The Flow Country

The peatlands of Caithness and Sutherland

R A Lindsay, D J Charman, F Everingham, R M O'Reilly,
M A Palmer, T A Rowell and D A Stroud

Edited by D A Ratcliffe and P H Oswald

Contents

The Flow Country

The peatlands of Caithness and Sutherland

R A Lindsay, D J Charman, F Everingham, R M O'Reilly,
M A Palmer, T A Rowell and D A Stroud

Edited by D A Ratcliffe and P H Oswald

Contents

Acknowledgements

This report describes a large area of Scotland and a programme of survey which has extended over several years. The survey is the result of the efforts of a considerable number of people, whilst the report itself, during the 18 months of its production, has involved an even larger number of people, to all of whom we owe grateful thanks.

The Peatland Survey of Northern Scotland was funded by the Nature Conservancy Council's Chief Scientist Directorate, supplemented by the Scottish Field Survey Unit in 1984/85. We are most grateful to all the owners and occupiers for permission to survey their land and for the great kindness and interest shown by many of them during the course of our discussions with them. We thank the estate gamekeepers and agents who gave generously of their time and local knowledge. We are also indebted to the Forestry Commission and Fountain Forestry for permission to survey areas within forest industry holdings.

We thank Dr David Goode for initiating the project, Dr Derek Langslow for continued support in later years, and Dr Peter Pitkin for organising the Scottish Field Survey Unit's work on the peatlands.

The principal fieldwork was undertaken by Richard Lindsay, John Riggall, Fiona Burd, John Ratcliffe, Fiona Everingham, Sarah Garnett, Bob Missin, Sara Oldfield, Dr Jane Smart, David Stroud, Sylvia White, Dr Elizabeth Charter and Naomi Duxfield. Dr Chris Ferreira kindly offered much valuable information and advice during the course of the work, which we gratefully acknowledge.

We owe a great debt to the staff of the NCC's North-West Scotland Region, in particular to Dr Peter Tilbrook, Regional Officer, for his constant support and sound advice, Sandy MacLennan, Deputy Regional Officer, who was instrumental in setting up the original survey, and the Assistant Regional Officers for Caithness and Sutherland, Dr Stewart Angus, Lesley Cranna, Dr Terry Keatinge and Kristin Scott. Ian Mitchell also provided valuable information. Their help over the years has done much to ensure the smooth running of the survey programme.

The main stages of data analysis would not have been possible without the considerable efforts of John Riggall and Fiona Burd, who went to great lengths to tailor existing computer packages into a unified system which could accept the various types of data obtained from the survey. They were assisted by Carol Fox, Ian Cheesman and Sara Oldfield, to whom we are also grateful. Dr Stuart Ball provided a most valuable computerised mapping programme, whilst Dr Chris Goody, Head of Data and Information Division, and his team, Brian Marsh, Bob Beattie and Valentine Francis, gave much help and support from central computing services.

Much of the map analysis has been carried out with the assistance of Doric Computer Systems Ltd, using the Arc/Info Geographic Information System. Indeed the majority of maps and associated area calculations which appear in the later chapters of this report could not have been produced in the time available but for the Arc/Info system and the efforts of Doric staff. Colin Willers in particular has spent a great deal of time on this work, for which we are especially grateful.

Several people gave valuable advice on particular aspects, notably Rob Soutar on forestry matters, Dr Ian McLean and Edward Milner on invertebrates, Dr Sarah Woodin on acid deposition, and Dr Martin Holdgate on the mires of southern Patagonia.

A number of people read and commented on the first draft of this report. The final version owes a substantial amount to the generous efforts of six people - Professor Hugo Sjörs, Emeritus Professor of the University of Uppsala, Sweden; Professor R S Clymo of Queen Mary College, London; Dr D A Ratcliffe, the NCC's Chief Scientist; Dr Stewart Angus; Dr Terry Keatinge; and Lesley Cranna. Professor Sjors provided an enormous amount of information based on his lifetime's experience of bog systems around the world. Professor Clymo provided a critical review of, and much valuable detail for, the early chapters on peatland ecology. Dr Ratcliffe kindly took on the job of general editing, making a substantial contribution to the overall structure of the report and providing, in addition, the final chapter, which draws together all the threads in the conservation argument. Stewart Angus, Terry Keatinge and Lesley Cranna provided detailed, critical reviews based on the local perspective. We extend our deepest gratitude to all six for their efforts.

Other people who read the report and provided valuable advice and comments were Professor John Allen, Dr Martin Ball, Professor John Birks, Dr John Cross, David Duncan, Dr Tony Fox, Dr Martin Holdgate, Dr Peter Hulme, Dr Derek Langslow, Sandy MacLennan, Dr John Miles, Dr Michael Pienkowski and Dr Peter Tilbrook.

We are very grateful to Stuart Wallace for preparing many of the diagrams and to Fiona Burd, Lynda Davis and Alison Rothwell for several other illustrations. We also thank Janet Southey for her helpful advice and supervision of the illustrative material, Sandra Lackie and Sylvia White typed several sections of text, whilst David Dyer assisted with the collation of the list of references. Sylvia White also typed and formatted some of the larger tables.

Finally we record our warmest thanks to Philip Oswald for checking the bibliographical references and editing the text for publication.

Introduction

The north-west Highlands and Islands of Scotland contain some of the most spectacular scenery in Britain. They are celebrated as a region of high mountains and rugged moorland, where steepness of slope and abundance of bare rock prevail. These dramatic landscapes occupy much of Wester Ross and west Sutherland. In sharp contrast, however, the far north-eastern corner, in Caithness and east Sutherland, is a district of low-lying, gently undulating or even flat moorlands, more akin to the desolate rolling tundras of the Arctic regions.

The high mountains of the west have long invited exploration by naturalists, and their importance for plants and animals has become fairly well known. The importance of this western district was recognised in *Nature Reserves in Scotland* (Cmd 7814) with the proposal for a Special Conservation Area here, though this recommendation was not followed through in practice. The undramatic moorlands to the east remained largely unknown, though they had been described in 1911 by C B Crampton, a remarkable geologist whose interests included botany and plant ecology. By the late 1950s, Nature Conservancy surveyors had penetrated the east in places and described it as "the flow country" from the huge expanse of almost level bogland, "flow" being a northern term for any flat, deep and wet bog, This was clearly the largest continuous expanse in Britain of the type of peat moorland known to ecologists as "blanket bog". When more scattered areas in west Sutherland were included, the total extent of blanket bog in these two Districts (Caithness and Sutherland) proved to be 4000 km^2.

Priorities for survey nevertheless lay elsewhere and, after the identification of a number of outstandingly important areas of bog in apparently near-pristine condition, the Caithness and Sutherland flows were left to await fuller study in future. There was then nothing to indicate that they were under immediate threat from land-use change. A concerted effort at exploration and survey was finally mounted in the late 1970s, by which time the great scientific interest of these peatlands and their conservation importance internationally were clear.

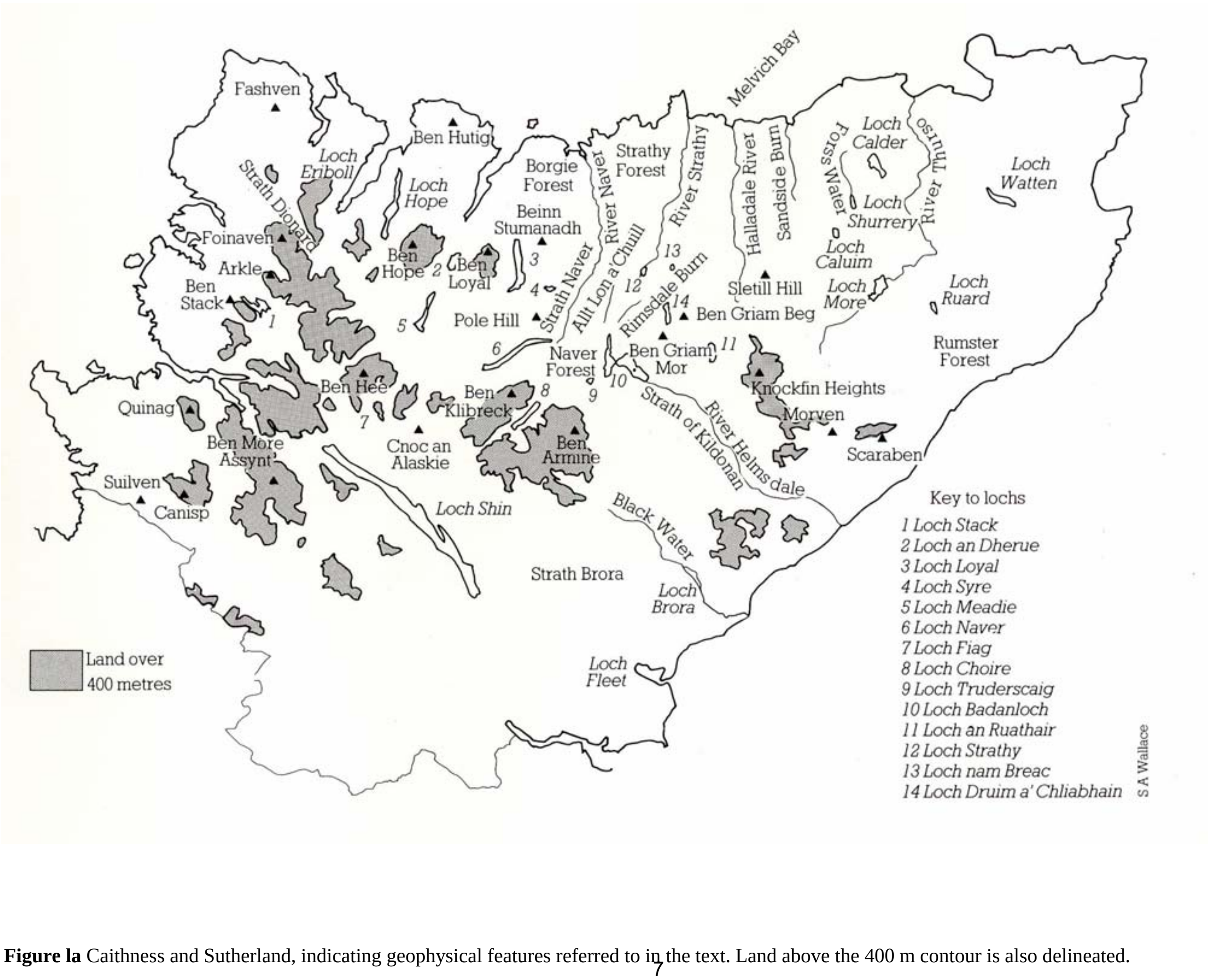


Figure la Caithness and Sutherland, indicating geophysical features referred to in the text. Land above the 400 m contour is also delineated.

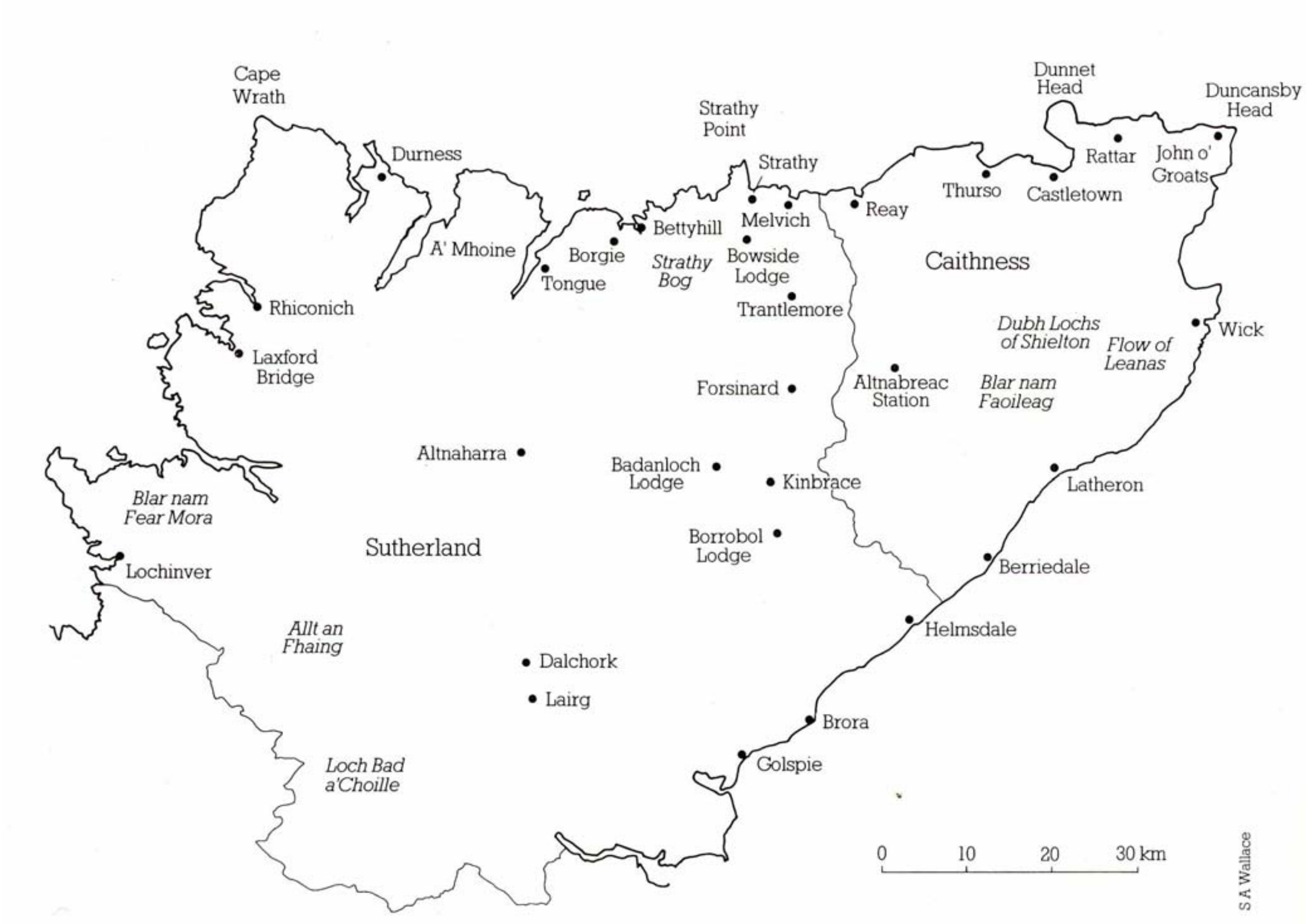


Figure lb Caithness and Sutherland, indicating place names referred to in the text.

The Flow Country represents a complex ecosystem. It is covered with a deep mantle of peat containing, in its preserved pollen grains and other plant remains, a record of its development and controlling environment, beginning several thousand years ago. The surface is mostly a spongy, living layer of *Sphagnum* bog-moss which continually builds its level higher by upward growth but is in many places thrown into strange and distinctive patterns by swarms of small peaty pools. There are numerous larger lochs, some mainly peaty but some with firmer, stony or sandy margins, and many streams of varying size and character drain the moorlands. The whole is the summer breeding haunt of a fascinating bird fauna, which has much in common with that of the true Arctic tundras and represents a group of mainly northern and boreal species here inhabiting a southern and oceanic region. Spread over this large area, the numbers of several local moorland birds represent a substantial proportion of their total European populations south of the Baltic.

An account of this bird fauna, its nature conservation value and the threats to its future has already been presented in the Nature Conservancy Council's report *Birds, Bogs and Forestry* (Stroud, Reed, Pienkowski & Lindsay 1987), which contains a summary description of the peatlands as habitat. The present report deals in detail with the peatlands - their development, structure, relations to environment, vegetation and flora. It is prefaced by an account of peatlands in general and blanket bog in particular, to provide a context for assessment of the scientific and nature conservation value of the Caithness and Sutherland examples. The main part of the report gives the results of the NCC's Peatlands Survey in characterising the field of ecological variation in these blanket bogs as the basis for a conservation strategy and programme. The impact of afforestation, as the main threat to the continued existence of these blanket bogs, is discussed briefly. The nature conservation requirements are then defined, in terms of peatland areas requiring protection.

In addition, the NCC has conducted surveys of lochs and of rivers in Caithness and Sutherland as separate studies. Although the river survey is incomplete, enough information has been gained to make parallel assessments and recommendations for conservation of these freshwater habitats. This analysis is presented in a separate section. For completeness, a summary of the bird surveys and recommendations is also given, and there is a final composite statement of the total nature conservation requirement, in terms of protected areas, when all three sets of interests are combined.

Part I Peatland ecology

1 The development and hydrology of mire systems

Mires (bogs) are natural 'museums', where objects which have elsewhere vanished long ago are sometimes kept in a remarkable state of preservation. Celebrated examples are Lindow Man, now on display at the British Museum, and Tollund Man in Copenhagen Museum. This ability to preserve material is derived from a particular combination of environmental conditions. Wherever the ground surface is waterlogged and deoxygenated, decomposition of accumulated dead plant material is slowed down relative to areas of better oxygenation. Where this reduction in the rate of breakdown causes at least some dead plant material to be retained and carried over into the next season, the deposit resulting from this steady accumulation of organic matter is known as peat. The Scandinavian term *myr*, anglicised from Old Norse to "mire", refers to any ecosystem which accumulates peat (Goode & Ratcliffe 1977) and is therefore used here as the general term for peatlands, whatever the nutrient status or water flux.

Fraser (1948) discussed the range of conditions which lead to peat formation. Various factors promote waterlogging of the ground. Both the amount and distribution of precipitation, and factors which affect evapo-transpiration (water loss from the vegetation-ground surface) such as atmospheric humidity and air temperature, are important. Topography (slope and ground-form) and permeability of soil are also crucial factors. Then there are the factors which independently affect the rate of microbial decomposition of dead organic remains, notably pH, nature of plant material, degree of aeration (related to stagnation of waterlogging) and soil temperature.

Table 1 shows the interaction of the various factors which result in the formation of peat. Broadly, conditions for peat development are optimal in basins or on flat ground, underlain by clay or impermeable bedrock, in areas of acidic catchment, covered with especially fibrous vegetation, and under a climate with high, evenly distributed rainfall and relatively low temperatures. Fraser (1948) points out that soil temperature is affected by cloud cover, the interception of sunlight being an important factor in maintaining relatively low soil temperatures. The proximity of mountain masses helps in this, particularly as the lowered temperatures affect the decomposer bacteria more than plant growth. Stach *et al.* (1975) - quoted by Hobbs (1986) - describe the ideal temperature for decomposition of organic material as between 35°C and 40°C, so that many wet areas in the tropics do not develop peat because the rate of decomposition outstrips that of accumulation. Under such conditions, peat accumulation is dependent on the acidity of the system rather than simply on waterlogging, because active bacteria generally prefer a neutral or alkaline pH. In contrast, fungi are more acid-tolerant, but generally demand oxygen (with the exception of yeasts) and are much slower at breaking down plant material. Thompson & Hamilton (1983) state that pH values of less than 5.5 are necessary in Africa for peat accumulation. In cooler climates, peat accumulates under conditions of high pH, but it is then often more highly humified and may itself be neutral or alkaline and base-rich: it is then usually known as fen peat.

Ivanov (1981), Clymo (1983) and Hobbs (1986) all give excellent summaries of the development and properties of bog systems, while Sjors (1983) summarises the ideas of numerous previous workers concerning the origin of peat development. He identifies three primary pathways.

Pathways of peat development

1 Terrestrialisation of water bodies

Bodies of stagnant or near-stagnant open water develop anoxic layers in their bottom sediments. When dead aquatic or fen vegetation collapses into these layers at the end of the growing season, the remains cannot be attacked efficiently by the decomposer fauna and flora, so these accumulate year by year. Decomposition occurs even under the most anaerobic conditions, probably involving sulphur-metabolising bacteria (Clymo 1983) and perhaps also those which metabolise methane (Professor H Sjors pers. cornm.), but the process is much slower than under aerobic conditions.

With continued accumulation, the former water body eventually becomes completely filled with peat, but the general ground water table maintains anaerobic

	Inhospitable Extreme	Character	Hospitable Extreme
1	Low	Precipitation	High
2	Low	Number of days on which rain falls	High
3	Low	Atmospheric humidity	High
4	Low	Cloud cover	High
5	High	Temperature range	Low
6	High	Mean temperature	Low
7	High (90°)	Angle of slope	Low (0°)
8	Convex	Topography	Basin
9	High	Substrate permeability	Low
10	High	Substrate water pH and base-content	Low
11	High	Substrate-water aeration	Low
12	High	Nutrient status of vegetation	Low

Table 1

Factors affecting peat formation. These are the factors which are generally considered to play a significant part in determining the rate of peat accumulation in any locality. An extreme tendency to 'inhospitable' in 6, 7 and 11 will prevent peat formation however suitable the other factors may be. Blanket bog formation requires a marked or extreme tendency to 'hospitable' in 2,3,5,6,7,10 and 11.

conditions. At this point, however, if the climate is sufficiently wet, the central part of the peat expanse continues to accumulate material, whilst the margins, where the water table falls or becomes influenced by the mineral-enriched catchment, are subject to more rapid decomposition. The result is a steady elevation of the central part of the peat mass relative to the margins, forming the classic dome of a "raised bog". See Ivanov (1981, pp. 16-18) for a detailed account of this process.

2 Primary mire formation

Sjors (1983) regards this as an under-recognised means of peat formation, whereby wet ground freshly exposed by processes such as crustal uplift forms peat directly on previously unvegetated mineral ground. Examples of this can be seen around the Isle of Hailuoto, in the Gulf of Bothnia, where isostatic recoil exposes many hundreds of hectares from beneath the Baltic every century.

3 Paludification of dry ground

Where ground which was once dry subsequently becomes wet and then covered by peat, the process is known as paludification. Examples of this are many and various, though perhaps the most frequently quoted are areas paludified by wetness of climate. Godwin (1981) gives a striking photograph of a paludified rock capped by a significant thickness of peat. In sufficiently cool, wet climates even quite steeply sloping ground can become paludified; under such conditions terrestrialisation may not necessarily occur, but the two processes are often juxtaposed, so that basins become peat-filled by terrestrialisation, whilst the surrounding slopes become peat-clad by the more direct process of paludification. The total peat mass then usually becomes continuous at the surface, so that stratigraphic study is necessary to elucidate the range of developmental processes involved.

The two major processes of acidic bog formation in Britain have been terrestrialisation and paludification. Together they have produced more than 1,300,000 ha of commercially exploitable peat reserves (Robertson & Jowsey 1968) and an even greater total area of peat soils, a large proportion of which is located in northern and western parts of Scotland (see Figure 2). The total area of peat-covered ground is, however, not accurately documented because of problems in definition and survey. Most quantitative reviews (e.g. Robertson & Jowsey 1968) are therefore restricted to peat deposits which have some potential for exploitation.

Peat and blanket bog development

In cool, continuously wet regions with predominantly gentle relief, conditions are suitable for the paludification of entire landscapes. Constant precipitation with low evaporation tends to leach porous terrain such as glacial till, leading to the production of an iron pan. This podsolisation further helps to waterlog the base-deficient leached soil and create conditions in which the acidophilous members of the genus *Sphagnum* can begin to carpet the ground in a process of paludification (Fraser 1948; Pearsall 1950; Hobbs 1986). *Sphagnum* species are chemically poor in nitrogen and phosphorus and are therefore not easily broken down by soil micro-organisms (Gorham 1966; Coulson & Butterfield 1978; Dickinson 1983, Figure 5.3). In addition, although all living tissues produce H^+ ions, *Sphagnum* has such a high cation exchange ability (CEA) that it easily binds metal ions to its surface at the expense of H^+ ions, which are released from the plant into the external solution, thereby making the surrounding soil water increasingly acidic (Clymo 1967).

Much the same process of acidification occurs in the central parts of basins which are in an advanced state of terrestrialisation. Where basins are surrounded by a zone of substantial water

Figure 2 Major deep peat (bog) deposits in Britain (based on Taylor 1983, LANDSAT imagery and unpublished NCC survey data). This does not show the total extent of peat soils, which would cover a much wider area. Isopleths for annual average number of "ram days" (1901 -1930) are shown. The close correlation between the isopleth for 200 "rain days" and the limit of extensive peat formation is evident, although the warmer conditions of East Anglia cause this relationship to break down. A "ram day" is defined by the Meteorological Office as a 24-hour period during which at least 0.25 mm precipitation is recorded.

movement, the mound of peat is confined by that seepage (Ivanov 1981; Ingram 1982). However, where the basin is not delimited by such a feature, the mound of peat encourages swamping around its marginal slopes by water flow from the dome and general impedance of the surrounding ground water table. Mire development may thus extend outwards from the original basin quite rapidly if the surrounding relief is gentle, to form massifs with shallow gradients and wide marginal fens of up to 2 km (Ivanov 1981). This is an intermediate state of development, which may continue its lateral expansion if the topography is suitable.

If the climate is sufficiently cool and wet, therefore, basins, plateaux and gentle slopes come to be swamped by peat, formed from acidic vegetation composed largely of *Sphagnum* bog-mosses. Slopes of up to 20° are commonly cloaked in this way, and in extreme conditions even 30° slopes may be thus affected (Ratcliffe 1964; Ingram 1967; Goode & Ratcliffe 1977). Where both terrestrialisation of basins and paludification of plateaux and gentle slopes occur at different places in the same landscape, the individual mire units may eventually begin to coalesce to form what Ivanov (1981) calls *mire macrotopes* (see Chapter 2). These are equivalent to Sjors' (1948) mire complexes, which combine several congruent and hydrologically interrelated mire sites into a continuous peatland system. Even the influence of base-rich rock (including limestone) may be overridden by paludification, except on steep slopes, and the tendency to an enveloping mantle of peat led H Godwin to describe it as "blanket bog" in preference to Osvald's "cover moss" (Osvald 1949; Pearsall 1950). Within any one area of such bog, the underlying peat varies considerably in depth and humification, according especially to the angle of slope and degree of waterlogging.

Atmospheric flushing and rate of peat formation

High rainfall, however, creates contrasting effects - waterlogging, which tends to encourage peat accumulation, and flushing, which tends to increase peat breakdown. The total annual rainfall and number of wet days can combine to produce optimal conditions for vigorous blanket bog development, but Bellamy & Bellamy (1966) have suggested that, if the annual volume of precipitation exceeds the limits of this optimum, the mire surface may become subject to marked "atmospheric flushing", resulting in reduced rates of peat accumulation. Evidence for flushing is visible to a certain extent in all examples of ombrotrophic mire in Britain. For example, *Sphagnum papillosum* is regarded as a species of minerotrophic mires in Finland but is the dominant species on many of Britain's ombrotrophic bogs.

The effect arises because larger volumes of precipitation entering a site produce an increase in the flux of oxygen and electrolytes through the surface layers of peat, particularly in oceanic areas where spray can contribute significant quantities to precipitation. The greater the flux, the greater the rate of humification of freshly-dead plant material before this can reach the anoxic lower layer or *catotelm* (see below). Ingram (1967) discusses the role of increased water flow and nutrient flux associated with water-tracks, or flushes, on mire expanses and emphasises the important role played by the *rate* of electrolyte supply, as opposed to the *concentration* of dissolved solids, which is normally measured when oligotrophic vegetation is being investigated. He also points out that the species composition of such areas is often *Molinia*-dominated. His field measurements at Inverpolly, however, suggest that the dominance of *Molinia* is not necessarily always linked to high oxygen flux in the peat as proposed by Jefferies (1915). He suggests instead that high concentrations of toxins such as hydrogen sulphide in relatively stagnant areas of the mire surface might be more of a limiting factor. The presence of *Molinia* in mire systems can therefore be used as an indication of low concentrations of hydrogen sulphide.

Armstrong & Boatman (1966) provide evidence which supports Ingram's (1967) suggestion of hydrogen sulphide toxicity, by demonstrating that living *Molinia* roots are only found where hydrogen sulphide is absent. They show that such conditions occur in flushed peats, which have high oxygen levels to depths of 16-18 cm, whereas in stagnant conditions oxygen penetrates to less than 6 cm.

Coulson & Butterfield (1978) have demonstrated that the decomposition rate of peat is limited by the "palatability" of the dead plant material. Where this has grown under conditions of high nutrient supply, the decomposers in the peat are able to break the material down more rapidly than plant material grown under normal oligotrophic conditions. N was found to be a limiting factor in this process. Increased rainfall amounts can thus be expected to generate vegetation richer in nutrients and so increase the rate of peat decomposition. However, the increased input of dissolved solids to oceanic areas is generally high in cations such as Na, K and Mg but low in particulate matter rich in N and P (Groenendael, Hochstenbach, Mansfeld & Roozen 1975).

Under conditions of maximum stagnation and waterlogging, therefore, the peat is composed largely of *Sphagnum* in an unhumified condition; in better-drained or in flushed situations, the remains of vascular plants make a much larger contribution and occur in a more humified condition. The climatic and biotic "peat template" (Bellamy & Pntchard 1973) produced in blanket bog is nevertheless too severe an environment for most plants, and a highly specialised range of species comes to characterise the peat surface.

Characteristics of peat soils

There are at least three ways in which the hydrology of peat systems differs fundamentally from that of mineral soils.

First, the great mass of peat which forms a bog is not simply a superficial deposit interposed between bedrock and surface vegetation to a thickness determined largely by geomorphologic processes. The peat depth and shape are both products of biological processes directly comparable with organic growth. The factors which determine this growth are climate, the nature of the immediate terrain, and the rate of peat accumulation. A peat body is thus not only of a biologically determined shape, but is generally a continually growing feature. Such characteristics are in marked contrast to most mineral soil deposits.

The same arguments apply to the shape of the undulations on a bog surface. In a mineral soil, such undulations and irregularities are largely a product of physical processes, whereas the patterns of pools, hummocks and ridges on a mire surface are a direct result of organic growth and surface hydrology.

Finally, because the components of peat soil are organic rather than inorganic, drying such material tends to produce physical changes resulting from aeration, shrinkage and decomposition of the organic matter (98% of the soil - see below). Such changes are irreversible, and a peat soil thus affected can only recover from such effects by fresh growth of vegetation and subsequent accumulation of peat. In mineral soils, the process of 'dewatering' is reversible (except in some clays). The ability of bog peat to hold water is quite remarkable. Individual *Sphagnum* plants can absorb many times their own weight of water, and Hobbs (1986) gives figures of 6% (by volume) of solids to 94% water in a 5 metre sample core of peat. In other words, as Goodwillie (1987) observes, there are fewer solids in peat than there are in the same volume of milk.

Three types of water are generally recognised as forming part of the peat matrix, though the boundaries between these three states are not sharp - the intracellular water, tightly-bound intraparticle water, and loosely-bound interparticle (interstitial) water, which is the only source of mobile water under most natural conditions. Despite their high water content, bogs have a significant shear strength because peat has a fibrous nature even when highly decomposed. The great physical stability of the peat mass is derived from the immense cation exchange ability (CEA) of *Sphagnum* peat (Hobbs 1986). The low rate of cation input from rainfall means that up to 80-90% of exchange sites may still retain the weakly bound H^+ ion instead of a metallic ion. The proportion of H^+ ions still attached to exchange sites is lower than this in blanket peat and fenland peat and is also lower in coastal areas, where rain and spray contribute considerable amounts of magnesium ions which bind strongly to the exchange sites. The ash (i.e. non-organic) content of peat can be as low as 2%, though Iceland's volcanic activity gives some blanket peats there an ash content of 20% (Clymo 1983, and see Chapter 3). Higher rates of solute uptake, associated with water flow through the peat, can also increase the ash content. Lefebvre, Langlois, Lupien and Lavallee (1984) give values of 30% for flushed muskeg. Blanket bog peat, though not flushed to this extent, typically has a higher ash concentration than raised bog peat.

The high CEA gives peat a very high liquid limit -i.e. the limit at which the peat, under pressure, begins to flow. The mound of peat is not therefore generally in danger of collapsing, despite its essentially liquid state. Increased humification, which increases the concentration of metal ions in the peat matrix, lowers this liquid limit.

With these characteristics, the dynamics of peat masses are evidently more complex than is generally the case for mineral soils, and their hydrology far more sensitive to interference. The fundamental differences between peat and mineral soils are perhaps most clearly revealed by examining the way in which the character and shape of a peat body, or "mire unit", are controlled.

Morphology of the peat body ("diplotelm" dynamics)

Granlund (1932) and Wickman (1951), in some of the earliest studies of mire hydromorphology, generated a model which identified a link between climate, bog diameter and maximum height of the dome. This tentative model has since been developed by Ingram (1982) into the Ground Water Mound Theory. This theory is based on the original concept of ground water mounds as defined by Childs (1969), as well as work carried out at Dun Moss and a substantial body of Russian research now available through Ivanov (1981). Whilst Clymo (1984) has shown in general terms that bog growth is limited by the quotient of input to decay in the lower layer of a bog, Ingram's model permits the calculation of the outer limit of stable shapes for a site under a given set of conditions.

The model demonstrates that, under a given climatic regime, a hemi-ellipse is generally the maximum upper limit to the domed profile for the bog to remain stable. This maximum profile can be described with the use of the Dupuit-Forchheimer Approximation. It is determined by a function of bog diameter, the amount of precipitation, and is related to the duration of the severest drought period. The bog retains its stability through dry summers and wet winters by swelling and contracting in what Prytz (1932) described as *mooratmung* (mire-breathing). Fox (1984) has demonstrated this process for Cors Fochno in Wales, where an annual surface rise and fall of 15 cm was recorded.

Essentially, the Ground Water Mound theory is concerned with the lower layer of peat, often many metres thick, which gives the mire its overall shape.

This is termed the "catotelm" and represents the body of compressed peat, which slows down water flow from the bog to such an extent that the mound of peat remains fully saturated simply through precipitation (Ingram 1982; Ingram & Bragg 1984).

The upper, surface layer, or "acrotelm", is extremely shallow (only 10-50 cm) and includes the living surface of vegetation. This thin but tough layer covers the deep mound of dead but saturated peat of the catotelm. The acrotelm is the layer of most active water movement, with water flowing many times faster through its structure than through the more amorphous, and often more humified, peat of the catotelm. It is also the layer in which the vegetation, root mat and, more strikingly, most of the small-scale surface patterns so typical of bog systems occur (see Figure 3).

Ivanov (1981) summarises the character of the two layers as follows -

Catotelm

(Ivanov's "inert layer")

- a constant or little changing water content;
- a very slow exchange of water with the subadjacent mineral strata and the area surrounding it;
- very slow hydraulic conductivity in comparison with the acrotelm (a difference of 3-5 orders of magnitude);
- no access of atmospheric oxygen to the pores of the peat soil;
- no aerobic micro-organisms and a reduced quantity of other kinds in comparison with the acrotelm.

The thin surface layer, which sits upon the catotelm, cloaking it from external influences, has the following properties -

Acrotelm

(Ivanov's "active layer")

- an intensive exchange of moisture with the atmosphere and the surrounding area;
- frequent fluctuations in the level of the water table and a changing content of moisture;
- high hydraulic conductivity and water yield and a rapid decline of these with depth;
- periodic access of air to interstitial spaces during periods of lowered water table;
- a relatively large quantity of aerobic bacteria and micro-organisms facilitating the rapid decomposition and transformation into peat of each year's dying vegetation;
- the presence of a living plant cover, which constitutes the top layer of the acrotelm, and which binds the whole surface together into a 'skin', preventing the water-saturated catotelm from starting to flow, even under heavy rains.

Acrotelm dynamics and surface patterns

Crampton (1911) was one of the first authors to describe the maze of peat lochans *(dubh lochain)* which occupy the higher, flatter parts of the Caithness flows. Since then a wide range of explanations has been proposed for the striking surface patterns which are found on so many boreal mires, from the early accounts of Osvald (1923), Aario (1932) and Tansley (1939), through the papers by Sjors (1948), Ratcliffe & Walker (1958), Ruuhijarvi

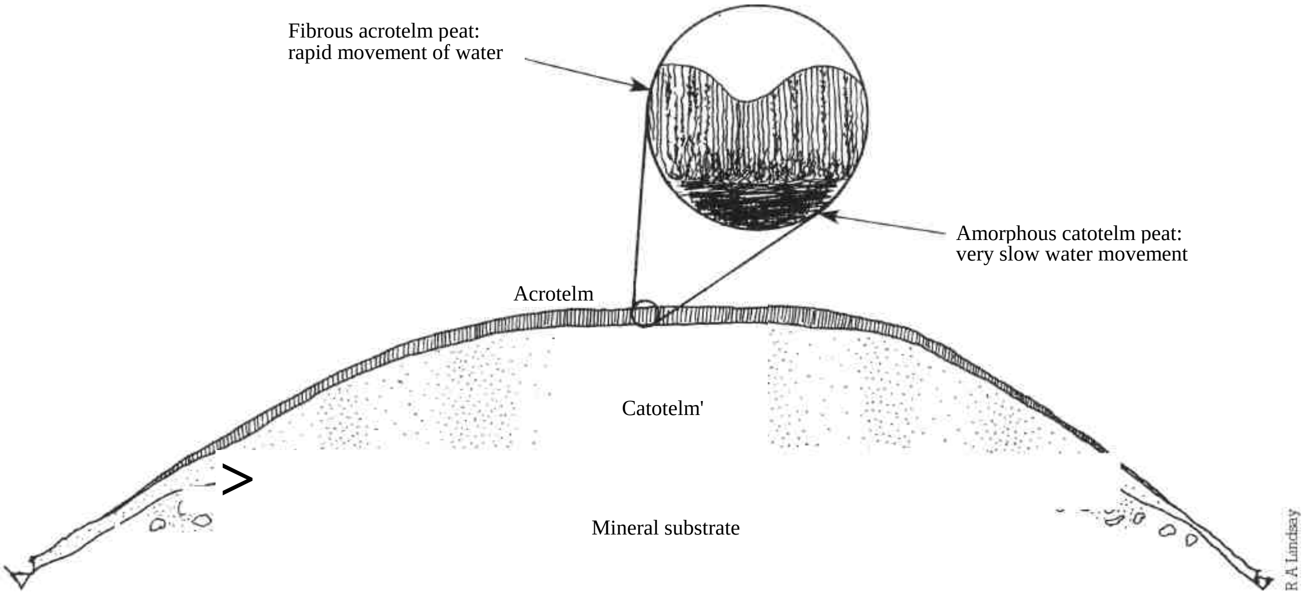


Figure 3 The "diplotelmic" profile (Ingram 1982) of a watershed blanket bog, illustrating (inset) the change in detailed structure from the surface layer ("acrotelm") to the underlying peat ("catotelm"). The vertical scale, particularly of the acrotelm, has been greatly exaggerated.

(1960) and Eurola (1962), to the detailed studies carried out on British patterned mires by Boatman & Tomlinson (1973), Goode (1973), Boatman, Goode & Hulme (1981), Barber (1981) and Hulme (1986). Indeed the use of surface pattern classifications is now becoming widespread in national peatland inventories (e.g. Moen 1985; Wells & Zoltai 1985; Eurola & Holappa 1985; Lindsay, Riggall & Burd 1985). The origin and dynamics of these patterns have been, and continue to be, the subject of much conjecture and debate.

The well-documented patterned landscapes of the tundra, where ice-action plays such an important part in generating the surface pattern, offer little in the way of mechanisms to explain patterns in the most oceanic regions of the boreal. The majority of such oceanic fringes remain relatively free from ice throughout the year and therefore some mechanism other than freezing is required to explain the origin of their patterning. Even in less oceanic parts of the boreal, patterns may not be generated by freezing, but could be accentuated by its effects.

Osvald (1923) suggested the term *regenerations-komplex* in relation to the hummocks and hollows of the Swedish raised bog Komosse, and this term was adopted by Tansley (1939), Godwin & Conway (1939) and Pearsall (1950) as "regeneration complex" to mean cyclic replacement of hummocks by hollows and *vice versa*, through differential upward growth of these contrasting surface features.

Troll (1944) proposed that the patterns might result from some form of soil creep. Pearsall (1956) subsequently theorised that open pool formation, as found at Strathy and Druimbasbie Bogs in Sutherland, was not necessarily part of the cyclic system, but might instead result either from peat splitting owing to surface tensions resulting from downslope movement, like crevasses in glaciers, or from furrowing due to shrinkage of the peat body since the onset of what he considered to be the contemporary dry climatic regime.

Pearson (1954) and Moore & Bellamy (1974) present evidence from Muckle Moss, in Northumberland, which clearly demonstrates that mass movement can occur, because a fence line has twice been bent, then broken, in a downslope direction. A series of crescentic pools is taken as further evidence of surface splitting and peat movement. There is no doubt in this case that the peat body has moved, and it is therefore interesting to note the difference between this site and normal patterned mires. First, the site lies in a climatic region within which open pools are not recorded on ombrotrophic mire surfaces (see Figure 4). The nearest example, apparently itself on the limit of such patterning, is Butterburn Flow, on the Cheviot divide, within a slightly wetter climatic region than Muckle Moss. Secondly, the pools are not orientated in the same way as typically crescentic or circular boreal patterns, but are clearly of a type and orientation consistent with mass downward movement and surface splitting. Thirdly, the mire is actually a valley mire which is only barely, if at all, ombrotrophic and therefore has a significantly different pattern of water movement from that of entirely ombrotrophic peatlands. Finally, the moving fence was erected by the Forestry Commission when it drained and planted the lower end of the valley mire. Such drainage and consequent shrinkage could be expected to have a marked effect on such a wet, deep peat deposit, including the mass movement of the peat body by gravity slide, particularly in view of Hobbs' (1986) observations on the liquid limit of peat.

Sjors (1961) discusses the phenomenon of patterning throughout the boreal zone, particularly in relation to the so-called "string fens" or *aapa* mires. Here he points out that the patterns of ridges and pools (or "flarks") are not correlated with downslope movement of the peat because extensive patterns develop on very shallow gradients. He also points to the historical stability of these patterns, stating that there is little evidence for infilling of flarks. He identifies two general forms of patterning, namely those which are derived purely from peat growth, and those which are influenced by, or are a product of, permafrost. Most importantly, Sjors regards the tundra ecosystem, with flooded frost polygons overlying permafrost, as being quite different from the patterns of boreal peatlands where permafrost is absent.

The generalised diagram of ombrotrophic mire surface patterns in Britain provided by Lindsay *et al.* (1985) is modified in Figure 4 on the basis of interpretation from more detailed aerial photographs. Overall trends in surface patterning are apparent, with increasing proportions of hollows and pools making up the pattern as the climate becomes progressively cooler and wetter to the north and west.

Goode (1973), using Darcy's Law of water flow through a porous medium, has constructed a model which defines a relationship between the scale of surface microtopography and the overall gradient of the mire surface (see Figure 5), and he re-emphasises the relative stability of such patterns on the Silver Flo we (Boatman, Goode & Hulme 1981). Hulme (1986) has also shown the stability of these patterns. Smart (1982) confirms both the relative persistence of such patterns and the early genesis of pools, from a site in Caithness, suggesting that Pearsall's ideas of surface movement due to the build-up of peat (Pearsall 1956) were incorrect. Korchunov, Kusmin & Ivanov (1980) demonstrate the genesis and relational stability of both hollows and pools throughout the development sequence of a raised mire system.

The link between slope, surface pattern and vegetation is described in detail by Ivanov (1981), confirming the general relationship between surface pattern and slope identified by Goode (1973). Ivanov's synthesis of Russian research shows that the stability of the surface layer determines the stability or otherwise of the massifs major water exchanges.

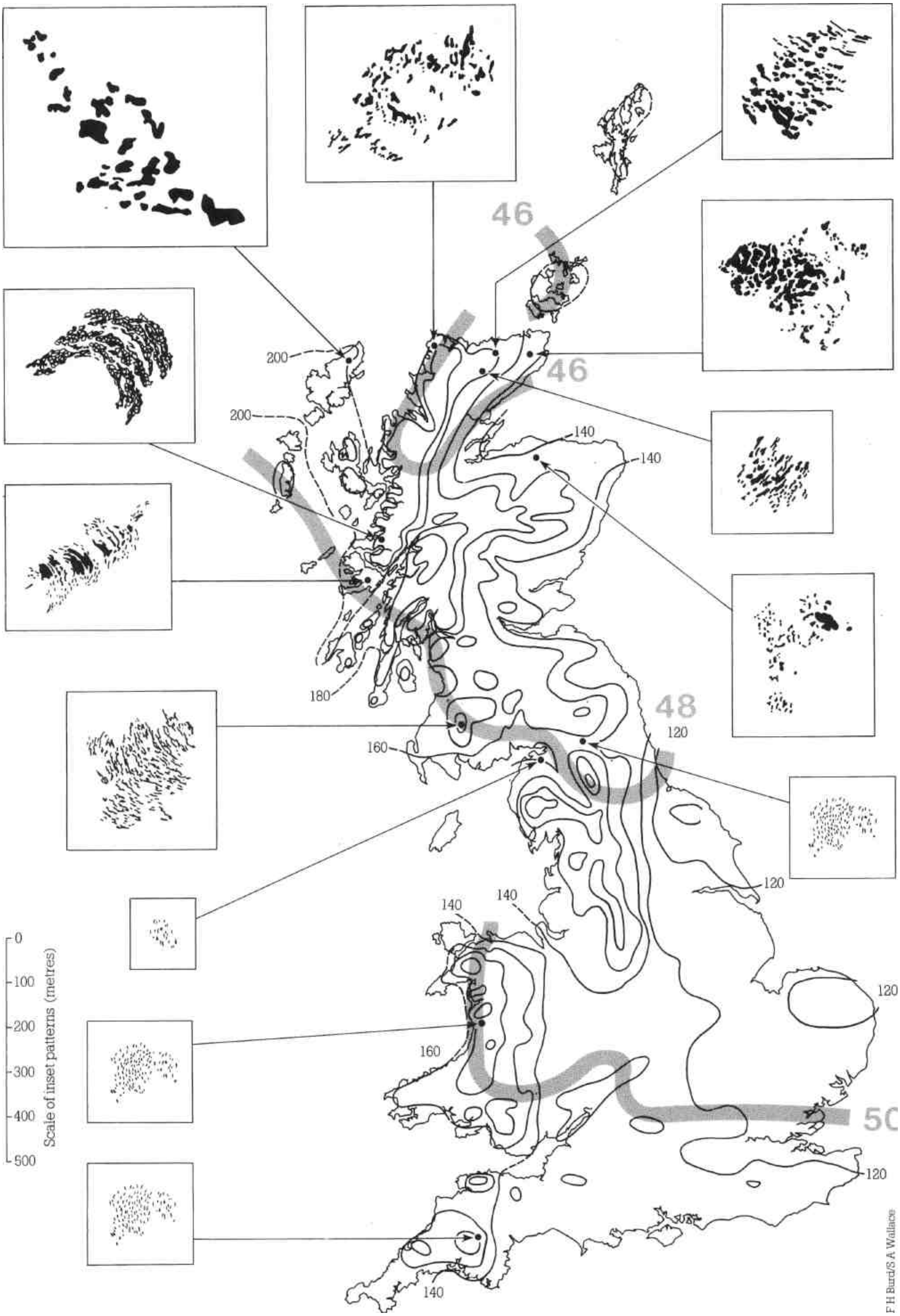


Figure 4 Distribution and general structure, seen from above, of bog surface patterns recorded from a range of sites throughout Britain. Patterns have been mapped directly from aerial photographs standardised to the same scale. Pools and hollows are shaded black, ridges and hummocks white. Isopleths for annual average number of "wet days" are also indicated, as compiled by Ratcliffe (1968) from data published in *British Rainfall* (1951-1960) (see Figure 12b). Superimposed are the isotherms for three average means of daily mean temperatures over the period 1901-1930 - 46T (7.8°C), 48°F (8.9°C) and 50T (10°C).

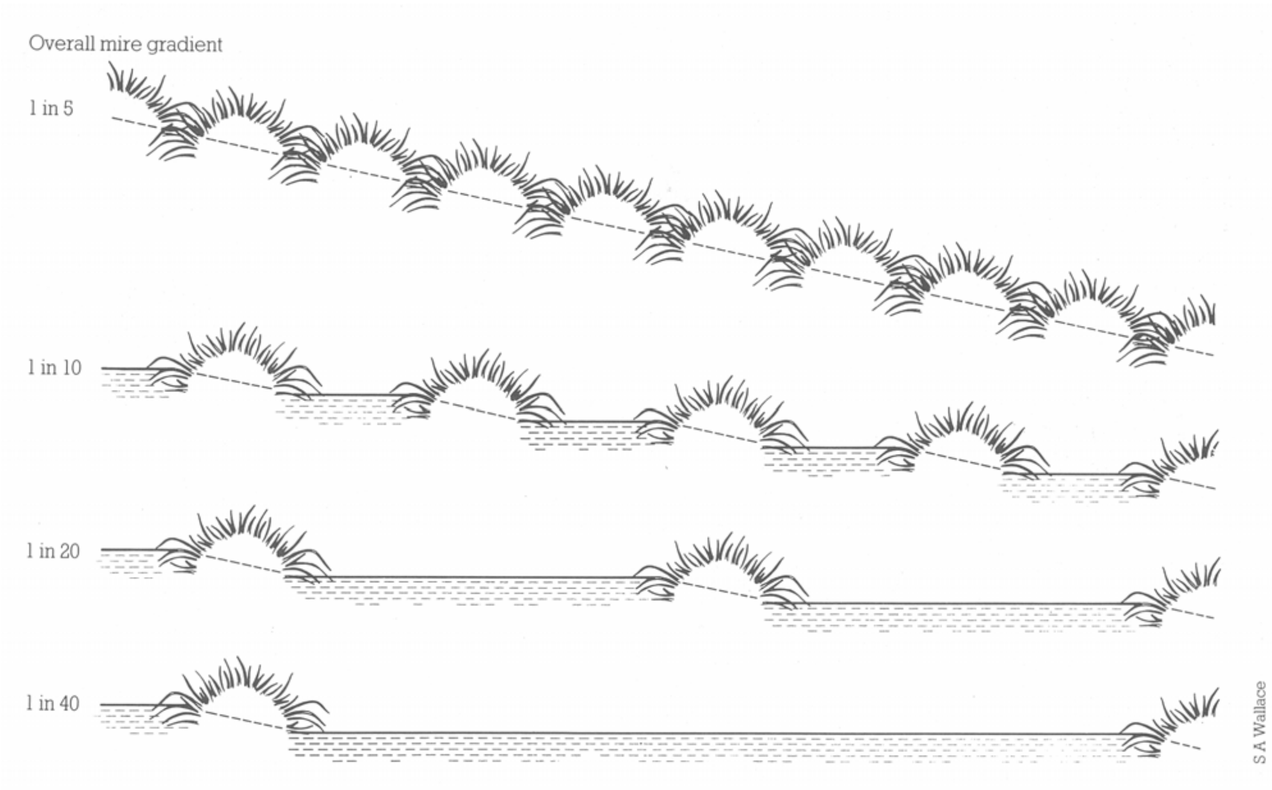


Figure 5 Generalised model indicating the relationship between ridge microtopes and pool microtopes on sites possessing differing overall hydrological gradients. If the gradient of the water table within ridges is maintained at 1:5, for example, bogs with overall shallow gradients support wider pools than areas with steeper hydrological gradients. (Based on Goode 1973.)

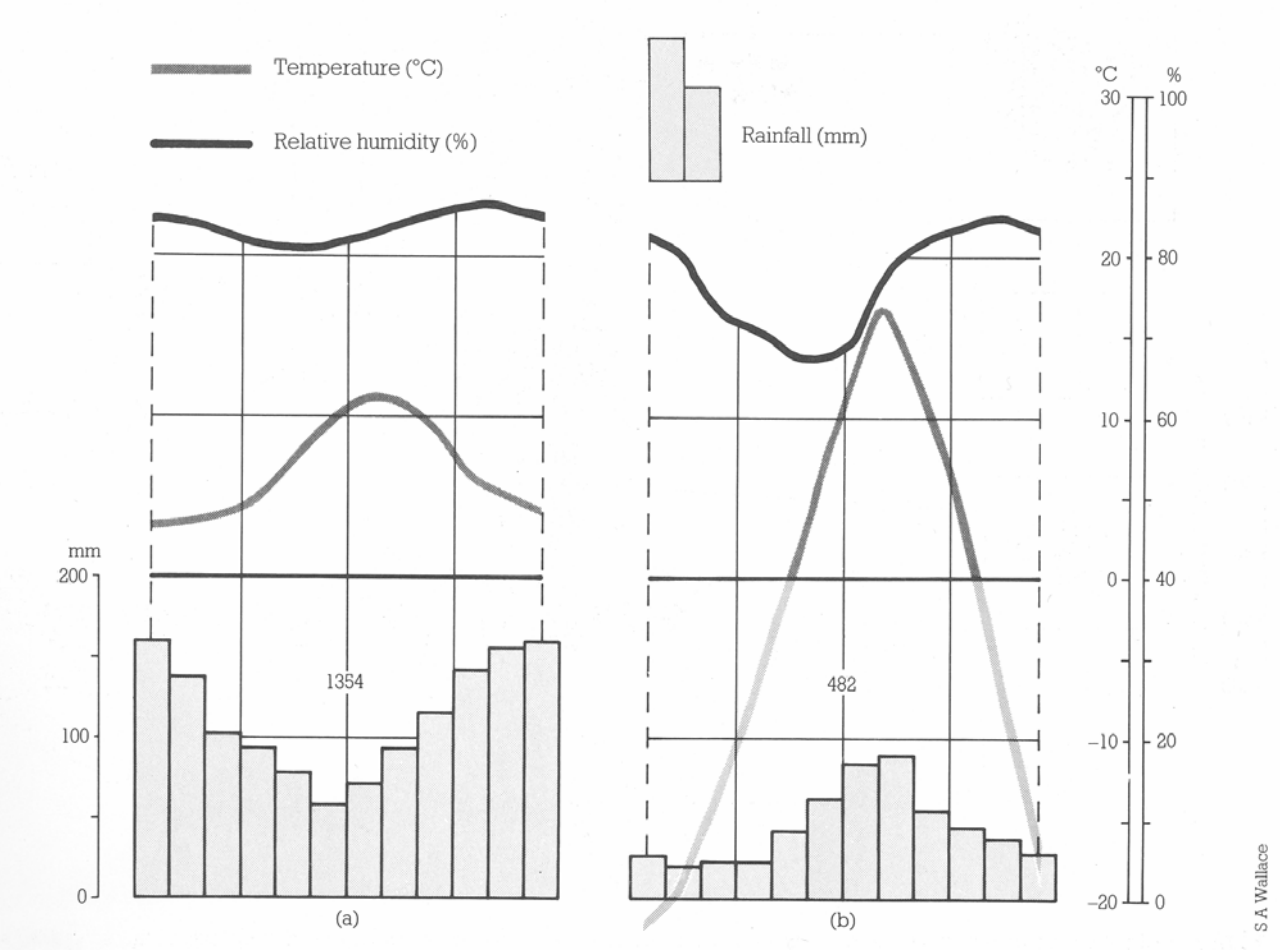


Figure 6 Climate diagrams for (a) Fort William in Highland Region and (b) central Siberia. (Taken from *Physico-geographical Atlas of the World* (Academy of Sciences of the U. S. S. R. 1964).)

The stability of this surface layer is ensured by the surface "strip-ridge" pattern or microtopography (Ivanov's "microtope"; see Chapter 2 and Figure 5). The vegetation both generates and is then controlled by the surface pattern. Ivanov subsequently gives a wide range of mathematical solutions for the arrangement of surface patterns (microtopes), demonstrating that these patterns are in fact the major source of hydrological stability within the mire system rather than, as is so frequently suggested, being products of instability.

The patterned ground of the tundra

Vast tracts of organic terrain characterise certain regions of the Arctic, such as the enormous expanse of the Hudson Bay lowlands in Ontario and Manitoba or the drainage basin of the Ob and Yenisey in western Siberia. Here, the landscapes take on a superficial resemblance to the Caithness and Sutherland plain, with vast numbers of shallow lakes lying in a peat matrix and forming what Ivanov (1981) terms a "bog-lake complex". The relatively dry climate, the prolonged freezing in winter and the short but warm summers in these regions are, however, in marked contrast to the permanently cool, but never really cold, and extremely humid conditions described above and also in Chapters 3 and 4 for blanket bogs in northern Scotland. Farther south, within the *taiga* zone, the juxtaposition of forest or the presence of an open or depauperate tree growth on or around the organic deposits also contrasts with the treeless character of British and Irish blanket bogs.

The great flows of Caithness and Sutherland have a quite striking resemblance, at first sight (see Sage 1986, Plates 2.2 and 5.5), to some of the tundras of the Arctic region - a correspondence often remarked on by overseas visitors. This analogy with Arctic tundra should not be taken too literally because the similarity is ecologically superficial. However, Pruitt (1978) notes that the word "tundra" originates from the Finnish word *tunturi*, a region in northern Finland which is simply "beyond the poleward limit of trees" and which consists of many vegetation types. Arctic tundra also includes dry types, but the wet types most resembling blanket bog are especially developed on areas where permafrost maintains permanently waterlogged ground during the period of summer thaw, but most often under conditions of low annual precipitation and atmospheric humidity (see Figure 6). The organic layer is usually much shallower than in blanket bog. Patterning, including pool and hollow development in the tundra also gives superficial similarities to many of our blanket bog pool and hummock systems.

2 Classification of mire systems

The vernacular terminology for peatlands in Britain is far too loose to be of value in classification. "Peat moss" (or, in place names, "Moss") and 'flow' are applied in northern England and Scotland to areas of flat, deep peat bog in both lowland and upland situations, while "mire" is a term used widely for a variety of bogs, but especially lowland fens. The taxonomy of peatland systems in Britain and Ireland has, in fact, lagged behind that in continental Europe, and a brief review of different approaches is relevant. While this report follows the Scandinavian use of "mire" as a general term for peatlands, it deals with types which in Britain are usually known as "bogs", and we have preferred to use "blanket bog" because it is so well established a name in the literature.

The taxonomy of peatlands is complex, and blanket bogs give special problems. Moore (1984) has observed that "one group of mires in Europe, the blanket mires... has been neglected in the development of classificatory work". This chapter will examine the wider application of these concepts, the range of categories and the relevant terminology developed by peatland ecologists around the world. It is intended as context to the treatment of the Caithness and Sutherland mires.

General criteria for peatland classification

Dierssen (1982), following Grosse-Brauckmann (1962), summarises a wide range of criteria which have been used in mire classification. The main attributes used for distinguishing between mire systems include -

1 Morphology - whether the site is domed, producing raised mire, or undulating, with blanket bog.

2 Ecological development (ontogeny) - based on what the peat record indicates of the site's development, including the ideas of primary, secondary and tertiary peat development (Moore & Bellamy 1974). It also includes the concepts of topogenous, soligenous and ombrogenous (von Post and Granlund 1926), as well as Du Rietz's (1954) concepts of ombrotrophy and minerotrophy (rain- and groundwater-fed).

3 Geographic or topographic relationships - i.e. plateau, saddle, basin, valley. These have been commonly employed in broad classifications of British and Irish accounts of minerotrophic (fen) systems (e.g. Goode & Ratcliffe 1977; Wheeler 1984) but they are also one of the commonest systems for distinguishing separate units within blanket mire landscapes (Osvald 1949; Ratcliffe & Walker 1958; Goode & Ratcliffe 1977).

The geomorphology of a site is given some prominence by the Austrian Mire Conservation Catalogue (Steiner 1984) on the grounds that geomorphology influences the pattern of water flow through, across or round a site. This source of variation is also used extensively in the USSR, where mire systems are defined on the basis of geo- and hydromorphology (Ivanov 1981).

Steiner (1984) describes 14 geomorphological classes, whilst the hydromorphological system used in the USSR (Ivanov 1981; Botch & Masmg 1983) employs nine classes, which are divided into 20 sub-classes.

4 Vegetational and floristic features - perhaps the most constant feature of any mire description. Two major techniques have become established - that of the northern European school, quantitative ordination, and that of the southern and central European school, phytosociology. In Britain, phytosociology is commonly perceived as an inflexible system unable to cater for geographical variation in either vegetation composition or ecological amplitude of species. It is also prone to nomenclatural absurdities. Thus the major Class for bog hollows is Scheuchzerio-Caricetea nigrae (Nordh. 36) Tx. 37, yet *Scheuchzeria palustris* is almost completely absent from the bog hollows of Britain and Ireland. The various attempts to bring about a unified system of classification have concentrated on bridging this major divide, but as recently as 1985 the unresolved differences have led to suggestions that a unified system is neither practicable nor desirable (Sjors 1985b). Nevertheless, the wider application of phytosociology by those formally trained in the method (e.g. Dierssen 1982; Rybnicek 1985; Maimer 1985) has given a clearer insight into the usefulness of the system in north-west Europe and has led to a number of published accounts for Britain and Ireland employing the concepts, or the formal structure, of phytosociology (e.g. McVean & Ratcliffe 1962; Moore, J.J. 1968; Birks 1973; Wheeler 1980a,b,c; Birse 1980, 1984; O'Connell, Ryan & MacGowran 1984; Proctor & Rodwell 1986).

At the same time, development of computer-based ordination and classification techniques has stimulated the use of more 'objective' techniques typically favoured by British workers. Many recent analyses of mire vegetation, notably those of Daniels (1978), Ratcliffe & Hattey (1982) and Proctor & Rodwell (1986), have used M O Hill's TWINSPAN package (Hill 1979) or modified versions or precursors of this.

The advantage of phytosociology is that it provides a single standardised classification system to which subsequent workers can relate their results, whereas 'objective' ordination and classification techniques allow more flexibility for the infinite variety of nature but rarely produce the same vegetation type from two separate analyses; indeed the same analysis processed and interpreted by different people will often give different results.

To some extent the two methods appear to be drawing closer together through TWINSPAN, because some of the more formal schools of phytosociology in central Europe (e.g. the Botanical Institute at the University of Vienna) have begun to use TWINSPAN for the initial ordering of raw relevé tables.

5 Palaeobotanical features - Some systems make use of the sequence of mire development displayed within the peat profile to classify mire types (e.g. that of Tolpa, Jasnowski & Dalczynski 1967; Moore 1973b). However, this is not a practicable method for large-scale surveys and classification systems covering a wide geographical region. *A Nature Conservation Review (Ratcliffe* 1977), however, does recognise the importance of sites which have contributed significantly to our knowledge of peat development, vegetational (or sometimes human) history or climatic change through the record revealed in their profiles.

6 Soil chemistry and water relations - Initial ideas relating to the simple distinction between base-poor bog and base-rich fen have since been found merely to describe the two ends of a continuum (Sjors 1950a; Maimer & Sjors 1955; Wheeler 1984). Five general categories of base status are suggested by Succow (1974, 1980) and Succow & Lange (1984) and are used extensively in Central Europe. For Britain, Goode & Ratcliffe (1977) restrict the classification of mires in terms of base status to oligotrophic, mesotrophic and eutrophic systems.

7 Chemical and physical variables for exploitation - A number of classifications have considered mires in terms of their workability and potential for exploitation, particularly in Scotland for forestry or peat extraction (Fraser 1948; Tolonen, Pairanen & Kurki 1982; DAFS 1965, 1968). These give useful data about the depth and condition of the mires investigated, but they cannot be used to produce a classification for general application in their present form. Recent initiatives sponsored by the EEC will produce a review of exploitable peat resources within the next four or five years.

Levels of functional hydrology: the classification system of the USSR

Four levels of functional hydrology are listed by Ivanov (1981) and are equivalent to the structural features described in western literature, but they are defined as active features which both control, and are themselves controlled by, the underlying hydrology. The synthesis of Russian work provided by Ivanov (1981) clearly demonstrates that the shape of such features is a key factor in controlling hydrological stability. Figure 7 illustrates many of the concepts embodied in the Russian classification system.

Mire macrotope

Where mires escape their immediate hydrological confines to coalesce into larger composite units, the resulting complex is termed a mire macrotope. Thus a "ridge-raised" (Moore & Bellamy 1974) or "partly-

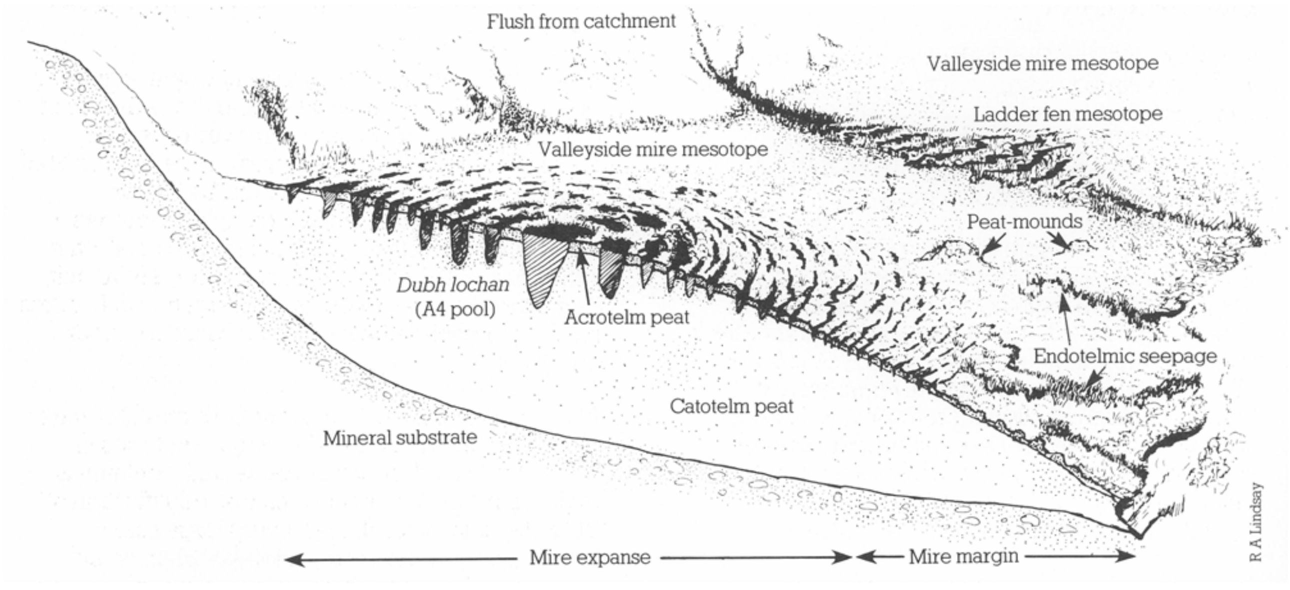


Figure 7 Two valleyside mire mesotopes linked by a ladder fen mesotope. Surface microtopes of pools and ridges are indicated, as are peat-mound microforms. The entire complex, including the hill slope catchment, forms a blanket mire macrotope. The vertical scale has been exaggerated. For explanation of terms see Chapters 1 and 2.

confined" (Hulme 1980) mire, where two raised mires coalesce, is one of the simplest types of macrotope. The Silver Flowe, in Galloway, is a more complex example, where parts are clearly mesotopes of blanket bog, others of raised bog, and others intermediate between the two. Ultimate expressions of macrotopes are the extensive blanket bogs of Britain and Ireland, the Red Lake Peatland and James Bay, the muskegs of central Canada, and the *taiga* mires of western and eastern Siberia.

The macrotope is a complex hydrological entity combining the hydraulics of the component mesotopes including their microtopes. Each level of hydrological interaction is dependent upon the other levels for stability (see Chapters 1 and 5), and it is generally impossible to affect one part of a macrotope without affecting the functioning of at least one or two other elements within that macrotope. In Siberia some of these macrotopes are "many thousands of square kilometres" in extent (Ivanov 1981), whereas the macrotopes identified for Caithness and Sutherland are more modest features (see Chapter 8).

Mire mesotope

The mesotope is equivalent to the mire massif or mire unit, being a body of peat which has developed as a single hydrological entity. Thus a single raised mire or a valleyside mire would represent a mire mesotope, the surface of which may contain a range of microtopes.

Mire microtope

This term relates to the arrangement and combination of surface features (microforms) which particularly characterise ombrotrophic mires, for example the regular organisation of ridges and pools across a mire expanse.

Mire microform

This term relates to the individual surface features within the patterning of a mire, for example a single hummock or pool.

Classification of mire complexes (macrotopes)

Moore & Bellamy (1974) emphasise through a diagram that blanket bogs are complexes possessing primary, secondary and tertiary peats in the one overall system. Moore, Merryfield & Price (1984) describe the habitat as a "complex unity" combining flushed and ombrotrophic mire types which occupy a variety of geomorphological positions and which "become inextricably linked in an interdependent, but floristically and hydrologically diverse, series".

Russian peatland specialists have, for many years, employed the concept of a mire complex for a wide range of peatland types. The method of classification which they have developed embodies many of the principles required also for the classification of blanket bog habitats. Faced with the problem of classifying extensive tracts of organic terrain, they have employed aerial stereo-photography as a rapid and resource-effective means of mapping and classifying mire systems. It has proved possible to identify four major levels of information from the air photographs, and a combination of these is used in classification. The information consists of geomorphology of the catchment, the shape of individual mire units (massifs), the surface patterns (microtopes) within the massifs, and the "flow-net" of water movement within and between these massifs and microtopes (Ivanov 1981).

When this technique is used, the definition of whole mire complexes forms a simple and logical step in the classification process, because the hydrological links between individual mire massifs are clearly revealed, thereby emphasising the need to define a boundary which does not traverse or truncate these functional connections.

The concept of a mire macrotope or mire complex, as described by Ivanov (1981), is not new. Cajander (1913) described whole *aapa* moor complexes in Finland as single functional units, whilst Sjors (1948), Ruuhijarvi (1960) and Eurola (1962) further developed this approach within Fennoscandian classification systems.

The Norwegian mire conservation programme embodies the concept of a mire complex *(sensu* Ruuhijarvi 1960; Sjors 1948), employing a classification based on hydromorphology, surface pattern and vegetation for the process of site selection (Moen 1985). The emphasis on hydromorphology is also adopted in the Austrian Mire Conservation Catalogue, although a more extensive classification of geomorphological location is employed than that described for the Canadian system (Steiner 1984). The system is similar to that described by Wells & Zoltai (1985) for Canada (see below).

Moen (1985) also highlights the important distinction between units for classification and the definition of site boundaries for conservation purposes. The conservation unit, often a complex, is defined as "the entire extent of a mire as bounded by the dry mineral ground". Within such complexes are what are termed "synsites", which correspond generally with Sjors' (1983) concept of an extended mire unit, being the entire area of ground and range of features naturally associated with a particular mire unit or mesotope.

In practice it is difficult to adopt the concept of mire mesotopes as a means of defining boundaries in blanket bog landscapes because such continuous expanses of peat do not permit the identification of discrete units, other than at a very large scale. Ivanov (1981) acknowledges this problem when discussing the hydrology of similar types of organic terrain, as found, for example, in the Ob-Irtysh water divide, where a mire complex can occupy many thousands of square kilometres.

In Fennoscandia problems are encountered with the delineation of the appropriate limits for mire complexes for conservation management purposes, because many fen *(aapa)* systems extend and interlink over wide areas of gentle terrain. Indeed the word *aapa* simply means vast. The delimitation of boundaries of ecologically coherent and self-supporting units is therefore not an easy task. In Britain similar problems are encountered in such fenland areas as Broadland, but there can also be an acute problem in some extensive blanket bog landscapes, where the arbitrary limits to this peatland category make site definition a difficult process.

In terrain normally characteristic of blanket bog, peat development within a basin is often defined by the surrounding slopes, whereas on a plateau the maximum extent of deep peat is limited by the point at which the ground slopes too steeply from the plateau for significant peat formation (e.g. a rock face). These steeper slopes often support flush systems associated with seepage from the plateau above, or, where the ground slopes steeply before levelling out into a further area of peat, flushes may contribute to the margins of this lower-lying area of peat. In such cases, the boundary of the mire mosaic includes these flushed slopes.

The mire complex, or macrotope, is adopted by Moen (1985) and Wells & Zoltai (1985) for the practical definition of boundaries around areas requiring protection. In terms of classification, however, both use the smaller mire unit, or synsite (Ivanov's mesotope), as the classification unit.

Classification of mire units (mesotopes)

The most familiar classifications of peatland deal with this level of organisation. Goode & Ratcliffe (1977) followed established British practice, in using a broad classification according to topographic-hydrological (hydromorphological) features, giving six main categories - raised mire, blanket mire, open water transitions and flood-plain mire, basin mire, valley mire and soligenous mire. Within each category, further subdivision according to vegetation was recognised. Raised and blanket mires, belonging to the ombrotrophic (rain-fed) class, have only acidophilous vegetation, but the others have vegetation varying from calcicolous to acidophilous according to the base-status of the ground-water supply.

Blanket bogs are a widely recognised but highly localised global type (see Chapter 3). Raised bogs belong to a broad zone within the boreal and cool temperate regions, with only moderate rainfall and fairly cold winters - a relatively continental climate. They are the principal class of ombrotrophic bog in Sweden, Finland, much of central Canada, the USSR and the main expanse of central Patagonia. *Palsa* mires occur in sub-arctic conditions, where frozen blocks of ice are cloaked with a mound of peat which insulates the ice sufficiently to prevent its thawing in the summer. Typically the vegetation of these *palsa* mires is somewhat minerotrophic, through the influence of snow-melt. *Palsa* mires are found throughout northern Norway, Finland and Sweden, and also in northern Canada. *Aapa* mires are essentially minerotrophic and soligenous, receiving the bulk of their water inputs during summer snow-melt. Narrow ridges form across the line of water flow in the appearance of a ladder, with wide pools between the 'rungs', leading to their common name of "string fens". Such patterned fens are characteristic of central and northern Fennoscandia, as well as central parts of Canada, USA and USSR.

As well as the classification of overall bog type, a further level of mesotope classification relates to the topographical location within the overall mire macrotope. This is particularly relevant with blanket bogs, as the differing patterns and vegetation are closely related to gradients determined by the hydromorphology. Thus a site may be a saddle mire or a valleyside mire. The range of hydromorphological types is discussed in more detail in Chapter 8.

Classification of microtopes within mire units (mesotopes)

Sjors (1948) identifies three main sources of variation *within* the mire unit for Swedish mires -

- the mire margin-mire expanse gradient;
- the rich-poor nutrient gradient;
- the gradient of wet to dry within the hummock-hollow pattern.

In Sweden, the transition from forest to open mire highlights a series of quite clear zones from the edge of the peat onto the central open mire. The mire margin is often characterised by growth of small trees and shrubs which increase in height towards the edge of the mire, whilst the mire expanse is generally characterised by an open vegetation dominated *by Sphagnum* mosses and dwarf shrubs. The conditions of nutrient supply and hydrology on the mire margin are very different from those of the mire expanse, and this is reflected in the marked vegetation differences.

While British raised mires show a transition from mire margin to central expanse, such a distinction is necessarily less clear on extensive blanket bogs. Variations in peat depth and surface wetness have more complex relationships to topography, but they exert an important influence on the distribution of breeding waders, the pattern of invertebrate populations and the distribution of plant species that require higher fluxes of oxygen or dissolved solids.

Another approach not often employed in accounts of British mires is the use of surface pattern to characterise mire types, as demonstrated by Ruuhijarvi (1960) for Finland and more recently by Moen (1985), Zoltai & Pollett (1983), Eurola, Hicks & Kaakmen (1984) and Dierssen (1982) for Norway, Canada, Finland and north-west Europe respectively. The British tradition is centred more on straightforward vegetation classification (e.g. McVean & Ratcliffe 1962; Ratcliffe 1964; Birks 1973; Daniels 1978), although a number of accounts examine the relationship between vegetation and Sjors' (1948) wet-dry gradient (Ratcliffe & Walker 1958; Goode 1970; Goode & Lindsay 1979; Lindsay, Riggall & Bignal 1983; Boatman 1983; Lindsay *et al.* 1985).

Vegetation pattern and mire unit (or hydromorphological type) have both commonly been used either singly or together in British classification systems (McVean & Ratcliffe 1962; Ratcliffe 1964; Moore 1968; Bellamy 1968; Birks 1973; Goode & Ratcliffe 1977; Daniels 1978; Birse 1980; Hulme & Blyth 1984; Proctor & Rodwell 1986). However, the smaller- and larger-scale variation provided by surface patterning and mire complexes respectively have tended to be ignored as a basis for classification. The presence of surface patterns has been used by many of the above authors to characterise certain classes of vegetation, but the classification of surface patterns themselves, in the manner adopted by Ruuhijarvi (1960) or Eurola & Ho lappa (1985) for Finland, is used only rarely in Britain (e.g. Bellamy & Pritchard, 1973; Lindsay *et al.* 1985).

Dierssen (1982) summarises the range of surface features found on mire systems throughout northwest Europe and gives a general account of the overall configuration adopted by these microforms on mire types.

Classification of microforms within a patterned microtope

Lindsay *et al.* (1985) examine the range of microforms found on British ombrotrophic mires and compare these with features described by Sjors (1948), Ratcliffe & Walker (1958), Eurola (1962), Goode (1970) and Goode & Lindsay (1979). The generalised regime of niche zonation identified from their work is shown in Figure 8.

The total range of features identified by the various authors comprises a wide list, a high proportion of the features being found in Caithness and Sutherland. Descriptions below are taken from Dierssen (1982) or Lindsay *et al.* (1985).

1 Hummocks (T3)

These are defined as mounds of (generally) *Sphagnum* which can be up to 1 m high and 1-2 m in diameter, with a variable cover of vascular plants. Some are crowned by *Racomitrium lanuginosum,* hypnaceous mosses or lichens. Ordinarily, they are somewhat lower than 1 m, and the vegetation forming the hummock therefore lies approximately 30-75 cm above the average water table.

2 High ridge (T2)

This is characterised by a dominance of dwarf shrubs, particularly *Calluna vulgaris* in Britain, often growing in a senescent *Sphagnum* carpet, and lies

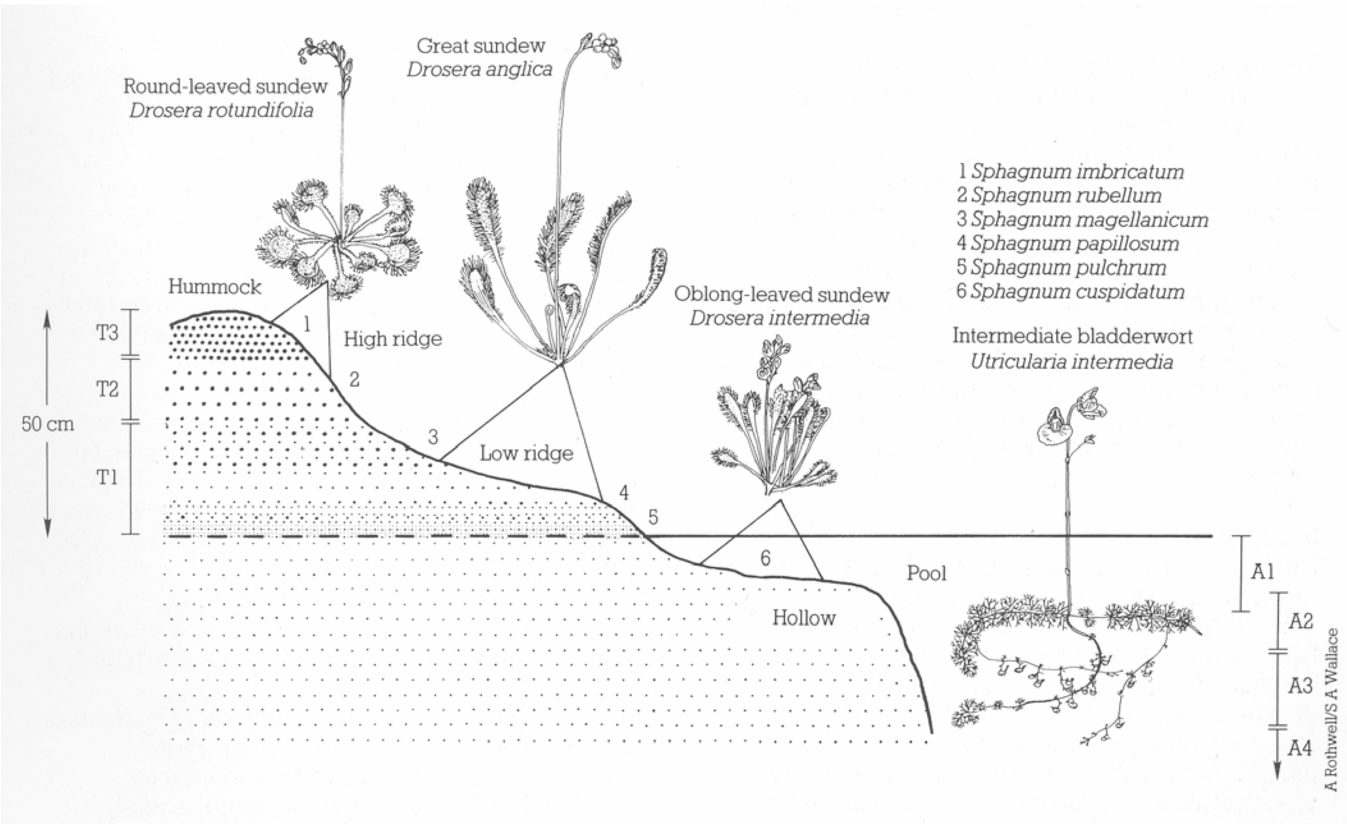


Figure 8 Distribution within the pattern of surface microforms, indicating niche zonation. (Zones based on Lindsay, Riggall & Burd 1985.)

between 10 and 20 cm above the water table. This microform appears not only as narrow ridges between pools but also as wide expanses of drier vegetation within pool systems.

3 Low ridge (Tl)

This is distinguished from high ridge because it tends to be far less dominated by dwarf shrubs. It is characteristic of soft, undamaged mire systems, in which it is the major ridge component. On most sites it forms a *Sphagnum-rich* fringe to the expanses of high ridge and hummocks. The *Sphagna* are especially *S. tenellum, S. magellanicum* and *S. papillosum.* It occupies the first 10 cm of the mire surface above the water table and is characterised by a reduced cover of *Calluna* and increased cover of *Erica tetralix,* or it may have few dwarf shrubs at all.

4 *Sphagnum* hollows (Al)

Sjors (1948) terms this zone "carpet" and distinguishes it from the "lawn" (Tl low ridge) because this is essentially an aquatic zone. Although free water is often not visible, the dense carpet of *Sphagnum* sits in an aqueous matrix and cannot support any great weight. In Britain this level is defined particularly *by Sphagnum cuspidatum* on areas of patterned bog, with *S. auriculatum* and *S. pulchrum* locally. In slightly enriched conditions these are replaced by *S. recurvum.* In northern Europe species such as *S. balticum* and *S. majus* may instead predominate (Sjors 1983), usually with *S. balticum* above *S. cuspidatum* or *S. majus.*

5 Mud-bottom hollows (A2)

This occurs at the same level as *Sphagnum* hollows, but may also extend to 20 cm below the water table, and it is distinguished from the "carpet" by being relatively limited in its moss cover, but with a significant occurrence of higher plants. The zone is characterised by a fairly firm peat base to the hollow, above which is a depth of up to 20 cm of free water. These areas often dry out during the summer months, though characteristic species such as *Drosera intermedia* can continue to trap food even if submerged all year.

6 Drought-sensitive pools (A3)

These are not specifically defined by Lindsay *et al,* (1985), being combined with permanent (A4) pools. They have since been recognised as distinct from permanent deep pools as a result of further observations of systems in severe drought conditions, where the deepest pools remained water-filled but many others exposed a soft, highly humified peat matrix.

7 Permanent pools (A4)

These are found only on watersheds and may be several metres deep in extreme cases, There is no evidence that they are "fen windows" extending down to the mineral ground, but some examples are clearly almost as deep as the peat deposit itself. The only vegetation normally recorded in these pools comprises floating columns of *Sphagnum cuspidatum* bound together by rhizomes and roots of *Menyanthes trifoliata.*

8 Erosion channels (TA2)

These also were not formally defined by Lindsay *et al.* (1985), but Dierssen (1982) describes them as a distinct feature *(Erosionrinne)* and Goode & Lindsay (1979) give vegetation data for erosion channels in the Outer Hebrides. They are coded as TA2 because they are similar to mud-bottom hollows, but spend most of the year exposed as dry peat.

9 Erosion hags (T4)

When bogs become eroded their surface microtopography usually becomes accentuated because the range of water table fluctuations becomes very much greater, Deep erosion gullies trace a network of water channels around dissected ridges and isolated hummocks which occur as steep-sided upstanding blocks of peat. Water tables are often more than 50 cm lower in these blocks of peat, or erosion hags, than in the ridges or hummocks of non-eroding bogs. Erosion hags are a small-scale version of the summits which form a dissected-plateau landscape. The hag tops lie at the original level of the undamaged bog surface, but, in cutting deeply into the bog plain, erosion leaves the surviving ridges as dry hags dominated by dwarf shrubs and *Racomitrium lanuginosum,* with little *Sphagnum.*

10 Peat-mounds (T5)

These are tall structures (for a bog), which can attain heights of 1-2 m above the general surface and are 5-15 m in diameter. They look like small paisa mounds, but the latter are formed around a permanent ice core (see above) and no such cores have been found in peat-mounds. Their existence has only recently been recognised, and their status is therefore still somewhat uncertain. However, they are discussed in more detail in Chapter 9.

Composite classification systems

The Canadian and United States wetland inventories both use a hierarchical approach to wetland classification which incorporates many of the factors discussed above (Wells & Zoltai 1985; Cowardin, Carter, Golet & LaRoe 1979). Although the systems are not identical, together they provide a basis for classification of wetlands throughout the North American continent.

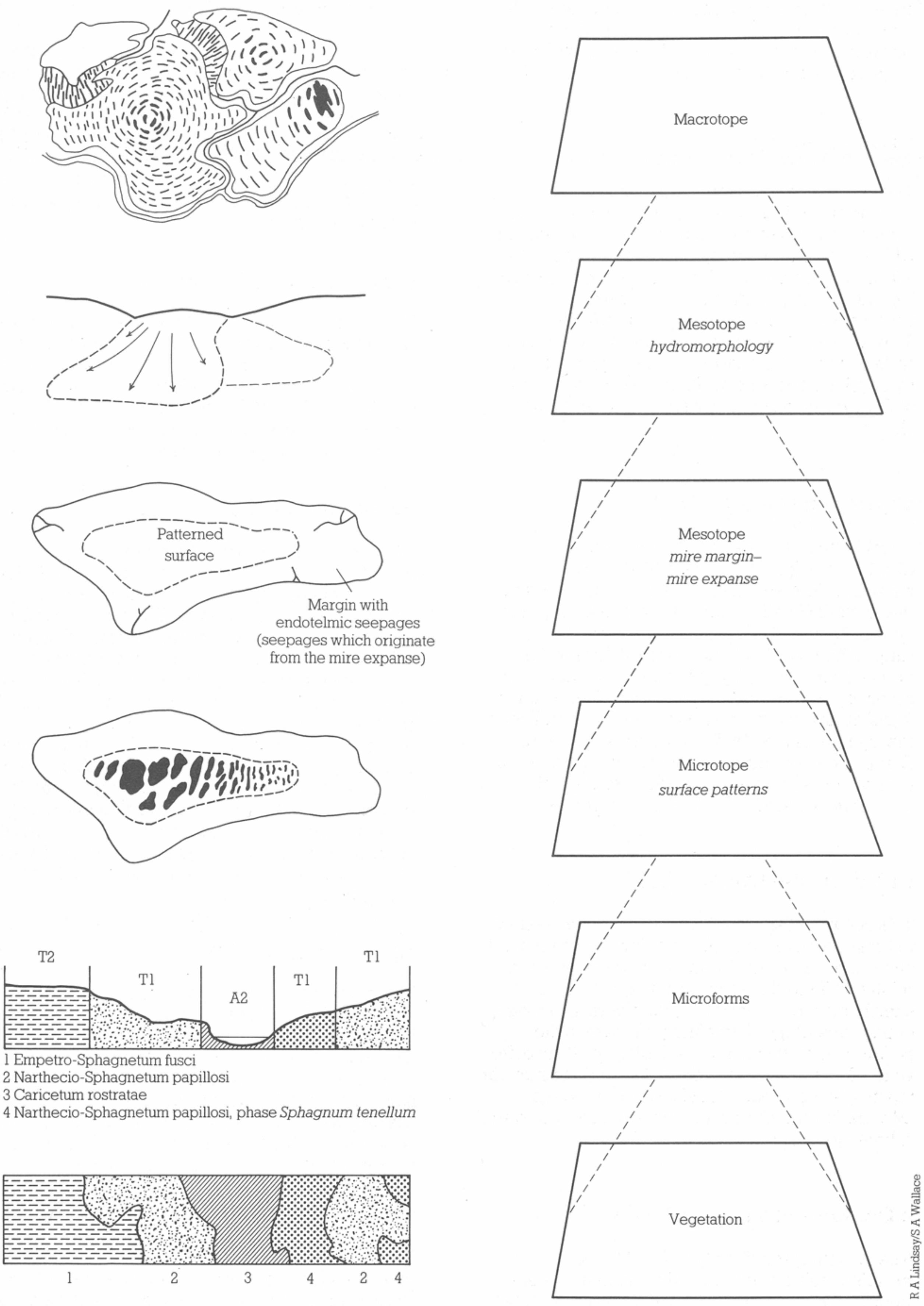


Figure 9 Classification system used by the NCC for bog systems, particularly blanket bogs, incorporating the four levels of functional hydrology - macrotope, mesotope, microtope and microform - described by Ivanov (1981). (Vegetation maps taken from Dierssen 1982.)

The United States system is perhaps the simpler of the two, intended for rapid assessment by relatively unskilled workers. It is designed to be used in hierarchical steps, the first step being a division into five gross types of wetland "systems" - estuarine, palustrine, riverine, lacustrine and marine. Subsequent divisions are made on the basis of vegetation physiognomy and substrate type.

The Canadian system uses certain ecosystem attributes for wetland classification which are of particular relevance in mire habitats. It uses four levels of information (Wells & Zoltai 1985). The first level identifies major wetland classes such as bog, fen and swamp. Each of these is then subdivided into what are termed "wetland forms", recognised on the basis of morphology, topography and overall surface physiognomy. These "forms" are subdivided at the third level into "wetland types" based on the broad categorisation of the surface physiognomy, for example the presence of wet *Sphagnum* lawns or dry *lichen-Sphagnum* hummocks. The final level of division depends on the application to which the classification is being put and recognises such "specialisms" as engineering, vegetation, forestry and energy. Each has its own range of sub-classes at this final level which are tailored to enable the classification to be applied to the specific problem in hand. Both the Canadian and the United States systems recognise as a further selection step that biogeographical gradients play an important part in the distribution of plant and animal species and that the "regionality" of systems must therefore be considered if the full range of site conditions is to be represented. This is echoed in Ivanov's (1981) observation that mire systems are essentially zonal in terms of their climatic responses.

The NCC's system of classification for blanket bog

The classification adopted by the NCC is derived from the Canadian hierarchical approach and incorporates several levels of classification based on many of the attributes discussed above (see Figure 9). For a detailed account of the methodology employed for each level in the Caithness and Sutherland survey, see Chapter 8.

1 At the highest level, areas assessed for conservation value and possible protection are described at the scale of the *macrotope* or mire complex. This definition ensures that as many of the ecosystem links as possible are incorporated into the site boundary. While this approach cannot prevent widespread impacts such as acid deposition from affecting the site, it attempts to define an area as isolated as possible from the effect of land-use changes which may occur on land immediately adjacent to the site. As far as possible, therefore, a site defined at the macrotope scale is a self-contained unit in terms of vegetation and hydrology, though clearly the protection of the more mobile birds and other animals cannot be wholly catered for in this approach.

2 Making up the macrotope are .one or more *mesotopes* or mire units. Each mesotope is classified initially in terms of *hydromorphological type* (e.g. saddle mire, watershed mire, ladder fen).

3 The mesotope is then divided into the broad categories *of mire margin* and *mire expanse.* In general, but by no means always, this division is based on the distinction between patterned and non-patterned ground.

4 Within the area of mire expanse, the overall pattern of surface features, or the *microtope pattern,* is recorded. On mires with little or no surface water the pattern may be very simple or homogeneous. However, with increasing numbers of hollows and pools, the range of patterns adopted by these features becomes increasingly significant. The general orientation and shape of pattern adopted by the microtope therefore form the basis of this level of classification.

5 The relative frequency of the individual surface features within the microtope pattern (e.g. hummocks, low ridges and pools) is used to classify sites according to *microform.* This can be one of the more difficult parts of the classification process, as measurements of the area of these features are not usually feasible without a considerable period of painstaking work. However, at its simplest, this level can be based instead on subjective estimates after field survey, or even on the simple presence or absence of particular microforms.

6 Finally, it is possible to locate different classes of *vegetation type* within these various structural levels. At the finest level of detail, *vegetation associations,* or, more usually, *variants* can be identified within the range of microforms present on the bog (see e.g. Dierssen 1982, p. 249; Lindsay *et al.* 1983). The difficulties of providing accurate, measured figures of microform abundance also apply to the vegetation within microform patterns. Sampling within the various levels of microform ensures that the range of variation in vegetation within and between these structural elements can be recognised. However, to obtain an estimate of abundance for each community would generally require a sampling frequency which is not feasible within the resource constraints of most survey programmes. Consequently it is often necessary to use a simple, subjective system such as the DAFOR scale, or merely to note the presence or absence of communities.

At a broader scale *National Vegetation Classification (NVC) communities* and phytosociological *associations* or even *Orders* are more appropriate for descriptions of the mire margin-mire expanse or that of microtope pattern. The NVC recognises the phytosociological distinction between pools and ridges within areas of patterning and therefore generally describes a mosaic of two or even three communities for the mire expanse and one or more from the mire margin.

3 Climate and world blanket bog distribution

Blanket bog development requires a climate which is continuously both wet and cool (Chapter 1). An annual mean precipitation of 1000 mm is probably a necessary minimum, but above this level the total amount becomes much less important than its distribution, especially as measured by length of drought periods. Since it is difficult to measure the rate of bog growth (i.e. peat formation) directly, ecologists have looked for parameters of climate which appear to coincide most closely with the geographical limits of blanket bog occurrence.

Tansley (1939) pointed to the general correspondence between the distribution of blanket bog in Britain and Ireland and the map of mean annual number of "ram days". (A "ram day" is the meteorological category of a period of 24 hours with precipitation of at least 0.25 mm.) Goode & Ratcliffe (1977) considered that an even better correlation is found between blanket bog distribution and "wet days" (a "wet day" being a period of 24 hours with precipitation of at least 1 mm). The geographical limits of blanket bog correspond well with the isoline of 160 wet days, though this takes no account of possible climatic changes over the whole Postglacial period of blanket bog development and is only a crude present-day correlation. Pearsall (1956) deduced that blanket bogs in northern Scotland were in a senescent state under a drier climate than hitherto, because the present annual precipitation appeared to be too low to allow active growth. This highly questionable interpretation appeared to result from an insufficient appreciation of the importance of distribution of rainfall rather than its total amount.

Both rain days and wet days tend to be closely correlated with length and frequency of drought periods, but the wet day appears to be a better index of effective wetness for vegetation than the ram day. The point at which evapo-transpiration changes from an annual water deficit to a water surplus may also be significant for peat development. Stroud *et al.* (1987) have shown that another close correlation exists in Britain between extensive occurrence of blanket bog and evapo-transpiration surplus of over 200 mm during the six months April-September.

The other important element of climate is temperature regime. Absolute temperatures must not be so low as to limit the growing season unduly through a prolonged winter, nor so high during summer that they promote too rapid decomposition of plant remains. An equable temperature regime with annual means for the warmest month in the range 9-15°C appears to be necessary and occurs mainly in the oceanic regions of the cool temperate zones.

These climatic considerations explain why blanket bog is limited to fairly high elevations in south-west England but occurs widely almost down to sea level in northern and western Scotland and in western Ireland. The relatively dry climate of the North York Moors appears to be close to the limits for blanket bog development and contrasts with the similar moorland plateau of Dartmoor, where it is well represented under a wetter climate.

As climate diverges from these rather narrowly defined parameters, so does blanket bog become replaced by other types of mire with similar peat characteristics but different structural and hydromorphological features. There are transitional types, even in Britain, and in districts such as Cumbria and Galloway there are extensive bogs which might be best regarded as an intermediate category between blanket and raised bogs. It becomes a matter of opinion where the limits of blanket bog are drawn in practice.

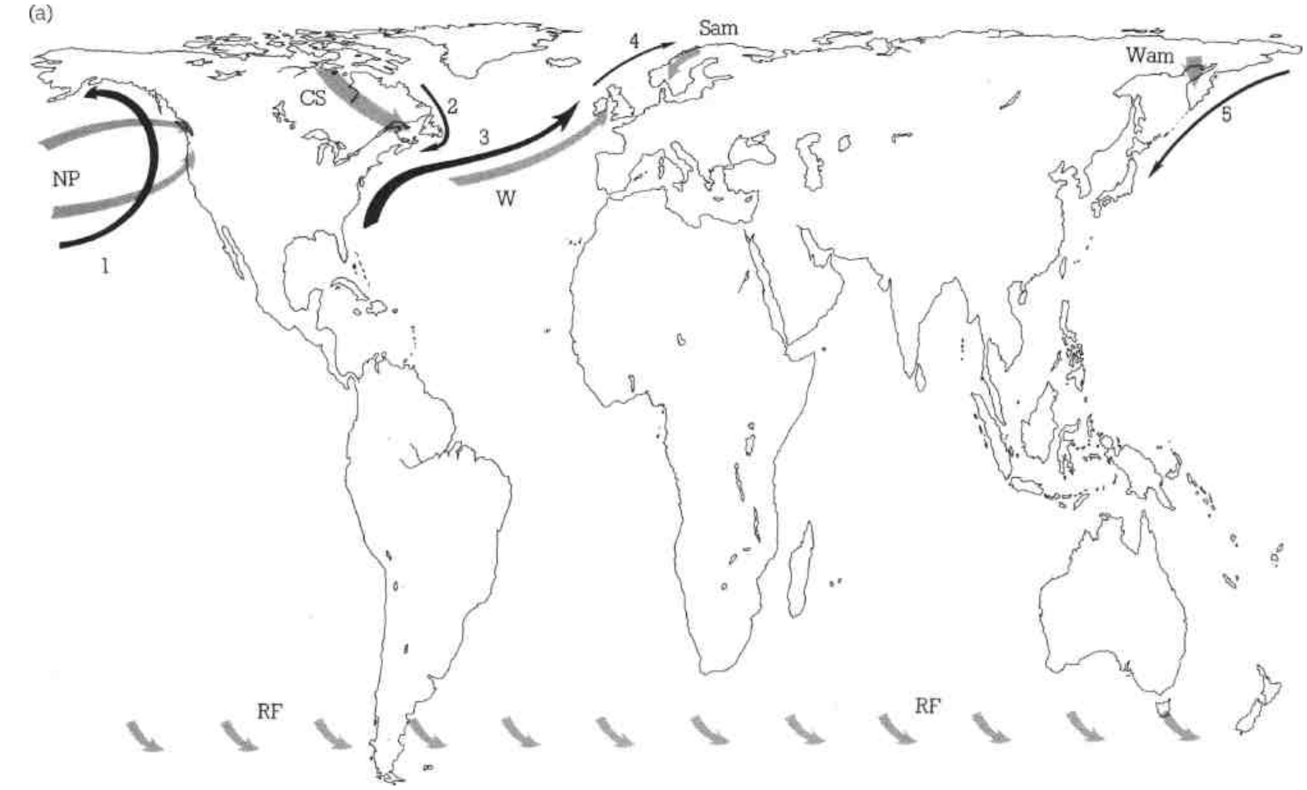
There are thus problems in specifying accurately the distribution and extent of blanket bogs in other parts of the world. For some of these there is little published description of blanket bog vegetation or survey information on distribution and area. With increasing distance between locations, the floristics of blanket bog become ever more divergent. The British and Irish blanket bogs are most similar to each other, and both have much in common with those of Fennoscandia. There is far less similarity between European and North American types, while those of the southern hemisphere are almost completely different from all of these northern blanket bogs. The common features are peat characteristics, bog structure and relationships to topography.

The following assessment is thus compiled from direct field experience of European blanket bogs, published work and verbal information, and prediction based on occurrence of suitable climate.

The combination of conditions generally regarded as necessary for blanket bog formation can be summarised as -

- a minimum annual rainfall of 1000 mm;
- a minimum of 160 wet days;
- a cool climate (mean temperature less than 15°C for the warmest month) with relatively minor seasonal fluctuation.

Examination of climatic patterns from around the globe, using either the range provided by Walters & Leith (I960) or *Physico-geographical Atlas of the World* (Academy of Sciences of the U. S. S. R. 1964), reveals relatively few stations where these conditions are met. Although the number of wet days



1 North Pacific current
2 Labrador current
3 Gulf Stream
4 North Atlantic Drift
5 Kamchatka current

NP North Pacific air-masses - summer above, winter below
CS Winter winds from the Canadian Shield
W Westerlies
Sam Summer air-mass
Warn Winter air-mass
RF Roaring Forties

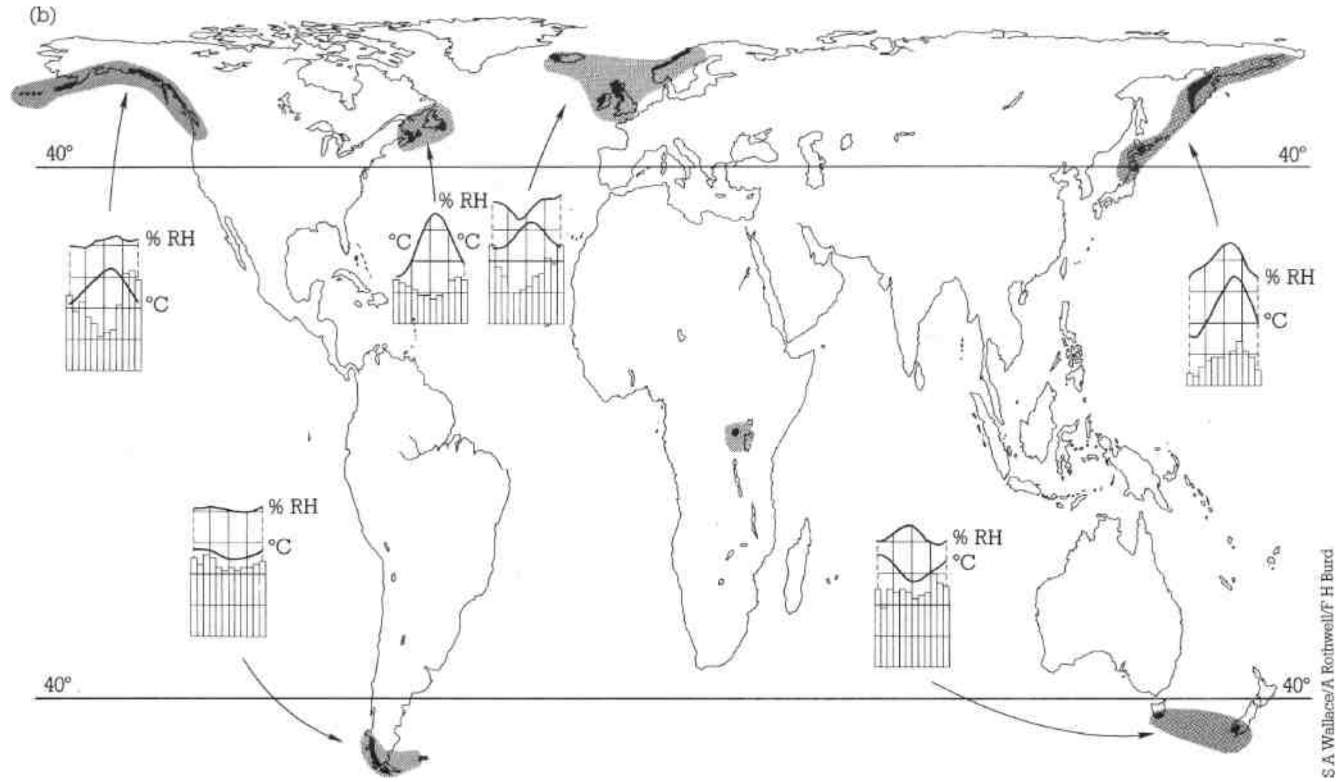


Figure 10 World distribution of blanket bog -
(a) General pattern of air and water masses. (Based on *Physico-geographical Atlas of the World* (Academy of Sciences of the U.S.S.R. 1964).)
(b) Identified localities. Shaded areas indicate areas of the globe with climate suitable for blanket bog formation, based on climate diagrams from *Physico-geographical Atlas of the World* (1964). Dark shading indicates regions where blanket bog is recorded, rather than the actual extent of the resource.

is not available from these sources, relative humidity-is an integral part of the climate diagram, and this is therefore taken as a broad indication of their frequency.

Figure 10 indicates those parts of the globe where the climate appears suitable for blanket bog development on the basis of these climate diagrams. As can be seen, nearly all examples are situated on the fringes of the great oceans and, because of the temperature restriction, are also limited to latitudes between 45° and 60°. This distribution accords well with that given by Goodwillie (1980) for Europe and the accounts given by various authors in Gore (1983b) for the distributions of peat types in a range of countries. The combined information obtained from Sjors (1950b, 1985a), Roivainen (1954), Wace (I960), Katz (1971), Neiland (1971), Goodwillie (1980), Dierssen (1982), Gore (1983b), Ryan & Cross (1984), Banner, Pojar & Trowbridge (1986) and Dr Martin Holdgate, Dr Richard Weyl, Dr Antti Huttenen, Dr Stephen Talbot and Professor Hugo Sjors, (pers. comm.) has been used to draw up the provisional map of world blanket bog shown in Figure 10. The Peters Projection has been used in this map because the projection shows correctly proportioned land areas.

Regions of the world potentially able to support blanket bog can be identified quite clearly by their climate diagrams, the pattern exemplified in Figure 6 being characteristic of such areas (see Figure 10b) and easy to pick out amidst the range of other climatic zones mainly by the relationship between temperature and humidity shown in Figure 6.

Professor H Sjors (pers. comm.) has observed that attempts to assess the global distribution of blanket bog should not be unduly influenced by treelessness as a criterion for blanket bog. In some areas of the globe there are trees better adapted to hyperoceanic conditions or wet peat substrates than in Europe. Thus trees grow on blanket bogs along the Pacific seaboard, although they are dwarfed and scattered on the large mire expanses. Tall trees only occur on blanket peats where ground is better-draining, on shallower peats, in marginal areas or on very small deposits.

Ireland

Plateau blanket bog occurs widely in most of the mountain massifs of Ireland where topography is suitable, including those in the east (e.g. Wicklow). The largest areas are, however, at fairly low levels in the extreme west, especially in Counties Mayo, Galway, Sligo and Donegal. The mountains of Kerry and Cork are climatically suitable but too rugged to have more than highly dissected occurrences of blanket bog. The largest single area was the Bog of Erris in north Mayo, which closely resembled parts of the Caithness and Sutherland flows. Since 1945 extensive commercial working of the larger areas of blanket bog (and of the once extensive raised bogs of the central lowlands) for fuel peat has greatly reduced the total original area of about 700,000 ha.

The Irish blanket bogs are botanically quite similar to those of northern Scotland. The *Sphagna* and abundant vascular plants are mostly shared in common, but the distinguishing feature of the western Irish bogs is the constancy and local codominance of black bog-rush *Schoenus nigricans* in the Tl and T2 communities. Dwarf shrubs are more poorly represented, though in a few areas the Lusitanian species *Erica mackaiana* is represented. Patterned surfaces are much less well developed than in Scotland, but occur in Mayo and Donegal.

The rest of Europe

Goodwillie (1980) states that blanket bog occurs in Iceland, the Pyrenees, western Norway, Britain and Ireland. However, he states that "blanket mire is better developed in Ireland and Scotland than elsewhere in Europe". Although Goodwillie shows Iceland with a fringe of blanket bog, he also states that much of this is actually fen vegetation because volcanic ash regularly enriches the peat surface. Only the western fringe of Iceland supports true oligotrophic blanket bog (D A Stroud pers. comm.). Norway has a large belt of blanket bog country running west of the central highlands between Rogaland and Nordland and onto the Lofoten Islands and Andoya (Dierssen 1982), but the extent of any one mire system is apparently quite limited because of the rugged terrain. Whilst examples of Norwegian blanket bog are perhaps closer in floristics to British and Irish types than anywhere else in the world, the climatic pattern of Norway is different in two important respects. First, it lies at a higher latitude than mainland Britain. Secondly, whilst Britain and Ireland are subject to westerly winds all year round, during winter months Norway has a high prevalence of northerly winds blowing down from cyclones in the Barents Sea *(Physico-geographical Atlas of the World* 1964). The effects combine to give the majority of blanket bog areas in Norway less equable temperatures than those experienced by such areas in Britain and Ireland.

An interesting type of mire which is orogenic (mountain-generated) rather than oceanic occurs in Austria and might be classed as a very special form of blanket bog. It is more accurately described by Steiner (1984) as "condensation mire" and occurs on steep, rocky avalanche debris on mountain slopes. Cold air is funnelled down through this blocky scree from glacial regions high in the Austrian Alps. When this cold air eventually emerges in the warmer valleys it causes water vapour to condense around the scree slopes, providing enough constant moisture for deposits of 1-2 m of peat to develop on slopes of 45°.

East coast of Canada

Zoltai & Pollett (1983) state that the Atlantic Oceanic Wetland Region (which is the only one of their regions stated to contain blanket bogs) occurs around the northern coast of New Brunswick, on

Cape Breton Island and along both west and east coasts of Newfoundland. However, the recently published map of Canada's Wetland Regions *(Department of Energy, Mines and Resources, Canada* 1986) indicates that the Atlantic Oceanic Wetland Region, typified by blanket bog, is restricted to part of the south-easternmost tip of Newfoundland (Avalon Peninsula).

Zoltai & Pollet (1983) present some striking air photographs to illustrate the wetland types of Canada, from which it is possible to see the close similarity between the patterning of the plateau raised bogs from the Atlantic Oceanic Wetland Region and the patterns of raised bogs in western Ireland. However, the clearly "confined" (Hulme 1980) nature of this type is evident (p. 262), when compared with the "unconfined" blanket bog also illustrated.

The climate of the region is of interest because it has a markedly continental temperature range, with mean summer temperatures of + 15°C and -7°C in winter *(Physico-geographical Atlas of the World* 1964). It seems likely that this continentality results from a combination of winter winds which often blow from the north-west, coupled with the effect of the cold Labrador Current, which flows throughout the year down from Baffin Bay through the Davis Strait and past Newfoundland's Atlantic coast, further insulating the area from the moderating influence of the Gulf Stream *(Physico-geographical Atlas of the World* 1964). However, the Avalon Peninsula has a fairly mild winter.

The vegetation of Newfoundland blanket bogs differs from its relative this side of the Atlantic in lacking *Calluna*, which was originally absent from the North American continent. Its place is taken by *Chamaedaphne calyculata* (leatherleaf) and *Kalmia angustifolia.*

North American Pacific coast

The distribution of blanket bog in this region is still the subject of some debate. Wells & Zoltai (1983) describe the Pacific Oceanic Wetland Region as being dominated by slope bogs, raised bogs and flat fens, a description confirmed by the map of Canada's Wetland Regions (1986). Neiland (1971) and Banner *et al.* (1986) give detailed accounts of the mires of, respectively, the Alaskan 'panhandle' and British Columbia's Pacific coast, of which a high proportion are considered to be blanket bog (Banner *et al.* 1986; Dr J Pojar pers. comm.). Both publications also give photographs of the types. From these and the descriptions it is clear that blanket bogs of the Pacific seaboard are not treeless, scattered small pines *(Pmus contorta* subsp. *contorta)* usually being found across the mire expanse. These mires have a general character more akin to boreal mire regions of Fennoscandia, e.g. the open forest-mire landscape around the summit of Finland's Riisitunturi, a gently contoured mountain with just the beginnings of open blanket bog development.

The deep ombrotrophic bog defined by Banner *et al.* (1986) is dominated by *Pin us contorta* and species of *Chamaecyparis, Trichophorum* and *Sphagnum.* The *Pinus contorta* is extremely stunted ("bonsai"), whilst dwarf shrubs such as *Empetrum nigrum, Ledum groenlandicum, Juniperus communis* subsp. *nana, Kalmia polifolia, Vaccinium uliginosum* and *V. vitis-idaea* form a dominant shrub layer. Terraced pools occur, characterised by either *Rhynchospora alba, Eriophorum angustifolium, Menyanthes trifoliata* or *Nuphar lutea* subsp. *polysepala.* Banner *et al.* also describe a sloping *Trichophorum*-dominated bog which occurs at high altitude and which sounds remarkably similar to the ladder fen type discussed in Chapter 8.

The Aleutian Islands are likened by Dr Stephen Talbot of the United States Fish and Wildlife Service (pers. comm.) to the peat-draped landscapes of the ancient foreland of western Sutherland, with thin, saturated and treeless peat cloaking steep rocky outcrops and peat-filled hollows showing varying degrees of standing water and patterning.

Sjors (1984) recognises the vegetational and occasionally topographical similarity to west European blanket bog, but points out various differences, such as the often extreme topography and the growth of trees, sometimes abundantly, sometimes only scattered. He concludes that he is unwilling to classify the Alaskan 'panhandle' fully as blanket bogs in European terms. Floristically, the blanket bogs of the North American Pacific coast are of a type unique to that area with regard to their much richer vascular flora, but their cryptogamic flora is strikingly similar to that of hyperoceanic western Europe.

The "Magellanic Tundra Complex" of South America

The overriding feature of the climate in the southern tip of America is the constant westerly airflow. Pisano (1983) describes how the interaction of the South Pacific and South Atlantic Polar Fronts produces summers of high humidity, high winds and low temperature and winters of similar humidity but somewhat lower temperatures and windspeed. He also points to the extreme west-east divide across the area caused by the Andean spine which runs down the west coast, causing extreme climatic differences. Rainfall can be 5000 mm in the west and only 220 mm in the trans-Andean Patagonian region. Similar, but less extreme, differences occur in Norway and on South Island in New Zealand, and to a lesser extent in Britain.

Auer (1933, 1965) and Roivainen (1954) give detailed accounts of the mires of the main island of Tierra del Fuego, whilst Pisano (1983) provides a classification for the whole "Magellanic Tundra Complex". The blanket bog systems of this complex are different from those of the northern hemisphere in being formed largely of 'cushion plants', rather than bryophytes. In a fine example of convergent evolution, species such *as Donatia fascicularis* and *Astelia pumila* can form raised lenses of ombrotrophic peat very similar to the classic raised mires of the north. Indeed, mixed within these areas of cushion mire are true *Sphagnum* raised mires dominated by *Sphagnum magellanicum* in its *locus classicus.*

Roivainen (1954) produces 19 types and sub-types of vegetation, five of which he regards as rain-dependent - ombrogenous meadow bogs with *Marsippospermum grandiflora,* flat cushion bogs dominated by *Donatia fascicularis* and *Astelia pumila,* raised cushion bogs with *Racomitrium lanuginosum* and *Chorisodontium magellanicum,* ombrogenous "white" moors with *Tetroncium magellanicum,* and ombrogenous heath with *Empetrum rubrum.* This accords fairly well with Pisano's (1983) classification, but Pisano defines only the cushion bogs as blanket bog, assigning the remainder of Roivainen's types to raised bog, dwarf heath or "Magellanic Tundra".

Godley (I960) and Dr M W Holdgate (unpublished notes) give accounts of the blanket bogs of Isla Wellington, at the northern limit of Pisano's Magellanic Tundra Complex, and of blanket bog systems on the southern (wetter) side of Isla Navarino, at the southern tip of the complex. Neither area was visited by Roivainen, but Pisano classes both regions as low-altitude cushion bogs. Holdgate confirms this classification, listing *Astelia, Donatia* and *Oreobolus* as the dominant blanket bog genera.

The Falkland Islands are covered with blanket bog, although, lying in the rain shadow of the Chilean Andes, they are quite dry, with only 340-635 mm of rain a year (Roper undated). Apart from the influence of the sea, conditions are remarkably similar to those of the Caithness and Sutherland plain. It is well known in the Falklands that "all the water sits on top of the hills" (M Felton pers. comm.), which suggests that the majority of blanket bogs are either watershed or saddle mires. However, the depth of peat and extent of patterning are considerably more restricted than in Caithness and Sutherland. Both cushion- *and Sphagnum-bogs* occur, the former characterised by *Oreobolus obtusangulus* and *Astelia pumila* (Holdgate unpublished notes).

New Zealand and other Southern Ocean islands

The island groups which lie within the appropriate latitudes of the Southern Ocean (40° to 60°) may support some form of blanket bog where they are not too steep. Schwaar (1977), for example, describes the blanket peat of Gough Island, which lies at 40° S in the South Atlantic. It receives 3250 mm annual rainfall, and the average temperature is 11.7°C, making it rather warm for a blanket bog region. Peat depths of 1 m are given, the vegetation consisting of ferns and the shrub *Phylica arborea* below about 300 m, with peat-forming herbaceous vegetation dominated by grasses above and bryophyte communities covering upland valley and plateau mires. Gore (1983a), quoting Schwaar's (1977) account, likens the peat composition to that of Moor House in the Pennines, but Wace (1961) describes nothing immediately recognisable as ombrotrophic blanket bog and Holdgate (pers. comm.) considers that only certain of the upland plateau mires are truly ombrogenous. Islands like Heard Island, which rise steeply to 3000 m, are unlikely to encourage blanket bog development, but Kerguelen Island, Marion Island (Bakker, Winterbottom & Dyer 1971), the Crozet Islands and Macquarie Island are possible locations, and South Georgia seems to have quite extensive peat deposits. However, the total area of blanket bog in the Southern Ocean islands is likely to be minute.

Thompson (1980) states that blanket bogs occur in the Otago Mountains of New Zealand's South Island but gives little information about their nature. Campbell (1983) describes cushion mires in the mist-shrouded uplands of South Island but regards these as isolated mire units rather than part of a blanket bog complex. He also describes a widespread type from the humid west coast (where Hokitika has year-round monthly rainfall in excess of 200 mm and temperatures from +5° to + 15°C) known as *pakihi.* This is a gley podsol with variable peat cover extending in many small units over an area of some 300,000 ha, but it should perhaps be regarded as incipient rather than true blanket bog.

North-east Asia

Few climate diagrams are known for north-east Asia, *Physico-geographical Atlas of the World* (1964) giving records for the south-west tip of Kamchatka and eastern Hokkaido. Both diagrams suggest climates within which blanket bog could occur, though both have distinctly low winter temperatures owing mainly to the winter cyclonic pattern, which subjects both areas to prevailing winds from central Asia, whilst summer conditions ensure prevailing winds from the southern Pacific. Both areas are, however, subject to the cooling effects of the Oya Shio current flowing south from the Bering Sea.

Botch & Masing (1983) describe the Western Kamchatka Province as "one of the most paludified territories in the USSR", with 80% of the province covered by blanket bog types. Quoting Neishtadt (1935, 1936), they divide the mires into wet *Sphagnum* bogs and dry *Cladonia* bogs, both of which are treeless. The hollows are dominated by *Sphagnum lindbergii, S. papillosum* or mud bottoms, whilst the ridges and hummocks consist largely of *S. fuscum.* The true character of this type is not clear, however, because the Western Kamchatka mires are also classed as a special raised mire type (Lyubimova 1940), whilst Nikonov (1955) classes the province as dominated by peat basins and Katz (1971) describes the mires of Kamchatka as domed mires. The problems of access into this area make confirmation of the mire type difficult.

Japan lies at the southern latitudinal limit for true blanket bog in the northern hemisphere, but Gore (1983a) states that simple, unpatterned blanket bog occurs on the slopes of Mount Taisetsu in Hokkaido and several mountains on Honshu. Gimingham (1984) describes the Oze mire complex on Honshu as a series of patterned raised mires lying in an upland valley. The hydromorphological similarity between this complex and that of the Silver Flo we in Galloway, described by Ratcliffe & Walker (1958), is noteworthy.

Africa

Finally, in complete contrast to the oceanic conditions discussed so far, Thompson & Hamilton (1983) describe blanket peats from central equatorial Africa. These are peats of purely orogenic origin, being formed on the higher slopes of the Ruwenzori Mountains in Uganda and fed by a bimodal rainfall pattern resulting from adiabatic cooling of first northerly, then southerly airstreams as they pass over the Ruwenzori range through the year. These are described as "sedge mires" and are therefore yet another distinct variant in the range of blanket bog forms. However, these mires, the less extensive, very strongly sloping and very shallow ones on Mount Kenya and the mountain mires of Lesotho in southern Africa could as well be regarded as sloping fen.

Global resource of blanket bog

Total estimates for the global blanket bog resource are difficult, partly because definition of the type is itself sometimes difficult, defeating even the most experienced worker (see Sjörs 1984), partly because it is not clear whether all areas defined as blanket bog truly fall into this category (see comments about Kamchatka above) and partly because the habitat is typical of some of the least accessible and least visited parts of the globe. The basic climatic requirements for the habitat limit its total possible distribution to something around 100 million ha, of which it appears that only 10% or so actually supports blanket bog, because of unsuitable terrain, vulcanism and other factors.

With 1,300,000 ha of mire, the larger part originally blanket bog, it appears that Britain supported something like 13% of the total world resource. Clearly, this is a very rough estimate, but the fact remains that Britain and Ireland are regarded throughout the world as the 'type' regions for blanket bog. Hugo Sjörs, Professor Emeritus at the University of Uppsala, Sweden, and one of the most experienced and widely travelled mire ecologists in the world today, has commented that "nowhere occurs the blanket bog in more impressive expanses than in Ireland and Scotland. This is especially true of the lowland type found in northernmost Scotland and in Mayo and Connemara in western Ireland."