# The Flow Country

## The peatlands of Caithness and Sutherland

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Edited by D A Ratcliffe and P H Oswald

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# Part II The peatlands of Caithness and Sutherland

## 4 The physical environment

The extreme development of blanket bog in Caithness and Sutherland results from the combination of two essential conditions - suitable climate and suitable topography. Because topography results in local modifications of the regional climate it will be considered first.

### Topography and geology

A key feature of the eastern half of the region is the large extent of low, gently contoured or almost flat upland. East Sutherland has a considerable expanse of such ground, and in Caithness these uplands descend north-eastwards to merge imperceptibly into lowland plain. To the west the softly undulating moorlands become increasingly interrupted by high mountain peaks and ranges, but these finally give way to an Atlantic coastal zone of low but rugged, ancient foreland. The simplified map (Figure 11) shows that, although geological changes tend also to run in an east-west direction, the topography most suitable for blanket bog development is not confined to any one main rock formation. The largest continuous areas of blanket bog are spread over the Old Red Sandstone of Caithness, the large granitic intrusion along the Caithness-Sutherland boundary and roughly half of the area of Moine granulites and schists in Sutherland.

Old Red Sandstone ("Caithness Flags") forms most of the north-eastern expanse of low moorland and coastal plain, covering much of Caithness. The drift deposits of this area contain calcareous shell material, brought in from the east at the last glaciation. Further west the boulder clay is more sandy and free from lime (Crampton 1911). This geological combination and the low elevation produce the only good-quality agricultural land of the region, graded as Class 3 (Soil and Land Capability for Agriculture: Futty & Towers 1982). This tract of fertile land is interrupted only by an outcrop of granite at Helmsdale on the coast. Much of this land was previously peat-covered but has been cut and reclaimed during more than a millennium of human habitation. Apart from this north-eastern and coastal agricultural zone, most of Caithness is covered by a vast, almost continuous expanse of peat, and there are still outliers behind the coastal headlands of Dunnet and Duncansby. In the south, the peatlands are interrupted by the abrupt peaks of the Morven range, the most conspicuous landmarks in Caithness.

Crampton (1911) suggests that the present surface vegetation of the Caithness peat is largely insulated from the effects of underlying geology, but identifies two processes whereby the hydrogeology of the basal deposits has a bearing on the present vegetation. First, areas of springs and seepage in the central plain are rarely capable of supporting more than base-poor fen vegetation of the Caricion lasiocarpae or the Caricion curto-nigrae type because the underlying deposits of granite, schists or drift are themselves base-poor. However, the shelly drift and calcareous flags of north-eastern Caithness have in places afforded the opportunity for extremely base-rich fen communities to develop.

Secondly, and by contrast, the ice-sheet which moved over the western parts of Caithness and most of central Sutherland brought with it a mixed type of drift which varies from stiff clay to loose sands and gravels (DAFS 1965). Crampton suggests that this looser drift at the base of the peat encourages water flow at the peat-drift interface, leading to sub-surface water scouring and tunnelling beneath the peat. The final effect of this is the appearance of "sink-holes" and associated erosion complexes within bog-pool systems. These features are discussed in more detail in Chapter 5.

By far the largest of the rock formations is the central expanse of Moine granulites and schists. The landform of this section is, for the most part but especially in the eastern half, a series of low summits, mainly below 650 m. Between the hills is gently sloping ground covered with a maze of water bodies ranging in size from tiny pools to large lakes, most of them lying within a vast expanse of peat, which cloaks much of this landscape. As in Caithness, it is the relatively gentle gradients of this terrain which allow such large areas of peat to form. Westwards, several high upland massifs rise above the general level of the plain, notably Ben Hope, Ben Hee, Ben Loyal, Ben Armine and Ben Klibreck. However, these peaks occur as isolated landmarks within an otherwise almost level and waterlogged

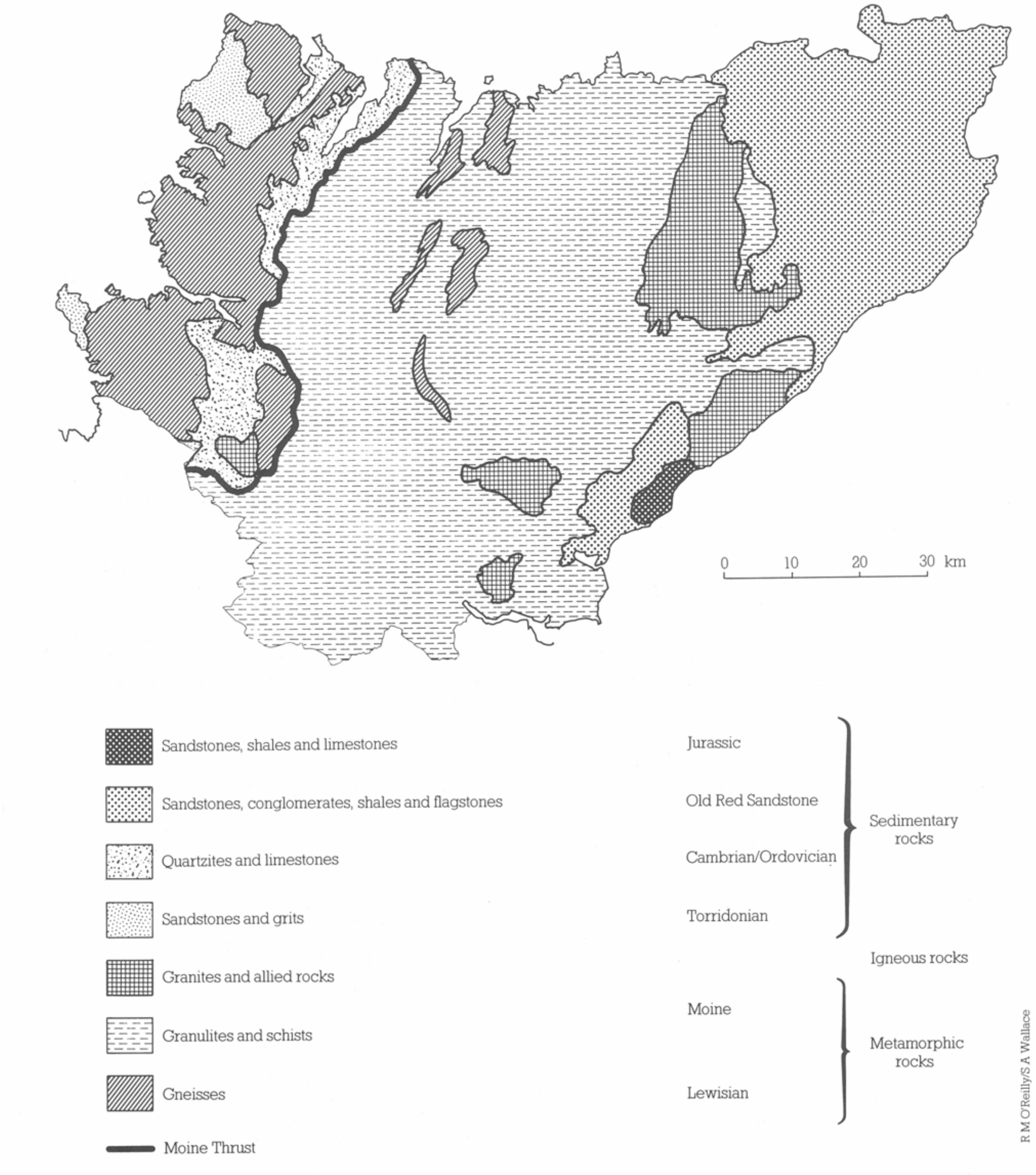


**Figure 11** Simplified map of the solid geology of Caithness and

landscape. All the rocks of the Moine Series and its intrusions are hard and resistant to weathering: they are mostly non-calcareous and acidic and so give rise to mainly infertile, base-deficient soils. Agriculture is largely confined to coastal strips and the bottom lands of the main straths.

To the west, high ranges become more continuous along the line of the Moine Thrust, which runs from Loch Eriboll to Ben More Assynt and beyond. Variably composed of Moine rocks, Cambrian quartzites and Lewisian Gneiss, these steep and rugged massifs create an extensive break in the peatland topography, though all of them have small areas of bog. These dramatic landforms give way to a much lower coastal zone running parallel to the Minch, composed mainly of Lewisian Gneiss and Torridonian Sandstone. The gneiss forms a complex, irregularly undulating tract of low moorland, with a large number of mostly small lochs, much bare rock exposed as slabs and bosses, and a variable cover of glacial drift. The sandstone produces the striking peaks of Suilven and Quinag, but also forms part of the low hills of the Parphe behind Cape Wrath. Apart from the Durness Limestone, which gives a few small areas of fertile land, the rocks west of the Moine Thrust are mainly hard and acidic. While they favour acid peat formation, the irregular topography gives an extremely variable and patchy development of blanket bog. The Parphe has some fairly large areas, but farther south it is much dissected and mostly shallow.

## Climate

Climate is of overriding importance in the development of blanket bog (see Chapter 3). The widespread occurrence of this vegetation and its associated deep peat across Caithness and Sutherland suggests that the climate of the whole region is, or has been, suitable for its development. The combination of high and regular precipitation, high atmospheric humidity, relatively cool mean temperatures and small annual temperature range required for the growth of ombrotrophic bog is eminently well satisfied across the region. There are, nevertheless, various gradients of climate which need to be considered.

The prevailing westerly airstreams from the Atlantic impose an underlying gradient of climatic wetness from west to east. The moisture-laden air gives high rainfall and atmospheric humidity in western, coastal areas, and there is a decrease in both conditions with distance eastwards, so that the eastern coastal areas are drier. As in other parts of Britain, the presence of a high range of mountains close to and parallel with the west coast greatly amplifies this broad geographical gradient. The western mountains of Sutherland produce extremely high orographic rainfall (up to 2500 mm) and then a marked rain shadow effect eastwards, so that precipitation rapidly declines to 1200 mm in central Sutherland and is only 700 mm at the north-east tip of Caithness (see Figure 12a).

There is an anomaly, in that the high mountain topography which produces the heaviest rainfall is also the least conducive to extensive waterlogging and development of blanket bog. Although also very wet and humid, the lower western zone of coastal moorlands is also mostly too rugged and irregular to allow extensive growth of bog. In both these zones of Sutherland there is a general prevalence of heavily leached and acidic soils, with surface horizons of 'mor' humus or shallow peat with frequent occurrence of deeper peat wherever topography allows.

Extensive development of blanket bog occurs in east Sutherland and Caithness under conditions of lower rainfall but optimal topography and geology. On the other hand, under conditions of extreme rainfall,

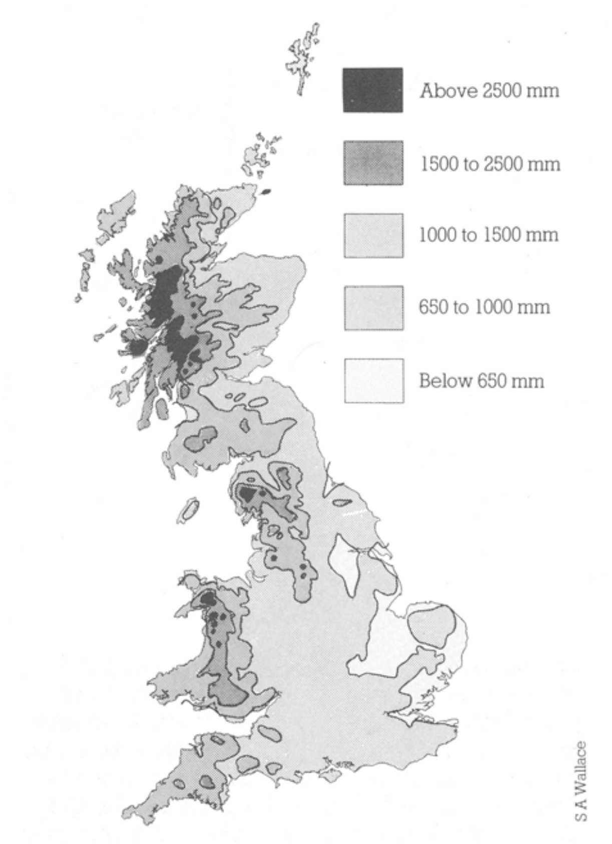


**Figure 12a** Average annual rainfall, after *Climatological Atlas of the British Isles* (Meteorological Office 1952).

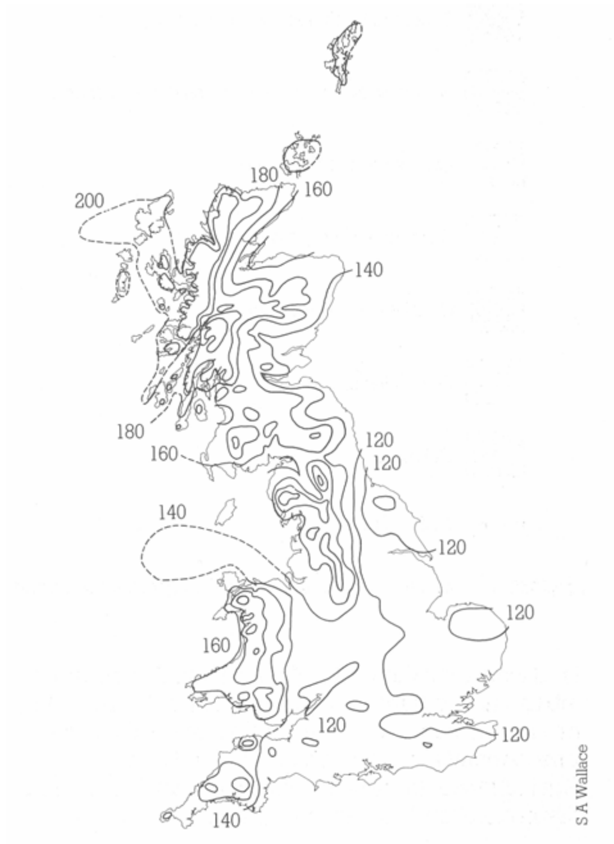


**Figure 12b** Distribution of "wet days". A "wet day" is a period of 24 hours during which 1 mm of precipitation is recorded. (Compiled by Ratcliffe (1968) from data published in *British Rainfall* (1951-60).)

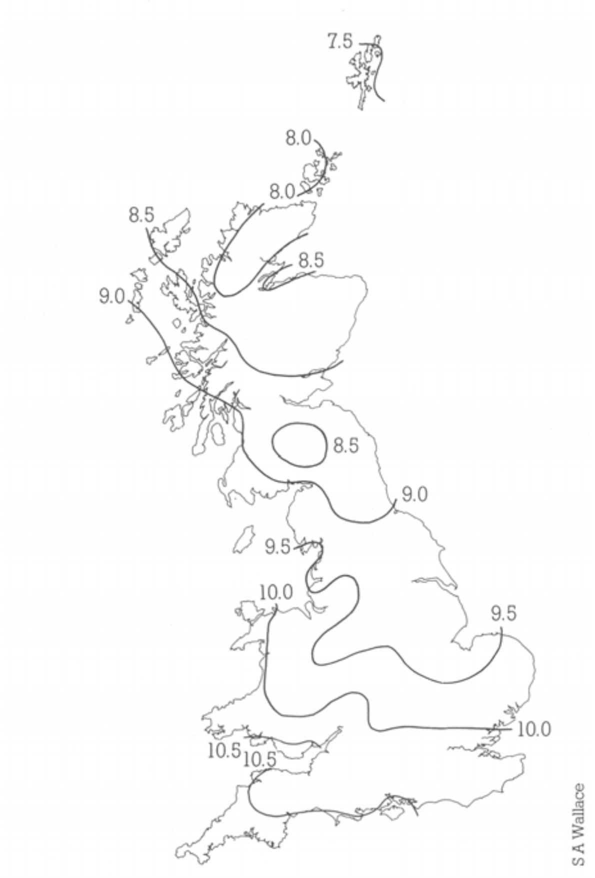


**Figure 12c** Average means of daily mean temperature, after *Climatological Atlas of the British Isles* (Meteorological Office 1952).

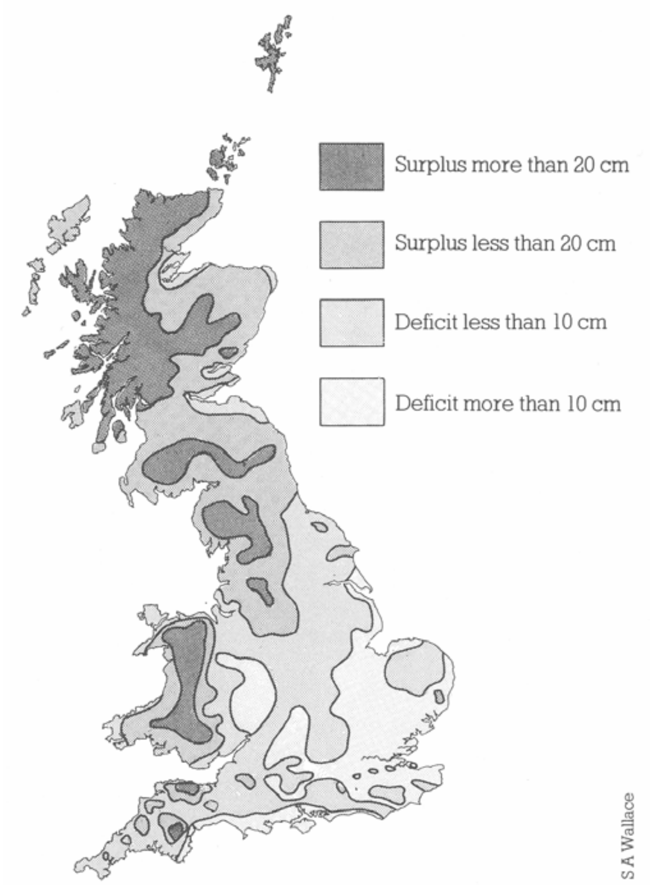


**Figure 12d** West to east gradients of oceanicity across Britain. This index of climatic wetness is the difference between precipitation and evapo-transpiration for the six months April to September. (Redrawn from Macdonald, Wood, Edwards & Aldhous 1957.)

shallow peat occurs on slopes of up to 20°, or even steeper angles on shady north aspects.

The relatively low rainfall in the east of the region has led some ecologists (Crampton 1911; Pearsall 1956) to wonder whether it was sufficient to allow active bog growth at the present day. Their doubt appears to have resulted from an insufficient appreciation of the importance of rainfall frequency and low mean temperature in maintaining constancy of ground moisture. Boatman & Armstrong (1968), in describing a patterned blanket bog in the far west of Sutherland, point out that the rainfall recorded close to the site is, at 1400 mm, barely half that on the Silver Flowe, a series of similar patterned bogs in Galloway. While the rainfall of Caithness is similar to that of, say, Dorset, this gives no idea of the large number of days with drizzle and dampness or simply complete cloud-cover and of the general coolness of the summers. Figure 13 shows both the even distribution of rainfall, measured as frequency rather than amount, and the consistent differences between two Sutherland locations, both of them in the Flow Country. Figure 14 shows even more clearly the lack of correlation between amount and frequency of rainfall over a larger area of the northern Highlands and Islands.

Crampton (1911) gives rainfall and temperature records for Caithness which indicate a range of 50-100 mm of rainfall each month and a temperature range from 3°C on the high plateau in winter to 14°C on the lowland plain in summer. He points out that the warmest months (though even these are relatively cool) have a consistently high rainfall. Wilson & Womersley (1975) state that, although the mean January temperature is similar to that of Kew (4.4°C), the mean July temperature in Wick is 12.7°C whereas that of Kew is 17.7°C. They note that Caithness has a relatively low rainfall but that this is spread over a total of 225 rain days. This regular precipitation is reflected in the fact that between May and September the average daily insolation is only about 4.6 hours and the relative humidity averages 85% throughout the year. Wilson & Womersley also comment on the small number of days with no wind. Records for the north coast give annual average windspeeds of 30 km per hour, with north-easterly gales in spring and north-westerly gales in autumn.

The map of mean annual numbers of wet days (Figure 12b) - regarded as the best ecological index of precipitation (see Chapter 3) - shows that virtually the whole region has more than 160 wet days, which appear to be around the critical limit for development of blanket bog in Britain and Ireland. When this is compared with the map for mean annual temperature (Figure 12c), the favourable combination of general wetness and coolness of climate in this far northern region of Scotland is made clear.

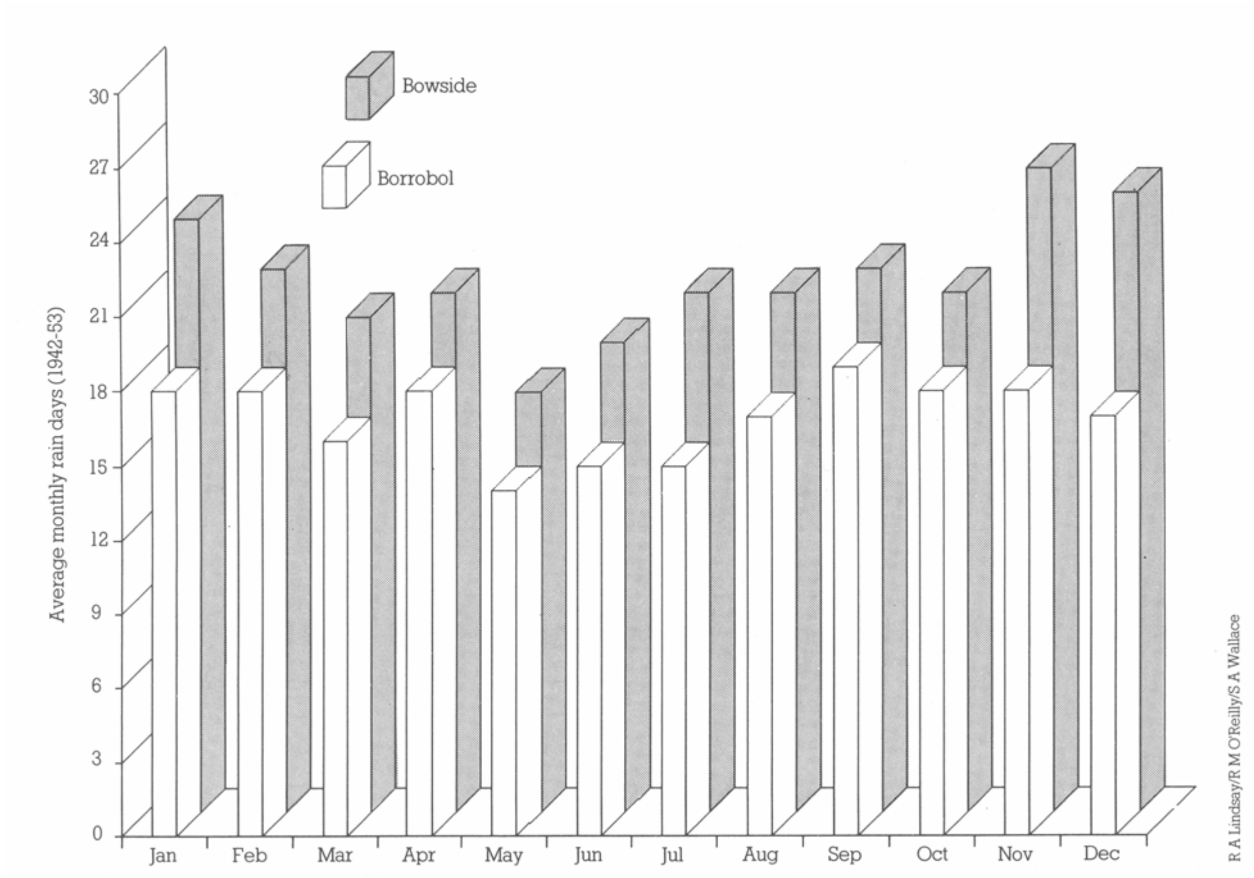


**Figure 13** Average monthly distribution of "rain days" (see Figure 2) for Bowside in northern Sutherland and Borrobol in central Sutherland. (Figures taken from *Scottish Peat Surveys*, Vol. 2 (DAFS 1965), provided by courtesy of the Meteorological Office.)

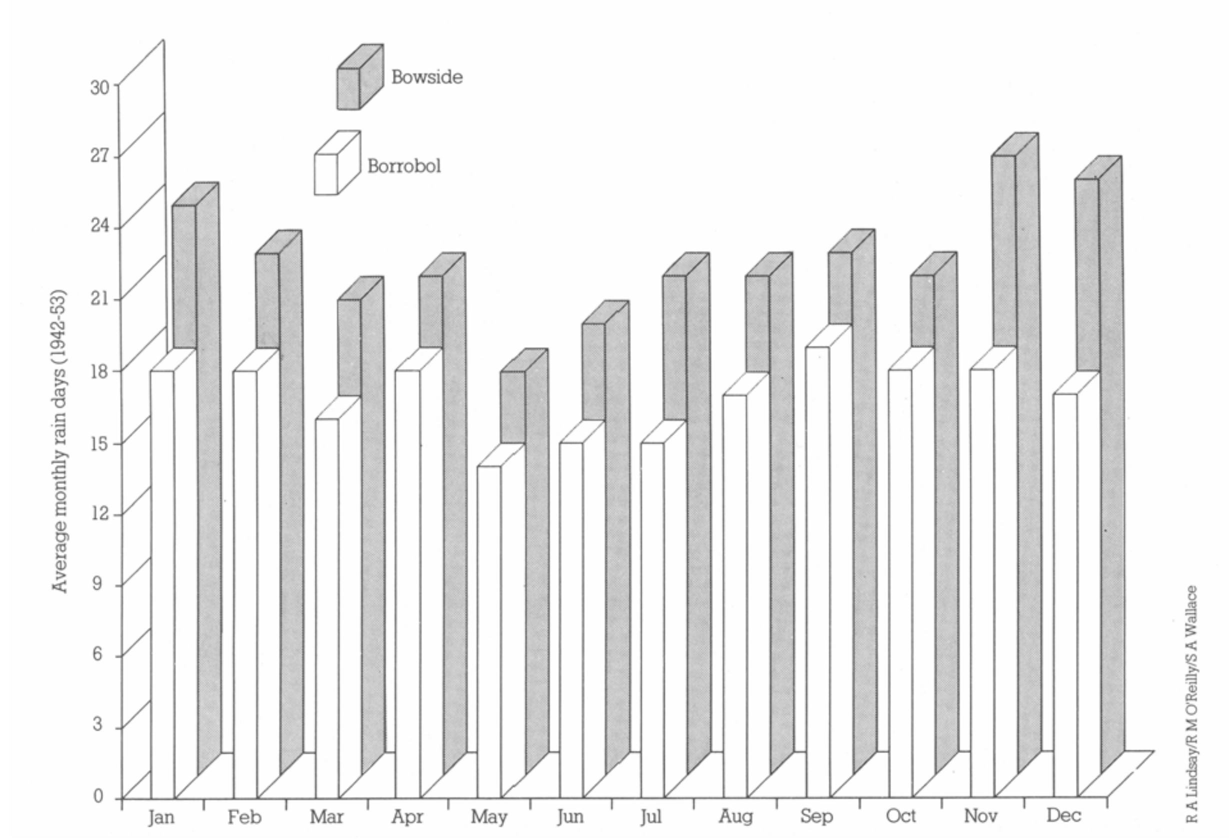


**Figure 14** Average annual "rain days" and total rainfall (mm) for Borrobol in central Sutherland, Bowside in north Sutherland, Stornoway in Lewis, Laggan on Islay and Portree on Skye (1942-1953). (Figures taken from *Scottish Peat Surveys*, Vol. 2 (DAFS 1965), provided by courtesy of the Meteorological Office.)

The modern concept of evapo-transpiration has been valuable in integrating various aspects of climate into an ecologically meaningful index of effective wetness (Green 1964). The map in Figure 12d suggests that a water surplus (excess of rainfall over evapo-transpiration) during the six months April to September favours the development of blanket bog. The whole of Caithness and Sutherland experiences such a water surplus, and indeed over all but the eastern coastal zone the excess is 200 mm or more.

Precipitation, humidity and cloud cover increase with altitude, while temperature and evapo-transpiration decrease. Other factors being equal, there is thus a tendency for increasing altitude to favour blanket bog development, and this is especially noticeable in more southern and climatically marginal districts for this formation, such as Dartmoor. The altitudinal effect thus produces local, orographic gradients relevant to the understanding of blanket bog distribution and characteristics within Caithness and Sutherland. The reduction in temperature with increasing altitude also affects plant growth directly. Birse (1971) uses accumulated temperature in day-degrees (see below) as a measure of temperature for plant growth. In Caithness and Sutherland an accumulated temperature of 275-550 day°C is estimated for the highest ground (e.g. Ben Klibreck, Ben More Assynt). On the coasts and in north-east Caithness, the figure is 1100-1375 day°C. Most of the peatland area occurs well within these two extremes at 825-1100 day°C (Birse & Dry 1970).

Birse & Robertson (1970) also consider exposure and accumulated frost. Both factors attain moderate values for the majority of the peatland area. Exposure increases towards the west coast, and winters are very mild on all coasts, especially the west. Altitude increases both exposure and frost throughout the two districts. The winters, then, are mild in comparison with the rest of Scotland, especially the Grampian Highlands, but exposure is generally quite severe and little different from that in other northern Scottish regions.

The two maps of Birse & Dry (1970) and Birse & Robertson (1970) are combined by Birse (1971) to construct a map of bioclimatic sub-regions in order to relate climatic conditions in Scotland to climate categories employed in Europe (e.g. Tuhkamen 1987). Thermal zonation (south to north, low- to high-altitude), oceanicity and moisture status are the determinants of bioclimatic zones. These categories are used as ecologically relevant subdivisions of climate for blanket bog development and differentiation.

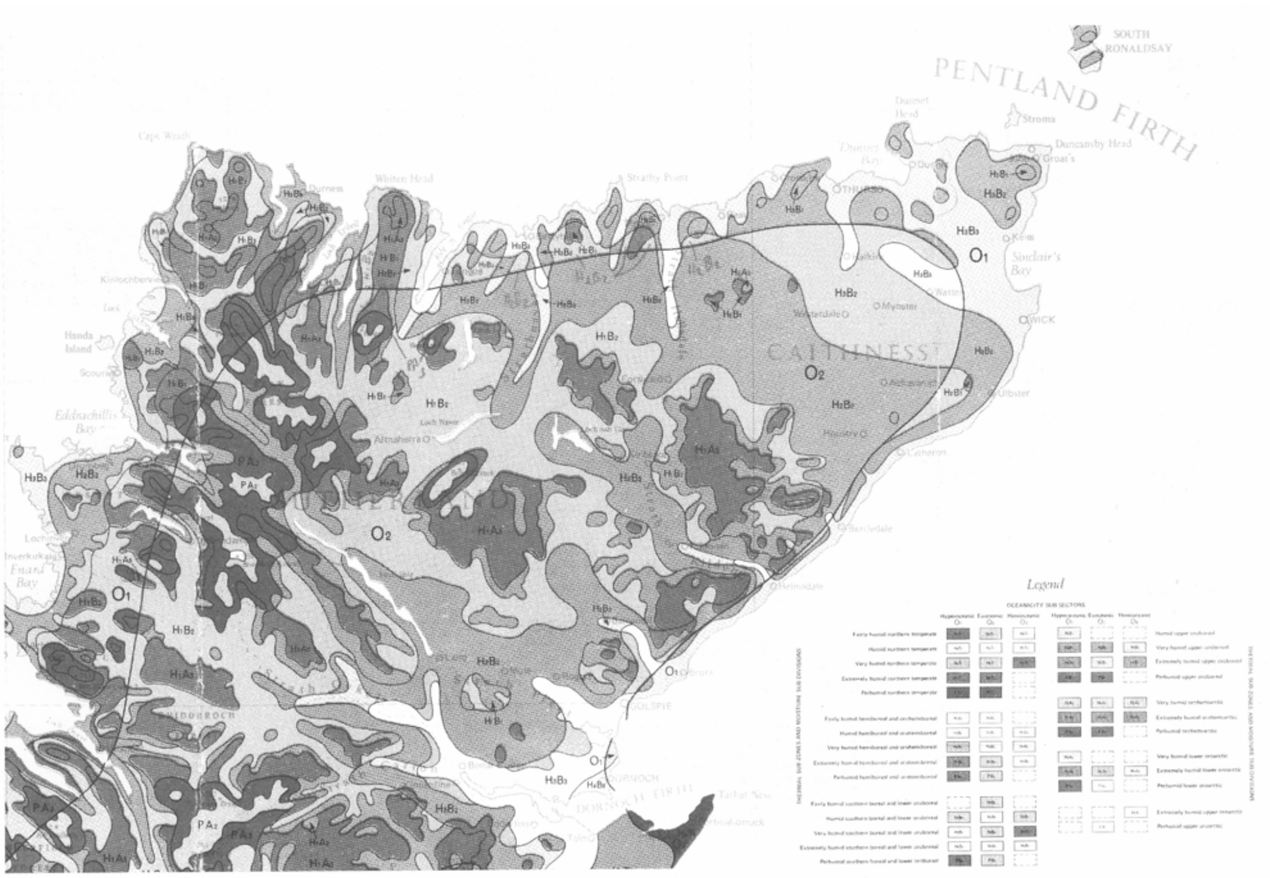


**Figure 15** Bioclimatic sub-regions for Caithness and Sutherland, derived by Birse (1971). For explanation of categories, see text. (Copyright Macaulay Land Use Research Institute.)

## Bioclimatic zones of Caithness and Sutherland

Birse (1971) derives a total of 62 bioclimatic sub-regions for Scotland, which are grouped into three categories of oceanicity and seven thermal/moisture subdivisions (Figure 15). The primary separation in Caithness and Sutherland is into a coastal hyperoceanic zone (01) and an inland euoceanic zone (02), on the basis of length and intensity of growing season, relative humidity and degree of windiness. Within each oceanicity zone, 01 and 02, there are seven thermal sub-zones and two moisture divisions, the wetter of the two (Humid) divided into four subdivisions of annual potential water deficit.

Of the 62 sub-regions identified, 27 occur in Caithness and Sutherland, from the hyperoceanic perhumid lower oroarctic (01.PA2) on the summit of Foinaven to the euoceanic fairly humid hemiboreal (02.H4/B3) around Dornoch (see Figure 15).

The main peatland areas are subject to a somewhat more moderate range of conditions. Of the 27 bioclimatic zones which occur in Caithness and Sutherland, half are associated with the peatlands, the remainder being concentrated amongst the complex landforms of the Moine Thrust zone. The conditions which characterise each bioclimatic zone can be seen in Figure 16.

The entire coastal strip is distinguished from more central parts by the moderating influence of the sea, with some parts experiencing less than 20 day-degrees of frost a year. This is in contrast to inland high-level ground such as Knockfin Heights (altitude 450 m) which may experience up to 230 day-degrees of frost. However, the price of such mild winters is high incidence of gales, so that the coastal belt shares with Knockfin Heights mean wind speeds of 6.2-8.0 m/s, whilst the more sheltered central plain experiences speeds of 4.4-6.2m/s and the straths have wind speeds only half those of the coastal and high-level zones.

The bulk of the peatlands area is divided into five main lowland climatic zones and two high-altitude zones, together with one or two others which are of particular note.

**01.H3/B3 Hyperoceanic humid hemiboreal**

The zone occurs at its most extensive in Scotland across the wide agricultural belt of north-east Caithness. Its other main occurrence is along the west coast of the Uists, but it also affects a narrow coastal fringe around Lewis and the westernmost strip of Sutherland and Wester Ross. The extreme exposure of these other areas is in contrast to the apparently sheltered nature of the Caithness agricultural interior.

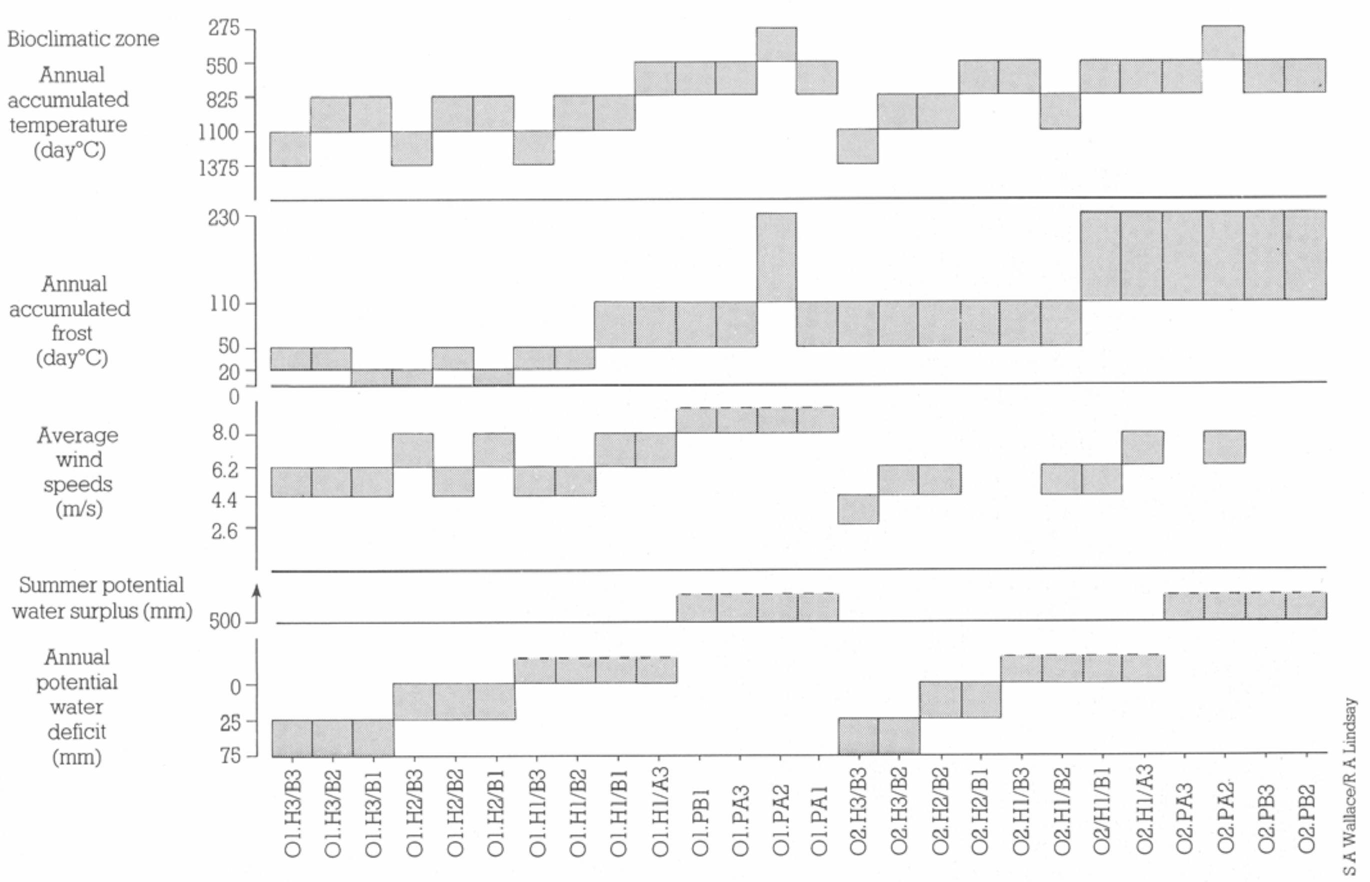


**Figure 16** Climatic regime for the bioclimatic sub-regions which occur in Caithness and Sutherland, based on Birse & Dry (1970), Birse & Robertson (1970) and Birse (1971).

### 01.H3/B2 Hyperoceanic humid southern boreal

The centre of distribution is Shetland, where a high proportion of the lower-lying ground dominated by thin peat and organic soils falls within this category. In Caithness, which is its other major occurrence in Scotland, it prevails over low-lying coastal ground which has not yet been subject to intensive agricultural development and is therefore still largely peat-covered.

### 01.H3/B1 Hyperoceanic humid upper oroboreal

In contrast to H3/B3, this zone is largely restricted to the Orkneys, with only a few small localities in Caithness and Sutherland, which support peat of a thin, maritime heath type rather than deep ombrotrophic peat.

### Ol.Hl/Bl Hyperoceanic extremely humid upper oroboreal

This is an extremely localised zone, restricted to the far west coast and associated with high-level ground. It is characteristic of central Barvas Moor and the great sweep of peat to the north of Achmore in the Outer Hebrides, as well as of the lower slopes of the Trotternish Ridge on Skye. In Sutherland it occurs mainly in the north-west corner, where the peninsulas of A'Mhoine and Cape Wrath represent its major centre of occurrence in Scotland.

### 02.H3/B2 Euoceanic humid southern boreal

This coincides with the other major zone of agricultural reclamation, where a number of substantial mire systems remain. Effectively the zone occurs nowhere else in Scotland, and it contains one of the 'classic' Caithness mire sites in the Dubh Lochs of Shielton.

### 02.H2/B2 Euoceanic very humid southern boreal and lower oroboreal

Although forming the major climatic zone of the Caithness and Sutherland lowland plain, this zone is also represented - perhaps rather surprisingly - on the northern slopes of the Moorfoot, Lammermuir and Pentland Hills. The difference between the two regions appears to be that the more southerly occurrence is essentially oroboreal and therefore has the potential for a more extended growing season than the true southern boreal zone of Caithness and Sutherland. The contrast in altitude (300-500 m for the Southern Uplands as opposed to 150 m for the Flow Country) and latitude (less than 56°N for the Southern Uplands and more than 58°N for the Flow Country) throws the difference between the two areas into sharp relief.

This zone corresponds to the major area of peat formation throughout the low-lying areas of the Flow Country. It is also the bioclimatic zone within which the majority of recent afforestation has taken place.

### 02.H1/B2 Euoceanic extremely humid southern boreal and lower oroboreal

Like the previous zone, this has a discontinuous distribution across Scotland, though with a major occurrence in Caithness and Sutherland. The different areas where this zone is found display some of the same contrasts as described for H2/B2, although the zone is clearly somewhat orogenic even in the Flow Country. It occupies the higher flat ground in the west of the region, rising in places to 330 m, in contrast to a limit of 700 m in the Southern Uplands. However, its general distribution in Caithness and Sutherland also demonstrates the phenomenon of "north-west oceanicity" alluded to by Pearsall (1956). This arises because Ben Klibreck, Ben Armine, the Ben Griams and Knockfin Heights generate markedly higher rainfall over ground lying to the north-west of their summits during the frequent north-westerly gales. Rannoch Moor, lying in a high-level basin within the Grampian Mountains, is also characterised by this climatic zone.

### 02.H1/B1 Euoceanic extremely humid upper oroboreal

This occurs widely throughout Scotland as the zone associated with the lower slopes of upland massifs within the central climatic belt. It thus occurs locally in the Southern Uplands, as a central band through the Grampian Mountains, and fringing all the highest plateaux in Caithness and Sutherland.

### 02.H1/A3 Euoceanic extremely humid orohemiarctic

Characterising all high ground above 330 m, apart from mountain summits such as Ben Klibreck and Ben Hope, this zone characterises the altitudinal upper limit of blanket bog formation in Caithness and Sutherland, mainly because any higher land tends to be too steep rather than because of any climatic limit. It combines the high precipitation levels typical of an oceanic climate with a temperature regime more usually associated with northern boreal conditions. This is borne out by records of the northern boreal/sub-arctic spiders *Hilaria frigida, Valckenairia clavicornis* and *Rhaebothorax morulus* taken from the pool systems on Knockfin (E Milner pers. comm). In the Monadhliaths, ground with this climate has been found with snow patches as late as July on north-facing aspects (NCC unpublished). Although there is extensive peat, conditions for its formation must be severe, in view of the combination of frost action and powerful scouring by frequent rain.

## Conclusion

Present climatic conditions may differ in some degree from those of the earlier periods which saw the origin and development of these peatlands. Nevertheless, the present vigour of the bog surface as peat-forming vegetation across so much of Caithness and Sutherland suggests that the present climate is probably as favourable for the growth of blanket bog as at any previous time in its history. Where bog surfaces have lost this vigour, the cause appears to be mainly human disturbance, or just possibly a natural senescence of bog growth, rather than any shift in climate.

Caithness and Sutherland east of the Moine Thrust satisfy the essential combination of conditions for ombrotrophic bog development - cool, humid climate, gentle topography and acidic substrates - more extensively than any other part of Britain or Ireland. The only other peatlands of comparable size likely to have existed in these islands during the Flandrian period were predominantly of rich fen type - the Fenland of East Anglia and the Bog of Allen in central Ireland, both of which have been largely drained out of existence. Other extensive and important areas of low-level blanket bog include Barvas Moor on Lewis, Rannoch Moor in Perth and Argyll and the Wigtownshire-south Ayrshire Flows; but they do not compare in size with the Caithness and Sutherland Flows.

# 5 Human impact

The peatlands of Caithness and Sutherland are one of the most extensive examples of a near-natural landscape still surviving in Britain, and one not far removed from the original primeval scene before early man began to exert a significant influence on our environment. As a region, Caithness and Sutherland nevertheless have had a long history of human occupation, as evidenced by the Neolithic burial chambers of the Grey Cairns, at Camster, and the discovery that Caithness flagstones were exported to the continent at about the same time.

The intensity and effect of many land-uses in pre-Clearance times is difficult to judge, and the relationships between man-induced changes and natural processes as factors affecting bog systems are still the subject of considerable debate. Nonetheless it is possible to identify two major activities which have undoubtedly played a long-established and significant part in determining the current state of vegetation and surface patterns on the Caithness and Sutherland mires - crofting and sporting estate management. Forestry represents a far more recent, and dramatic, type of land-use change. Although some of its impacts are similar to those of more traditional land-uses, afforestation is considered mainly in the next chapter.

The effects of game management and crofting tenure overlap, but together they are responsible for four key modifiers of the mire system - drainage, peat-cutting, burning and grazing. The phenomenon of peat erosion is considered in relation to these activities, and the possible effect on the peatlands of atmospheric pollution generated in distant regions is also discussed.

## Drainage

Drainage has been general practice on wet ground for centuries. This is partly to improve the quality of grazing and partly to remove the hazard to stock. More recently, however, intensive drainage has represented the first stage in preparing open ground for afforestation. Because sites already completely ploughed for forestry were not included in the sites selected for our survey, Figure 17 refers mainly to the form of hill-drainage known as "moor-gripping" (Stewart 1980), rather than to the more intensive type of drainage required for forestry. Until the early 1930s the method was laborious, involving hand-digging. The development of crawler tractors and the Cuthbertson plough meant that extensive areas could be "gripped" in a short time. Many crofting communities therefore pooled their resources to hire drainage contractors, with all parties benefiting from the availability of

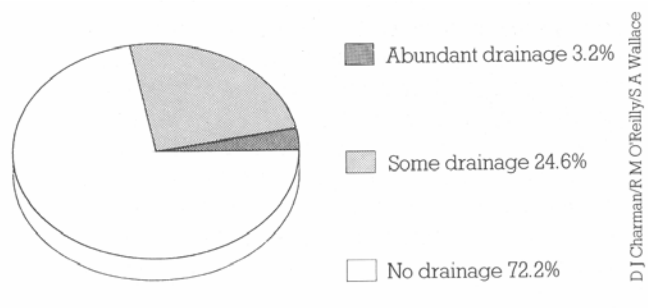


**Figure 17** Proportion of sites in the NCC's Peatland Survey of Caithness and Sutherland affected by differing intensities of drainage.

government grant-aid designed to encourage land drainage for agriculture.

The extent to which this policy can be said to have been successful is vividly apparent on aerial photographs for many parts of Caithness and Sutherland - for example the area of Forsinard Flows north-west of Forsinard Station. Figure 17 shows that a quarter of the sites surveyed by the NCC had been drained to some degree, though few had suffered comprehensive drainage. The wide spacing of moor-grips means that such drainage is not generally recorded as "abundant". Consequently the 24.6% of sites with "some drainage" largely represent those which have been moor-gripped.

Recent advances in the understanding of peatland hydrology suggest that a thorough reappraisal of peat drainage is required, particularly in terms of its impacts on nature conservation value. The first indicators of change are often of no interest to (and are therefore not recorded by) developers, but these indicators may herald larger changes which then become of great significance to the developer.

Ivanov (1981), in providing the definitive modern work on peatland hydrology, emphasises the need to understand the impacts of Russia's long-established peat development programme on local and regional hydrologies and to consider the nature and implications of future schemes. He catalogues the effects of drainage thus: "Intensive drainage and lowering of the average water table ... lead to the disintegration of mire systems through the desiccation of their peat... the main thickness of peat becomes extremely dehydrated, its temperature rises and biological processes leading to the decomposition of organic material are activated. Decomposition reinforced by the pressure of the peat's own weight (which, after the lowering of the water table, is no longer suspended in water) and by capillary tension, also resulting from lowering of the water table, leads to a shrinkage of the whole peat deposit, a gradual increase in its mineral content and the disappearance of its organic components."

Ingram (1982, 1983) and Ingram & Bragg (1984) combine much of their own original research with that described by Ivanov (1981) to suggest that recourse to normal soil hydrophysics is not appropriate when studying bog systems, because the hydrology of a bog is compartmentalised between the acrotelm and the catotelm (see Chapter 1). The fundamental role played by this "diplotelmic" (two-layered) structure in maintaining the stability of the entire bog unit is, they feel, widely overlooked by land managers, despite its extreme sensitivity to a wide variety of land-use practices.

The effects of peatland drainage fall into two broad categories. First, there is a change in profiles and gradients of the drained surface, sometimes extensive enough to affect the entire shape of the bog. This is the response most readily recognised by drainage engineers, although there are a number of features unique to peatland soils. Secondly, there is the much more subtle response of the living vegetation within the acrotelm. This latter response is often ignored completely, yet is probably the most important, and the unique, aspect of peatland drainage when the likely impact on the nature conservation importance of a site is being considered.

More so than with other soils, the effects of drainage on peatland are likely to be dramatic and irreversible only where the drainage system is regularly cleaned out, because the growing surface of *Sphagnum* moss will tend eventually to choke ditches which are not maintained and thereby to stabilise the hydrology of the area. However, there are circumstances where drainage has the effect of setting off a sequence of events which destabilise the hydrology. This can occur to such an extent that no further maintenance is required and the bog becomes self-draining.

## The physical response to drainage

Hobbs (1986) details the various factors which an engineer will encounter when working with peat soils and demonstrates that, for many aspects of its behaviour, peat is similar to an unconsolidated clay. However, he identifies certain marked peculiarities, not least the high water content of peat bodies, but also, after drainage, the sequence of primary consolidation, followed by shrinkage, secondary compression and finally wastage or subsidence.

**Primary consolidation** is usually the major response of a soil to increased loading. As indicated by Ivanov's (1981) comments above, this increased loading can result purely from drainage. Wet, unhumified peat soils certainly exhibit a rapid initial response, with consolidation of 1.5 m in a peat depth of 10 m within 12 months if the water table is maintained at 1 m depth (Hobbs 1986). Primary consolidation occurs because void space within the soil is reduced as the weight of the overburden (in this case the layer of drained peat) compresses the wet soil beneath, leading to expulsion of water from these diminishing pore spaces. Igarashi, Akazawa, Matsushita & Umeda (1984) point out that unhumified peats typically have large void spaces and therefore tend to undergo substantial primary consolidation. This large void ratio is in contrast to conditions in clayey soils, where primary consolidation is the only marked response to loading; the scale of response is thus much smaller in clay soils.

**Shrinkage** Where loading is caused by drainage, the layers thus removed from regular inundation experience physical shrinkage of structural parts. Hobbs (1986) recorded this shrinkage as typically 35-45%. Amorphous peat shrinks more than unhumified peat because its fibres are not aligned in any way. Unhumified peats, on the other hand, show marked lateral shrinkage but little vertical shrinkage because individual *Sphagnum* stems, which tend to remain upright in unhumified peats, have little capacity for vertical shrinkage. Shrinkage in such peats therefore tends to induce cracking rather than significant surface lowering. Only when the peat is significantly humified will both phenomena occur (see Figure 2 in Pyatt 1987). Hobbs (1986) illustrates the irreversible changes which occur to the peat colloids and structure once drying out has occurred by pointing to the usefulness of dried peat bales as stable, lightweight fill for use in conditions of permanent waterlogging. Despite constant inundation, which prevents oxidation and wastage (see below), the peat-fill can be relied on not to re-expand and thereby affect any graded contours.

**Secondary compression** begins once pore water pressure falls to zero above atmospheric pressure (Igarashi *et al.* 1984) and occurs as a "creep-like" process with gradual rearrangement of the peat fibres and steady loss of more tightly bound water from micropores (Hobbs 1986). The process occurs over a much longer period than primary consolidation and is linear with time on a log scale. Hobbs emphasises that this is the major response of peatland systems to loading (including drainage) but says that its effects are often omitted from engineering considerations in favour of the more dramatic and ubiquitous response (for most soils) of primary consolidation.

**Wastage/subsidence** Finally, and almost uniquely to peatland soils, there is the phenomenon of wastage. This is often difficult to separate from the effects of secondary compression and shrinkage, but arises when the organic components of peat oxidise to gaseous compounds and water, leaving only the tiny mineral component as a residue. Like secondary compression, this is a long-term process, one of the most vivid examples being the famous Holme Fen post in Cambridgeshire, where loss of peat has measurably lowered the ground level by almost 4 m since 1854 (Godwin 1978). The overall effect of subsidence is described by Prus-Chakinski (1962) and Eggelsmann (1975), who describe the general lowering of the mire surface on drained ground as a result of the various processes of shrinkage, subsidence and slumping.

Whilst these processes occur throughout an area of drainage, Pyatt (1987) notes that one of the most obvious effects is in the widening of original drain lines. An example of such a response can be seen in Figure 18, for a raised mire in Cumbria. The central drain was dug before 1939 and has been repeatedly-cleaned out since. The width of the drain itself is only 0.5 m, but the effect on the mire surface gradient can be seen to extend to at least 100 m on either side.

Ingram's (1982) Ground Water Mound Model is based not on the average state of water balance, but on the very worst conditions of drought experienced by the mire. The long-term effects on surface gradients and stability of the entire system therefore depend on how the hydrology of the drained part of the mire behaves under such extreme conditions. Ivanov (1981) states that a mire surface which has its surface vegetation replaced by a non-peat-forming community and whose natural drainage remains (or is repeatedly) disrupted will experience gradual loss of peat until eventually all trace of an organic soil will be lost. In the case of forestry, the periods of site preparation at the first and second rotations will ensure complete disruption of the surface hydrology and encourage extensive wastage, whilst the phases of closed canopy will induce deep oxidation of the peat and extensive secondary compression as the weight of timber overburden increases. Whilst it is therefore possible to point to likely changes to the peat underlying forestry plantations, the implications for areas of open mire sharing the same hydrological unit as the plantation has been only partially answered.

The scale of consolidation and wastage around drain lines is often less in upland blanket bogs, which tend to be shallower and much more humified. They are presumably also less prone to surface drying, because the constant precipitation helps to keep the soil saturated for most of the time. The depth of drains and their configuration in an overall system are also important in affecting the rate of water removal and, hence, of lowering of the water table.

Ingram & Bragg (1984) point out that the acrotelm is so structured as to buffer the catotelm from all outside influences, so that the aerated layer never falls into the catotelm under natural conditions. In the event of drainage, only those areas which lose this thin surface layer will suffer the effects outlined above. Obviously, therefore, the important question is over what lateral distance will the acrotelm be disrupted?

## The response of the acrotelm and surface vegetation to drainage

A recurring assertion through much of the literature on peat hydrology is that the effect of drainage is limited to a few metres either side of a drain and in general merely aids surface water run-off (Boelter 1972; Galvin 1976; Stewart 1980; Stewart & Lance 1983). Such apparently modest effects of drainage generally reflect situations where an acrotelm is no longer present at the peat surface, but the profound changes to both catotelm and acrotelm described here and above are most pronounced when a well-developed, *Sphagnum*-rich acrotelm is drained. Pyatt (1987) comments that "aeration of the fibrous layer improves as soon as the water table is

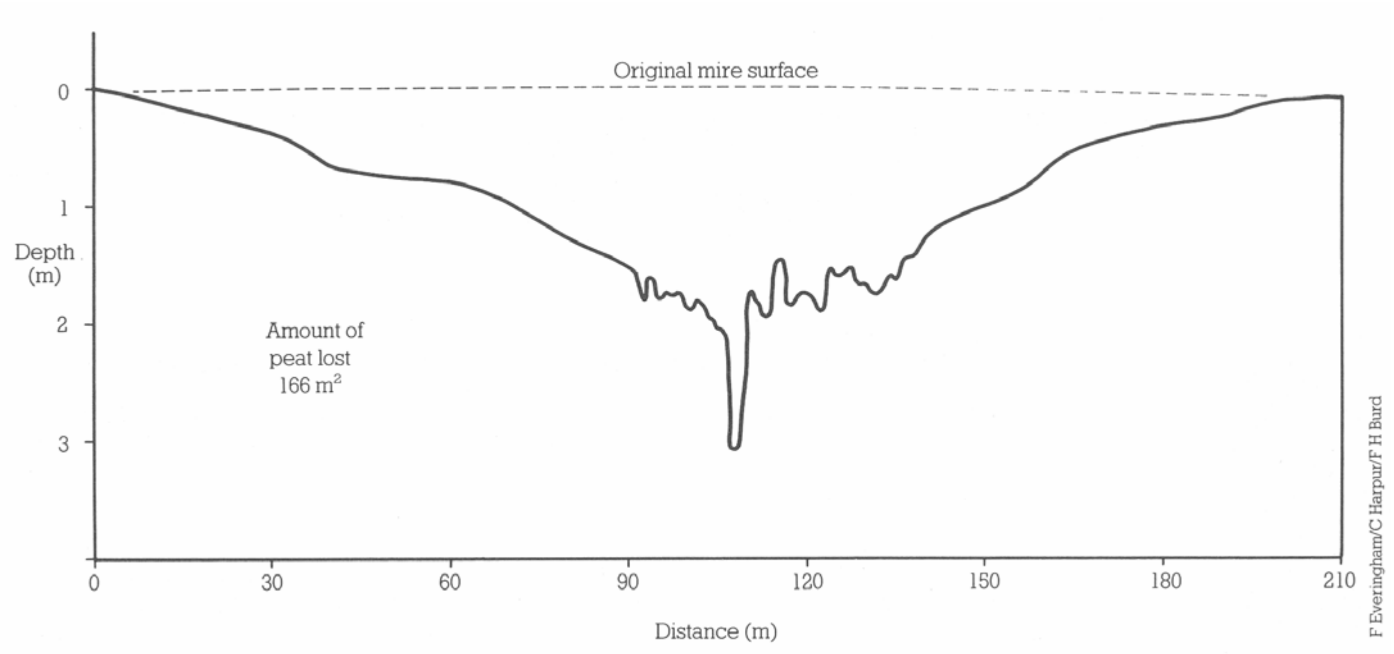


**Figure 18** Cross-section of a drain cut into the peat of Wedholme Flow in Cumbria. The gradually sloping profiles on either side of the drain (which has been repeatedly cleaned out) indicate the extent of primary consolidation, secondary compression and wastage since the inter-war years. The horizontal scale has been compressed to display more clearly the extent of surface lowering.

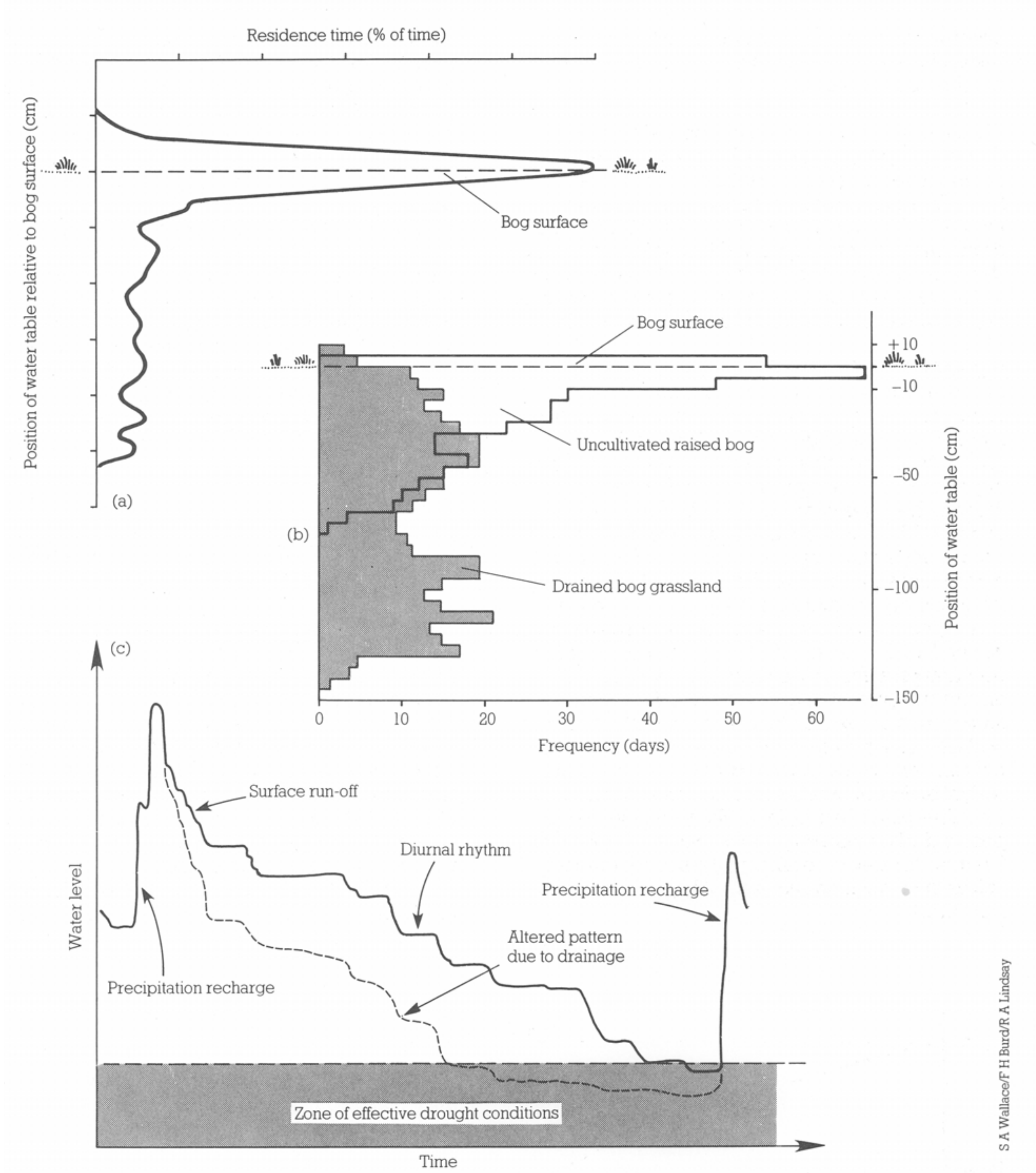


**Figure 19** The effect of drainage on the water table in the acrotelm -
(a) Location of the water table in relation to the bog surface, expressed as proportion of time spent at particular depths ("residence time"). (Taken from Bragg 1982.)
(b) Pattern of residence times for bog water tables from a natural and an undrained bog in West Germany. (Taken from Ingram 1983.)
(c) Continuous recording of the water table, showing run-off and diurnal rhythm, from an undrained bog in Argyll (NCC unpublished data) and a generalised indication of the effect of increasing the surface run-off by, for example, drainage.

lowered". However, as Ingram & Bragg (1984) and Hobbs (1986) note, this fibrous surface layer is the acrotelm, and increased aeration (or reduced flooding) of this layer has profound ecological implications for the overall arrangement of species and surface patterns (microtopes) on a mire system, according to Ivanov (1981). He states (p. 199): "The maximum difference in mean long-term [water] levels which does not lead to a change in the quantity or floristic composition of mire plant communities is very small. For several varieties of moss cover it is less than 4-5 cm."

The small scale of the niches taken up by bog plant communities has been discussed in Chapter 2, but Rydin & McDonald (1985) demonstrate that species typical of Al hollows or T1 lawns, such as *Sphagnum tenellum*, are actually unable to grow at positions in the microtope just 10 cm above their normal niche. Clymo & Hayward (1982) also show that some of the more common bog *Sphagna* are extremely sensitive to desiccation. After 16 days of drought, plants of *S. papillosum* and *S. magellanicum* were found to be incapable of resuscitation, whilst *S. rubellum* showed some recovery response. Only *S. imbricatum* seemed entirely unaffected by the event. This accords with field observations of drained peatlands where scattered *S. imbricatum* hummocks may still be found although the majority of the *Sphagnum* cover has been lost. This species and *S. fuscum* nevertheless become more vulnerable to fire once the water table is lowered.

The proportion of time during which the water table stands at any given depth in the peat is known as the "residence time". In an undisturbed bog, the water table lies within a few centimetres of the ground surface for more than 90% of the time (see Figure 19a); the surface layers are thus said to have a high residence time. Drainage changes this pattern of residence times (see Figure 19b).

A typical sequence of water table movements producing a curve such as that shown in Figure 19a is displayed in Figure 19c. Also shown is the effect of increasing the rate of surface water removal - commonly asserted as the only effect of drainage. From Figure 19c it can be seen that drought events experienced by the *Sphagnum* carpet are determined by the rate at which water is lost from the surface layers between rain events. If the rate of loss is increased, by drainage for example, drought conditions between rain events will increase in frequency and become more prolonged. Such a change in acrotelm hydrology can be expected to have a significant effect on the surface vegetation, as predicted by Ivanov.

The outcome of such changes is not necessarily loss of *Sphagnum* in itself, and Ivanov explores alternative responses by mire systems to changed hydrological circumstances, particularly in terms of the relationship between hydrological stability and surface pattern ("arrangement of microtopes"). Ivanov demonstrates that the resilience of mire systems to hydrological change depends almost entirely on the presence of at least two distinct elements in the surface pattern, each having markedly differing hydraulic conductivities. Under conditions of increasing water content, the acrotelm requires a large proportion of the surface to possess a high rate of surface seepage, and therefore the aquatic element of hollows and pools, which have very high hydraulic conductivities, increases to form the dominant microtope across the mire. Where conditions become increasingly dry, the rate of surface seepage through the acrotelm must decrease, and so the mire surface becomes dominated by ridge and hummock communities, which have lower hydraulic conductivities.

This alternating pattern of "strip-ridge", as Ivanov terms it, forms an interconnected mosaic whereby the stability of each part of the pattern depends on the stability achieved by the sections of pattern further upslope (Scottish Wildlife Trust 1987). Equally, the rate of water percolation downslope is determined by the abundance of low-conductivity ridge structures. Such features become more abundant in the natural transition from flat mire expanse to the sloping mire margin, providing hydrological stability to the latter.

The effect of drainage anywhere within this system, therefore, is to impose a new set of gradients to which the acrotelm must adapt, if it can, though there is always the additional danger of catastrophic change such as the formation of erosion complexes within pool systems or the occurrence of bog-bursts in high-rainfall areas.

The first response to drainage involves the reduction, or even loss, of the wetter element within the mire surface pattern. However, although such flexibility can occur over areas which are dominated by hollows and shallow pools, the deeper A3/A4 "endotelmic lakes" consist of physical structures which cannot alter their surface area. Such areas of pattern therefore become unstable, leading to a lowering of the water level in the lake and an accompanying fall in the mean water table in surrounding parts of the microtope. The presence of peat 'cliffs' around larger *dubh lochain* in Caithness and Sutherland is common where part of the mire has suffered damage.

The general pattern of loss of hollows resulting from drainage is illustrated by Woike & Schmatzler (1980); see Figure 20. The possibility that partial drainage can alter the entire surface pattern is consistent with the changes observed by Chapman & Rose (1986) at Coom Rigg Moss (see Chapter 6). Tubridy (1984) also demonstrates a marked correlation between absence of pools and presence of peat-cuttings on Mongan Bog in County Offaly (see Figure 21). Only on the side of the bog furthest from extensive peat-cutting are bog pools common.

Such changes may also explain a number of cases where anomalous species distributions point to the original presence of pools or hollows on mires which no longer possess such features. Thus Cors Fochno, near Aberystwyth, was intensely drained on the west side in the early 1960s. It has since been found to support *Rhynchospora fusca* and the damselfly *Ceriagrion tenellum* only in flooded peat-cutting hollows, yet both are typical of bog pools and are reputed to have occurred originally on the mire expanse. The site shows no evidence of such pools today, having only shallow *Sphagnum* hollows (Dr A D Fox pers. comm).

The sometimes dramatic effects of drainage within pool systems can be seen in a number of localities in Caithness and Sutherland. Single moor-grips or forest drains entering pools on the edge of a pool complex have caused them to deteriorate.

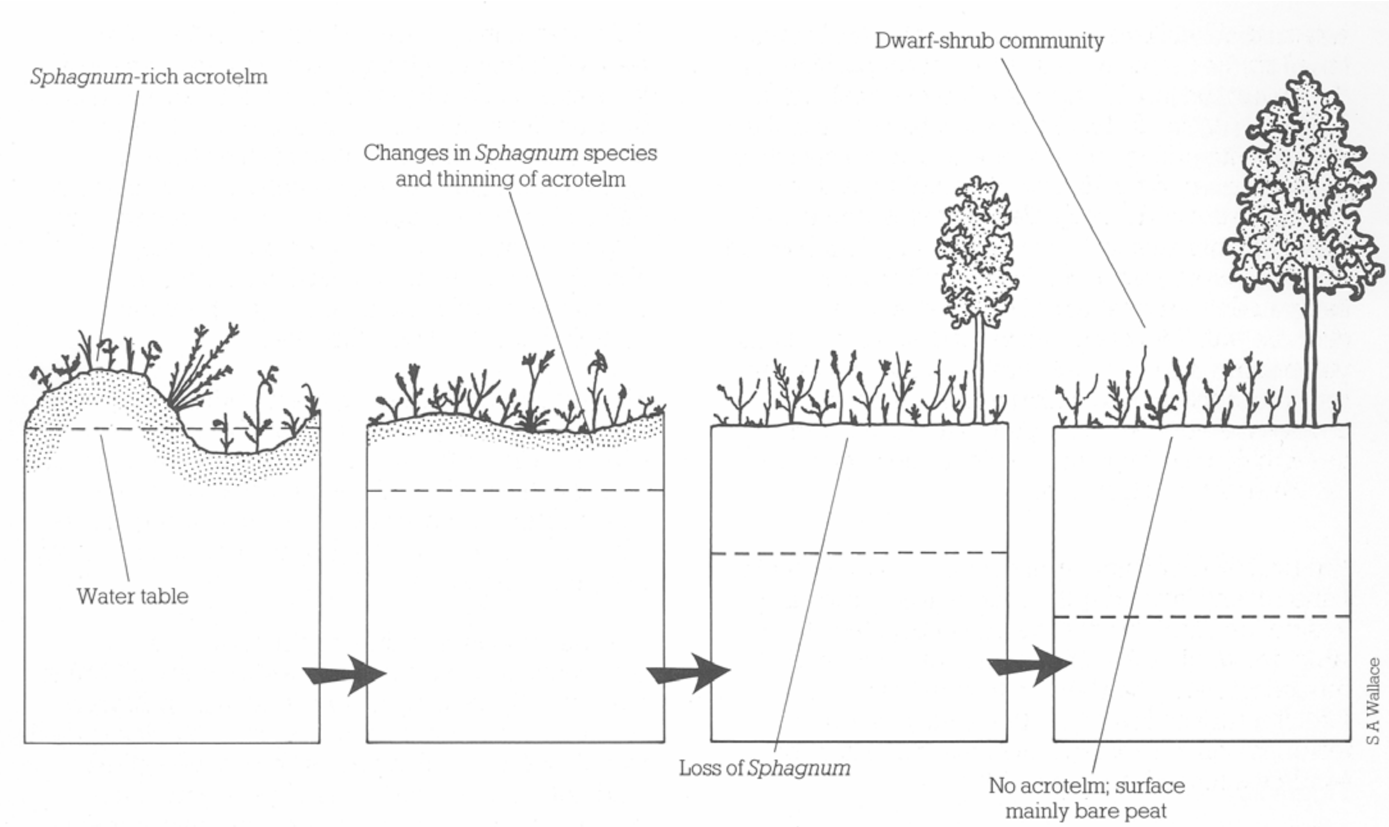


**Figure 20** Changes in the surface and vegetation of an ombrotrophic bog with lowering of the water table (after Woike & Schmatzler 1980).

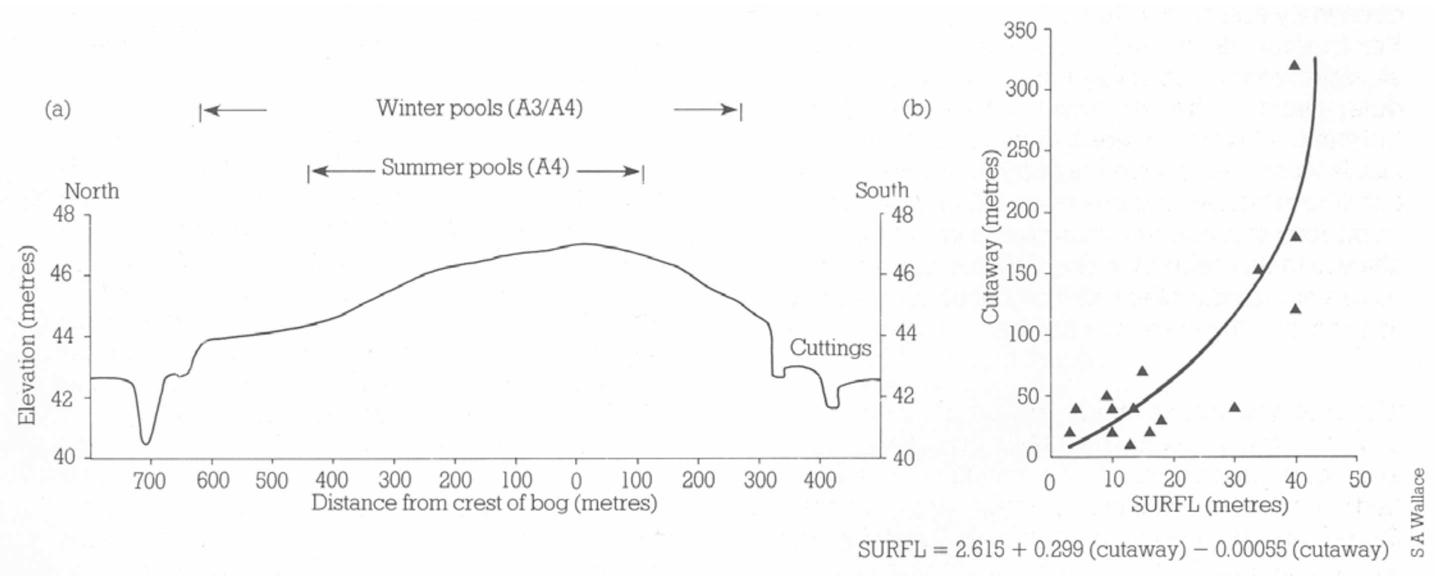


**Figure 21** Relationship between the distribution of winter pools and the removal of peat by turf-cutting (for fuel) from the south side of Mongan Bog, County Offaly - (a) distribution of pools and location of cuttings; (b) regression analysis showing significant asymetry of pool distribution correlated with distance from peat-cuttings. (Taken from Tubridy 1984.)

## Peat-cutting

Another of the more obvious impacts, which can show clearly for hundreds of years, is the widespread cutting of peat for fuel. Extensive peat banks are still worked by residents of Wick and Thurso along the Camster road, but a number of sites in both Caithness and coastal Sutherland attest to extensive past working. Rattar Moss beside the Castle of Mey, for example, has clearly been completely cut over and subsequently abandoned, allowing an interesting, if modified, vegetation to regenerate. The same is true for such sites as Loch Hempriggs, south of Wick, and Moss of Greenland, east of Castletown.

In Shetland it is not unusual to find peat banks far removed from any likely habitation, past or present, with traditional 'peat-tracks' indicating the route taken by the peat-cutters and their peat-laden cattle or ponies. Little evidence was found from the central peatlands of Caithness and Sutherland to indicate that pre-Clearance peat-cutters had strayed far from the immediate vicinity of the straths. Figure 22 shows that only 5% of sites examined had distinct evidence of peat-cutting. Commercial extraction of peat is restricted to a single operation in Caithness, using the 'sausage peat' method, but an experimental peat-fuelled power station was operated for some years in the district during the 1950s, and there are suggestions that peat-fuelled power stations may be considered seriously in the future,

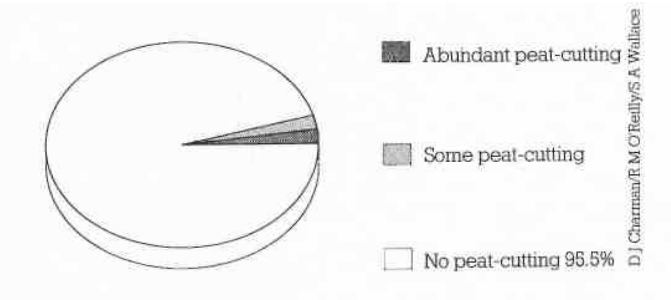


**Figure 22** Proportion of sites in the NCC's Peatland Survey of Caithness and Sutherland affected by various intensities of peat-cutting.

## Burning

Both of the traditional land-uses of the Flow Country are based on forms of grazing: crofting depends on sheep-grazing, and sporting estates on grazing by deer and grouse. In order to maintain or enhance the quality of this grazing, both employ fire as a management tool. This has undoubtedly been the oldest form of human impact on these mires, even to the extent that it has been suggested as the origin of their treeless character. Burning is also the most widespread of the land-use practices: Figure 23 reveals that only just over one third of sites examined had no obvious signs of recent burning. More than 10% were severely burnt, with peat showing a greasy bituminous layer as described by Conway & Millar (1960) for Burnt Hill in the northern Pennines.

The difficulty in assessing the true extent and impact of burning is that the ecosystem response to fire is still poorly understood. Although this is surprising in view of the large amount of work done in relation to grouse, deer and sheep management over the years, it is perhaps less so when the sources of variability in

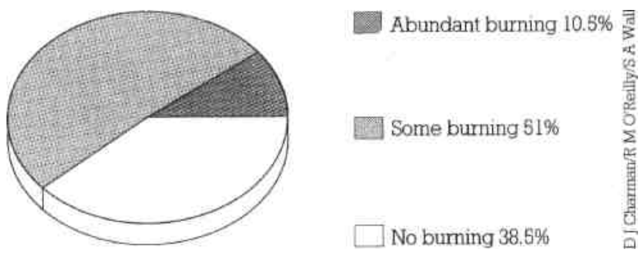


**Figure 23** Proportion of sites in the NCC's Peatland Survey of Caithness and Sutherland affected by various intensities of burning.

'fire events' are considered, e.g. wind-speed, air temperature, ground temperature, degree of waterlogging, chemical composition of the vegetation, fire temperature, depth of burn, fire speed and nature of the peat surface (Eigner & Schmatzler 1980; MacLean, Woodley, Weber & Wein 1983; McVean & Lockie 1969).

Fire affects three major aspects of the peatland ecosystem -

- nutrient cycling;
- hydrology;
- vegetation pattern.

### Nutrient cycling

There are two distinct phases in the response of nutrient cycling to fire. The first is concerned with redistribution of nutrients during the fire, and the second concerns the subsequent longer-term impact on the cycle (MacLean *et al.* 1983).

#### Changes during the fire

**Loss of nutrients through volatilisation and smoke** This can include significant losses of carbon, nitrogen and sulphur, as well as cations such as potassium, magnesium and calcium. Phosphorus is not lost in great amounts, but losses increase in step with increasing fire temperature (Allen 1964). MacLean *et al.* (1983) consider that such volatilised materials are generally not returned to the site of the fire, but blown to other areas, as are significant quantities of mineral-rich fly-ash.

Accumulation of nutrient-rich ash on the peat surface The ash content of many dwarf shrubs is high in phosphate and cations such as potassium and calcium. Where the bryophyte surface remains largely intact, the high cation exchange ability (CEA: see Chapter 1) of *Sphagnum* tends to bind the newly-deposited minerals and prevent large-scale losses. Where the peat surface has been significantly degraded, the post-fire sequence of events often results in a net loss of nutrients from the ecosystem.

**Deposition of waxes/bitumens** During the passage of the fire, a layer of bitumens derived from peat waxes (Clymo 1983) may condense on the peat surface. This forms a water-repellent film and effectively protects the lower layers from leaching (Chistjakov, Kuprijanov, Gorshkov & Artsybashev 1983). However, any ash layer is more likely to be lost in surface run-off because downward leaching into the peat profile is more difficult.

#### Post-fire changes

**Nutrient leaching** Where the organic surface mat has been destroyed, losses through leaching can be highly significant. Allen (1964) considers that regular losses from smoke and leaching together can result in a rate of depletion which would rapidly remove all available nitrogen from the system. A single fire can remove 45 kg/ha of nitrogen, leading Allen to suggest that nitrogen loss is the most serious consequence of burning.

However, being highly mobile, phosphorus is also susceptible to leaching (MacLean *et al.* 1983; Burke 1975). Most, but not all, of these losses can be made good from atmospheric input within a 10-12-year cycle of burning, and phosphorus and nitrogen are therefore liable to suffer gradual depletion under such a regime. This is a particular problem in oceanic areas such as Caithness and Sutherland because such regions have a relatively low input of particulate matter, generally rich in phosphorus and nitrogen, compared to more continental areas. Precipitation is instead rich in mineral salts derived from the sea (Groenendael *et al.* 1975; Bellamy & Bellamy 1966). Thus, whilst mineral salts are replaced rapidly, the two major nutrients limiting to plant growth, nitrogen and phosphorus, are liable to suffer serious depletion in western areas under all but the longest fire cycles.

**Other nutrient effects** The normal pattern of nutrient cycling is altered after fire by a number of factors relating to changes in decomposition rate. First, the nutrient release from ash deposits increases the pH of the surface layers, thereby improving conditions for bacterial rather than fungal decay (Fraser 1948). Through its lowered albedo (reflectance), a blackened peat surface tends to absorb heat more easily, thereby increasing the average temperature of the upper profile. This again tends to increase the rate of decomposition (MacLean *et al.* 1983; Hobbs 1986), whilst Komarek (1971) states that increased temperatures on blackened tundra soils stimulate the rate of nitrogen fixation.

Komarek (1971) also states that increased levels of calcium, phosphate and potassium in the ash deposit greatly stimulate the activity of nitrifying bacteria. Coulson & Butterfield (1978) have subsequently demonstrated that higher nitrogen concentrations lead to increased microbial activity, which in turn increases the nutrient flux. However, Hobbs & Gimingham (1987) point out that, although burning may produce a greater availability of plant nutrients, these are also more prone to losses through leaching on a surface where the moss layer has been lost.

## Hydrological impacts

MacLean *et al.* (1983) state that the active surface layer becomes deeper after fire, whereas McVean & Lockie (1969) comment that the surface layer of oxygenated peat is destroyed or reduced by burning. Ingram & Bragg (1984) also describe the effect of burning on the diplotelmic mire, stating that many mires have been so severely burnt that the surface layer or acrotelm has been destroyed, creating what they term a single-layered (haplotelmic) mire. The difference between these two views appears to centre on the definition of the "active layer" or acrotelm. MacLean *et al.* (1983) refer simply to the zone of water table lowering, irrespective of its structure. Ingram & Bragg (1984), on the other hand, are referring to the formal concept of an acrotelm, which comprises a highly-structured profile from the surface to the acrotelm base, overlying amorphous peat of the catotelm (see Chapter 1).

Severe burning undoubtedly destroys the genuine acrotelm and exposes varying depths of the catotelm to oxygen penetration. In cases where the catotelm peat was relatively unhumified before a fire, subsequent loss of the protective acrotelm can result in much deeper atmospheric penetration in the short term. However, the generally increased level of decomposition arising from this will eventually increase humification and reduce hydraulic conductivity of the catotelm peat to a point where the layer of oxygen penetration, as defined by MacLean *et al.* (1983), is reduced, though it is generally still deeper on average than that experienced within an undamaged acrotelm. The point should also be made that any oxygen penetration whatsoever into catotelm peat exposes it to the combined processes of wastage and erosion.

Brown (1983) emphasises the ease with which burning can induce severe gully erosion and thereby give rise to increased sediment loads in previously clear rivers or lakes.

## Vegetation changes

The underlying assumptions behind the use of burning as a management tool on moorland systems are that it removes old, unpalatable vegetation and adds a certain amount of fertiliser to the ground in the form of ash, the two effects combining to stimulate fresh growth. Whilst fresh growth of grasses and sedges is undoubtedly stimulated by fire, the response of heather is more variable and the overall range of species produced does not always represent a steady improvement of grazing quality.

Pearsall (1950) and McVean & Lockie (1969) list the factors which affect the vegetation's response to burning on peat as -

- temperature and duration of the fire;
- type of ground (degree of drainage, slope, altitude);
- interval since the last fire.

*A Guide to Good Muirburn Practice* (DAFS 1977) recommends that burning be carefully controlled, with sufficient manpower, and that areas of deep peat, particularly those with patterns of pools and hollows, should not be burnt under any circumstances. McVean & Lockie (1969), however, point to the problems of implementing such recommendations: "Present day economics of grouse moor and hill-sheep farming management preclude the employment of the necessary staff to carry out moor burning in the way that past experience has shown it should be done." Even in Crampton's (1911) time the problem of uncontrolled burning in the Caithness peatlands was recognised: "The licence to burn is frequently abused, not only by burning at a time later than is allowed by law, to the danger of nesting birds, but also by burning too extensively and indiscriminately."

The problem is little better today. Unlike forestry, sporting interests receive no subsidies, and even agricultural support does not allocate resources to the manpower required for safe and efficient burning. Sporting, grazing and nature conservation would all benefit if the supervision of fires was better supported. Some estate keepers have expressed concern that the quality of the ground is steadily declining as a result of current burning practices, but, with the present staff reduced to a handful of estate workers, they also felt that this state of affairs was unavoidable if the deer were to be kept on the estate for the stalking season.

A well-managed fire will clip off the above-ground vegetation but leave the peat surface and below-ground parts untouched. Damage only occurs when the fire affects or enters the bryophyte-rich ground layer. When this happens, a whole range of effects comes into play. Pearsall (1950) states that burning tends to decrease the cover of *Sphagnum,* encourage the development of vascular plant tussock-formers such as *Eriophorum vaginatum* and induce an uneven surface, and that the increased nutrient flux encourages other bryophytes such as *Aulacomnium palustre, Polytrichum* spp., *Campylopus introflexus, Pohlia nutans* and *Ceratodon purpureus* to colonise the peat surface.

Evidence from Moor House, in the Pennines, indicates that, although *Eriophorum vaginatum* rises to dominance over a seven-year period after fire, it then declines in favour of *Calluna.* This then achieves maximum cover 11 to 17 years after the fire (Rawes & Hobbs 1979). In Sutherland and, to a lesser extent, in Caithness, the place of *Eriophorum vaginatum* is largely taken by *Trichophorum cespitosum,* whilst the dwarf shrub sward is a more open and mixed type than that typical of the Pennines. The fire succession is analogous in northern Scotland, in that *Trichophorum* tends to rise to dominance at the expense of dwarf shrubs. In the west, where *Molinia caerulea* is often the codominant with *Calluna* on shallow peats or peaty gleys, burning also promotes its ascendancy by altering the competitive balance with *Calluna.* Grazing, combined with fire, favours the monocotyledons at the expense of the dwarf shrubs.

Clymo & Duckett (1986) have established that *Sphagnum* regrowth can occur from stem fragments some 10-20 cm below the peat surface. If a fire were to burn into the *Sphagnum* carpet to below this depth, regeneration would be unlikely. The rate of regeneration on Glasson Moss NNR, Cumbria, which suffered a disastrous fire in 1976 (Lindsay 1977), indicates that eight years or so are required for significant numbers of new *Sphagnum* shoots to appear and only after 10 years are sensitive species such as *Sphagnum pulchrum* able to show significant signs of recovery (NCC unpublished data). It seems likely that a fire interval of at least 20 years would be required for the site even to hold its own as a *Sphagnum-rich* peatland, while recovery of the features typical of an intact mire surface would take much longer. A few hummocks of *S, imbricatum* were present on Glasson Moss in 1956 but now seem to have disappeared, and *S, fuscum* was much reduced in abundance in 1987.

The behaviour of fire within peat is reviewed by Wein (1983), who states that peat will ignite at a moisture content of 20-30% and temperature of 270-280°C. However, after five minutes' heating at 50-60°C, he found that lethal temperatures for most plant propagules were experienced up to 5 cm into the peat, whilst under drier conditions the peat ignited and lethal temperatures reached a depth of 12 cm. He points out that, after fire, the ground became drier because the fire-front had caused evaporation and irreversible drying-out of peat which had not ignited but experienced high temperatures. Lethal temperatures were thus more easily reached and penetrated further in the event of a second fire over the same area. Maltby (1980) describes the slow regeneration of vegetation on the North Yorkshire Moors, where severe fire in the 1976 drought killed large numbers of seeds within the peat by heating them above their lethal temperature.

Rowe (1983) considers the range of strategies adopted by different plants to fire and describes four basic types -

- resisters, such *as Eriophorum vaginatum,* which can actually tolerate and survive fire; there are few examples of this strategy in Britain;

- endurers, such as *Arctostaphylos uva-ursi* and *Empetrum nigrum,* which regenerate from below-ground organs;

- evaders, which are species able to set seed in the peat and germinate after fire;

- avoiders, such as *Hylocomium splendens,* which are species which cannot tolerate fire in any form and rely on long fire cycles to allow reinvasion and recovery from populations surviving elsewhere.

All but the first of these strategies fail, however, when fire gets into the peat. When this happens, the fire can burn for a few days to several months (even years in some documented cases from the U.S.S.R.: see MacLean *et al.* 1983, p. 84). The constantly humid climate of Caithness and Sutherland means that fires of such extreme duration are not likely, but even a fire of a day or so under the wrong conditions can reduce an extensive area of former grazing to a state of relative species-poverty and expose the unstable bare surface to the highly erosive action of heavy rainfall.

Where burning has been severe but the peat has not suffered a long, smouldering fire, the surface layers tend to be reduced to a state of almost complete humification, which is recognised by its gelatinous, rubbery texture (Hobbs 1986). McVean & Lockie (1969) point out the difficulty experienced by higher plants in becoming established in such a layer, where the water is either bound too tightly to the peat to be usable by the plants or forms a surface gel of such high water content that the roots suffer anaerobic waterlogging. The development of an algal skin on the peat surface also promotes surface water run-off.

In such circumstances, colonisation is generally by deeper-rooted species such as *Eriophorum angustifolium* or species which can grow on the waterlogged surface. In the west, the high mineral content of rainwater appears to encourage algae such as *Zygogonium* to colonise such areas before other species, thereby rendering further colonisation very difficult. A similar phenomenon is described by Boatman & Tomlinson (1973) for western bog pools, where algae out-compete aquatic *Sphagna.* However, where *Zygogonium* does not become the dominant immediately, the commonest species is *Sphagnum tenellum,* which appears to act as a form of 'scar-tissue' on such surfaces. It is common on wet, burnt surfaces from Dartmoor to Shetland, but it is found at its most abundant on heaths where wet bare peat is common or on areas of formerly dry bog where the water table is slowly returning to a position near the peat surface. Thus it has become extremely common on Roudsea Woods and Mosses NNR in Cumbria since a series of dams was installed across several old drainage ditches. In time, this *S. tenellum* sward will generally give way to a mixed carpet of *Sphagnum* species, as observed, for example, on Cors Fochno in Wales (Dr A D Fox pers. comm.).

In Caithness and Sutherland *Sphagnum tenellum* is most frequently found in the "microbroken" complex (see Chapter 10, Community 23), forming a mixed mat with *S. cuspidatum* over a wet, bare peat surface. This might in time be expected to reduce the rate of water flow through the erosion channels, thereby also reducing the risk of rain-scouring, and eventually to form the basis of a regeneration complex (see later section on erosion). Its ability to act as an agent of recovery after fire appears to be limited in eastern parts of the two districts, whereas in the west it regularly forms an association with *Campylopus atrovirens* and mat-like *Racomitrium lanuginosum* over wet bare peat. *Sphagnum compactum* often behaves similarly and is a characteristic species of the shallow peat of wet heaths in many areas.

Rowe (1983) points out that some of the severest fires recorded in the boreal forests had little effect because the ground was either wet or frozen, and Allen (1964) states that areas of *Sphagnum* are only exceptionally affected by fire because the genus is generally only dominant over areas which are permanently wet. In natural circumstances the fire frequency for any particular area of peatland ecosystem in Nova Scotia and Maine is of the order of once in every 400 to 500 years, and the major initiator is lightning, usually between the months of May and September (Wein & MacLean 1983).

On the other hand, Wein (1983) states that the frequency of deep-burning fires increases when the ground is drained, and, as raised mires in the Solway region have dried out during recent decades, so they have become ever more prone to damaging fires. Although in a completely natural system the fire frequency may be extremely low, widespread use of moor-gripping and the repeated action of man-induced fires on the margins of peatland sites render many of the Caithness and Sutherland peatlands more prone to fire damage than in former times. This is reflected in the abundant evidence of recent burning found during our survey (see Figure 23).

## Grazing and manuring

Blanket bogs are characterised by low primary (plant) production and the low nutritive quality of their vegetation (Heal and Smith 1978). While they thus have low carrying capacity for large herbivores, most British blanket bogs form part of the grazing range for sheep and/or red deer or are used as grouse moor. Burning regimes usually form part of the management for these animals. Grazing is mostly of a low intensity, except where blanket bogs are associated with substantial areas of high-quality grazing land, which may create a spill-over effect.

The impact of grazing *per se* on blanket bog vegetation is not well known. Its obvious effects, in combining with fire to favour the competitive balance of plants such *as Eriophorum, Trichophorum* and *Molinia* against dwarf shrubs, have been noted. Grazing must, though its extractive effect, help to maintain nutrient poverty and high acidity in the vegetation and the surface layer of peat. Except where animals may transfer nutrients from adjoining more fertile ground, the effect of dung and urine is probably one of localised enrichment which, over a long period of time, averages out as a pattern of recycling rather than addition. Several coprophilous mosses (e.g. *Splachnum* spp. and *Tetraplodon mnioides)* are characteristic of dung and other animal remains on blanket bog.

Conspicuous green flushes of vegetation often occur in pools and spongy hollows where sheep or deer have drowned and their decomposed remains have produced nutrient enrichment. Some blanket bogs which have had long-established and large colonies of breeding gulls have been subjected to substantial enrichment by calcium, nitrogen and phosphorus, but it is not known whether former gull colonies on some of the Caithness flows produced measurable effects of this kind. Individual tall bog hummocks are often used as favourite perches by peatland birds and defecation sites for foxes, and the associated nutrient enrichment may modify the hummock community (T3). White-fronted and greylag geese are selective grazers on *Rhynchospora alba* and *Eriophorum* spp., but their long-term effects on these species are unknown.

Conspicuous sheep and deer tracks across many bogs point to the influence of trampling when this is highly concentrated, and the possible effect of this factor in initiating peat erosion is noted below. Nevertheless, over most of a blanket bog surface trampling is usually light and unlikely to have marked effects.

## Erosion

Peatland ecologists have long debated whether the phenomenon of blanket bog erosion, so widespread in the British and Irish uplands, is a natural condition or one initiated by human activity of some kind. The high-level plateaux are most affected by erosion, a general feature of high-level blanket bogs in Britain noted by Tansley (1939), Bower (1962), Tallis (1964b, 1981), McVean & Lockie (1969), Taylor (1983), Bowler & Bradshaw (1985) and many others. Peat erosion is extensive in Caithness and Sutherland, and Figure 24 shows that more than half the sites examined during the survey contained erosion and that of these just over a quarter were severely eroded. The phenomenon is widespread, but not evenly so.

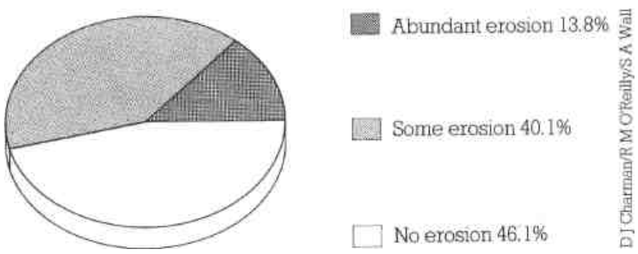


**Figure 24** Proportion of sites in the NCC's Peatland Survey of Caithness and Sutherland affected by various intensities of erosion.

It is clear in some instances that adverse management can initiate peat erosion and that, once begun, such degradation may be beyond the control of land managers. One of the most dramatic effects of burning is its ability to reduce a formerly *Sphagnum-rich* mire to a maze of deep erosion gullies. Excessive drainage has also proved to be a major cause of erosion in parts of Sutherland. This does not necessarily mean that erosion is always man-induced; sometimes it may be a natural end consequence of bog development, but which influence is predominant in any one locality is often unclear.

There are much wider understanding and agreement on the subsequent agents of erosion than on the initiatory causal factors. The role of wind, desiccation, frost and rain have long been identified as key elements in the erosion process (Geikie 1866; Moss 1913; Osvald 1949; Bower 1962).

Tallis (1981) records rates of erosion from the blanket peats of the Peak District of between 10 and 25 mm per year. Perhaps the most dramatic descriptive and pictorial evidence of the role played by heavy rain in the erosion sequence is the account given by Hulme & Blyth (1985) for an area of Shetland blanket bog. After a month of dry weather, they noted that erosion gullies had been baked into a 'mud-crack' pattern of polygonal flakes varying from 10-200 mm in diameter and 1-20 mm in thickness. At the onset of heavy rain the erosion channels rapidly filled with running water. The majority of the peat flakes were lifted from the peat surface by this water and washed away downslope through the erosion complex. Within one hour, most of such dislodged peat had entered main stream-courses. Hulme & Blyth (1985) recorded that up to 20 mm thickness of peat can be lost thus in a single storm. They also highlight the importance of this mud-crack and outwash process in exposing bare peat which is normally relatively protected from rain-scouring by algal mats.

Bower's (1962) classic account of peat erosion reviews a range of erosion types and suggests a series of possible causes, these being fire damage, climatic change, inherent hydrological instability and atmospheric pollution. Crampton (1911) favoured climatic change towards drier conditions as an explanation for many apparently moribund mire systems in Caithness, but there is no supporting meteorological evidence and Bowler & Bradshaw (1985) demonstrate that peat development in the Wicklow Mountains of Ireland is as vigorous as ever, even in areas of intense erosion. Taylor (1983) reviews a range of evidence gathered since Bower's original investigations and concludes that the process of headward erosion of watercourses is probably a major cause of erosion complexes, linked to the vulnerable topographic location of many blanket bog units. However, he considers that biotic factors such as burning, grazing and atmospheric pollution are probably important in initiating erosion in certain localities.

A probable example of burning-induced erosion can be seen near the western shore of Loch Rimsdale in central Sutherland. A well-patterned area of mire, rich in *Sphagnum* hollows and with no evidence of erosion, can be identified on the RAF's 1948 aerial photographs. The site was visited during 1980, after extensive spring fires, and the system was found to be completely surrounded by badly burnt peat, with the pools system itself almost totally destroyed. Most ridges had been broken down to little more than low hags, and the pools were reduced to an erosion network of gullies. Whilst no proof can be provided to show that burning caused this breakdown, it seems the most likely factor in view of the rapid change since 1948 and the abundant evidence of fire damage within and around the site.

Burning is also recognised as a major initiator of erosion in the Peak District, where problems of peat erosion are extreme (Phillips 1981; Tallis 1981). Crampton (1911) and McVean & Lockie (1969) highlight the particular problems of fire in habitats and localities where growth is slow or the growing season short, such as the higher plateaux and wet blanket bog, the latter authors attributing much of the widespread blanket peat erosion on upland plateaux in Britain to this factor.

The increased level of erosion in the west (see Chapter 12) may also be related to the lack of atmospheric nitrogen- and phosphorus-rich particulate matter in such regions, as discussed in Chapter 1 (Groenendael *et al.* 1975). Repeated burning on an area may need to be on a much longer time-cycle in the west in order to allow a longer period of nitrogen and phosphorus accumulation. If insufficient time is given for this recovery between fires, the nutrient leaching possible in areas of such heavy rainfall and the consequently poor plant vigour and vegetation renewal may lead to breakdown and erosion in the event of another fire.

Yalden (1981) describes how preferential sheep-grazing at the edges of bare peat expanses can increase the area of the exposed peat and points out that the sharp hooves of a sheep exert twice the pressure of a human. In view of the results described by Slater & Agnew (1977) for the effect of trampling on *Sphagnum,* it appears that trampling pressure from grazing animals could on occasion be a contributory factor to erosion, by acting as the catalyst to its onset. Perhaps most significant is Dr M W Holdgate's (unpublished) observation that the only areas of significant peatland erosion that he noted in the islands of Tierra del Fuego were associated with the world's most southerly sheep farm.

During our survey, evidence was found in many areas or ground severely trampled by red deer. On the basis of observed damage resulting from the single passage of 20 or so deer across a previously surveyed area, it is clear that the regular passage of even small numbers across areas of patterned bog could induce breakdown of ridges and subsequent erosion. The extensive erosion encountered in the mires around Ben Armine may be partly due to the large numbers of deer which use this area, though the problem appears to be exacerbated by widespread burning. This effect of trampling is particularly important when the movements of animals are restricted. Mire systems which are adjacent to natural barriers such the steep eastern face of Ben Armine or artificial barriers such as forestry fences will inevitably be more prone to erosion by trampling than sites in a more open position.

Two forms of hydrological instability which explain some examples of erosion have been well documented. The first of these is the "bog-burst" and the second the features known as "sink-holes" or "swallow-holes". John Leland in his itinerary of about 1535-43 describes the great bog-burst of Chat Moss in Lancashire (Smith 1910, pp. 42-43), when this large raised bog suddenly turned liquid and literally spilled out over the surrounding countryside, causing widespread damage and some deaths. Chunks of peat washed down the River Glazebrook were even reported to have reached the shores of Ireland. Since Leland's time a number of similar occurrences have been documented, and the evidence for such events can be seen today on aerial photographs. It seems almost certain, for example, from the jumbled nature of its surface patterns and the almost floating nature of the surface, that the small bog beside the road at the southeastern tip of Loch Meadie, Altnaharra, has suffered a bog-burst.

In normal circumstances, the cation exchange ability of peat retains the bog in a coherent mass, despite the fact that the water content may exceed the liquid limit of the structure (see Chapter 1 and Hobbs 1986). In effect, the bog is a liquid mound held together by strong attractive forces in the peat. A bog-burst appears to occur when these forces are exceeded, as may occur with exceptionally heavy rainfall or if the integrity of the peat matrix is altered in some way (Hobbs 1986). Areas of quaking mire could be expected to be prone to the phenomenon if disturbed, yet the available evidence suggests that bog-bursts have always been rather unusual and chance events. The small example at Altnaharra is therefore particularly interesting,

On a small scale, as at Altnaharra, the process appears not to have induced more widespread damage and erosion, but, as Taylor (1983) points out, many mires are highly prone to such instability by their topographic position. Bog-bursts or peat slides from large upland plateaux could be expected to result in widespread erosion. In fact evidence of such erosion is hard to find, and it appears that the steady headward erosion of streams is the more usual cause of erosion in such locations. Landslips after heavy rain, where relatively steep slopes (often with soligenous mires or sometimes where drainage has broken the root mat) become over-charged with water and suddenly slump away, are much more common. They are usually quite small, but in 1983 such landslips cut back into the edge of the plateau blanket bog on Pennygant Hill, in the central Southern Uplands of Scotland, and resulted in substantial erosion of both mineral soil and peat over an area of several hectares.

A rather different type of erosion is described by Crampton (1911), whereby certain pools amongst the normal *dubh lochain* appeared to be linked to underground 'pipes' in the peat, often causing the affected pool and those in the immediate vicinity to drain away. This peat-piping and its associated sink-holes are currently the subject of investigation by the Institute of Hydrology and Dundee University. It is thought that two types of sink-hole exist, the first representing the last vestige of a watercourse which has been overwhelmed by peat growth and the second resulting from sub-surface erosion along natural lines of weakness at the peat base or within the peat, which then emerges as a sunken hole at the peat surface.

Evidence of the first type is possibly seen towards the northern part of Blar nam Faoileag, in Caithness, and at the foot of An Teallach in Wester Ross, where parts of the mineral terrain would clearly have supported a watercourse but the area is now swamped by peat. Along the line of the ancient watercourse a series of sink-holes can be seen which appear to have developed in harmony with the peat cover rather than as erosion features which have developed after peat formation.

However, evidence of the second type is far more abundant, particularly on high-level plateaux and intensely dissected sites. Here the hydrological stability of the pool system appears to be genuinely disrupted by sink-hole formation. Indeed it is possible to create a sink-hole. Dr D A Goode (pers. comm.) found that a pool on Knockfin Heights which had been sampled with a soil auger the previous day was completely empty 24 hours later, the water apparently having drained away down the auger hole. Such a phenomenon reveals just how sensitive parts of the system can be to either natural or artificial breaching of their hydrological integrity.

It thus seems that erosion may sometimes be a natural process, either representing the final stage in bog development or forming part of a long-term cycle of erosion and regeneration. Bowler & Bradshaw (1985) found evidence of rapid regeneration within peat erosion in the Wicklow Mountains, and there is considerable evidence on Moor House and elsewhere in the Pennines and in the Migneint in North Wales of regenerative phases in certain locations.

The fact that erosion appears to be a natural part of peatland development and hydrology, at least in some instances, requires that representative examples of the full range of erosion types should be conserved. They form an important part of studies on catchment hydrology, environmental monitoring and peatland ecosystem dynamics, and, in situations where peat erosion is man-induced, it is important to understand the details of the process for the possible insights that this may yield for improved moorland management practices.

## Acid deposition

An important contributory factor to erosion identified in the Peak District and elsewhere in the Pennines is the impact of acid deposition on blanket bog vegetation, particularly *Sphagnum* species. Although bog systems are naturally acidic (Clymo 1983), this acidity is derived from organic rather than mineral acids. A substantial volume of evidence has now been published exploring the relationships between acid deposition, *Sphagnum* vigour and acidification of waters (e.g. Press & Lee 1982; Press, Ferguson & Lee 1983; Battarbee, Flower, Stevenson & Rippey 1985).

Early accounts of conditions on the Pennines at the turn of the century describe enormous quantities of soot falling on the vegetation from factory chimneys located down on the Lancashire Plain. Conway (1949) noted that the average figure in 1948 for Dore and Ewden, near Sheffield, was about 0.4 g per $m^2$ per month. However, such events were not restricted to the Pennines, and records exist of "black ram" falling in Scotland during 1862 and 1863. Brimblecombe, Da vies & Tranter (1986) suggest that these deposits probably came from locations many hundreds of kilometres from the sites of deposition, and they point to more recent records of "black rain" in the Cairngorms area which also appear to be derived from distant sources.

Tallis (1964c) records the decline and extinction of some *Sphagnum* species in the Pennine blanket bogs since the description by Moss (1913), establishing, amongst other things, that the once-abundant *Sphagnum imbricatum* has completely vanished from the southern Pennines during the last 150 years. The most common species in the modern vegetation recorded by Tallis was *Sphagnum recurvum,* which is a species of high sulphate tolerance (Ferguson, Lee & Bell 1978; Smart 1983). Although Tallis recognises that climatic change may be the cause, he points to the correlation between the Industrial Revolution and the beginning of *Sphagnum* decline.

Ferguson *et al* (1978) consider the loss of *Sphagnum* in such blanket bog areas to be the outstanding vegetation change in Britain attributable to atmospheric pollution. Work at Manchester University and Abisko Field Station in Sweden has concentrated on the physiological mechanisms behind such effects and has revealed that *Sphagnum* species are sensitive to increased levels of sulphate and bisulphite (Ferguson *et al.* 1978; Lee, Press, Woodin & Ferguson 1986). However, the most marked effects of acid deposition appear not to be related directly to the sulphur content and associated acidity, but instead to levels of deposited nitrate (Woodin 1986).

Woodin (1986) has established that, in unpolluted conditions, *Sphagnum fuscum* rapidly assimilates all nitrate deposited during precipitation. Ammonium is also readily assimilated, despite the fact that *Sphagnum* species possess only a single ammonium assimilation pathway (Meade 1984). Higher plants occasionally rely on other strategies for their scource of nitrogen (e.g. the insectivorous sundews *Drosera* spp.), but most depend on subsequent remineralisation of nitrogen within the peat. Thus the bulk of nitrate deposition, whether natural or as a pollutant, tends to have its primary effect on the *Sphagnum* layer rather than the higher plant cover (Woodin 1986).

Woodin has established that nitrate levels above the optimum cause an uncoupling of nitrate reductase activity, which leads to increased concentrations of nitrogen in the tissues, a reduced ability to immobilise the inorganic nitrogen supply and reduced growth, though without any outward sign of damage. She points out that the resulting increased availability of nitrogen in a system where normally only ammonium is in ready supply may have widespread effects on the higher plant cover.

Measures of acid deposition in northern Britain suggest that levels are low (Fry & Cooke 1984), but the peatlands of Caithness and Sutherland are considered by Woodin (pers. comm.) to be prime "acid deposition sensitive" ecosystems, because they have-

- a non-calcareous, highly resistant bedrock;
- acid soils with low buffering capacity;
- water bodies (dubh lochans) with low alkalinities;
- a short growing season;
- a solute supply of largely atmospheric origin;
- high altitude (in places);
- high precipitation, including considerable occult (mist and fog) deposition (Tomlinson, Brouzes, McLean & Kadlecek 1980; Grant & Lewis 1982; Klmg & Grant 1984; Gorham, Bayley & Schindler 1984).

The last factor, that of occult deposition, is particularly significant because it has been shown to expose vegetation to much higher concentrations of solutes than those measured in rainfall (Skeffington & Roberts 1985). Mrose (1966) states that coastal fog in Germany has a lower pH and solute concentrations six to ten times higher than those measured in rain. Moreover, Woodin (1986) has demonstrated that the physiological response of *Sphagnum* to simulated occult nitrate deposition is much greater than its response to similar amounts of nitrate in rain.

The implications for Caithness and Sutherland are clear. Whilst it is most unlikely that concentrations of pollutants ever reach lethal concentrations in the region, the increased cumulative stress imposed by even occasional acid rain events is likely to render the vegetation less resilient to burning and drainage. Recovery times are likely to be longer, and particularly so on the higher plateaux, where the cumulative effects of regular, if very low volume, occult deposition are liable to give rise to a particularly sensitive vegetation cover. Failure to recognise this sensitivity, coupled with too frequent and poorly controlled burning, may have combined with the slow regenerative powers of western and upland mires to produce the widespread erosion found today in the region.

Erosion is a widespread feature of western mires in Ireland, where acid deposition is low. Osvald (1949) describes many erosion features similar to those in north-west Scotland, and Bowler & Bradshaw (1985) explore the possibility that erosion in the Wicklow Mountains is a product of reduced peat growth or acid deposition. They establish that peat regrowth is currently as rapid as the fastest recorded rates for the Pennines over the last 5000 years and also that acid deposition products are at sufficiently low levels to make it unlikely that erosion is a product of atmospheric pollution. Bowler & Bradshaw's evidence from Ireland gives no information about the regularity of burning or intensity of sheep-grazing, and the authors offer no alternative cause for erosion to their original hypotheses of reduced peat growth and atmospheric pollution.

# 6 Forest history

The degree to which the area of the Caithness and Sutherland peatlands was once forest-covered and the reasons for its present treelessness have become matters of some interest. The evidence for Post-glacial (Flandrian) spread of forest across Britain has been documented by Godwin (1975), and various studies have gradually filled in the picture for Scotland. In many parts of the British uplands, there is direct visual evidence, from tree remains buried in the peat, that ground now occupied by treeless blanket bog was once covered by forest, at least in part. Ecologists have been concerned to understand how and when this transformation in vegetational character occurred.

## The original extent of forest

Whilst the evidence from tree remains points to the former extensive occurrence of forest in northern Scotland, recent work suggests that this was by no means continuous, even within the altitudinal limits for tree growth (c. 300-400 m at present, but probably higher at the Climatic Optimum). The widespread occurrence of Scots pine *Pinus sylvestris* stumps in Sutherland blanket bogs suggest that pinewoods were once fairly extensive in this District (i.e. during the Boreal period and probably much later). Many of the remains indicate small-sized trees, suggesting that Scots pine was here approaching its natural climatic limit. The scarcity of even fragments of surviving pinewood amongst the very patchy present-day native woodlands of Caithness and Sutherland led McVean & Ratcliffe (1962) to suggest that, during the period of the last 2500 years, the predominant forest type of the region has been of birch *Betula pubescens*, with rowan *Sorbus aucuparia*, hazel *Corylus avellana*, willow *Salix* spp. and alder *Alnus glutinosa.* Durno (1958) reported pollen analyses from five peatland sites within central Sutherland and Caithness. The absence of data for absolute pollen frequency makes it impossible to gauge the extent of tree cover at any site, but the consistent average excess of birch pollen over pine pollen at each site suggests that birch has been the more important forest species throughout the region during the whole Flandrian period.

Moar (1969a, b) examined two sites in Orkney and one in the extreme north-west of Sutherland (Scourie) for evidence of past tree cover. In Scourie he found a high percentage of arboreal pollen consisting of birch as the forest dominant, together with pine and mixed oak forest, all of which showed a marked decline but not until the Sub-boreal. He concluded that the forest cover was extensive in west Sutherland until quite recent Post-glacial times. On Orkney, by contrast, the pollen data suggest that tree cover was never extensive during Flandrian times and that birch and hazel scrub in sheltered spots was the main woodland type.

Peglar (1979) describes a pollen diagram taken from the Loch of Winless in central Caithness. She deduces from the results, which show very little arboreal pollen throughout the profile, that the area has a similar forest history to Orkney (Moar 1969) and Shetland (Johansen 1975; Birnie 1984), namely that there is no evidence of significant forest cover in the Flandrian. She concludes that the area, which currently borders one of the largest expanses of low-lying flow land in the Caithness-Sutherland Plain, was "probably the least forested area of mainland Britain throughout the Flandrian".

Peglar's findings are confirmed by the direct visual evidence from peat profiles exposed down to the underlying mineral soil along new forest roads cut in the flows of the Thurso River catchment: over long distances there are no traces of tree remains, indicating absence of Post-glacial forest cover. Occasional remains of pine and birch are to be found in more favourable situations close to streams, where there was probably more shelter and fertile soil. This contrasts with the situation, farther west, where pine and birch remains are often plentiful in newly exposed peat faces. The reasons for this earlier lack of woodland cover in central Caithness are not yet understood. The earlier scarcity of woodland cover in Orkney, Shetland and the Outer Hebrides has been assumed to result from climatic severity, including the wetness, high winds and lack of summer warmth associated with extreme oceanicity.

## Forest decline and the development of blanket bog

As far back as the time of Leland in 1538-43 (e.g. Smith 1910, pp. 16-17), writers have commented on the presence of tree stumps within or beneath areas of deep peat. The massive 'bog oaks' which have been unearthed from drying peat in the Fenland and many other records of woody deposits at the base of raised bog profiles led Tansley (1939) to construct one of the classic sequences of raised mire development, involving the development of carr and oak woodland over terrestrialised basins and then subsequent swamping of this woodland by the rising water table and renewal of bog growth at the onset of the warm but wet Atlantic period (7500 BP).

Geikie (1866) and Lewis (1905, 1906, 1907) describe many examples of tree remains within Scottish peats, the former citing a number of cases where he considers buried tree-stumps to represent forest swamped by peat development. He suggests that this came about when Britain became separated from the continental land mass and thus lost its continental climate. Geikie noticed that in Scottish bogs there were often two distinct tree layers, one on the underlying mineral substratum and the other about halfway up the peat profile, and he called these the Lower and Upper Forestian Layers. The clear implication was that, after a phase of active bog growth with no forest, conditions again favoured the spread of trees across the drying bog surface, but that a further increase in wetness then suppressed the forest in favour of bog. In Scandinavia, Blytt (1876) and Sernander (1908, 1910) later interpreted basal and upper tree layers in bogs as evidence of cyclical climatic change - dry Boreal, wet Atlantic, dry Sub-boreal, wet Sub-atlantic (see Godwin 1975). It was tempting to apply this interpretation to the British situation, but the ecological evidence has proved to be a good deal more complex.

Lewis (1910) describes extensive birch remains at the base of the peat in Caithness and Sutherland and, though stating that his "upper forest zone" with *Pinus sylvestris* is present in Caithness and Sutherland, gives no evidence for this. He remarks that some of the "upper forest zone" records for the area are represented by *Betula alba* L.(i.e. *B. pendula)* rather than *Pinus sylvestris* and that the zone is in fact absent except in the area towards Morven and Ben Alisky. Crampton (1911), in his account of the Post-glacial succession of Caithness (pp. 13-16), draws on Lewis's (1910) proposed sequence of events to describe a landscape at first covered by birch *taiga,* then its gradual paludification as the climate ameliorated. He proposes an interruption to this peat growth due to a period of drier climate, leading to the expansion of pine over many of the bogs. The subsequent loss of this woodland he takes to be the result of climatic change.

The occurrence of tree remains, mainly of Scots pine and birch, at the base of blanket bog peat is fairly general across Scotland. Their frequent association with charcoal remains has led some ecologists to speculate that the forest was not overwhelmed by the natural, climatically generated growth of bog, but that its disappearance was the result of human land-use, which paved the way for soil acidification and peat accumulation. Moreover, while many of the deeper blanket bogs began to form around the onset of the Atlantic period, there is a wide range of date of origin, spanning several thousand years, and this militates against the hypothesis of control by cycles of climatic wetness and dryness. Evidence has accumulated to suggest that initiation of blanket bog is a result of Neolithic, Mesolithic or Bronze Age forest clearance (Conway 1954; Simmons 1963; Tallis 1964a, 1975; Smith 1970; Birks 1970, 1972; Moore 1973a; Simmons & Cundill 1974; Moore & Wilmott 1979). Much of this evidence, however, concerns peats from England or Wales. Further north, in Orkney, Keatinge & Dickson (1979) attribute a decline in tree pollen around 5000 BP to increasing windspeeds and a deteriorating climate, although they consider that agriculture contributed in later stages to the decline of woodland cover.

Birks (1975) has studied the distribution and age of pine stumps in Scottish bogs and found that basal remains are of widely varying age (7400-2000 BP). There are also wide variations in the presence, abundance, vertical distribution and age of pine remains at levels above the basal peat. Birks identifies two distinct time patterns. Pine stumps in the north-west of Scotland all appear to date from 4500 BP to 4000 BP, whilst those from the south and east of Scotland show a much wider range of ages, from 7000 BP to 2000 BP. She speculates that the synchronism of the north-west pine stumps indicates climatic change, concurring with Pennington (1974) that such relatively sudden and comprehensive loss of tree cover is more likely to be a natural response to climate than due to man's influence, whilst loss of tree cover farther south and east in Scotland requires additional explanation.

Pears (1975), in attempting to establish the original tree-line for Boreal forests, gives a wide range of dates for supposedly concurrent Post-glacial events, but points out that local topography and slope geometry can play a major role in buffering individual areas from overall climatic trends for extended periods of time. On this basis, he finds his results in close agreement with those of Birks (1975). Onset of blanket bog formation can thus still be climatically determined, even when spread over thousands of years.

Paludification can be a continuing and observable process. George, Earl of Cromertie, (1711) is one of the earliest authors to record an apparent sequence similar to Tansley's (1939), but for blanket bog. He describes the overwhelming of a pinewood in the "Parish of Lochbrun" by a developing moss within the space of 15 years. The trees were old and dying when he first encountered them and, by the time of his second visit, had apparently been blown over by strong winds, to be absorbed into the growing moss, which itself subsequently proved to be a good source of peat fuel.

While it is far from clear that all blanket bog in Britain is a climatic phenomenon alone, even such workers as Dr P D Moore (1968, 1973a, 1984), who have studied blanket bog origins for many years, remain equivocal about man's role. There are undoubtedly remains of charcoal at the bottom of many blanket bog deposits (Tallis 1975), but it is not yet possible to distinguish fires started by Neolithic or Mesolithic man from those arising through natural catastrophes such as lightning fires (a major source of fire in northern boreal ecosystems: Wein & MacLean 1983). If it is proposed that the blanket bogs of Britain and Ireland are anthropogenic, rather than a product of the climate, it must also be explained how other areas of treeless blanket mire around the world have come about and why the origins of British-Irish blanket bog should be different.

Perhaps it is best to regard the process of bog initiation as resulting from both factors, climatic wetness and human impact, with the balance of their influence varying geographically and possibly also in time. What cannot be disputed is that the oceanic climate of Britain and Ireland has played a major role in generating a landscape type which is now regarded in other countries around the world as characteristic of cool, oceanic areas and for which Scotland and Ireland are generally considered to be the 'type' locations. Such a landscape is entirely restricted in other parts of the globe to regions which have the same climatic pattern, whether there is a history of human activity or not.

## Present lack of forest cover as a natural condition

Regardless of whether human forest clearance sometimes preceded blanket bog initiation, it is inescapable that the subsequent scale of this bog development in Britain could only have occurred under a climate strongly favourable for ombrotrophic peat growth. In addition, trees cannot persist or establish themselves under the extreme conditions of waterlogging and *Sphagnum* dominance which have characterised so many of the main flow areas, often for thousands of years. Birks (1975) has reviewed the physiology of Scots pine and points out that it can be killed by a single wet season. She concludes that most British blanket bogs are unsuitable for pine establishment and growth without artificial ground treatment.

In the boreal forest zone of Scandinavia and Canada there is abundant evidence of the natural relationship between tree cover and ombrotrophic mire development. Depending on the steepness of the gradient from dry ground to soaking *Sphagnum* surface, there is a variable transitional zone of increasingly depauperate trees at the bog-edge, ending with tiny, stunted individuals in 'check' scattered sparsely over the bog centre. On some of the larger mires, even this checked growth is confined to a peripheral zone. Where bog development is so extensive as to restrict development of seed-bearing trees over large areas, the possibilities for even such abortive colonisation are much less.

Zoltai & Pollett (1983) comment that the tree cover within the Atlantic Oceanic wetland region of Canada, which is characterised by extensive blanket bog, is restricted to stream-courses or sheltered depressions. They illustrate the region (p. 262) with a photograph showing a completely treeless landscape, yet the human impact on the area in prehistoric and historic times has been slight. Botch & Masing (1983) describe the West Kamchatka Province as dominated by blanket bog and quite treeless, even though one of the major types is a relatively dry *Cladonia*-dominated mire. Pisano (1983) illustrates both the expanses of *Sphagnum magellanicum* bog and the cushion mires of Tierra del Fuego (pp. 314 and 319). In his caption to the photograph of the *Sphagnum magellanicum* mires, he notes the *Nothofagus betuloides-N. pumilo* forest limited strictly to the line of the watercourse, whilst the high-level *Donatia* cushion mires are attended by a scrubby development of *Nothofagus* on rocky outcrops. Dr M W Holdgate (unpublished) states that the area is perhaps no more than 10% wooded. The Norwegian blanket mire plateaux are unwooded, as are those of Iceland and the Faeroes. There are, nevertheless, some areas of blanket bog in other countries which have sparse or stunted growth of trees (see Chapter 3).

On the extensive flows of east Sutherland and Caithness, the record in the peat itself demonstrates irrefutably that a treeless blanket bog landscape, barely distinguishable from that of today, has existed for at least the past 4000 years. Many pool systems have demonstrably occupied the same positions, relatively unchanged, for a large part of this time. The remaining question is about the former extent of tree cover on the shallower peat of the bog edges and the wet heaths of steeper ground and on the mineral soils of dry slopes and stream-sides. Most probably there was a patchy growth of woodland in these better-drained situations. Its extent would have increased westwards and towards the coasts and main straths, as the bog areas became increasingly dissected or replaced by ground of different character, more suited to tree growth. This patchwork of woodland is, however, likely to have been far more restricted than the area covered by woodland which existed before the bogs began to form. The patchwork has been largely cleared by man, probably beginning mainly around 2100-2600 BP (Birks in press), and has been prevented from re-establishing itself by continuous grazing and repeated fires.

The conclusion is, therefore, that in the absence of man some parts of the Caithness and Sutherland peatlands would today have had more woodland cover (mainly of a *taiga* birchwood kind) than at present, but that other quite large areas would have been almost as treeless as they are today. Whatever its origins, the flow landscape is undoubtedly an ancient one. There are few places in Britain now where it is possible to look across a landscape and share much the same view as Neolithic man. Up to 1979, this was still possible over much of Caithness and east Sutherland.

## New afforestation

Afforested ground is quickly transformed from bog to forest. When the trees close to form thicket woodland at 10-15 years, the original vegetation is almost totally destroyed by the dense shade and litter fall. Observations on failed plantations of lodgepole pine killed by pine beauty moth infestation show that, after this short time under scrub, the peat has dried so much that the immediate changes are to a surface vegetation quite different from that of the original bog community. Vascular plants typical of drier ground become abundant (e.g. *Calluna, Trichophorum, Molinia, Eriophorum vaginatum),* evidently growing from buried seed, and often also the invasive rosebay willowherb *Chamaenerion angustifolium.* When the forests are cleared in the normal rotation, the best that can be hoped for is that a damp heath community of similar kind re-establishes itself, but this will only persist for a short while, since it is clearly intended to retain this land under forest indefinitely.

Whether a blanket bog community, with high *Sphagnum* cover, could ever regenerate is thus largely an academic question. The peat surface will continue to waste and contract downwards as described in Chapter 5. Cracking of the peat under the young trees is already widespread (Pyatt 1987), and such structural changes may become more marked with time. Possibly, if all the key points in the drainage system were blocked, water tables would begin to rise and conditions for recolonisation of *Sphagnum* might return, first in flooded drains. It could take a long time for an acrotelm to redevelop and active bog growth to be resumed more generally on a ploughed and deforested area, and, where patterned surfaces have been destroyed, some form of erosion would be more likely to result.

For all practical purposes, the planted ground ceases to be bog. It remains to consider the effects of afforestation on the ground not actually covered with trees - the enclaves of unplanted bog, the adjoining bogs outside the plantations, and the streams and lakes within the catchment containing forest. The linear systems of rides within the forest are far too narrow to represent the original peatland communities, for they inevitably dry out and become heavily modified, even though many of the original species may persist for a time (Ratcliffe 1986b).

## Effects of forestry on the vegetation of adjacent mire systems

It is only relatively recently that large-scale afforestation has been able to invade areas of prime peatland and that cultivation techniques have become available to plough deep, wet peat right up to the edge of pool systems. There are, accordingly, no forests in Caithness and Sutherland old enough to enable any critical judgement to be made about their effects on adjoining peatlands. However, in Northumberland and Galloway large forestry plantations already exist in close proximity to areas that were in the past considered as good examples of peatland systems, although they are very different from the flows of Sutherland and Caithness. So far the only detailed attempts to assess changes after afforestation have been in the large plantation area in west Northumberland generally referred to as Kielder Forest. This is an area of about 50,000 ha, of which almost 40,000 ha is planted with conifers. A small proportion of the remaining area is remnant blanket bog, too wet to afforest during the planting period. The assessments of changes in Kielder are from two sources.

Chapman & Rose (1986) repeated a 1958 survey of Coom Rigg Moss (Chapman 1964) to assess vegetation changes on this site up to 1986. At the time of the 1958 survey, afforestation had occurred on only one side of the site. Subsequently this National Nature Reserve was to become almost completely surrounded by conifer plantations, with some planting actually on the hydrological unit of the mire itself.

The original survey used a grid to locate sample areas, random quadrats being taken within these areas. Fixed-point photography allowed some direct comparison of the overall appearance of particular areas, but the small number of original photographs did not permit extensive use of this method.

At a community level, Chapman & Rose (1986) found that what had originally been a wet peatland vegetation had become, over the intervening years, a mosaic of community types dominated by either *Calluna vulgaris, Deschampsia flexuosa* or *Eriophorum vaginatum. Calluna* showed little overall change in abundance but had increased in some areas while decreasing in others. *Deschampsia flexuosa* showed an overall increase, this being concentrated in several patches at the edge of the site. *Eriophorum vaginatum* showed an overall decrease, but, in the areas over which it is now a dominant, it has taken on a dense tussocky form of growth, very different from its appearance in the mid-1950s. Other individual species were found to have suffered dramatic changes in their pattern of distribution or abundance. Some of the more important species changes are discussed below.

Perhaps the most striking change recorded was the apparent extinction during the intervening period of *Sphagnum imbricatum* and *Drosera anglica* , both species generally regarded as indicators of high-quality undamaged mire. More than 75 individual hummocks of *S. imbricatum* were identified and mapped in 1958, whereas, despite a thorough search, no such hummocks were recorded in 1986.

*Drosera anglica* is a species typical of pool margins and low ridge (T1/A1 transition: Figure 8). Chapman (1964) recorded a series of shallow pools dominated by *Sphagnum cuspidatum* in central and northern parts of the site. Chapman & Rose comment that these *Sphagnum cuspidatum* hollows could not be found in 1986 and that *Sphagnum cuspidatum* had all but vanished. A photograph taken in 1958 shows an example of such a hollow in the foreground, amongst a vegetation type which is typical of soft, wet mire. Chapman & Rose (1986) found neither the structure nor the vegetation type.

Amongst the bog 'constants' that have declined, *Drosera rotundifolia* shows perhaps the most dramatic change, diminishing from 55% frequency at the sample points to 4% - a relative decrease in its abundance of 90%. *Sphagnum magellanicum, S. papillosum, S. capillifolium, Odontoschisma sphagni* and *Narthecium ossifragum* have all declined by at least 35% in the intervening 38 years,

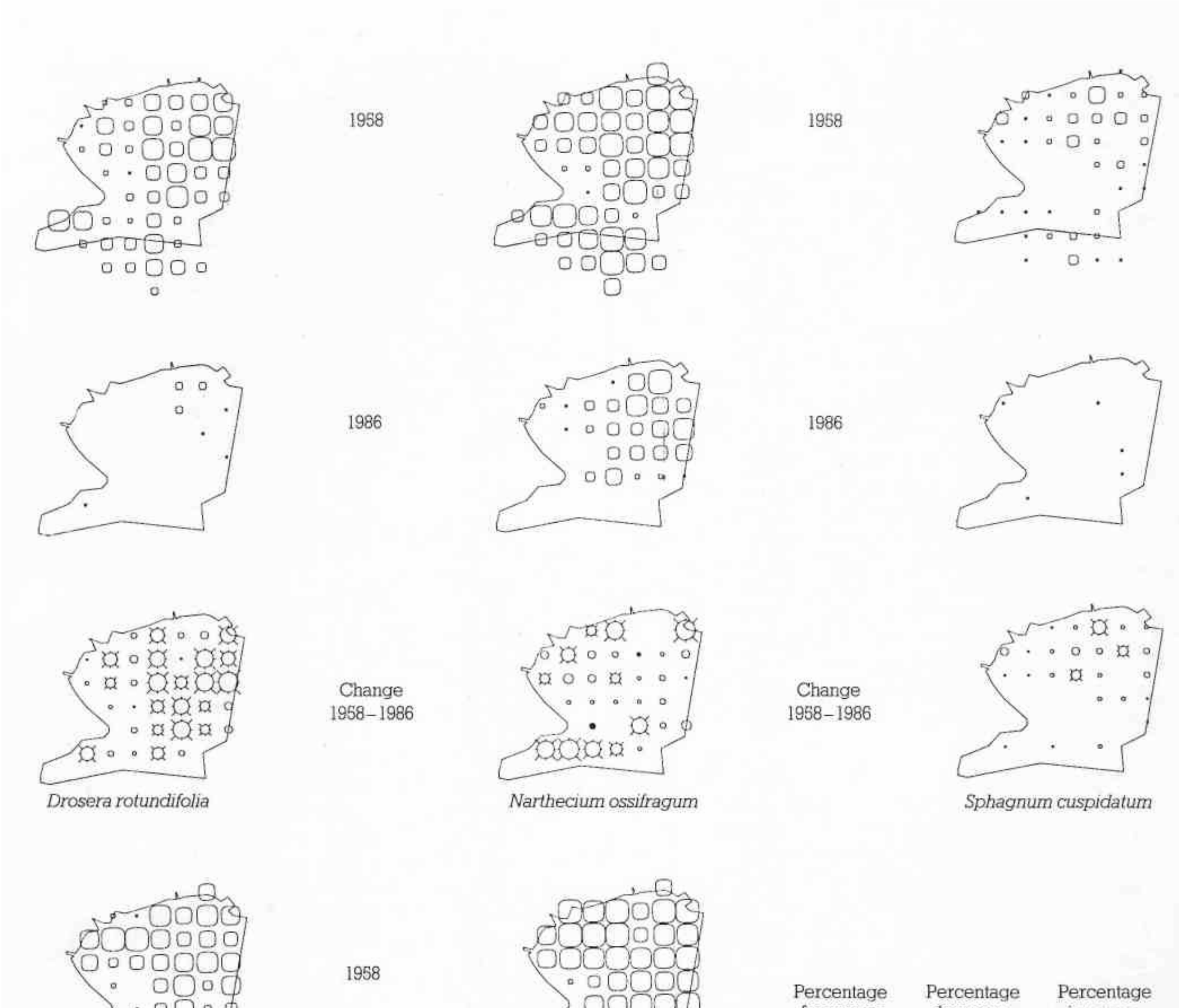


**Figure 25** Changes in species abundance on Coom Rigg Moss recorded for the period 1958-1986. (Taken from Chapman & Rose 1986.)

| Species | 1958 | 1986 | Relative change | Absolute change | Z | Number of significant squares |
|---|---|---|---|---|---|---|
| Drosera rotundifolia | 54.85 | 3.71 | -51.14 | 51.14 | 14.87 | 19 |
| Sphagnum magellanicum | 62.86 | 16.57 | -46.29 | 49.14 | 12.51 | 17 |
| Sphagnum papillosum | 85.43 | 37.43 | -48.00 | 48.57 | 13.05 | 16 |
| Sphagnum capillifolium | 62.23 | 22.00 | -40.29 | 44.29 | 10.79 | 16 |
| Odontoschisma sphagni | 46.86 | 12.00 | -34.86 | 40.00 | 10.12 | 16 |
| Narthecium ossifragum | 72.00 | 34.86 | -37.14 | 40.00 | 9.85 | 11 |
| Eriophorum vaginatum | 82.86 | 47.43 | -35.43 | 37.14 | 9.84 | 10 |
| Calluna vulgaris | 38.86 | 34.57 | -4.29 | 36.86 | 1.18 | 12 |
| Lepidozia setacea | 49.71 | 20.00 | -29.71 | 35.43 | 8.25 | 11 |
| Eriophorum angustifolium | 74.57 | 43.14 | -31.43 | 33.71 | 8.45 | 8 |
| Andromeda polifolia | 49.71 | 22.00 | -27.71 | 31.71 | 7.64 | 7 |
| Erica tetralix | 86.57 | 61.14 | -25.43 | 31.14 | 7.66 | 9 |
| Sphagnum tenellum | 54.57 | 32.00 | -22.57 | 29.43 | 6.03 | 4 |
| Calypogeia trichomanes | 35.14 | 8.86 | -26.29 | 26.86 | 8.39 | 6 |
| Trichophorum cespitosum | 50.29 | 37.43 | -12.86 | 26.00 | 3.43 | 2 |
| Mylia anomala | 34.00 | 43.43 | 9.43 | 25.43 | 2.56 | 5 |
| Vaccinium oxycoccos | 54.86 | 53.14 | -1.71 | 22.29 | 0.46 | 2 |
| Gymnocolea inflata | 22.00 | 6.57 | -15.43 | 20.00 | 5.83 | 3 |
| Deschampsia flexuosa | 2.00 | 17.43 | 15.43 | 18.29 | 6.89 | 7 |
| Sphagnum cuspidatum | 18.57 | 1.43 | -17.14 | 17.14 | 7.56 | 3 |
| Pleurozium schreberi | 2.29 | 15.14 | 12.86 | 15.14 | 6.03 | 4 |
| Cephalozia bicuspidata | 14.29 | 7.71 | -6.57 | 14.57 | 2.78 | 1 |
| Empetrum nigrum | 12.86 | 7.14 | -5.71 | 12.00 | 2.52 | 3 |
| Cephalozia connivens | 7.71 | 4.28 | -3.43 | 10.86 | 1.91 | 1 |
| Polytrichum commune | 6.29 | 12.00 | 5.71 | 9.71 | 2.62 | 0 |
| Calypogeia fissa | 5.14 | 4.29 | -0.86 | 8.29 | 0.54 | 0 |
| Aulacomnium palustre | 7.43 | 5.14 | -2.29 | 8.00 | 1.25 | 1 |
| Sphagnum recurvum | 6.29 | 4.29 | -2.00 | 7.14 | 1.18 | 2 |
| Molinia caerulea | 2.00 | 4.00 | 2.00 | 5.43 | 1.55 | 1 |
| Sphagnum subnitens | 1.71 | 4.00 | 2.29 | 4.57 | 1.82 | 0 |
| Polytrichum juniperinum | 3.14 | 2.86 | -0.29 | 4.29 | 0.22 | 0 |
| Rhytidiadelphus squarrosus | 0.57 | 3.71 | 3.14 | 3.71 | 2.87 | 1 |
| Hypnum cupressiforme | 0.86 | 2.86 | 1.43 | 3.14 | 1.52 | 0 |
| Cladonia uncialis | 3.14 | 0.00 | -3.14 | 3.14 | 3.34 | 0 |
| Cladonia impexa | 2.29 | 1.14 | -1.14 | 2.29 | 1.16 | 0 |
| Vaccinium myrtillus | 0.29 | 1.14 | 0.86 | 1.43 | 1.35 | 0 |
| Galium saxatile | 0.00 | 1.43 | 1.43 | 1.43 | 2.24 | 0 |
| Pohlia nutans | 0.29 | 0.86 | 0.57 | 1.14 | 1.00 | 0 |
| Carex panicea | 0.29 | 0.86 | 0.57 | 1.14 | 1.00 | 0 |
| Sphagnum palustre | 0.00 | 1.14 | 1.14 | 1.14 | 2.01 | 0 |
| Carex echinata | 1.14 | 0.00 | -1.14 | 1.14 | 2.01 | 0 |
| Plagiothecium undulatum | 0.00 | 0.86 | 0.86 | 0.86 | 1.74 | 0 |
| Juncus acutifolius | 0.29 | 0.29 | 0.00 | 0.57 | 0.00 | 0 |
| Campylopus flexuosus | 0.29 | 0.29 | 0.00 | 0.57 | 0.00 | 0 |
| Phragmites australis | 0.57 | 1.14 | 0.57 | 0.57 | 0.82 | 0 |
| Agrostis stolonifera | 0.29 | 0.29 | 0.00 | 0.57 | 0.00 | 0 |
| Zygonium ericetorum | 0.29 | 0.00 | -0.29 | 0.29 | 1.00 | 0 |
| Riccardia pinguis | 0.29 | 0.00 | -0.29 | 0.29 | 1.00 | 0 |
| Plagiothecium denticulatum | 0.29 | 0.00 | -0.29 | 0.29 | 1.00 | 0 |
| Dactylorhiza maculata | 0.00 | 0.29 | 0.29 | 0.29 | 1.00 | 0 |
| Pinus sylvestris | 0.00 | 0.29 | 0.29 | 0.29 | 1.00 | 0 |
| Nardus stricta | 0.00 | 0.29 | 0.29 | 0.29 | 1.00 | 0 |
| Parmelia physodes | 0.00 | 0.29 | 0.29 | 0.29 | 1.00 | 0 |
| Carex rostrata | 0.29 | 0.57 | 0.29 | 0.29 | 0.59 | 0 |
| Deschampsia cespitosa | 0.29 | 0.29 | 0.00 | 0.00 | 0.00 | 0 |

**Table 2**

Percentage frequencies of species present at Coom Rigg Moss National Nature Reserve in 1958 and 1986, together with percentage changes over this period and the significance and extent of these changes. (Taken from Chapman & Rose 1986.)

some by more than 50%. The original and present distributions of some of these species can be seen in Figure 25, with a quantitative measure of change. Table 2 lists all the species recorded, their relative change and the statistical significance of that change.

A different approach to the problem was adopted by Charman (1986), who sampled 15 mire sites within the plantation area, all of which were completely surrounded by forest. Significant correlations existed between the numbers of ombrogenous mire species and the sizes of the mires. There were also indications that fewer species occurred on sites that had been surrounded by trees for longer periods of time. R Smith & D J Charman obtained 510 samples from 34 sites. These so far unpublished data confirm the earlier work, finding correlations between area, age of plantation and shape of site, on the one hand, and occurrences of ombrogenous mire species at a cover of greater than or equal to 5%, on the other. Large round or square sites surrounded by young plantations hold more mire species than small irregularly-shaped sites surrounded by mature plantations. A similar but converse relationship was found for species mainly of dry moorland communities.

It seems clear that the vegetation on mires which become surrounded by plantations can change over a relatively short period of time. What are not yet clear are the mechanisms by which these changes occur. In the case of the Kielder sites, there has been a change in management associated with the forestry operations. Prior to extensive plantings the moorland was grazed at low stocking rates and would have been lightly burnt occasionally, even on the wet areas (Chapman & Rose 1986). This would have reduced dominance of any species, such as *Calluna vulgaris,* which might otherwise smother more sensitive mire species.

Chapman & Rose found that the various existing vegetation types at Coom Rigg were correlated with peat depth and slope, whereas the vegetation types in 1958 showed no such correlation. They suggest that cessation of grazing and burning may have allowed these hidden influences in the vegetation pattern to be expressed. However, this does not explain the loss of pools from the site or of 'typical' mire species from the deepest areas of peat. Another possibility is that the water supply to the mire is reduced or its retention impaired. Forestry operations involve ploughing and the cutting of deep drains, not always restricted to the area eventually planted. Drains adjacent to mire systems may cause sufficient water table drawdown to affect particular species or types of surface pattern (see Chapter 5). On some of the Kielder sites there are also drains which cut across the mire surface. The effects of drainage have been considered in detail in Chapter 5. It may also be possible that the increased evapo-transpiration due to the surrounding conifers reduces any surface seepage to the mire. This may be particularly so where plantations are upslope of mires. Seedling invasion of the drier parts may become a problem, as at Belleray Flow in Kielder Forest, further reducing water supply by evapo-transpiration and interception by the canopy.

Most coniferous plantations are refertilised during each rotation, usually by air. This inevitably involves some drift onto adjacent areas, particularly if they are pockets of open land in the forest. Williams, Davis, Marrs & Osborn (1987), for example, record drift of up to 1000 m from herbicide sprayed from helicopters. Enrichment ensuing from fertiliser drift, combined with possible increased aeration from water table drawdown, would tend to result in increased oxidation and breakdown of surface peat and the decline of some *Sphagnum* species. It may also mean that nutrient conditions are no longer optimal for other peatland plants.

Microclimatic change has also been suggested as a possible causative factor. Afforestation reduces windspeed and may 'trap' moisture before it reaches the mire, particularly if it is in the form of mist or fog. Snow-lie is also reported to last much longer in isolated pockets within forests, and drifting along the edges of forests can result in the same effect, particularly along north-facing plantation edges (R Soutar pers. comm. Bragg (1982) has demonstrated that, when there is snow cover, the water table generally falls; free water does not readily become available again until snow-melt.

There is no proof that any of the above factors are the cause of the vegetational changes in Kielder Forest. It is, however, extremely unlikely that such changes would have been so rapid without afforestation. The nearest comparable site outside the forest is Butterburn Flow, and no such changes were recorded there. Future work is planned to elucidate the mechanism by which these effects occur, to include grazing and burning trials as well as investigations into hydrology, climate and peat chemistry.

## Impact on the mire margin

A major effect of forest drainage is the destruction of the mire margin complex, typically consisting of water-tracks (endotelmic seepages) and surface seepage, which together form the transition either to mineral ground or the next mire macrotope. These are naturally the main areas of water run-off from the mire edge and generally lead fairly rapidly to main watercourses. As a result, these are also the areas typically used in forest drainage schemes as the location for collector and feeder drains, catching the water as it flows from the main areas of ploughing and taking it to the major watercourses. In an ecosystem complex as limited in variety as blanket bog, the loss of this significant source of relative diversity, particularly in the invertebrate fauna, represents a serious reduction in the importance of the mire as a whole. Too often the margins are assumed to be expendable, yet, as discussed in Chapter 2, the mire expanse-mire margin gradient is one of the key features integral to a mire unit (Sjörs 1948; Malmer 1985).

New plantations thus appear to have considerable potential for affecting adjoining unplanted peatlands, especially where there is physical continuity of the peat body and catchment. There may, however, be beneficial effects, especially on bogs in different catchments, from the cessation of moor-burning which is usually required. The Silver Flowe in Galloway has benefited from a reduction in both fire and grazing since the adjoining but mostly separate catchment was afforested, and its vegetation is now in excellent condition. Much more work on the effects of afforestation on adjacent, unplanted ground is needed before general conclusions can be drawn.

While non-patterned flow at low altitudes is evidently the favoured ground for new planting, the leaving of numerous unplanted islands containing pool and hummock systems cannot be assumed to secure these as naturally-developing enclosures for the future. Any similarity to open peatlands within the boreal forests of Fennoscandia is superficial and misleading (see Stroud *et al.* 1987, Figure 6.1). Some of these unplanted pool systems are already tapped by drains, and the previous section has indicated the strong possibilities of adverse change.

Above all, there is no case, in ecological or any other terms, for arguing that afforestation is here restoring a more natural condition or putting back what was once present. The establishment of a cover of exotic trees, made possible only by treatments which radically alter the physical habitat and kill the existing natural and semi-natural vegetation, comes close to environmental engineering. The contrast between the resulting product and the real, natural boreal forest of Fennoscandia or Canada - or even the Highlands - has been described and illustrated recently (Nature Conservancy Council 1986, pp. 53-54). Indeed, the two have little in common, apart from the presence of trees.

## Present distribution of new forest

The total area of Caithness and Sutherland peatland either planted or approved for planting is believed to be 67,000 ha, representing 17% of the total peatland area (Stroud *et al.* 1987). Not surprisingly, in view of factors such as altitudinal limits and suitability

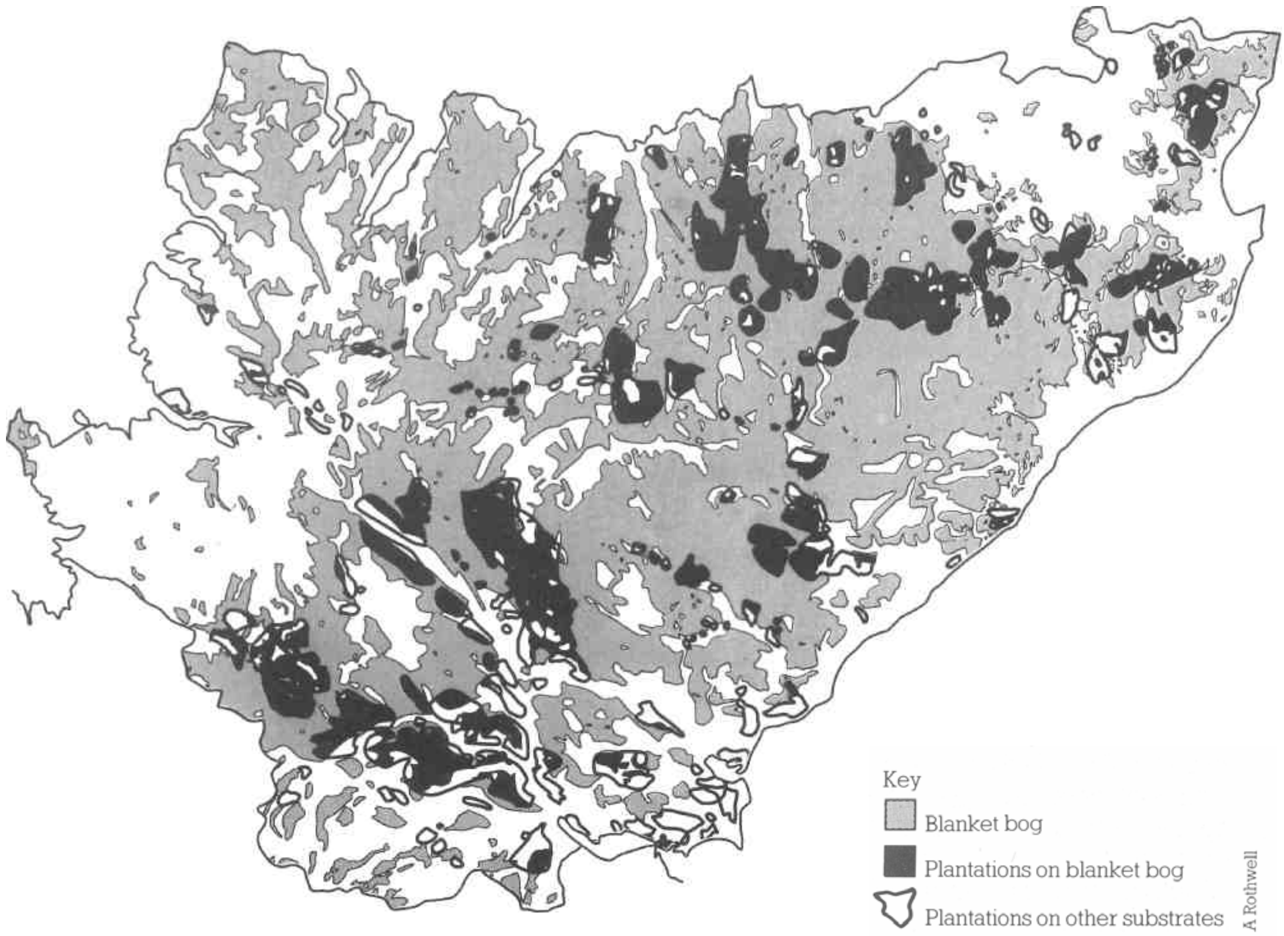


**Figure 26** Extent of blanket bog in Caithness and Sutherland, with areas of forestry (including land in Forestry Commission ownership or with Forest Grant Scheme approval) established on peatland and elsewhere.

of soil types, the distribution of forestry in the region so far is not uniform, although it is widely scattered, thereby spreading its effects over a large number of catchments. However, Figure 26 reveals that almost the entire pressure from recent forestry in the two districts has fallen on ground which is in the heart of the Caithness and Sutherland peatland complex.

Bioclimatic zones such as 02.H1/A3 are devoid of forestry because of altitudinal limitations, as are zones associated with the Moine Thrust, whilst the majority of the hyperoceanic Ol zone is also unafforested, almost certainly because most of it is in small units of ownership which preclude large-scale economies of planting. In the west much of the area is presumably too steep and rocky. Exposure to westerly gales may also be a limiting factor, but new planting round Loch Urigill, Ledmore, suggests that this is not a major consideration.

Clearly there are limitations other than land-class type which determine the nature of land acquired and planted, but it is obvious that the wetter types of land are more likely to be considered for sale to forestry interests than others.

# 7 Peatland distribution and area

## Basis for reassessment

Some statistics on the approximate extent and distribution of the peatland resource in the region, based on the soil maps produced for the Soil Survey of Scotland, have been presented by Angus (1986). The figures of peatland loss to forestry presented by Angus particularly emphasised the vulnerability of low-lying blanket bog in the Flow Country because he was able to show that the major pressure from forestry was clearly directed towards land below the 250 m contour. To develop this exercise further, the NCC required a more accurate assessment of the extent of peatland soils in the Flow Country, because evidence gathered during the course of its Peatland Survey of Caithness and Sutherland indicated that high-quality pockets existed that failed to meet the required size criterion for "exploitability", which was the primary purpose of the Soil Survey for Scotland assessment (see Chapter 8).

Angus's report used the soil units of the Macaulay Institute for Soil Research (MISR) - now the Macaulay Land Use Research Institute - to map a range of peatland categories. In mapping "peat" Angus used the MISR map units 3 (basin and valley peat), 4 (undifferentiated peat), 4d (deep peat > 100 cm) and 4e (eroded peat). There is no problem in using these categories to identify peatland for our purposes. Difficulties arise, however, with the next category, of "peaty soils", which includes a number of MISR map units, all of which have some peat but where either it does not constitute full cover or it is less than 50 cm deep.

For example, a large part of the region, particularly in Sutherland, is covered by MISR soil unit 23 (Bibby, Douglas, Thomasson & Robertson 1982). This is excluded from Angus's definition of "peat" but it is described by Bibby *et al.* (1982) as -

**Type 1:** "deep peat broken up by areas of peaty gleys, peaty podsols and shallow peat";

**Type 2:** "smooth slopes with shallow peat and peaty gleys... codominant and closely associated", with deep peat less common.

Type 1 is more common in Sutherland and Caithness. From such a description alone it is clear that a good proportion of this soil unit may have sufficient peat cover to form areas of significant peatland interest. This is also true of most of the other "peaty soil" categories. Units 26 and 29, which form the majority of the rest of the "peaty soils" in east Sutherland and Caithness, also have appreciable shallow and occasional deep peat elements. Unit 395, which covers most of the Lewisian Gneiss in west Sutherland, is mainly rocky, undulating ground with many small pockets of peat. The NCC's extensive Peatland Survey has shown that certain areas of MISR "peaty soils" are of importance for nature conservation and in this sense are little different from the deeper peats.

The MISR 1:250,000 map and Angus's report both use a scale which is only capable of detecting soil units occupying areas greater than 100 ha. This scale of mapping is often not appropriate for identification of more restricted peat deposits, which again may be of high conservation interest. This, incidentally, is probably one of the reasons for the low representation by MISR of basin and valley peats, which tend to occur as small units. For example, a valuable site at Loch Laxford does not register on the MISR map because of its relatively small size.

The peatland distribution described below represents an attempt to allow for all the above factors and to map peatland extent for conservation purposes. The categories defined by the MISR are designed particularly for the mapping of exploitable peat resources.

## Methods

The method followed was to examine the MISR soil units mapped at 1:50,000 scale and then to look more closely on 1:25,000 Ordnance Survey maps at those areas where "peaty soils" occur. The large scale of the later MISR series of maps means that many of the smaller areas of deep peat excluded from the 1:250,000 map available to Angus(1986) are now shown. From the descriptions given in Futty & Towers (1982), gradient was considered to be the most important determinant of peatland occurrence within "peaty" soil units. Knowledge of wide areas, gained during the peatland field survey and through examination of air photographs, was also used in interpreting the MISR soil units. In this way the marginal and mixed soil categories were divided into peat and non-peat units. The MISR peat distribution for the north-eastern section of Caithness, corresponding with O.S. sheet 12 (1:50,000 scale), was accepted as the best estimate of peatland in conservation terms.

The 1:50,000 maps produced in this way were then photo-reduced to produce a version at 1:250,000 still maintaining the detail of the larger-scale maps. Figures for the actual areas of peat and of peat/ forestry overlap could then be calculated by using a planimeter on the 1:250,000 map with a forestry overlay at the same scale. These figures were checked by means of the Arc/Info computing system.

## Results

The results are shown in Figure 27. The total extent of peatland is calculated as 401,375 ha. The total percentage peatland cover of the region is approximately 52.5%. From the map it is clear that the total area of peatland is much larger than the region identified by the RSPB as its "study area" (Royal Society for the Protection of Birds 1985; Bainbridge, Minns, Housden & Lance 1987).


**Figure 27** Peatland distribution in Caithness and Sutherland, based on the soil maps of the Macaulay Land Use Research Institute. All of soil categories 3, 4, 4d and 4e are included, together with parts of other categories which represent a mosaic of thin and deep peat. Deep peat within these 'mosaic' soil categories was identified on the basis of the NCC's Peatland Survey combined with an assessment of the topography displayed on 1:25,000 maps.

# 8 The Nature Conservancy Council's Peatland Survey of Caithness and Sutherland

The account by Crampton (1911) of the Caithness "moorlands" contained the first ecological description of the blanket bogs of this region, though it was generalised. Surprisingly, when Tansley (1939) compiled *his magnum opus, The British Islands and their Vegetation,* he made scant reference to the immense peatlands of Caithness and Sutherland and dealt with western Ireland as the classic area in his treatment of low-level blanket bog. Pearsall (1956) published a detailed description of two small areas of patterned blanket bog in Sutherland, but his account gives no impression of the abundance and diversity of blanket bog within this District. For many years after interest in peatland ecology developed in Britain, the importance of this far northern part of Scotland seemed to escape notice. Surveys by the Scottish Peat Committee (Department of Agriculture and Fisheries for Scotland 1965, 1968) to estimate workable peat resources were made in the 1950s, but then this concern died away. Ratcliffe (1964) gave another generalised description of these blanket bogs, drawing attention to their immense area (the largest in Britain) and the frequent occurrence of patterned pool-hummock surfaces.

During the last few years, the international importance of Britain's blanket mire habitat has become increasingly evident, with the result that it has become the focus of much greater attention than previously, emerging from relative obscurity (see Chapter 3 and Moore 1984) to be recognised as one of Britain's most important terrestrial habitats (NCC 1986).

Previous peatland surveys by the original Nature Conservancy and subsequently the NCC have been limited to the identification of exemplary sites within the range of variation shown by the peatlands of Caithness and Sutherland. Goode & Ratcliffe (1977) give an indication of the peatland types to be found in the region, but their account is limited to seven outstanding sites chosen on the basis of knowledge then available.

Extensive habitat survey had not been part of the research policy of the former Nature Conservancy, but, when the Nature Conservancy Council was set up anew in 1973, it accepted the need for systematic survey of semi-natural habitats as the necessary basis for a comprehensive conservation programme. A small peatlands survey team of two people was accordingly set up in 1977, with the remit to cover the whole of Britain. The advance of moorland reclamation and afforestation made it seem inevitable that the hitherto intractable flows of Caithness and Sutherland must eventually come under pressure for development. Recognising the supreme importance of the blanket bogs of this region, the NCC initiated a pilot study of the Caithness peatlands in 1978, to develop an appropriate methodology.

Problems over access limited the first two years' work to isolated areas of peatland within the Caithness agricultural plain. In 1980, however, a major programme of peatland survey for Caithness and Sutherland was launched and continued over the seven field seasons up to 1986. The original team has expanded to number six as the maximum at any one time - some of the authors of the present report and John Riggall, Fiona Burd, Sarah Garnett, Bob Missin, Sara Oldfield, John Ratcliffe, Jane Smart and Sylvia White. An additional survey team was organised by the Scottish Field Survey Unit and led by Liz Charter. This study has been supplemented by detailed botanical surveys of peatland sites conducted for the North-West Scotland Region of the NCC by Dr R E C Ferreira.

## Methods

The approach adopted for the NCC's Peatland Survey of Caithness and Sutherland is similar to that used for the NCC's Welsh Wetland Survey (Ratcliffe & Hattey 1982), where a programme of stratified survey and sampling was employed. This procedure involves, first, the delimitation of the complete resource for possible survey. The mapping of the peat deposits of Caithness and Sutherland is described in Chapter 7. The next stage consists of assessment to discard unsuitable areas. The entire region of Caithness and Sutherland was therefore examined by using the post-war air photographs housed at the Scottish Development Department. Sites were deleted from the survey programme only where -

- some other land-use had completely destroyed the peatland interest;

- they showed erosion in such an advanced state that extensive bedrock or sheets of bare peat were exposed, leaving little peat vegetation; thus sites with slight or moderate erosion were surveyed;

- the slope evident from stereo-photographs indicated that the peat was likely to be extremely thin, but, even then, only if it showed no signs of extensive flushing or any type of surface patterning;

• information obtained from local sources indicated that the area contained no peatland interest.

Finally, in the field, sites were stratified according to the level of peatland information they revealed. If, on initial survey, mire systems held very little interest, owing perhaps to recent damage, or were extremely uniform, the range of information gathered was limited and the time spent on such a site was much less than on one with good representation or a wide range of morphological, surface pattern or vegetation features.

## Aims

The survey aimed to identify and visit all peatland areas of significant interest to nature conservation within Caithness and Sutherland, to produce descriptions and evaluations of each area (identifying prime peatland areas) and to draw up a detailed classification of the blanket bog and vegetation types present. This was intended to provide the basis for a comprehensive conservation programme, having regard to both national and international requirements and including the peatland "key sites" already listed in *A Nature Conservation Review* (Goode & Ratcliffe 1977).

## Selection of sites for survey

By using a combination of existing knowledge, 1:25,000 maps, LANDSAT satellite imagery and air photos, 399 sites (mesotopes) were identified for survey. A further 84 areas were dismissed at an early stage because of signs of damage obvious on air photo images (see Figure 28).

At each site several features were noted, in order to allow comparison between sites and an assessment of the relative value of each site.

## 1 Mire unit morphology (mesotope)

This was characterised according to hydromorphology and geomorphological location (see Chapter 2), to give a number of broad categories -

- watershed
- saddle
- valleyside
- low watershed/valleyside
- spur
- ladder fen
- minerotrophic fens

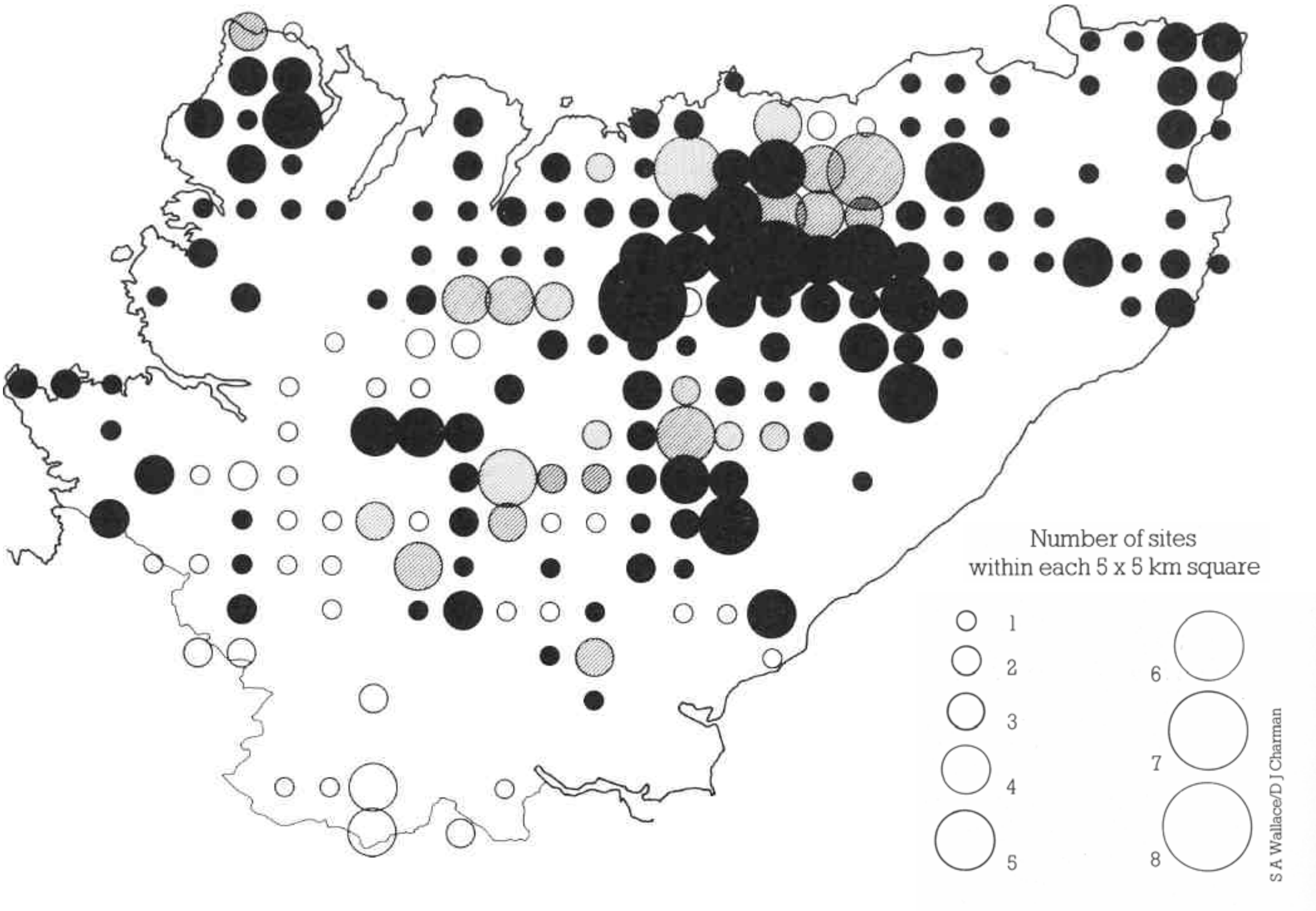


**Figure 28** Distribution of sites examined on aerial photographs, displayed by 5 km squares. Open circles indicate sites examined but not selected for field survey, hatched circles indicate a combination of surveyed and unsurveyed sites within the 5 km square, and filled circles represent 5 km squares where all sites examined were surveyed in the field.

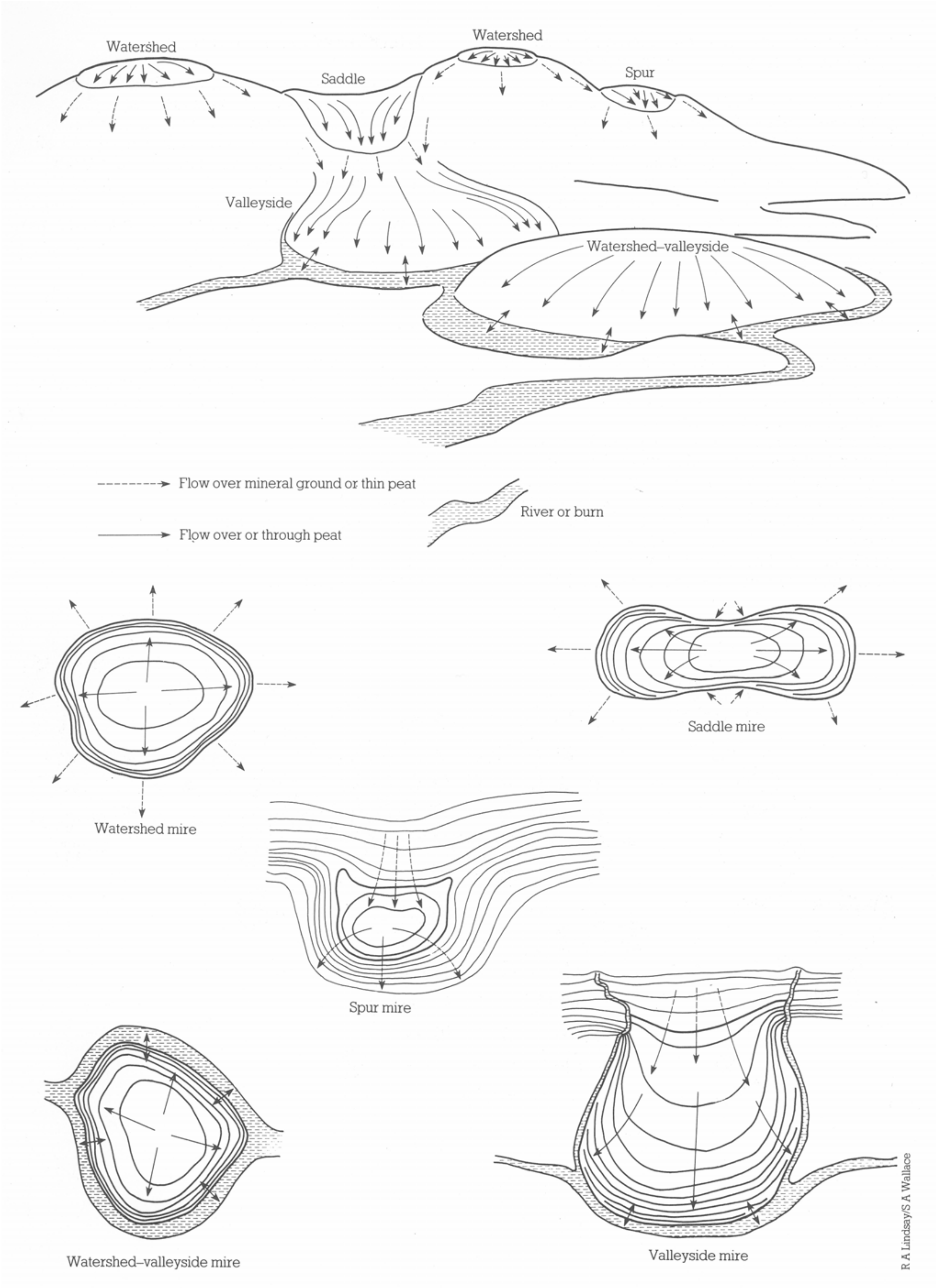


**Figure 29** Hydromorphological bog types (mesotopes) - generalised location within the landform, with an indication of surface water flow patterns, and generalised pattern (as seen from above) of surface water "flow-nets" (Ivanov 1981).

The general morphology and pattern of flow-nets for each of these is illustrated in Figure 29.

## 2 Surface pattern (microtope)

Ten discrete zones were identified for sites which possessed surface patterning, according to previously published accounts (see Chapter 2). Zones recorded were -

- T5 peat mounds
- T4 erosion hags
- T3 hummocks
- T2 high ridge
- T1 low ridge
- A1 *Sphagnum* hollows
- A2 mud-bottom hollows
- TA2 erosion channels
- A3 drought-sensitive pools
- A4 permanent pools

The relative abundance of each zone was recorded on the DAFOR scale (Dominant, Abundant, Frequent, Occasional, Rare).

## 3 Vegetation

The vegetation within the mire expanse and the mire margin was sampled by using 1 $m^2$ quadrats adjusted in shape to record visually homogeneous vegetation within each (separate) zone. These data were analysed by TWINSPAN (Hill 1979) followed by recombination of the "end groups" to produce noda which could usefully be identified in the field. The resultant groups were compared with existing classification systems including the National Vegetation Classification communities (Proctor & Rodwell 1986).

## 4 Damage

All damage to the bog surface and surrounding ground was recorded, with notes on the degree of damage, ranging from absent through to severe, in the following categories -

- burning
- erosion
- drainage

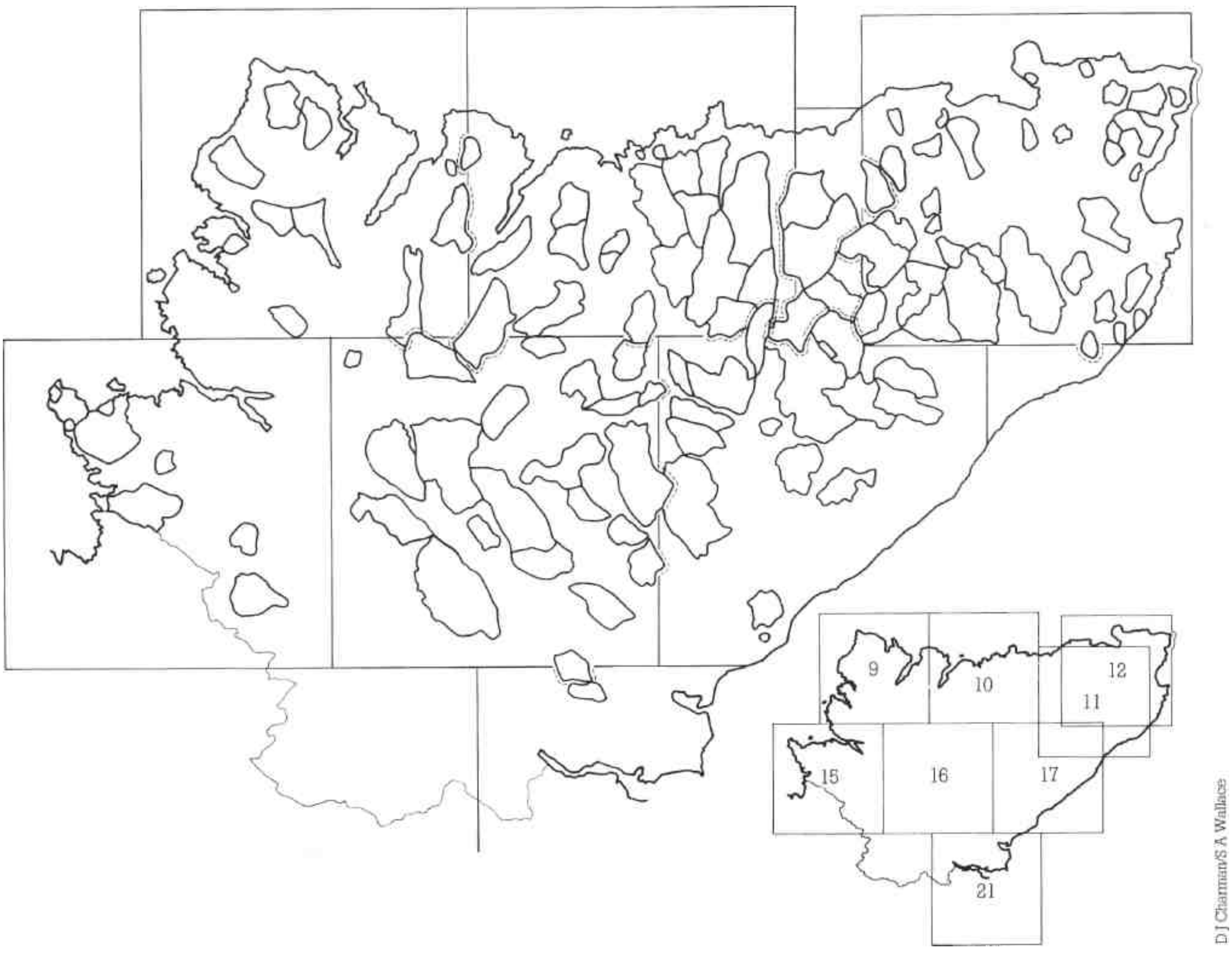


**Figure 30** Distribution of mire complexes (macrotopes) identified for detailed quadrat analysis during the NCC's Peatland Survey. Inset key shows 1:500,000 Ordnance Survey map coverage and map numbers.

- grazing/trampling
- afforestation
- peat-cutting

## 5 *Sphagnum cover*

An assessment of the total *Sphagnum* within the T (terrestrial) zones was made in the field -

0 - no significant *Sphagnum* cover; *I*- *Sphagnum* present;
2 - significant cover (patchy in extent);
3 - extensive to continuous cover over large areas of the site.

## 6 Quaking ground

This consists of *Sphagnum*-rich surfaces which show almost no sign of disturbance and which have such a high water content and low level of humification that the mire surface quakes when being traversed. It indicates a high degree of naturalness. Three categories were identified -

1 - present in small areas;
2 - common, scattered throughout site; higher ridges not quaking when walked over;
3 - extensive areas of quaking ground, making walking through the site very difficult; most of the ridges quaking, even the higher areas.

## 7 Notable plant species

Certain species are regarded as important owing to their localisation or as indicators of naturalness/lack of damage to the bog surface. Others indicate certain conditions (e.g. flushing or oceanicity) and some show bias in geographical distribution (sometimes linked to oceanicity).

The preliminary work attempted to identify as many as possible of what appeared to be significant mire units (mesotopes), for subsequent field study. These mire units were grouped into the seven topographic-water flow categories of Section 1 above. Within each mire unit, the detailed surface pattern (microtopes), vegetation and other key features were analysed according to the standard lists in Sections 2 to 7. Mire complexes (macrotopes) were then defined on the basis of hydrological boundaries (e.g. rivers or lake margins), where possible, but based on other limits where ecological discontinuities (such as pronounced changes in slope and vegetation or occurrence of rock outcrops) appeared on air photographs, peat/soil maps or 1:25,000 Ordnance Survey maps (Figure 30). This is the method adopted by Moen (1985) in Norway. Each mire complex contained at least one deep peat area, and some contained many such systems forming extensive mire complexes. While former mire units which are now largely afforested have been omitted, many of those included for survey contain some forest.

The process of classification was then based, as in Norway and Canada, on the variation between individual mire units (mesotopes) according to the differences displayed by their detailed surface structures (microtopes). The mire complexes, (macrotopes) were subsequently classified on the basis of the combination of differing mesotope and microtope features.