Sphagnum* and grass roots
206-256	$Dh^{2+} Sh^{1+}$	Nig^{3+}	$Sicc^3$	H^7	2	2	0	0	Dark brown, fibrous, saturated peat with fine leaf fibres and grass roots

Depth (cm)	Class type	Darkness (0-4)	Dryness (0-4)	Humif	Fine Fibres	Coarse Fibres	Wood remnants	Shrub	Written Description
256-292	$Sh^{2+}Dh^{1+}$	Nig^3	$Sicc^4$	H^8	2	3	0	0	Brown, smooth peat with fine leaf fibres and grass roots
292-300	$Sh^2 Dh^2$	Nig^3	$Sicc^4$	H^7	2	3	0	0	Fibrous *Sphagnum* peat with small black roots
300-310	$Sh^2 Dh^{1+} Dl^+$	Nig^3	$Sicc^{3+}$	H^8	2	3	1	0	Smooth, brown, greasy peat with wood and leaf fibres
310-332	$Sh^{2+} Dh^{1+}$	Nig^{3+}	$Sicc^{3+}$	H^8	1	3	0	0	Dark brown/ red brown, smooth peat with leafy fibres
332-344	$Sh^2 Dh^{1+} Gmin^+$	Nig^{3+}	$Sicc^4$	H^8	1	3	0	0	Dark brown/ red brown, smooth peat with leafy fibres with sand and gravel

Table A3.25: Stratigraphy from the top of Gully 2, Wessenden Head Moss (eroded).

	Troel-Smith Classification				Von Post Classification				
Depth (cm)	**Class type**	**Darkness (0-4)**	**Dryness (0-4)**	**Humif**	**Fine Fibres**	**Coarse Fibres**	**Wood remnants**	**Shrub**	**Written Description**
0-2	$Sh^2 Tb^2$	Nig^2	$Sicc^3$	H^7	2	3	0	2	Vegetation – *Eriophorum* spp. and *Calluna*, dark brown, saturated peat with fine grass roots
2-6	$Tb^{2+} Sh^{1+}$	Nig^4	$Sicc^3$	H^8	2	2	0	0	Dark brown, fibrous, saturated peat with leaf remains
6-10	$Tb^3 Sh^1$	Nig^{3+}	$Sicc^3$	H^8	2	2	0	0	Dark brown, very fibrous, saturated peat with leaf remains
10-12	$Tb^2 Dh^1 Sh^1$	Nig^3	$Sicc^{3+}$	H^8	2	3	0	0	Transition to more fibrous *Sphagnum* peat, dark brown
12-20	$Dh^2 Tb^1 Sh^1$	Nig^3	$Sicc^4$	H^7	2	2	0	0	Brown, fibrous peat with coarse and fine fibres and leaf remains
20-25	$Dh^3 Sh^1$	Nig^{2+}	$Sicc^4$	H^7	2	1	0	0	Light brown peat with fine leaf remains
25-32	$Dh^{3+} Sh^+$	Nig^3	$Sicc^4$	H^8	2	2	0	0	Coarse brown peat with leaf remains and grass roots
32-66	$Dh^3 Sh^1$	Nig^3	$Sicc^4$	H^8	1	2	0	0	Smooth, brown peat with grass roots
66-153	$Dh^{2+} Sh^{1+}$	Nig^3	$Sicc^4$	H^9	1	1	0	0	Very smooth, brown peat with few grass roots
153-173	$Sh^{21} Dh^1 Dl^1 Dg^+$	Nig^3	$Sicc^3$	H^8	1	2	0	0	Brown, saturated *Sphagnum* peat with coarse roots

Depth		Nig	Sicc	H					Description
173-200	$Sh^{1+}Dh^{1+}$ Dg^1	Nig^3	$Sicc^3$	H^7	2	1	0	0	Saturated, smooth, *Sphagnum* peat with fine fibres
200-226	$Sh^{2+}Dh^{1+}$	Nig^3	$Sicc^3$	H^8	2	2	0	0	Saturated, smooth, *Sphagnum* peat with leaf remains
226-267	$Sh^{1+}Dh^{1+}$ Dg^1	Nig^3	$Sicc^{3+}$	H^7	2	3	0	0	Fibrous peat with leaf remains
267-287	Sh^2Dh^{1+} Dl^+	Nig^{3+}	$Sicc^4$	H^6	3	3	1	0	More fibrous, dark brown peat with leaf remains and some wood, not saturated
287-327	Sh^2Dl^1 Dh^1Ag^1	Nig^{3+}	$Sicc^4$	H^9	2	1	1	0	Very smooth, greasy, dark brown peat with coarse and fine fibres and wood roots
327-331	Sh^2Dh^2	Nig^4	$Sicc^4$	H^8	1	1	0	0	Fibrous, grassy, dark brown/ black peat, not saturated
331-332	Sh^2Dh^2	Nig^4	$Sicc^4$	H^9	1	2	1	0	Dark brown/ black peat with twigs – not saturated
332-339	$Anth^{2+}$ Sh^{1+}	Nig^4	$Sicc^4$	H^9	2	2	0	0	Black, smooth, charred peat
339-340	$Gmin^{2+}$ $Anth^{1+}$	Nig^2	$Sicc^4$	H^0	0	0	0	0	Sand, peat mix

Table A3.26: Stratigraphy from the intact peat adjacent to Gully 2, Wessenden Head Moss (uneroded).

A3.3 Repeat ground based photographs from Wessenden Head Moss

A

B

Figure A3.6: Historical change in a gully system on Wessenden Head Moss.
A) 1981 (Photographed by Tim Burt). B) 2002.

Figure A3.7: Historical change in Gully 2 on Wessenden Head Moss. A) 1981 (Photographed by Tim Burt). B) 2002.

A

B

Figure A3.8: Historical change on the public footpath on Wessenden Head Moss. A) 1981 (Photographed by Tim Burt). B) 2002.