Chapter One

Introduction

1.1 The Aims of this Volume

The aim of this monograph is to report recent work on the geomorphology of upland peatlands, and review current understanding of erosion processes and the long-term evolution of eroding upland systems. The book is written not only for peatland geomorphologists but also to provide a useful reference on current understanding of the physical functioning of peat landsystems for those working on their ecology, whether from a research perspective, or involved in practical management. In essence this book provides a state-of-the-art appraisal of understanding of the geomorphology of upland peats and demonstrates the importance of a geomorphological perspective for the understanding and management of these important and sensitive upland systems.

In this chapter we outline the scope of the book and provide a framework for evaluating the geomorphology of upland peat landsystems. First we consider the thematic and geographical context of the study. This is followed by explanation of some basic terminology and definitions used to describe peat and the classification of peatlands. We then discuss the geography of blanket mire complexes and examine patterns and causes of peat erosion. This is placed in the context of the evolution of peatland geomorphological science culminating in the development of a peat landsystem model which is used as a general framework for the book as a whole.

1.1.1 Thematic coverage

Upland peat is the residual product of the functioning of a series of fascinating and highly complex moorland ecosystems. As such it is hardly surprising that writing about peat landsystems has been dominated by biologists and ecologists (e.g. Gore 1983). Central to understanding these wetland systems has been an appreciation of their hydrology and there is an extensive body of literature describing the hydrological functioning of upland peatlands (see for example Ivanov 1981; Ingram 1983; Hughes and Heathwaite 1995b; Baird et al. 2004). However, in addition to their ecological functioning, upland peats are important terrestrial material stores. The slow continual accumulation of peat in intact peat bogs preserves a prehistoric archive interrogated by palaeo-ecologists and archaeologists alike (Charman 2002). When environmental conditions change, whether naturally or through human intervention, the continual accumulation of peat can be interrupted, and when the surface vegetation is stressed or removed the deep accumulations of organic sediment may begin to erode. Under these circumstances both the morphology and the ecological and hydrological functioning of the system becomes strongly influenced by erosion processes. This is an aspect of peatland functioning which has been relatively little studied.

This volume covers the hydrologically and ecologically controlled forms of intact upland mires but the majority of the book is concerned with the geomorphology of peatlands where processes of physical erosion are dominant. This focus is pertinent to mire management and conservation since it is in eroding peatlands where an understanding of their geomorphology is central to contemporary management and prediction of future mire condition.

1.1.2 Geographical context

The core of the book is focused on the authors' work on the eroding peatlands of northern Britain, particularly in the Pennine ranges, but every effort has been made to place this work in a wider context with reference to the most up-to-date work on upland mire systems. The United Kingdom (UK) has the most extensive erosion of upland peat in the world, and the vast majority of academic work on the causes, mechanisms and consequences of peat erosion is based on UK sites. Approximately 90 per cent of the published work on the geomorphology of upland peat refers to material derived from work in the British Isles. This fact, together with the geographical location of the authors' work, inevitably means that there is a strong UK focus to this book. However, the implications of what is reported extend beyond concerns with the management of erosion in the UK.

There is much debate over the causes of the extensive erosion in UK uplands but whilst severe land-use pressure has certainly been a factor, there is strong circumstantial evidence that climatic changes have played a major role. Increased storminess (Stevenson et al. 1992; Rhodes and Stevenson 1997) and desiccation of the mire surface (Tallis 1995) are both implicated and are effects which might be exacerbated across much of the world's northern peatlands under projected global climate changes (Houghton et al. 2001). UK peatlands are therefore an important field laboratory for the development of a thorough understanding of the dynamics of eroding peatlands. This will be essential in developing strategies to mitigate the possibility of enhanced physical degradation of wider northern peatlands in response to climate change, and the major effects on biodiversity, the carbon cycle and water quality which this would entail.

1.2 Terminology, Definitions and Peatland Geomorphology

There are several peatland classification schemes with terminology varying between nationalities and professional communities. Excellent summaries of the main classification types are given by Moore (1984) and Charman (2002). In this section the peatland terminology adopted in this volume is defined and the main types of upland peatland considered are identified.

1.2.1 Definitions of peat

Peat is an accumulation of the partly decomposed or undecomposed remains of plant material. There is a large range of peat types whose main properties vary depending primarily on the type of plant material composing the bulk of the organic matter and the degree of humification of the material. In most common soil classification schemes peat is usually treated as a distinct class. Even under specific organic soil classifications, peat is a distinct end member (Myślińska 2003). Under the widely accepted USDA Soil Taxonomy, organic soils form one of the main 12 soil orders and are known collectively as Histosols. Histosols contain at least 20–30 per cent organic matter by weight and are more than 0.4 metres thick. They have low bulk densities and high carbon contents. These soils occupy approximately 1.2 per cent of the ice-free land surface globally and are usually referred to as peats or mucks (McDaniel 2005). Peat deposits are also normally defined in terms of the depth of peat present in a particular setting but local definitions may vary. In a British and Irish context the criteria for separating peat from mineral soil varies. The Soil Survey of England and Wales uses 0.4 metres as the minimum depth for a peat deposit (Cruickshank and Tomlinson 1990), whilst 0.5 metres is

Table 1.1 Key properties of peat and examples of the importance of these for peatland geomorphic processes. This is not a comprehensive survey. It is included to demonstrate the important link between the peat material properties and controls on surficial processes

Peat Property	*Importance*	*Reference*
Basic Properties		
Water content of peat	The water content of peat can vary from about 200% to >2,000% of dry weight. The ability to store large volumes of water is the most striking characteristic of peat.	Hobbs 1986
Permeability and hydraulic conductivity	Permeability is a fundamental property controlling water movement and consolidation in peat. Permeability decreases markedly with depth with the abrupt transition from the acrotelm (aerated upper surface layers) to the denser catotelm (lower layers). Hydraulic conductivity may vary up to eight orders of magnitude between the layers.	Ingram 1983
Bulk density	The degree of decomposition and peat bulk density are intrinsically related. Decomposition decreases pore size. Bulk densities are low and variable.	Eggelsmann et al. 1993
Gas content	Gas content in peat may be as large as 5% of the volume. Most of this is free gas which influences permeability, consolidation and loaded pore pressures.	Hanrahan 1954
Organic (carbon) content	A high organic content is an intrinsic property of peat. Typically carbon contents of peat are approximately half the organic matter content which has important implications for terrestrial carbon stores.	Worrall et al. 2003
Micromorphology of peat	Important for water flow and rewetting in peat and secondary compression of the peat mass.	Mooney et al. 2000

Hydrogen ion activity and pH	Soil water pH is strongly correlated with vegetation and peat type and the chemistry of the water supply. Values range 3.5 to 6. Organic peat acid can be associated with weakened peat slopes	Söderblom 1974
Geotechnical Behaviour		
Geotechnical behaviour – standard index properties	Standard index (consistency) tests are not easily applied to peat material. Liquid limits are useful in characterizing certain types of peat but plasticity tests cannot easily be applied due to a lack of mineral clay.	Hobbs 1986 Carlsten 1993
Stress-strain – primary and secondary consolidation	By virtue of a very high water content peat is an extremely compressible material. Rapid consolidation is followed by secondary compression which is the dominant process.	Fox and Edil 1996
Changes in mechanical properties with organic content	No systematic relationship exists between mechanical properties and organic matter – soils behave in a complex manner due to differences in the amount and type of organic matter present.	Farrell et al. 1994
Flowing properties of peat slurry	Liquefaction of basal peat deposits, transport of material in a peat mass movement runout zone and transfer of organic material in river systems.	Luukkainen 1992
Peat creep	Slope instability and surface rupturing.	Carling 1986a
Shrinkage and desiccation	Peat is susceptible to shrinkage due to high water content. Desiccation cracking may promote delivery of surface water to the subsurface hydrological system promoting elevated pore pressures and peat mass failure.	Hendrick 1990
Thermal behaviour	Peat and other organic materials behave very differently in the cold: dry peat has a very low thermal conductivity due to high air content; wet saturated peat can have 5× higher thermal conductivity; whilst frozen peat 28× higher.	Seppälä, 2004

used in Scotland (Burton 1996), and 0.45 metres (undrained) in Ireland (Bord na Móna 2001).

1.2.2 The physical and geotechnical properties of peat

Consideration of the physical processes of erosion affecting peatland surfaces requires an understanding of the physical characteristics of peat as an earth material. Many of the challenges of a process-based approach to the geomorphology and hydrology of peatlands stem from the unusual properties of peat. Hobbs (1986) provides an excellent review of the properties and behaviour of peat. In this account Hobbs refers to peat as an 'ordinary extraordinary material' due to its unusual characteristics as an earth surface material (Table 1.1). For example, some properties of peat are similar to the behaviours of clay, but due to the extremely high water content of the peat, simple relations with material strength cannot be easily established (Landva et al. 1983). The material structure of peat greatly affects the hydraulic properties and strength of the deposit (Hobbs 1986). Although peat varies enormously, a 'typical' peat might be composed, by volume, of 85% water, 2% ash or mineral material, 8% organic material, and 5% air. The bulk density of the peat will increase as the organic matter becomes more decomposed but conversely the water content of peat decreases with decomposition. It is therefore essential to have a means of describing the different forms of peat so that the behaviour of these materials can be properly characterized.

Several peat description schemes have been developed. However, the von Post classification (von Post 1924) is widely used to provide a semi-quantitative description of the physical, chemical and structural properties of peat deposits. The scheme is based on semi-quantitative assessments of the principal plant remains, degree of humification, water content, fibre content and woody fragments. Hobbs (1986: 78–9) provides a succinct description of the main method. The von Post approach provides a rapid assessment method for characterizing peat properties. Table 1.1 considers examples of some of these key properties and identifies the important interrelationships between the basic peat components (phases) and the importance of these for the peatland geomorphic processes which are considered in more detail in subsequent chapters of this book.

1.2.3 Peatland classification

The term peatland is used, in this volume, to refer to all landscapes where the dominant surficial deposits are accumulations of organic matter (peat) in excess of 0.4 metres depth. The literature on the classification of peat landscapes is extensive but perhaps the most commonly adopted distinction is based on the source of water input to the peat mass. A distinction is made between *bogs* (ombrotrophic mires) and *fens* (minerotrophic mires) where the former are rainwater fed systems, typically acidic and nutrient poor, and the latter are groundwater fed, and typically circum-neutral with higher nutrient status (Hughes and Heathwaite 1995a). The term mire is used to refer to all forms of peatland, both bog and fen, and is the most appropriate term for many of the upland peatlands considered in this volume. Although typically dominated by ombrotrophic mire types these are complex upland systems with variable nutrient status. The definition adopted in this volume is closely related to the original definitions of mire and bog by Godwin (1941, 1956) which emphasize the nature of the sediments and the hydrological context and are appropriate to considerations of upland mires as geomorphological and hydrological systems.

The term 'upland' is widely used but needs clear definition in the context of this work. We conceive of the uplands as wildlands or areas where agriculture is extensive. As such we are working with a rather UK-specific definition of upland, akin to that of Ratcliffe (1977), of uplands as lands beyond the limit of enclosed cultivation. However, peatland landscapes of the type we are concerned with are not confined to the UK or indeed to a particular altitudinal band. They are often associated with resistant lithologies. The resultant thin soils tend to produce marginal lands, and indeed thin soils over impermeable bedrock tend to produce the waterlogged conditions favouring peat formation. Thus the low altitude peatlands of Newfoundland, Tasmania, the Shetlands and the Falkland Islands would fall within our definition of upland.

Hughes and Heathwaite (1995a) classify UK mires on a morphological basis into soligenous (sloping) mires, basin mires, valley mires, floodplain mires, raised mires and blanket mires. Charman (2002) suggests that this classification represents a generic hydro-morphological classification with broad applicability (Figure 1.1). The most widespread upland peat type is the blanket mire. Blanket bog is a term first defined by Tansley (1939) (Wheeler and Proctor 2000), to describe widespread ombrotrophic mire which follows the underlying topography like a blanket. Blanket bog is extensive and may therefore link other mire types into a continuous upland wetland system. A blanket bog may incorporate former basin mires in topographic low points and areas of raised mire formed either on summits, interfluves, or developed from former areas of basin mire. Where blanket peat is dissected or encompasses lines of pre-peat drainage then valley or floodplain mires form part of the complex, and where valley-side springlines are exposed soligenous mires may also

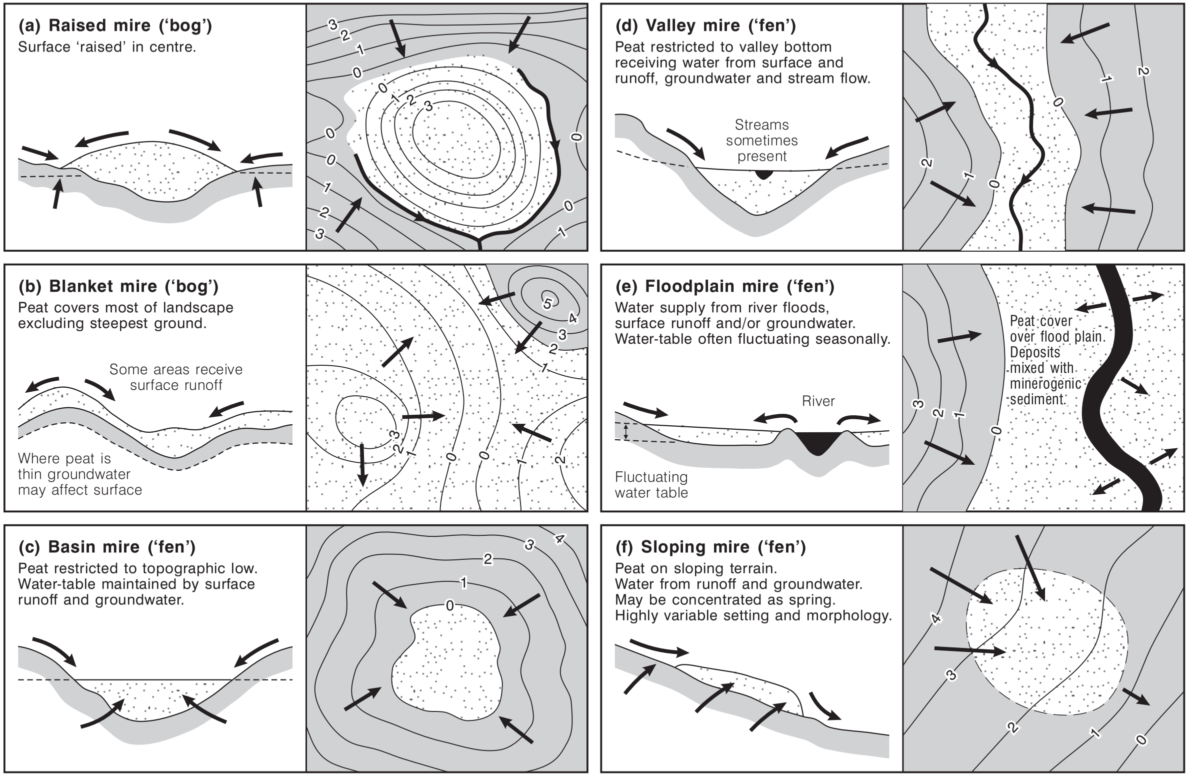


Figure 1.1 Hydro-topographical classification of mire types (after Charman 2002)

Table 1.2 Classification of scales of mire landforms (after Ivanov 1981)

Microtope	'A part of the mire where plant cover *and all other physical components of the environment connected with it* are uniform' Ivanov (1981: 6, emphasis added)
Mesotope	Isolated mire massifs with distinct patterns of microtopes and a single centre of peat formation
Macrotope	Complex mire massif formed from the fusion of isolated mesotopes through peat growth

form. Lindsay (1995) describes these mire assemblages, which span the full range of mire types identified by Hughes and Heathwaite (1995a), as blanket mire complexes. This usage is broadly synonymous with what we have termed upland mire complexes. Blanket peat is a necessary component of an extensive upland mire complex and in this volume, for reasons of style and respect for local usage, the terms upland mire complex, blanket mire complex and blanket peatland are used interchangeably.

Lindsay (1995: 22) notes that 'mire complexes are most frequently encountered in the uplands where several hydro-topographical units . . . fuse to form an extensive complex cloaking the landscape with peat.' To understand what Lindsay means by hydro-topographical units it is necessary to first review the basic classification of peatland landforms produced by Russian peatland scientists and summarized in Ivanov (1981) (Table 1.2). In the context of upland peatlands the macrotope is the upland mire complex identified above and the mesotopes which combine to form this macrotope might reasonably be characterized as any of the mire types identified by Hughes and Heathwaite (1995a). The mesotope therefore is essentially a unit at the scale of peat landforms and the macrotope describes the peatland landscape. In a sense the geomorphology of a landscape where peat formation occurs is the prime control over the mire type produced since local slope is the major determinant of the direction of groundwater flow relative to the centre of mire growth and consequently of the division between fens and bogs. Lindsay (1995) uses an explicitly geomorphological framework to subdivide elements of the blanket bog type following Ivanov's (1981) assertion that mire classification should include a geomorphological element. Lindsay describes watershed mires (probably better defined as summit mires), spur mires, saddle mires and valley side mires defined by their topographical setting. These hydro-topographical units are essentially mire mesotopes classified geomorphologically. Figure 1.2 illustrates the combination of a series

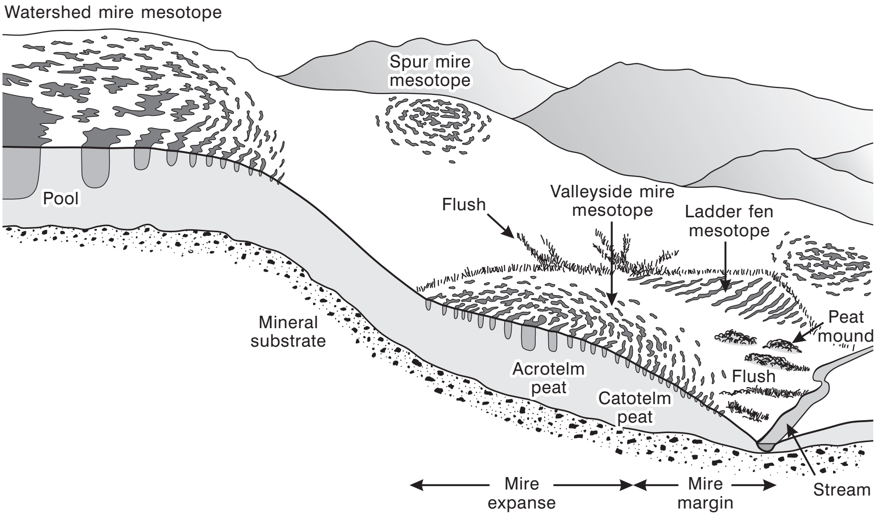


Figure 1.2 Combination of hydro-topographical units to form an upland mire complex (redrawn after Lindsay 1995)

of these hydro-topographical units to form an upland mire complex (macrotope).

At a smaller scale Lindsay et al. (1988) identify seven major microforms associated with UK blanket peatlands. These can be classified as follows:

<u>Hydro-ecological microforms</u>
hummocks
ridges, high or low
hollows, *Sphagnum* or mud-bottomed
pools, permanent or ephemeral
<u>Geomorphological microforms</u>
erosion gullies
erosion haggs
peat mounds

The hydro-ecological microforms are largely controlled by the close interaction of hydrological and ecological processes on the mire surface (Belyea and Clymo 1998; Bragg 2002; Laine et al. 2004). These processes have formed the focus of the vast majority of previous academic work on upland peatlands. The geomorphological microforms and the physical processes which control them have received much less attention.

Therefore, in terms of the classification of upland peats outlined above the focus of this volume is the geomorphology of upland blanket mire complexes.

1.3 The Geography of Blanket Mire Complexes

As primarily ombrotrophic systems, the distribution of blanket mire is closely controlled by climate. All mire systems require a positive water balance for their long-term growth and maintenance. In ombrotrophic systems the key components of the water balance are precipitation inputs and losses by evapotranspiration (e.g. Evans et al. 1999; Kellner and Halldin 2002) (see Chapter 2). Positive water balance is favoured by higher rainfall, consistent with the observation that blanket peatland is the dominant peatland type in hyper-oceanic areas of the world. There are numerous statements in the literature regarding the threshold climate conditions for blanket bog formation. Pearsall (1950) suggested that in England a threshold precipitation of 1,250 mm existed. Lindsay et al. (1988) suggested a more realistic set of limiting conditions based on four key criteria: (1) annual precipitation above 1,000 mm; (2) >160 rain days per year; (3) warmest month with mean temperature <15°C; and (4) limited seasonal temperature variability.

The key controls on the nature of the local water balance are the relative rates of precipitation input and evaporative loss. Hence, the location of areas favourable for mire formation is also affected by parameters controlling evaporation such as temperature, relative humidity and wind speed. The inclusion in Lindsay's scheme of a measure of rainfall frequency relates to the requirement to maintain positive water balance and hence a high water-table despite evaporative losses which occur throughout the year. The geographical implication of considering the controls on evaporation is that the more oceanic the climate and the lower the mean temperature the lower the precipitation input required to maintain a positive water balance. Since mean temperatures decline with latitude and elevation this explains why on the Shetland Islands blanket bog occurs down to sea level whereas in the Southern Pennines of England it is confined to elevations above 500 metres despite the two locations having similar mean annual rainfall (circa 1,200 mm). A similar effect of altitude is demonstrated by the distribution of Irish bogs (Figure 1.3) where low elevation 'Atlantic Bogs' are distributed west of the 1,200 mm isohyet but 'Mountain Bogs' occur in all upland locations (O'Connell 2002).

Figure 1.4 (after Lindsay 1995) is a global map of the locations which fulfil Lindsay's (1995) criteria for the support of blanket peat. This is a

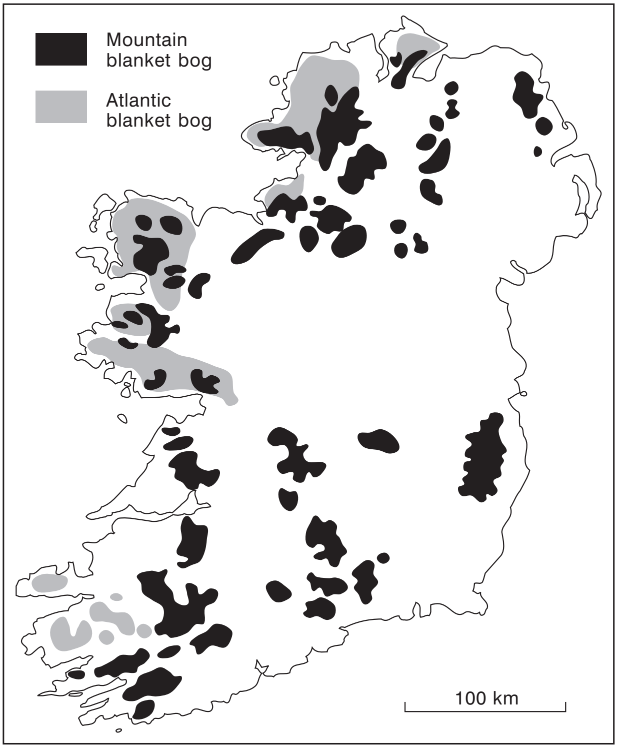


Figure 1.3 Distribution of blanket bog types in Ireland (redrawn after O'Connell 2002)

limited range of hyper-oceanic environments but blanket peat is recorded within all of these areas worldwide. In reality climatically-based predictions of the presence of blanket mire are simply a proxy measure using readily available data to approximate the water balance of a given region. It will be seen, however, in Chapter 2 that accurate measurement of the water balance in mires is far from straightforward so the climatic proxy approach is a useful initial approximation.

The primary research reported in this volume relates to the eroded upland blanket mire complexes of the UK. Where it exists we draw on a wider international literature relating not only to blanket mire but to all forms of ombrotrophic (rain fed) peatland. In part this is justified because of the range of mesotopes which may be encountered within a blanket mire complex, and in part it is recognition of the similarities of process across the spectrum of ombrotrophic peats.

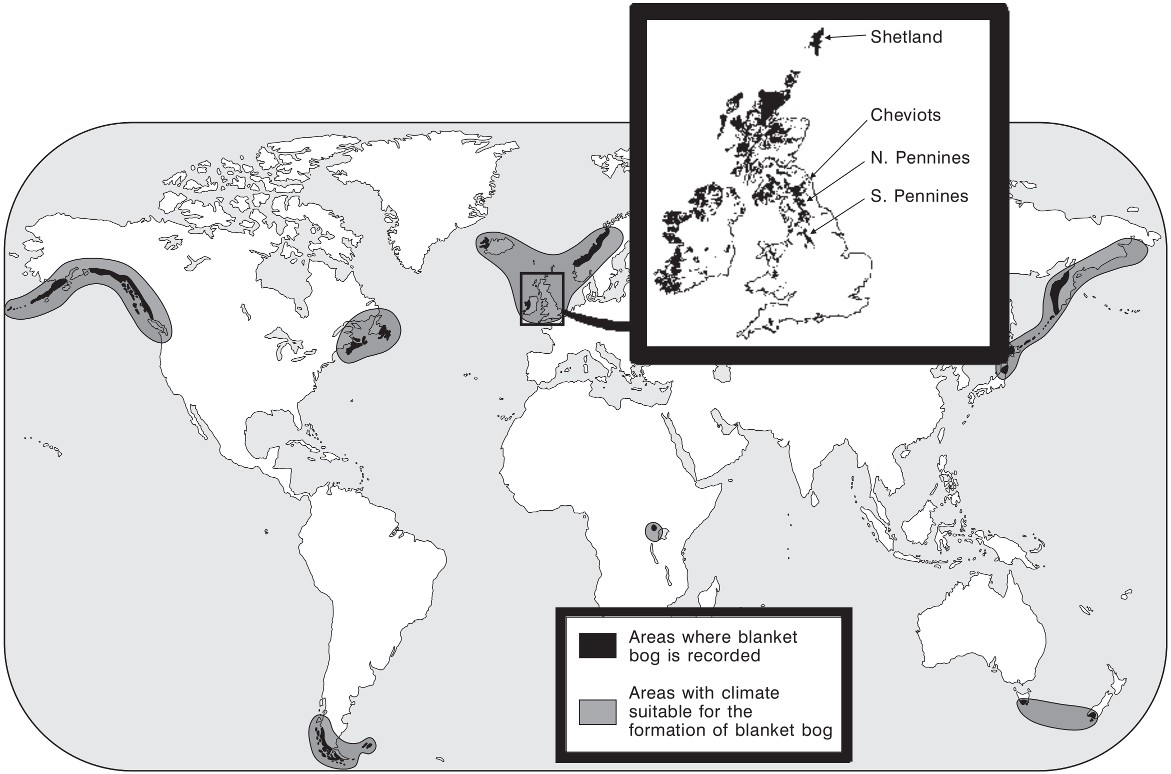


Figure 1.4 Global distribution of blanket bog (modified after Lindsay 1988)

Table 1.3 The extent of erosion of blanket peatlands in the UK and Ireland

Location	*Estimated area of erosion*	*Notes*	*Reference*
South Pennines, England	33 km^2 (6%) of eroded peat	Ground bare or partially bare	Philips et al. 1981
Moor House Nature Reserve, N. Pennines, England	8% eroded, 10% eroded and revegetated	Based on bare ground or morphological expression of gullying	Garnett and Adamson 1997
Wales	30% of peat degraded	Includes succession to less favourable mire types as well as physical erosion	Yeo 1997
Scotland	20% of blanket mire affected by gullying		Coupar et al. 1997
Scotland	6% of Scottish Uplands eroded 4.7% gullied		Grieve et al. 1994
Connemara, Ireland	27% of upland blanket mire eroding		Mckee and Skeffington 1997 (Geerling and Van Gestel 1997)
Wicklow Mountains, Ireland	33% of blanket mire affected by gullying		Cooper and Loftus 1998
Central and northwest Ireland	24% of blanket peat gullied		Large and Hamilton 1991
Northern Ireland	Blanket peats 29% eroded, 56% cut/drained, 15% intact	Total peat coverage estimated at 140,000 ha	Cruickshank and Tomlinson 1988

1.4 Patterns of Peat Erosion in Space and Time

An important context for understanding the geomorphology of eroded peatlands is knowledge of the distribution of erosion in time and space. Severe and extensive erosion of upland peat is a phenomenon which is almost unique to the UK and Ireland. Outside this area Glaser and Janssens (1986) describe local peat erosion in Newfoundland, and Foster et al. (1988) describe minor natural erosion of bogs in Labrador and in central Sweden. Peat erosion through decay of palsa mires or in areas of thermokarst development has been reported from permafrost regions (e.g. Gurney 2001; Oksanen et al. 2001; Zuidhoff 2002). Short duration local peat erosion due to fire, or localized livestock impacts are common in many blanket mire systems. For example in the Australian Alps severe damage to upland *Sphagnum* bogs has been recorded due to severe fire in 2003 and subsequent trampling by livestock (Victoria National Park Association 2005). Pitkanen et al. (1999: 454) report that 'erosion has a negligible role in Finnish peatlands' and, although there are local exceptions associated with specific impacts on the mire surface vegetation (grazing, fire, peat mining, etc.), this statement holds true for most peatlands outside of the extreme western fringe of Europe.

Although work in Britain and Ireland has tended to emphasize the erosion of peat by running water, many of the reports of peat erosion from other regions of the world typically emphasize the importance of aeolian erosion (e.g. Luoto and Seppälä 2000 [Finnish Lapland]; Zuidhoff 2002 [northern Sweden]; Selkirk and Saffigna 1999 [sub-Antarctic Macquarie Island]). Wind erosion of milled peatlands has also received considerable attention in North America (e.g. Campbell et al. 2002; Lavoie et al. 2003), with the resultant instability of bare peat surfaces proving a significant impediment to attempts to restore mined peatlands. Recent work on aeolian erosion of peats is reported in Chapter 6 of this volume. In contrast to these findings, Klove (1998: 213) concluded 'that rain is the major cause of erosion from peat mine surfaces' in a study of sediment delivery from a peat mine in northern Finland. Uncertainty regarding the dominant cause of peat erosion was a major theme in the early literature on erosion in the UK, particularly the relative importance of wind and water (Bower 1961; Radley 1962).

In the UK and Ireland extensive peat erosion occurs across much of the blanket mire surface (Table 1.3, Figures 1.5 and 1.6). McHugh et al. (2002), in a survey of erosion across the uplands of England and Wales, demonstrated that peat soils in the uplands are the most severely eroded soil class. Overall the picture which emerges of the upland mires of the UK and Ireland is very different from the rather limited peatland erosion

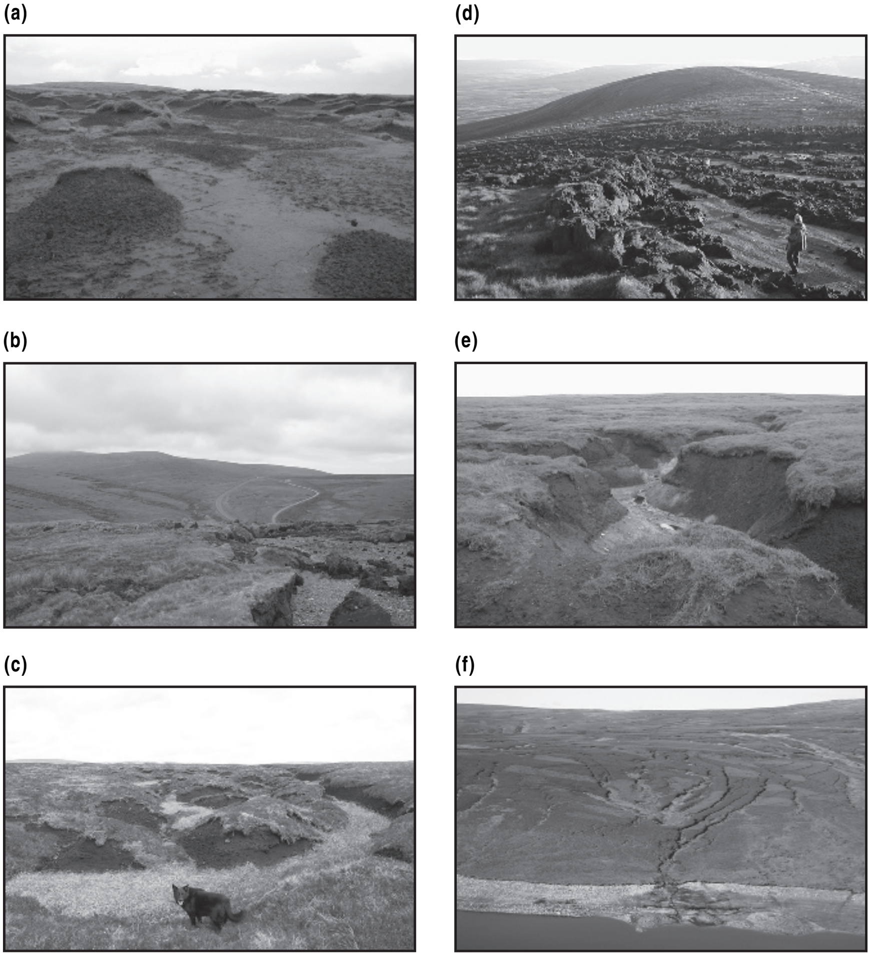


Figure 1.5 Example of peat erosion from around the UK and Ireland (a) Severe erosion on the summit of Kinder Scout, South Pennines. (b) Peat slide scar at South Channerwick, Shetland. (c) Eroded and partially re-vegetated peat haggs on Hard Hill, North Pennines. (d) Peat slide scar at Doon Carton, Co. Mayo. (e) Severe gully erosion on the Bleaklow Plateau, South Pennines. (f) Sediment delivery to Cow Green reservoir via an eroding moorland grip system

reported from other parts of the world. Regionally extensive peat erosion in the UK is in strong contrast to the global picture of very local peat erosion associated with particular environmental impacts. Sheet and gully erosion of blanket mires is commonplace in the UK and Ireland and a major part of the surface patterning of many mires is controlled by geomorphological microforms.

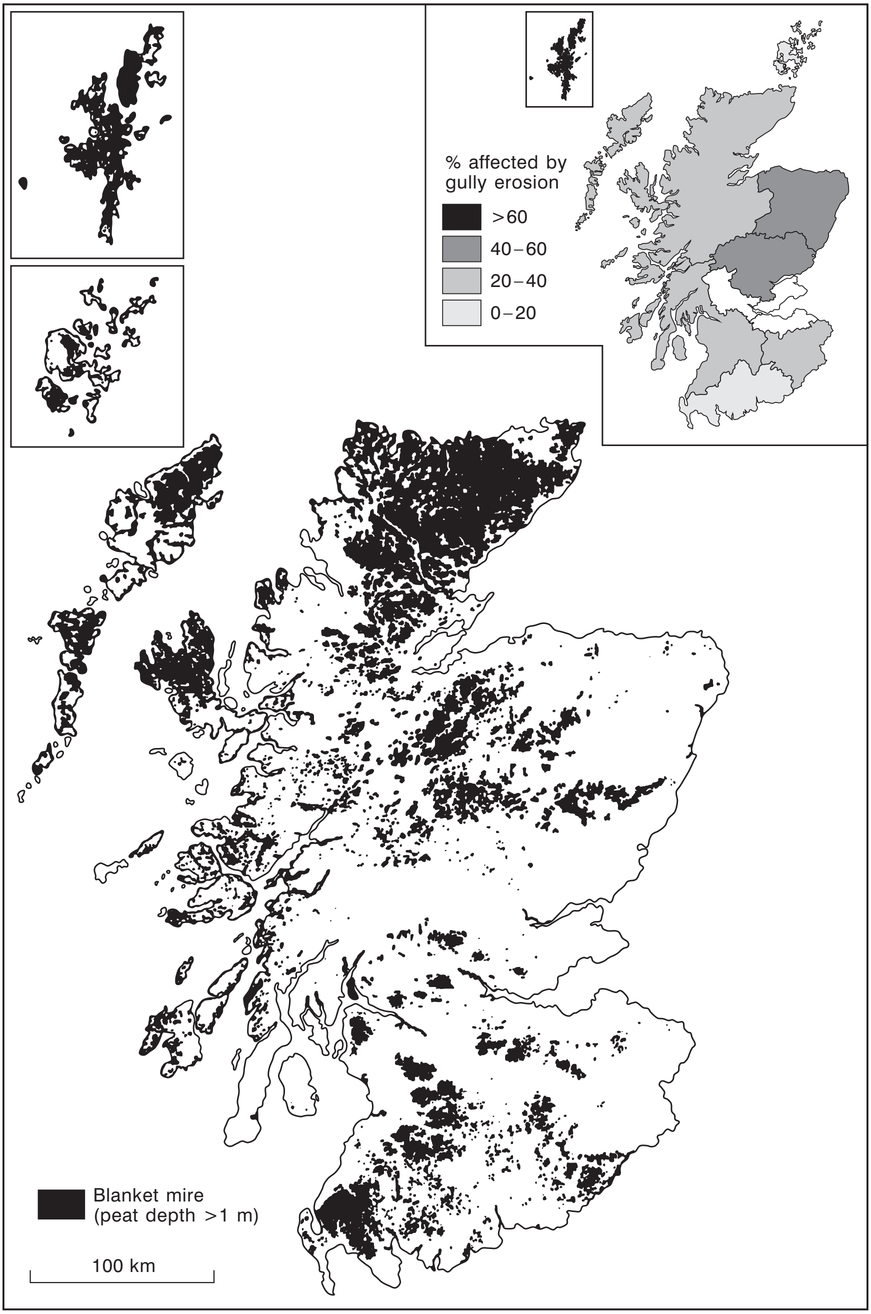


Figure 1.6 Distribution of gully erosion in Scottish blanket peats showing considerable regional variation in the extent of erosion (redrawn after Couper et al. 1997)

1.4.1 The onset of peat erosion

An explanation of the concentration of eroded upland mire in the UK and Ireland requires consideration of the reasons behind the onset of upland erosion. This question has preoccupied peat erosion researchers in the UK and Ireland for much of the last 40 years. The eroding upland blanket mires of the UK and Ireland support considerable depths of peat, typically in excess of a metre and locally up to 6 metres or more. It is clear therefore that the long-term character of these mires has been as sites of peat accumulation, but that at some stage in their history the nature of the mire system has switched from peat accumulation to erosion.

Arguably the most significant body of work on the initiation of peat erosion is that by Tallis (Tallis 1964a and b, 1965; Tallis and Switsur 1973; Tallis 1985a and b, 1987; Mackay and Tallis 1994; Tallis 1994; Tallis and Livett 1994; Tallis 1995, 1997a, b and c; Tallis et al. 1997; Tallis 1998). Tallis noted that the onset of significant gully erosion in a peat bog causes drainage and lowering of the water-table in intact peat immediately adjacent to the eroded gully. The vegetation and hydrology of blanket mire surfaces are closely linked so that the onset of erosion leads to changes in mire surface vegetation adjacent to the gullies. These vegetation changes are recorded in the peat stratigraphy as changes in the pollen and particularly plant macrofossil record. Gully-side peats represent an intact organic depositional sequence so they can be dated by radiocarbon methods thus providing a record of the timing of the onset of local erosion. Tallis's work on this topic is focussed on the heavily eroded peatlands of the Southern Pennine range in northern England.

Tallis (1997a and b) summarizes much of this work and suggests that in the Southern Pennines two main phases of gully erosion can be identified. The first, starting between 1250 and 1450 AD which is coincident with, or immediately postdates the Early Medieval Warm Period, is particularly associated with development of dendritic gully networks from existing hummock and pool topography. A second period of enhanced peat erosion is recognized post circa 1750 when there was considerable headward extension of gully systems into the peat mass. These patterns, together with the observation that within a gully system the dates of onset of erosion tend to get younger upstream (Tallis 1997b and c), emphasize the fact that gully erosion is an ongoing process rather than a particular event.

A second approach to the dating of erosion phases has been to investigate the depositional record in lake sediments downstream from eroded peatland landscapes. Rhodes and Stevenson (1997) studied seven lakes across Ireland and western Scotland with evidence of former peat erosion in their catchments. Rapid increases in the organic content of lake sediments, assumed to represent the onset of catchment peat erosion, date to between 900 and 1800 AD, with the majority erosion episodes occurring in the period 1500–1800 AD. The study rejects fire as a general cause of the erosion because there is no statistical relation between charcoal records from the lake cores and peat erosion. The relatively early onset of erosion also suggests that intensification of grazing and atmospheric pollution were unlikely to be the primary triggers. Rhodes and Stevenson suggest that the concentration of erosion episodes during the Little Ice Age (1500–1850) implies that more severe climatic conditions during this period are an important control on the onset of erosion.

In Ireland Bradshaw and McGee (1988) studied lake sediment sequences in Wicklow and in Donegal. Increases in organic content measured using loss on ignition together with evidence of reversal of radiocarbon dates was used to determine the onset of catchment erosion. The data suggest that catchment erosion began 3,000 years BP (radiocarbon years before present) in Wicklow but that erosion did not begin until 1500 BP further west in Donegal. The early dates of erosion recorded at two widely spaced sites suggest that natural processes rather than any anthropogenic impact were the key controls on the initiation of erosion.

It is clear that significant progress has been made towards the identification of major periods of onset of peat erosion. In the UK the evidence points to peat erosion being a phenomenon largely of the last millennium although earlier dates are recorded in Ireland (Figure 1.7). Dating erosion is however only part of the process of arriving at an apparent cause for the initiation of erosion. The main approach to identifying cause from the palaeoenvironmental record has been through the correlation of the onset of erosion with other known periods of environmental change whether from the historical record or reconstructed from proxy evidence. In this respect Tallis's work on intact mire sequences has significant advantages over the lake sediment evidence in that it tells us in considerable detail how peat surfaces develop and provides evidence of the mire surface mechanisms involved. However this approach cannot categorically identify cause. The onset or acceleration of peat erosion identified from several regions over the last 250 years (Mackay and Tallis 1996; Rhodes and Stevenson 1997; Tallis 1997b; Huang 2002) is coincident with intensification of upland agriculture, particularly sheep grazing (Shimwell 1974; Huang 2002), harsher climatic conditions in the Little Ice Age and impacts of atmospheric pollution on upland vegetation (Ferguson et al. 1978), all of which have been identified as potential causes of peat erosion.

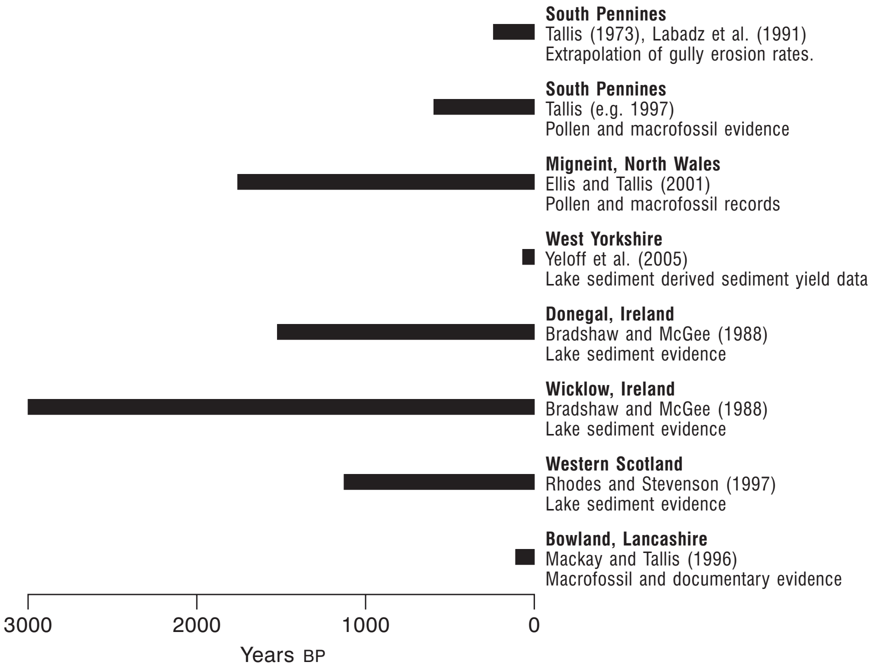


Figure 1.7 The timing of inferred periods of onset of peat erosion in the UK and Ireland

1.4.2 Direct observation of the onset of erosion

An example of the very rapid onset of erosion through instantaneous transformation of the bog surface vegetation is by wildfire events. Anderson (1997) reports a catastrophic fire on Burbage Moor in the Southern Pennines which damaged vegetation across 120 hectares. This fire occurred in the very dry summer of 1976 and in the subsequent September unusually high rainfall led to stripping of up to 1 metre of peat exposing the mineral surface beneath. Similarly Maltby et al. (1990) describe erosion of peat on the North York Moors of northern England in the aftermath of fires in the summer of 1976. Here significant removal of peat directly through combustion, through water erosion but also by deflation produced a surface of exposed mineral substrate and gullies in exposed peat. There is clear evidence that fire can produce dramatic and rapid erosion of upland peats (Radley 1960), and with the total areas of bare peat far exceeding locations where only gully erosion is dominant. In locations where natural vegetation regeneration is impaired, through for example pollution or grazing pressure, fire scars can be persistent features in the landscape (Anderson et al. 1997). In areas with relatively high burning frequency the aggregation of numbers of persistent fire scars in the landscape can make them a significant proportion of total erosion (Anderson et al. 1997). However because the impact of fire is local it is not a sufficient explanation for the widespread onset of erosion unless there is evidence of climate change likely to significantly increase fire frequency in moorland sites.

1.5 Causes of Peat Erosion

The initiation of peat erosion is a complex process which may be triggered by a variety of different impacts. Evidence shows that the dates of initiation of peat erosion in the UK are spread across the last millennium (Figure 1.7). Therefore, rather than search for specific causes of peat erosion in particular times and places, an alternative is to consider the onset of peat erosion as a threshold process (Schumm 1979). At the threshold the mire system switches from an intact system state to an erosional state, where rates of material flux from the system (including water and solute flux as well as sediment) and the principal controls on those fluxes are significantly altered. The mire system is in many ways analogous to badland systems (Tallis 1997a) where the friable peat layer is protected by a dense 'caprock' of vegetation. The initiation of erosion is controlled by the balance of the forces of erosion (frost, wind, rainfall, runoff) and the ability of the vegetation layer to resist erosion. Shifts between the two system states can therefore be produced either by increases in the erosive force or by a reduction in strength of the vegetation layer. The former is the mechanism invoked by Stevenson et al. (1992) in suggesting that colder, wetter and stormier Little Ice Age climates were central in triggering erosion. The latter encompasses the wide range of impacts of the mire surface which tend to stress the vegetation layer including fire, overgrazing, pollution, desiccation and trampling. Over time external changes, such as change in climate, and land management, shift the balance between the eroding and resisting forces potentially triggering erosion by crossing an extrinsic (externally forced) threshold.

It has also been argued that some local areas of intense erosion are a result of crossing intrinsic thresholds. Tallis (1985a) suggests that some erosion of blanket peat in the English Peak District has been triggered by marginal mass movements which he attributes to peat instability due to natural peat accumulation beyond a critical depth (Chapter 5). Nevertheless it is clear that a significant proportion of peat erosion is a response to external forcing of the mire system, removal of vegetation and exposure of bare peat surfaces to the elements. Overall it is possible to conceptualize

Table 1.4 Trigger factors for peat erosion on Holme Moss (after Tallis 1997b)

Date	*Impact*	*Effect*
1450	Desiccation Medieval Warm Period	Initiation of gully erosion
1770	Major fire	Produced extensive bare peat areas
1770	Marginal peat slides	Exposed bare soil and rock downslope
1800	Loss of *Sphagnum*	Reduced peat formation
1940	Overgrazing	Exacerbation of erosion
1976	Fire	Further bare peat areas
1983	Television mast construction	Major disturbance of mire surface

eroding peat landscapes as lying on a spectrum of erosion potential controlled by local climate and land use. Many of the external impacts are highly spatially variable, leading to a complicated mosaic of intact and eroding peat surfaces. This is particularly well illustrated by Tallis (1987; 1997b), who uses the example of heavily degraded blanket peat at Holme Moss in the Southern Pennines to illustrate the multiple triggers for erosion at a single site (Table 1.4).

The fact that we cannot readily identify regionally consistent causes for peat erosion should not be seen as detracting from the importance of the work that has been done to identify contributory factors. The question of causation has direct implications for the management of eroding peatland landscapes. Much of the legislatively defined value of blanket bogs is tied up with the unique vegetation and faunal populations which they support. This has led to re-vegetation of eroding peatlands as a conservation strategy with the focus as much on re-vegetation as an end in itself as on re-vegetation as an erosion control strategy. This restoration focus is appropriate if it is demonstrated that the onset of erosion is due to human intervention in a natural system. If in fact at least some part of the peat erosion observed in the landscape has natural origins then it can be argued that the gullies and remnant peat islands of an eroding peatland are a distinctive mire surface microform (Lindsay 1995), and merit conservation as part of the spectrum of natural mire surface conditions (see Chapters 8 and 9).

1.6 A Brief History of the Evolution of Peatland Geomorphology

Despite a relatively small body of literature, investigations of the geomorphology of peatlands have a long history. This brief chronology is not an attempt at an exhaustive review but rather an illustration of the development of the field. It relates to observation and measurement of the forms and processes of erosion, rather than the environmental conditions which predispose peatlands to degradation. The overall aim is to provide context for the work reported here.

1.6.1 Accounts of erosion in the natural science tradition

The earliest documentary references to peat erosion typically describe the dramatic erosional effects of rapid mass movements in peatlands (see Chapter 5).

These accounts are very numerous and range from scientific descriptions such as this account of a peat slide at Port Stanley on the Falkland Islands (Mulvaney 1879: 803):

> During the night of the 30th November 1878 there occurred a phenomenon of a most unusual type in the Falkland Islands, – an avalanche of peat which nearly overwhelmed the chief settlement. The peat bogs on the heights above Stanley, the chief town, gave way and the black oozy mud rolled down the hill with a momentum that neither the iron stanchions around the reservoir nor the barriers by the sea could withstand . . .

through to poetic (but surprisingly detailed) descriptions such as this account of the Crow Hill (near Bradford, UK) bog burst of September 24th 1824:

> But the summers heat the heaps of peat
> Had dry'd in many a gaping chink
> And when so dry the clouds on high
> Send down a flood to give it drink
> And as each flaw with greedy jaw
> Quaft with unsatiated thirst
> The lightenings flashed, the thunders crasht
> And its tremendous bowels burst

(Verses three and four of 'The Phenomenon', a poem on the Crow Hill bog burst by John Nicholson, Ogden, 1976)

1.6.2 Descriptive accounts of widespread peat erosion

The first references to extensive erosion occur in the early ecological accounts of British moorlands. An excellent review of these early descriptive accounts is given by Bower (1962) spanning early work on Scottish peat bogs by Aiton (1811), Geikie (1866), Lewis (1905) and Crampton (1911), later work on the Peak District blanket peats by Moss (1913), through to the influential first modern accounts by Pearsall (1950, 1956). These studies were based on description of the extent and form of erosion and largely treated this as an interesting variation on the ecology of the mires. The most detailed classification of eroding moorlands was undertaken by Bower (1960a; 1960b; 1961; 1962) who mapped erosion across the Pennine moorlands of northern England. Bower's work was highly influential but in common with much of the geomorphological work of the first half of the twentieth century inferred the nature of peat erosion processes from observation of the resultant landforms. As a consequence, qualitative interpretations of the dominant erosion processes varied between authors. Bower's work emphasized fluvial processes whereas Radley (1962) studying South Pennine moorlands suggested that aeolian processes were the principal cause of surface recession in areas of bare peat. Despite some attempts to reconcile these views (Barnes 1963) the quantitative measurements required to assess relative impacts of various processes were not available.

1.6.3 Quantitative observations of blanket peatlands

In common with many of the early descriptions of peatland geomorphology many of the early process measurements were made by ecologists. Crisp (1966) produced quantitative estimates of sediment yield from a small eroding peat catchment in the North Pennines and Tallis (1973) produced some of the first quantitative measurements of gully erosion in peat. These early studies began to provide estimates of the rates of gully development in eroding peatlands and calculated typical sediment yields, but there was relatively little attention on the processes controlling sediment flux. It was not until the 1980s that geomorphological studies of the processes of peat erosion were undertaken. Two important studies in particular began to examine the important role of sediment production on bare peat faces, as interpreted from temporal patterns of sediment export at timescales ranging from annual to the individual storm (Francis 1987; Labadz 1988; Francis 1990; Labadz et al. 1991). During the same time period extensive survey of reservoir sediments from catchments in the Southern Pennines began, giving a detailed picture of typical sediment yields from an eroding peatland region (White et al. 1996).

A second strand of quantitative work relating to the geomorphology of peatlands during the 1980s focussed on the material properties of peat and in particular the causes of peat slope failure. The widely cited work by Hobbs (1986) is still one of the best summaries of peat material properties. Carling (1986a and b) produced the first detailed process-based explanations of peat mass movements using observations of a series of slides in the North Pennines.

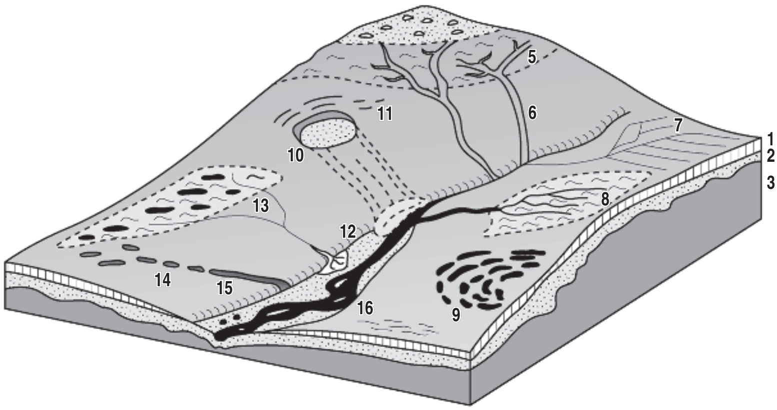
Over the past ten years a range of different approaches has been applied to further develop quantitative understanding of peat erosion processes. Yeloff et al. (2005) is one of the first studies to directly compare peat catchment sediment yields derived from reservoir sediments with the proxy records of catchment conditions (e.g. pollen) preserved in the lake sediment microfossil record. This approach has allowed more precise correlation of sediment flux with changing catchment conditions. A number of studies have also examined erosion processes at the sub-catchment scale on experimental plots, developing much needed understanding of the processes of sediment production, transport and deposition (e.g. Holden and Burt 2002c; Warburton 2003). At the same time there has been increased interest in upscaling and generalizing this understanding. Approaches have included the use of sediment budgets to examine in more detail connectivity in catchment sediment supply (Evans and Warburton 2005) and also the application of a range of remote sensing technologies (e.g. Haycock et al. 2004; McMorrow et al. 2004). Of these perhaps the most significant development is the availability of high resolution DEMs (2-metre scale) derived from LiDAR (Light Detection and Ranging) laser altimetry which offer the potential to explore the nature and topographic associations of gully erosion and provide the prospect of developing models of peat erosion applicable at the landscape scale (see Chapter 4, Figure 4.5).

These changing paradigms in peatland geomorphology reflect wider changes in the focus of geomorphology over the last century, from an early interest in descriptive landscape studies, through a period of detailed and quantitative process studies at the small scale, and culminating in contemporary interest in applying the quantitative understanding gleaned from this work to explain geomorphological change at landscape scales. Church (2005) provocatively suggests that modern geomorphology has become divided into two camps, one engaging with the 'scientific' problems of large-scale earth system science and the upscaling and generalization of present understanding of earth surface processes, and the other preoccupied with the application of this understanding at a local level to solve problems of environmental management. Both these tendencies can be recognized in geomorphological work on peatlands. An interest in environmental management has been a significant thread in peatland geomorphology and the need to preserve physical integrity of upland surfaces as a prerequisite for conservation of their ecological diversity has underlain much research. However, the potential importance of peatlands as carbon stores means that an understanding of peatland geomorphology is important in contemporary debates over climate change and the role of peatland carbon budgets (Worrall et al. 2003). There is a large literature on the role of dissolved organic carbon production (Couper et al. 1997) and export from peatlands (e.g. Waddington and Roulet 1997; Freeman et al. 2001a and b), but surprisingly, given the scale of the sediment flux from eroding sites, relatively little work on the role of erosion and consequent particulate carbon flux in the carbon cycle.

One of the aims of this volume is to summarize current knowledge of the physical processes, and to identify areas for future research required both as an input to global change debates but also to provide a scientific underpinning to much of the experimental practical conservation being undertaken on eroded moorland. Because of the importance of peatland preservation and the potentially rapid rates of change, management of the erosion of upland peats involves landscape-scale intervention, so that effective management of the environment and understanding of the controls on and trajectories of the evolution of the land surface are closely intertwined. Therefore for the geomorphology of peatlands at least the dichotomy of focus suggested by Church (2005) needs to be resisted. It is undesirable, if even possible, to separate the process knowledge required as a contribution to understanding global carbon balances from the conduct of local management of eroded moorland surfaces.

1.7 Structure of this Volume and the Peat Landsystem Model

Conceptual models of peatland landscapes tend to emphasize the hydro-ecologically determined forms of intact mires (e.g. Figures 1.1 and 1.2). In eroding peatlands the surface morphology is heavily influenced by erosional and depositional landforms at a range of scales. Figure 1.8 is a representation of the peat landsystem. It illustrates a series of common geomorphological forms of upland peatlands. Surface forms common to intact mires such as pools and hummocks are shown, as well as a series of erosional/depositional features. These include features associated with mass failure of the peat, the characteristic forms of gully erosion, collapsed pipe systems, eroded drainage channels and areas of peat deposition at the interface between peat slopes and upland river systems. Not all of these features are necessarily a feature of all upland systems, similarly the features presented may be present in a range of degrees of development. For example gully systems may range from shallow incipient erosion within the peat to severely eroded but re-vegetated systems which may have the morphological characteristics of an eroded system but a well developed moorland vegetation cover. Nevertheless the geomorphological functioning of most upland peatlands could be summarized using a selection of these features and an assessment of their degree of development. This conceptual model of the landforms and sediment system linkages in peatland environments is a necessary first step in the process of constructing an empirical sediment budget (Dietrich et al. 1982). The remainder



1	Peat deposits	**9**	Bog pool complex
2	Glacial/periglacial deposits (substrate)	**10**	Peat mass movement
3	Bedrock	**11**	Peat tears and tension cracks
4	Deflation surface remnant peat hummocks	**12**	Valley side peaty debris fan
5	Gully (Type I)	**13**	Eroded pool and hummock complex
6	Gully (Type II)	**14**	Collapsed pipe system
7	Artificial channels (grip network)	**15**	Peat block sedimentation
8	Peat haggs	**16**	Upland river system (mineral sediment)

Figure 1.8 The upland peat landsystem. Schematic representation of the range of features to be found in upland peatland landscapes. Not all features will be necessarily present at a particular site

of this volume aims to elucidate the details of this landsystem. Central to understanding the physical functioning of mire systems is the flow of water through and across them, hence Chapter 2 reviews the current state of knowledge of the hydrology of upland mires. Chapters 3–6 address key geomorphic processes operating in peatlands (sediment production, fluvial erosion, slope processes and wind erosion) and Chapter 7 identifies the morphological expression of the combination of erosion processes operating in upland mires. Chapter 8 examines the interaction of erosional and ecological processes and the consequences of erosion at the landscape scale. Finally, Chapter 9 explores some of the implications of widespread peat erosion, and provides conclusions.

Understanding peatlands is a fundamentally interdisciplinary endeavour (Charman 2002). Geomorphological understanding has advanced steadily over the past half century, but has been secondary to the large volumes of ecological and hydrological work. Our objective is that the summary of geomorphological understanding presented in the following chapters will give the geomorphological perspective on peatland functioning wider prominence.