ENGLISH NATURE

Proceedings of the Risley Moss Bog Restoration Workshop

26-27 February 2003

working today
for nature tomorrow

PEAT FORMING PROCESS AND RESTORATION MANAGEMENT

Richard A Lindsay *Head of Conservation, School of Health & Bioscience, University of East London*

THE restoration of bogs has received considerable attention in recent years. Given that no truly natural bogs remain in the lowlands of Britain (Lindsay & Immirzi 1996), those who take on the management of an ombrotrophic bog system, particularly in the lowlands, are generally faced with a site requiring significant, if not substantial, 'restoration' management.

A considerable body of experience about restoration methods for conservation purposes has accumulated over the years and its compilation in Brooks & Stoneman (1997) for the UK and, for example, Dupieux (1998) and Manneville, Vergne & Villepoux (1999) for France, complements the detailed review of restoration on commercially cut-over bogs undertaken by Wheeler & Shaw (1995).

Concept of 'restoration'

Ideally, the objective, and indeed the measure of success for such activities, might be based on complete restoration of all original features. Some components of a peat bog can, however, never be recreated (the peat archive, for example). The practical objective for peatland restoration must therefore be focused on the reinstatement of an ecological process rather than any particular end point. For the purposes of the EU Habitats Directive (EC Directive 92/43/EEC) the Commission definition of "*damaged raised bog capable of natural regeneration*" specifies that "*there is a reasonable expectation of re-establishing vegetation with peat-forming capability within 30 years*" (Romão 1996). Such wording makes it clear that, in the European Commission view, successful restoration is achieved when the potential for peat formation once again exists. In other words the resulting vegetation should be one that is widely accepted as being capable of forming peat. The timescale of 30 years can be regarded as a useful milestone that encourages judgments of success to be made within a specified period rather than leaving the question completely open-ended. The EC does not require the complete reconstruction of a peat bog, with all its structural features, within 30 years.

If the EC definition is taken as the yardstick of restoration success (and it is difficult to find specific or better alternative forms of yardstick within the literature), the key is clearly the establishment of appropriate peat-forming vegetation. Given this objective, it is very important to understand the mechanisms by which such vegetation types arise spontaneously when devising, evaluating or choosing restoration techniques for a particular bog.

Peat formation and restoration

This paper will consider the natural processes of peat bog formation and structure, as they relate to bog restoration via the establishment of peat-forming vegetation. It sets out a conceptual framework for these various approaches, and compares the benefits of differing restoration strategies.

PEAT FORMATION – THE TWO MAJOR PATHWAYS

Two conceptual models of peat formation have been suggested, the first by Weber (1902, 1908) and another by Cajander (1913). Weber set out the now-classic sequence of *terrestrialisation*, whereby through successional processes a water body becomes infilled with vegetation and organic material until eventually no open water remains and the site becomes peat-land. This is the classic 'hydrosere' of Clements (1916) - though it is worth pointing out that the validity of this whole concept has more recently been the object of iconoclastic treatment by Klinger (1996).

Cajander (1913) subsequently proposed a second major pathway for peat formation to explain the fact that not all peat deposits have evidence of an initial open-water phase. This second process also addresses the rather curious fact that the basal peat towards the margins of some peat bodies is sometimes found to be significantly younger than the basal peat in more central parts. According to Weber's (1902) model of terrestrialisation, the story should be quite the reverse. Cajander (1913) addressed these two anomalous observation by proposing that sometimes peat is able to form directly on ground that was formerly dry. He observed that such a phenomenon is possible if the climate is sufficiently wet, or if the ground becomes wet because of adjacent waterlogging. He termed this process *paludification*.

Although terrestrialisation is probably the better known process, Wheeler & Shaw (1995) comment that, within Britain as a whole, paludification has probably occurred far more extensively, citing the widespread development of blanket peat across many of the upland regions of Britain and in low-lying lands of the far north. They go on to observe that even the great peatland expanses of the East Anglian Fens almost certainly owe more to paludification than to terrestrialisation.

Terrestrialisation

The primary requirement for this process is that a water body should be sufficiently permanent for it to enable the various seral stages of the hydrosere to occur. The successional sequence additionally requires that:

- one or more plant species becomes established;
- the water chemistry is as required to support growth of these various species;
- other environmental factors (such as light and temperature) are appropriate for plant growth;
- conditions are sufficiently anaerobic for dead organic material to accumulate.

Peat continues to form as long as there is anaerobic water to submerge the dead vegetation. At the outset, the peat-forming system may remain wholly under the influence of the mineral-enriched ground-water. The terrestrialising vegetation is described as *fen*.

The system reaches an important ecological threshold once the peat has completely filled the basin. Further peat formation could take place above the mineral-rich groundwater, but will only do so if the resulting peat is waterlogged (and thus anaerobic) through, for example, regular inputs of rainfall. If the dead plant material does not remain anaerobic, it will decay and no further peat accumulation takes place under these circumstances. The terrestrialised site thus reaches a steady state in which minerotrophic fen (or fen carr) is maintained indefinitely, confined by the limits of mineral ground-water influence.

In the classic hydrosere described by Tansley (1939), peat accumulation may nevertheless continue even in this steady state. Increased compression under the weight of surface vegetation (which in Tansley's model includes trees and scrub) makes the peat denser, depresses it below the water table, and enables succession to proceed eventually to mature *Quercus* woodland. It is not entirely clear whether this theoretical woodland 'climax' has ever been reached in Britain, due to the lack of any sites in a totally natural state today. Observation suggests that some form of wetland would actually be the climax, perhaps in the form of fen woodlands described by Wheeler (1980), or 'swamp woodlands' described by Moen (1999) for the Nordic countries.

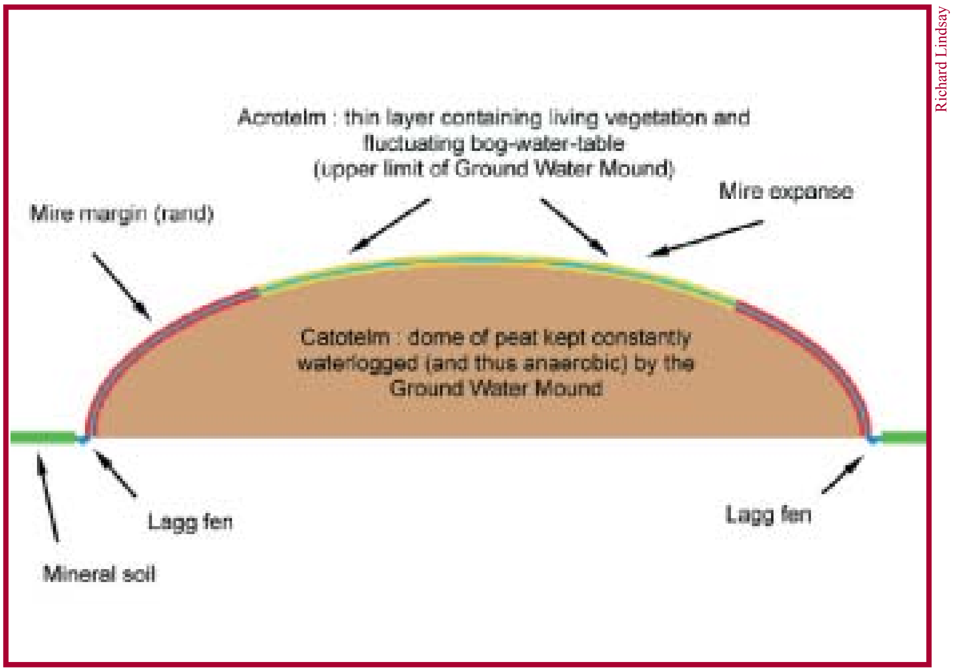


Figure 1: A raised bog dome formed by the retention of rainwater within undecomposed (largely *Sphagnum*) peat, thus forming a 'ground water mound'. The main bulk of the dome consists of the *catotelm*, which is protected from drying out by the thin *acrotelm*. The ground-water mound forms a hemi-ellipse, and so has a steep hydraulic gradient towards the bog margin (the *rand*) while central parts have a gentler gradient (*mire expanse*). The whole dome is bounded by the *lagg fen*.

Terrestrialising bogs – from minerotrophic to ombrotrophic conditions

If conditions are appropriate, however, a rainwater-dependent wetland may begin to rise above the confines of the ground-water, laying down layer upon layer of dead plant material at a rate of little more than 1mm of compressed peat per year as the accumulating material slowly rises above the surrounding landscape. It gradually begins to form a dome within which the rain-fed water table perches above the surrounding mineral ground-water table, rather like a single water droplet might sit on a flat surface. Such systems are termed *ombrotrophic mire* because they are fed directly by rainfall, and are specifically referred to as *raised bog*.

The conditions believed necessary to achieve this ombrotrophic breakthrough are still only broadly understood. Most accounts acknowledge the pre-eminent part played by the genus *Sphagnum* in bog formation. In some parts of the world, however, other species sometimes take the place of *Sphagnum* (e.g. *Donatia* and *Empodisma* in Australia and New Zealand - Campbell 1983; Agnew, Rapson, Sykes & Bastow Wilson 1993). This suggests that peat formation as a process is more closely linked to a particular set of conditions rather than to any single group of plants. The particular relationships displayed between peat-forming vegetation and hydrology, on the other hand, appear to be universal (Gibson & Kirkpatrick 1992; Mark, Johnson, Dickinson & McGlone 1995).

After terrestrialisation – the growth of the raised bog

Proctor (1995) provides an overview of the bog environment, and observes that maximum summer water deficit is probably one of the more critical factors in determining the geographical limits of bog growth, at least at low latitudes. Wheeler & Shaw (1995) conclude that the various interactions between precipitation, insolation, temperature, evapostranspiration and vegetation type are not sufficiently well understood to give precise parameters for the phenomenon of bog growth arising from a terrestrialisation sequence.

Nevertheless it is reasonably well established that a close link exists between regional climate and the overall shape of these domed bogs. This relationship was proposed by Ingram (1982) in what he termed the Ground Water Mound Theory (Ingram 1982, Ingram & Bragg 1984). The theory builds on earlier observations by Granlund (1932) and Wickman (1951) about the curvature of raised bog domes. It also provides an explanation for the link between structure, function and vegetation.

The dome of rainwater stored within the mass of peat ensures that the bulk of this peat is maintained in a constantly anaerobic and waterlogged state. The main waterlogged (and thus anaerobic) peat deposit may be as much as 10 metres thick at the crown of the dome. It forms the bulk of the peat body and is termed the *catotelm*. Covering this catotelm is a thin living layer of some 30 cm thickness within which the bog water-table fluctuates. This living 'skin' is termed the *acrotelm* (Ivanov 1981; Ingram & Bragg 1984). It generally displays an undulating surface consisting of what is frequently (but not entirely accurately) referred to as a "hummock-hollow" pattern (Tansley 1939; Godwin & Conway 1939).

During drought conditions, the acrotelm empties and water levels may fall to the junction with the catotelm but no further. As long as the surface of the acrotelm lies within 30cm or so of the waterlogged catotelm, the living vegetation is able to survive quite extended periods of drought. In turn, the acrotelm protects the catotelm from day-to-day variation in rainfall, sunshine and the drying effects of wind (Ingram & Bragg 1984).

The more steeply-sloping marginal areas of the dome, termed the *rand*, may support a somewhat more limited range of peat-forming species than flatter central parts but in the natural state they still nevertheless possess some form of active, protective acrotelm. This is possible despite the slope because the hemi-ellipse of the groundwater mound (Ingram 1982) shows a similarly steep curvature towards the margins of the dome, and thus the saturated catotelm lies close to the surface even in the most steeply-sloping parts (see Figure 1).

Richard Lindsay

Figure 2: Teicu Nature Reserve, Latvia. To the right of the photograph is the large raised bog itself, distinctive because it lacks any significant tree cover. This is in sharp contrast to the tall pine forest dominating the mineral ground to the left of the photograph. In the centre, forming a zone between the bog and the forest, is the wide lagg fen. The water depth in the lagg fen approaches 2 metres in places.

The area of fen surrounding the raised bog is known as the lagg. It is the contact zone between the rain-fed hydrology of the bog and the surrounding groundwater (see Figure 2). The edge of the bog, and hence the position of the lagg, may continue to move outwards, provided it is not constrained by the topography. It may expand by further terrestrialisation if there is open water in the lagg, or by paludification if the surrounding mineral ground does not rise too steeply.

Paludification

Cajander (1913) recognised that terrestrialisation was not the only route to peatland formation. He observed that paludification requires no prior terrestrialisation of an aquatic stage, merely sufficient ambient wetness to permit peat-forming species to colonise. Peat accumulation directly on mineral soil or rock surfaces was possible provided these surfaces were maintained in a sufficiently wet condition.

Climate and slope are usually the most important factors in the paludification process. In Britain the limit for paludification bogs arising from climatic humidity appears to be an annual rainfall of at least 700mm combined with a minimum of 200 'rain days' (see Lindsay *et al.* 1988).

When slope increases, water tends to run off more rapidly. Thus increasing slope-angle is also an important factor in limiting paludification. Slopes of up to 20 are nevertheless commonly paludified throughout the blanket mire regions of upland and northern Britain. Indeed peat-covered slopes of 30 are by no means unusual in the wetter parts of these regions (Ratcliffe 1964, Ingram 1967, Goode & Ratcliffe 1977, Lindsay *et al.* 1988).

'Contiguous' paludification and 'back-paludification'

Paludification is most commonly limited by climate, whereas terrestrialisation is more directly linked to landform. However, Cajander (1913) recognised that an area of ground may become influenced by the wetness of adjoining (contiguous) ground, or because water may be re-directed to flow onto areas of formerly dry ground. The University of Exeter Geography Department web-site cites a number of examples of this from Britain, including development of the fens (and some bogs) of The Wash, the Somerset Levels, Thorne & Hatfield Moors, and the Norfolk Broads. These areas became waterlogged because of rising sea levels, or through increased run-off from surrounding land.

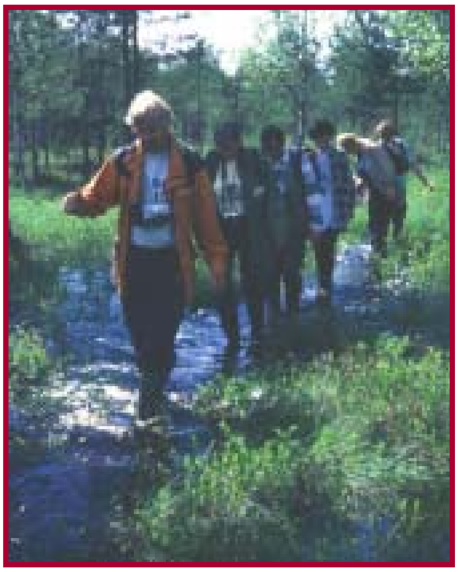
'Contiguous' paludification is also seen on the margins of bogs that may have had their origins in the terrestrialisation process. Where a raised bog is formed it is (in the classic model, at least) surrounded by a lagg fen which represents the junction between the ombrotrophic bog and the surrounding mineral ground. Kulczynski (1949) describes the way in which impeded drainage caused by peat accumulation progressively increases the surface wetness upslope from the peat deposit, and terms this 'back-paludification'. Heinselmann (1963), quoted by the University of Exeter web-site, states that:

> *"..upslope growth of peatland seems to be achieved by damming up incoming waters from mineral soils. This creates a wet area into which the swamp forests can advance…"*

Figure 3 demonstrates the way in which the raised bog seen in Figure 2 has 'ponded' the lagg fen and caused it to waterlog or even flood the surrounding mineral ground. This in turn gives rise to further peat formation around the bog, and thus the site has the potential to expand laterally through the process of paludification.

This process of expansion beyond the original terrestrialisation basin has been recognised by many authors (e.g. Moore & Bellamy 1974; Hulme 1980) and is discussed at some length by Wheeler & Shaw (1995). These last authors provide a number of bog profiles, illustrating the way in which terrestrialisation centres have grown beyond their original confines and then extended, through paludification, to coalesce across dividing ridges and low hills. It is this sequence of events that produces different ages for different parts of bog basal sediment, a phenomenon mentioned earlier; the terrestrialisation regions show a basal age of several thousand years, whereas the more recent paludification areas have much younger basal sediments.

The phenomenon of back-paludification (rather than climatic paludification) has already been used extensively in restoration programmes in Britain and Ireland, albeit without a widespread understanding or recognition of the underlying principles involved. It also offers considerable promise for future peatland restoration strategies on both little-damaged and industrially-worked sites.



Richard Lindsay

Figure 3: Teicu Nature Reserve, Latvia, after a particularly wet month. This illustrates the extent of flooding within the forest on the outer margins of the lagg fen seen in Figure 2. The more regularly such events occur, the more likely it is that paludification will extend the present bog environment further into the forest.

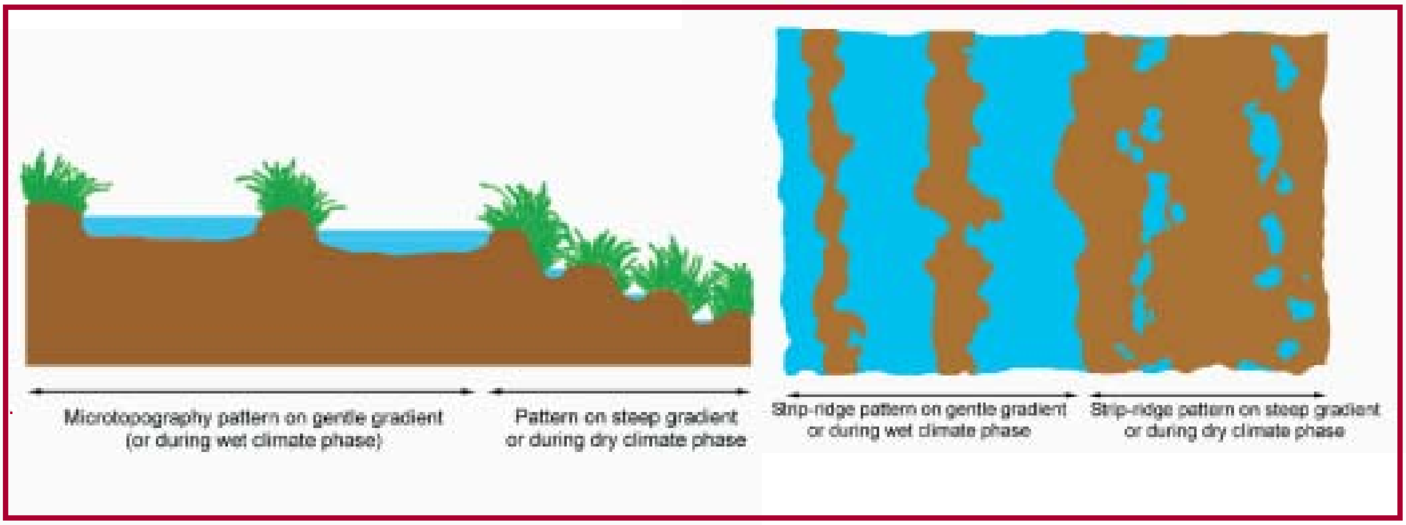


FIGURE 4: The relationship between small-scale surface pattern and hydrological gradient or climate regime.

LEFT: The relationship between gradient and pattern described by Goode (1973), in which steep gradients are characterised by a dominance of terrestrial zones while shallow gradients can support more extensive aquatic zones.

RIGHT: The 'strip-ridge' mechanism of Ivanov (1981) and the 'phasic model' of Barber (1982) in which wet conditions lead to a dominance of aquatic zones while dry conditions lead to a dominance of terrestrial zones.

PEATLAND RESTORATION - ECOLOGICAL AND CONSERVATION PRINCIPLES

The key test of restoration for the European Commission is whether a damaged site can be encouraged to undergo natural restoration to the extent that, in 30 years, it supports a vegetation capable of forming peat. The aim is to reinstate peat formation as a process, rather than replace or mimic what has been lost. Nevertheless, it has to be assumed that the quality criteria include the eventual development of all the structural and floristic elements of the original, subject to contemporary climatic conditions.

Starting conditions - does it have to be flat?
If terrestrialisation is to be used as the primary mechanism of restoration it is clear that the first stage involves the creation of open water – or at least areas with the potential to hold standing water. These will subsequently become colonised and undergo successional development. In order to achieve this, level areas of peat must be created in order to achieve extensive re-wetting of the bog surface.

It is rare for the post-extractive bog surfaces to be entirely flat, particularly where a variety of methods has been used. It is widely assumed that damaged sites require extensive re-shaping in order to remove areas of steep hydrological gradient, particularly if restoration is to be based solely on terrestrialisation and low gradients. In view of this perception, it is perhaps instructive (and may prove ultimately a great deal cheaper) first to consider the variety and magnitude of gradients typically found on natural raised bogs.

Natural gradients on mire systems
A raised bog, by its very definition, is raised above the surrounding landscape. Typically its surface may grow (or be supported by an underlying 'Ground Water Mound') to as much as 10 metres above its surroundings.

The gradient can be particularly steep in the zone close to the outer margin. Even in their natural state, the majority of raised bogs in Britain were less than 100 hectares in extent (Lindsay & Immirzi 1996), and many were substantially smaller than 100 hectares. This means that for a 30 hectare site the gradient from centre to margin might involve a drop of 10 metres in a distance of no more than 270 metres. This works out as an average slope of 1 in 27, but is likely to be less in the centre and more at the edge.

Wheeler & Shaw (1995) describe a number of raised bog profiles, and their Figure 1.1 includes a cross-sectional profile of Flanders Moss West in the Forth Valley, Stirling. It can be seen that the site consists of at least two parts. The main part is a gently-sloping dome that rises some 6 metres over a distance of 1,000 metres. In contrast, to the south is a steep dome that rises more than 12 metres in only 200 metres, then falls by the same amount in only 150 metres to the banks of the River Forth. The whole southern dome falls 12 metres from centre to margin in a distance of only 350 metres. A profile for Coalburn Moss, near Lanark is also displayed by Wheeler & Shaw (1995). This site shows a fall of 15 metres over a distance of 450 metres (1 in 30).

The values presented above show that gradients on natural bogs can be quite substantial. Many relatively natural raised bogs contain much steeper gradients than many of those found in cut-over sites.

Gradients that are often considered to be a problem for peat formation and restoration on cutover bogs appear to be entirely compatible with natural peat formation on hydrologically intact sites.

Vegetation, hydraulic gradients and acrotelm stability
The relationship between peat-forming species, rates of peat growth, and hydrological gradients is a significant issue for the restoration process. For northern-hemisphere temperate regions, this relationship consists particularly of the interplay between *Sphagnum*, the acrotelm and the catotelm. The specific ecological characteristics of *Sphagnum* have been reviewed in some detail by Clymo & Hayward (1982). Normally several *Sphagnum* species are involved in peat growth, and as different species have different growth-forms, this gives rise to the undulating *hummock-hollow* surface pattern so characteristic of bog surfaces.

Barber (1981), carried out an exhaustive review and investigation which, on the basis of his field observations, led him to reject the long-established model of the 'hummock-hollow regeneration cycle' proposed by Osvald (1923) and Tansley (1939) - in which the latter authors proposed that hummocks degenerated to become hollows and hollows infilled vigorously to become hummocks. Barber (1981) instead proposed a 'phasic' model of hummock-hollow dynamics in which these surface features are the primary means by which bog growth responds to climatic shifts. In this phasic model, the hummock-forming species of *Sphagnum* expand across the bog surface during dry periods of the climate. During wet phases, hummocks retreat and the species typical of hollows expand. The average effect of this over the centuries is that individual hollows and hummocks persist *in-situ* and simply expand or contract in response to changes in climate.

The functional stability provided by this phasic model is explained by an earlier theoretical framework for the surface eco-hydrology of bogs provided by Goode (1973) and Ivanov (1981), and set out in Figure 4. These three theoretical and field-based models can then be combined together to describe a simple but powerful mechanism for eco-hydrological homeostasis in bog systems:

Expansion of the more impermeable element of the surface pattern (hummock/ridge-forming species of Sphagnum*) slows down water loss, thereby either retaining essential water on the site during dry climatic periods, or preventing erosion by sheet-flow on steep marginal slopes.*

Expansion of the permeable element (hollow/pool-forming species of Sphagnum*, or open water) allows excess water to be shed more rapidly during wet climatic periods, or over areas of shallow gradient where water must flow across considerable distances before being shed from the site.*

Each element expands or contracts in situ according to the prevailing conditions. In this way, bog growth can continue at a fairly steady rate despite considerable changes in climate or local hydraulic gradients.

The theory arising from Goode (1973), Ivanov (1981) and Barber (1981) not only explains the dynamic relationship between individual hummocks and hollows in a much more satisfying way than the old hummock-hollow cycle of Osvald (1923) and Tansley (1939). It also provides a valuable insight into the overall mechanisms controlling bog growth through the changing environmental conditions of the last few thousand years. Furthermore, the phasic model has a number of important implications for bogland restoration.

Firstly, Goode's (1973) explanation of the relationship between surface pattern and physical gradient provides a fundamental insight into the main regions of a raised bog dome.

The regions are described by Sjörs (1948) as:

- the relatively flat mire expanse (which in Sweden is the zone devoid of trees);
- the more steeply-sloping margin to the bog, termed both the 'rand' and the 'mire-margin' (which in Sweden has scattered, stunted trees, whereas in Britain there is often now a dense fringe of *Betula* woodland);
- the lagg fenn at the outer margin (which is largely missing from bogs in the UK).

The mire expanse has a gentle gradient. According to the phasic model it is thus capable of supporting extensive areas of aquatic-zone features. In contrast, the model predicts that the steeply-sloping rand should be dominated by terrestrial-zone elements, such as ridges and hummocks. This prediction matches Sjörs's (1948) description of the rand as having few or no aquatic elements and being instead (in Sweden at least) characterised by the presence of stunted trees and hummock-forming *Sphagnum* species. Finally, the lagg fen is dominated by aquatic-zone species, particularly of the *Sphagnum recurvum* group.

The different regions of the bog can also be described in terms of their characteristic *Sphagnum* species. Areas of the central mire expanse, with low gradients, are characterised by a mixture of terrestrial <u>and</u> aquatic species such as *Sphagnum papillosum*, *S. magellanicum*, and *S. cuspidatum*. The more steeply-sloping rand is characterised by a more limited range of species dominated (in Britain at least) by exclusively <u>terrestrial</u> hummock-forming species such as *Sphagnum capillifolium*. Only the lagg is dominated by wholly <u>aquatic</u> species.

Paludification is generally associated with the establishment and growth of terrestrial species, while terrestrialisation is associated initially with aquatic species. It can be seen from the zonation of the main bog regions that terrestrial species of *Sphagnum* tend to dominate the major part of the bog, while an abundance of aquatic species typical of terrestrialisation is to be found only in the lagg fen or in pools. The zonation also has important implications for the restoration of peatlands containing significant gradients: it suggests that restoration measures are more likely to succeed, even on steep gradients, if encouragement is given to 'dry-phase' species such as *Sphagnum capillifolium* rather than 'wet-phase' aquatic species such as *S. cuspidatum*. Support for this idea comes from evidence about the relative rates of peat formation displayed by different species of *Sphagnum*.

Peat formation
and the Sphagnum assemblage

Stratigraphic analysis of peat bog systems reveals that the major peat formers tend to be species of hummock/ridge *Sphagnum*, rather than *Sphagnum cuspidatum* that characterises the hollow/pool elements. Proctor (1955) identifies these hummock/ridge species as the "*most important peat-forming Sphagna*". Clymo & Hayward (1982), Boatman (1983) and Hulme (1986) also emphasise the relatively small contribution to peat formation made by species typical of the hollow/pool environment.

When a mire stands at the threshold between minerotrophic and ombrotrophic conditions, the major part of the surface resembles the hollow/pool phase of a bog. Bellamy & Rieley (1967) describe the conditions of semi-ombrotrophy found on individual hummocks within a minerotrophic mire and emphasise that the micro-environment most closely resembling that of ombrotrophic bog is to be found exclusively on the tops of scattered hummocks. The system enters the ombrotrophic phase because the terrestrial hummock-forming species coalesce, or draw up the aquatic hollows with them. Indeed Belyea and Clymo (1998) develop a model of bog growth based on the differential growth and decomposition rates of the hummock and hollow (aquatic) elements of a bog. They propose that the slow rate of peat accumulation in hollows determines the overall rate of peat accumulation in a bog. As they observe:

"By analogy, one may imagine the hummocks as small but active dogs on leads, straining as far ahead as they can from the staid hollow that holds the leads in hand and controls the rate at which the convoy moves."

An abundance of aquatic-zone *Sphagnum* species may thus not be, of itself, sufficient to shift a naturally-developing mire surface from minerotrophic to ombrotrophic conditions. Such observations highlight an essential difference between the two main pathways of peat formation. Terrestrialisation relies initially on aquatic species of *Sphagnum*, and assumes that these will eventually be replaced by terrestrial species of *Sphagnum.*

Paludification begins with dry conditions that become increasingly wet, resulting in direct colonisation by terrestrial species of *Sphagnum*.

One question to be addressed, therefore, is which of the two processes - terrestrialisation or paludification - brings the quicker result? More specifically:

- how quickly do aquatic *Sphagna* form extensive carpets in terrestrialising structures?
- how quickly do terrestrial *Sphagnum* species directly colonise paludifying bare peat surfaces?
- do terrestrial *Sphagnum* species invade carpets of aquatic *Sphagnum* species created through terrestrialisation more quickly than they do paludifying bare peat surfaces?
- if they do, how long is the *combined* period of colonisation for aquatic, then terrestrial, *Sphagna* resulting from terrestrialisation, compared with the direct colonisation of peat surfaces by terrestrial *Sphagna* through paludification?

Peat forming process and restoration management

Richard Lindsay

Figure 5: Colonisation by *Eriophorum vaginatum* of abandoned, milled peat-field in Latvia. No active restoration work has been carried out on this site, but beavers have dammed up part of the drainage system on a distant part of the site.

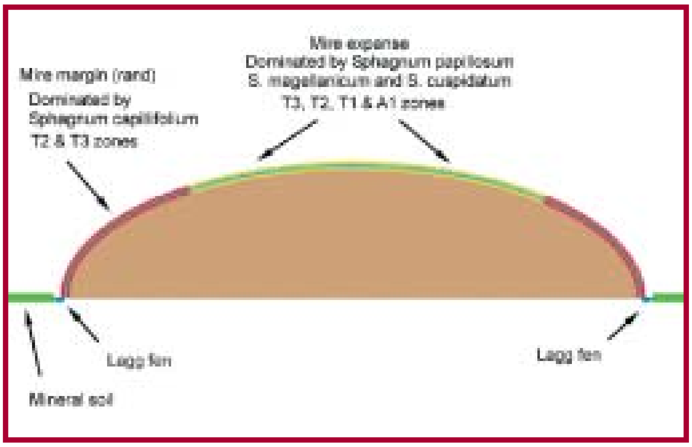
Restoration focus - catotelm or acrotelm ?

While re-establishment of a stable water table is clearly an important priority for restoration of bog environments, according to the European Commission definition (Romão 1996) success cannot be claimed until a vegetation capable of forming peat has been re-established. In fact it could be argued that the whole thrust of restoration action should be directed towards re-establishment of a functioning acrotelm rather than on the detailed shape of the catotelm. This is because even the most perfectly-shaped catotelm cannot survive without the protection of a functioning acrotelm. The large-scale engineering approach to terrestrialisation as a means to restoration is based on the principle that major effort must be devoted to shaping the peat body into something suitable for colonisation by appropriate aquatic vegetation, as a precursor to acrotelm formation.

Evidence from the field, however, suggests that paludification can go some way towards encouraging direct acrotelm re-establishment on existing surfaces without the need for large-scale engineering of the peat body itself. Much of this evidence comes from the range of peatland restoration work undertaken by conservation bodies both in Britain and abroad.

Even after extensive drainage, the catotelm can be sufficiently waterlogged to encourage at least incipient natural development of an acrotelm without any form of intervention - albeit perhaps rather slowly. Figures 5 and 6 illustrate the way in which vegetation – often the cotton grasses *Eriophorum vaginatum* or *E. angustifolium* – is capable of colonising areas of bare catotelm peat. Grosvernier *et al.* (1995) have demonstrated that such species are important in providing shelter from sun and wind for *Sphagnum* species, which subsequently colonise beneath the protective canopy of vegetation.

Where the water table is very low within the catotelm peat (particularly on upstanding blocks of peat within block-cut commercial workings) it is usual to find a range of typical heathland species on the raised baulks. Birch (*Betula pubescens*), bracken (*Pteridium aquilinum*) and heather (*Calluna vulgaris*) are characteristic. Nonetheless, the extremely low hydraulic conductivity of catotelm peat can mean that isolated, upstanding blocks of peat are still able to retain at least a semblance of an active acrotelm. The nature reserve area at Bolton Fell Moss, in Cumbria, for example, is just such a block surrounded by intensively-worked commercial peat cuttings. The vegetation of the reserve area was dominated by *Betula pubescens* woodland until the trees were removed recently. In spite of this, a thriving acrotelm community could be found that contained species typical of at least the hummock level (T3 - Lindsay, Riggall & Burd 1985) or even species of high ridge (T2 - Lindsay, Riggall & Burd 1985). The main direct influence of drainage is felt only at the margins of this block, where catotelm peat is exposed to the atmosphere at the cut peat face (Lindsay 1995).



Richard Lindsay

Figure 6: The major zonations on a raised bog, from aquatic lagg fen, through the steep (and thus largely terrestrial) rand, to the low gradients of the mire expanse.

The sequence of drainage effects expected for such a block of peat is described by Hobbs (1986) and outlined in Chapter 5 of Lindsay *et al*. 1988, but can be summarised as slumping, shrinkage and wastage. Ultimately, the peat within this upstanding block can be expected to shrink down to a new stable dome through a sequence of events dominated by oxidative wastage of the peat. Such a process is likely to occur at a rate of no more than 3mm per year, based on the rate of shrinkage observed at the former raised bog of Holme Fen and current exposure of the Holme Fen Post (5 metres since 1855). Holme Fen lies in the relatively low-rainfall area of the East Anglian Fenlands with a typical soil-moisture deficit of more than 180mm, compared with a deficit of between 60mm and 180mm for areas of England that still possess raised bog habitat (Bendelow & Hartnup 1980). The rate of oxygen penetration and consequent rate of oxidative wastage for Holme Fen is thus likely to be substantially greater than for areas such as Cumbria or even the Humberhead Levels.

Slow, oxidative loss of such catotelm peat means of course that, even though restoration work may be under way, some of the peat will continue to be lost through wastage until a new stable bog profile has been reached. In comparing the strengths and weaknesses of relying solely on terrestrialisation for restoration of worked surfaces that vary considerably in height, there are a number of benefits in developing a mixed strategy:

1. The present upstanding block is currently subject to its worst, most extreme state of water-table draw-down (assuming that no further peat extraction will take place around it). Any slumping and oxidative wastage thus tends to bring the living surface (the acrotelm layer) steadily closer to the GWM water table, thus in effect increasingly re-paludifying the bog surface over time.

2. Evidence from Switzerland (Schneebeli 1991; von Gunten 1994) indicates that drained or upstanding blocks of peat tend to develop a more highly humified region just beneath the acrotelm (as a result of oxygen penetration to greater depths through the acrotelm into former catotelm peat). This humified layer creates a somewhat waterproof layer beneath the acrotelm even on considerable gradients and helps to pond water within the acrotelm zone, thus increasing surface wetness (see von Gunten 1994 p.252). Consequently such upstanding blocks of peat may be capable of supporting relatively wet vegetation even while they settle to a new shape.

3. The peat archive within these slumping, oxidising blocks of peat inevitably undergoes breakdown and oxidative loss of some material. Nonetheless, a considerable proportion of the archive will still be retained, albeit in a more compressed and humified form. Highly humified peats are regularly used for palaeo-ecological research in blanket mire areas (Tallis 1964, Charman 1994, Barber 2000) and thus clearly still have much to offer. The major difficulties with blanket mire peats arise not from their humified nature, but from occasions when they have been re-worked by erosion, or where parts of the sequence have been removed by former domestic peat cutting. Furthermore, as a result of the widespread loss in lowland Britain of raised bog habitat reported by Lindsay & Immirzi (1996), many commercial peat workings now represent one of the few remaining examples of a peat archive in their region.

The strongest arguments for altering the shape of the catotelm rather than attempting to re-constitute an acrotelm are to be found on those occasions where upstanding blocks of peat pose sufficiently serious problems for some type of direct action to be required. On various occasions it has been found that substantial cracks appear in the peat towards the outer margins of the upstanding peat block (*e.g.* Cors Caron). These can act as drains, but can also be a fore-runner of peat collapse, where the cut face of the bog collapses outwards in a series of stages with successive slabs peeling away. Such a phenomenon is undoubtedly difficult to mitigate against. In such cases the active re-profiling of mire edges may be the most appropriate action if restoration is to be achieved within the 30-year deadline of the European Commission.

Several existing raised bogs are recorded as having suffered catastrophic bog-bursts in the past, the great Chat Moss bog-burst being described by Leland (Smith 1910), while more recent examples include the well-documented example of la Vraconnaz bog in Switzerland (Feldmayer-Christe & Mulhauser, 1994). Despite these calamitous events, sites such as Chat Moss appear to have recovered sufficiently to resemble typical raised bogs once more. Marginal collapse may make it more difficult to meet the 30-year milestone of the European Commission, but it appears not to be inevitably catastrophic for the future recovery of the bog, so that use of re-profiling and terrestrialisation may not even be appropriate under these extreme circumstances.

TERRESTRIALISATION METHODS: THE BUND-LAGOON TERRACE SYSTEM

A ‘bund-lagoon’ approach has been suggested as a possible route to restoration, based on restoration work on industrially-damaged peatland sites in Germany and the Netherlands. It is proposed by Wheeler & Shaw (1995) that flat areas capable of retaining precipitation (‘lagoons’), be created by scraping flat the industrially-worked peat surface using industrial machinery. Retaining walls (‘bunds’) are either created, or deliberately retained during the peat extraction process. These bunds are positioned according to appropriate contour intervals. Ultimately, the whole pattern of bunds and lagoons resembles a terraced paddy-field structure as Wheeler & Shaw (1995) describe and illustrate (see their Figure 5.6, p.9, and Plate 5.7, p.94).

Such an environment, while theoretically being appropriate for the re-establishment of a typical flora in the early stage of terrestrial succession, may not provide optimal conditions even for these early stages. This is for a variety of practical reasons:

- wave action is a disprupting influence that inhibits *Sphagnum* growth;
- the characteristic species that tolerate open water are *Sphagnum cuspidatum* and *S. auriculatum*, but these species are poor peat-formers, as discussed earlier; the other typical semi-aquatic species is *S. recurvum*, but this species can dominate areas for very considerable periods of time without being joined by other typical bog species;
- the truly aquatic environment (A1 to A3 of Lindsay, 1995) is an extremely species-poor environment in terms of other bog plants – although it is rich in aquatic invertebrates;
- areas of open water tend to attract water birds, resulting in high levels of nitrogen and phosphorus inputs – which tend to encourage non-bog species such as *Juncus effusus*.

Appendix 6 of Wheeler & Shaw (1995) lists the sites considered during their extensive review, and summarises the restoration works already attempted. This Appendix contains only a very few examples of the ‘bund-lagoon’ type system. None of the cited examples from the continent can demonstrate conclusively that peat is forming. The Leegmoor is described as having extensive carpets of *Sphagnum cuspidatum*, but, as discussed earlier, *S. cuspidatum* is a poor peat-former.

Wheeler & Shaw (1995) illustrate some practical results of the lagoon approach in three photographs. The first is their Plate 5.7, p.94, which shows lagoons dug at Gardrum Moss by the peat extraction company as an experimental exercise in restoration. It is very evident from the photographs, but also if one visits the site, that the bulk of the lagoon system is devoid of anything resembling bog vegetation – indeed the lagoons remain largely devoid of any vegetation today.

Wheeler & Shaw’s (1995) second and third illustrations are their Plate 4.2 (p.68) and Plate 5.10 (p.98), the first from Bargerveen, the Netherlands, and the second from Lichtenmoor, northern Germany. What is so striking about these photographs is the absolute monotony of the *Sphagnum* carpet, consisting as it does solely of *S. cuspidatum*. From personal observation, the only *Sphagnum* species present over large expanses of many such lagoons in northern Germany is either *S. cuspidatum* or *S. recurvum*.

As discussed earlier, most bog peat deposits consist largely of terrestrial species – that is, they belong to the part of the bog that is commonly described as ‘ridge’ or ‘hummock’. Although they occupy a niche only 10cm – 20cm above the bog water table, such species are nevertheless intolerant of flooding and submergence. Meanwhile hollows and pools are dominated largely by a few submergence-tolerant species – such as *S. cuspidatum* - that tend to lay down peat very slowly.

Dominance of *Sphagnum cuspidatum* may set the process of acrotelm formation in motion, but it is not yet clear when the more typical terrestrial species will begin to colonise nor what starting conditions are required. One site that does demonstrate the transition from aquatic to terrestrial Sphagna is the Haakbergerveen, on the Dutch-German border.

The site was extensively worked for peat, then abandoned around the Second World War. As can be seen in Figure 7, within the re-vegetated lagoons of old peat workings, signifcant areas of terrestrial species such as *Sphagnum magellanicum* and *S. capillifolium* have become established. It thus seems that the transition is possible within a 50-year period, but unfortunately there are no detailed records for the starting condition of these areas. The current terrestrial swards are patches within the overall site, and it is now very difficult to say why some areas have started to become terrestrial, while others have not. Perhaps palaeo-stratigraphy could help here, although even this evidence would only give a partial picture of the relevant factors.

Given the evidence from these terrestrialisation examples, it may instead be worth examining evidence for restoration through paludification. In particular, it would be valuable to establish restoration-response times resulting from the creation of wet (but not flooded) peat surfaces onto which terrestrial species can colonise through paludification.

PALUDIFICATION AND BACK-PALUDIFICATION: RESTORATION METHODS

Paludification through climate

Clearly there is no realistic possibility of increasing precipitaton at source, though tree and scrub removal can increase the *effective* precipitation across a bog surface. Interception rates for precipitation of 20% or more have been measured beneath conifer forest canopies (Newson 1985), while even dense *Calluna* stands can have a significant interception effect (NCC 1986). By removing the canopy, the ground surface receives a significantly higher proportion of the incoming precipitation. Sites which are undergoing draw-down through drainage cannot afford to lose any part of the ambient precipitation inputs. Controlling scrub invasion can thus be a vitally important component of any bogland restoration programme for this reason alone.

Back-paludification - blocking the lagg-fen ditch

In every example of lowland raised bog in Britain, the lagg fen has been wholly or partially modified by human activity. It is thus usual to find that the margins are the driest parts of British raised bogs (Lindsay & Immirzi 1996). Under such conditions there seems little scope for back-paludification of the type seen for Latvia in Figure 3 on page 24.

Roger Meade

Figure 7: Regeneration at Haaksbergerveen (Netherlands/German border). A detailed view of the vigorous mixed *Sphagnum* community that has developed in some parts of the site. Insert shows the general condition of the site, with areas of regeneration, areas of *Eriophorum* and some bare peat.

The edges of bogs in Britain are also usually marked by the presence of a deep ditch. These marginal ditches remove excess water from the adjacent land but also drain the lagg fen zone.

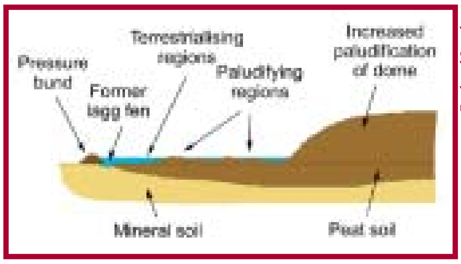
A limited degree of increased paludification can be achieved for such sites by tackling this zone. Dams can be placed in the lagg-zone drain system to re-create something similar to the former lagg fen. Water tables can only rise to the lip of the existing ditch, but under conditions of typical agricultural drainage where the water-table in the original lagg fen zone may have been lowered by 1 metre or more below the soil surface, this represents a potentially substantial rise in the base-level for the Groundwater Mound. This in turn gives rise to increased potential for paludification (*i.e.* increased water content) of the peat dome.

Back-paludification - restoration of the lagg fen through 'pressure-bunds'

An approach using the same general idea as blocking the lagg ditch, but involving a greater scale of direct intervention, has been used extensively at Cors Caron NNR in Wales. A line of bunds *(pressure bunds)* has been bulldozed into place around the outer margin of the peat body - *i.e.* not at the cut face of the artificially-truncated hemi-ellipse but at the outer limit of the peat soil deposit. The bund system is designed to retain precipitation that would normal flow out from the peatland site. More specifically, the system holds the water closer to the original natural level that would have been found at the edge of the mire in the lagg fen zone, before agricultural drainage and oxidative peat wastage caused the ground surface at the peat margin to sink.

In retaining the water at the outer margin of the peat soil, the system in effect re-creates the lagg fen in its originally waterlogged state. As the level of the lagg fen determines the base-level on which the hemi-ellipse of the Groundwater Mound sits, the new lagg fen raises the overall base-level of the Groundwater Mound for the bog. In this way the new lagg fen encourages at least some degree of increased paludification of the upstanding raised dome. The principle of the pressure-bund can be seen diagramatically in Figure 8, while the bunding lagoons at Cors Caron are illustrated on the cover of Wheeler & Shaw (1995).

The extent to which this type of action can produce increased paludification (*i.e.*



Richard Lindsay

Figure 8: The principle of the 'pressure bund'. A dam of (usually peat) material is created on the outer edge of the former lagg fen zone – *i.e.* at the outer edge of the peat body. Rainwater and seepage from the raised bog are retained within the ponded zone. Areas of open water have the potential to colonise through terrestrialisation, while areas that are saturated but not flooded have the potential to become paludified. The elevation of the water table within this zone raises the base-level of the ground-water mound, and thus may increase paludification of the remaining bog dome.

raised water levels) in the raised bog dome has not yet been well studied. Van der Schaaf (1999) believes that manipulating water tables in the lagg-fen zone is likely to have little effect on the GWM. In contrast, Bragg & Steiner (1995) present, for a site in Austria, a restoration strategy that is heavily based on the principle of controlling water levels in the original lagg fen and this restoration programme is now under way. It is also possibly worth considering the implications of an observation by King (1685) in his description of the bogs of Ireland that:

"Every red bog [raised bog] has about it a deep marshy sloughy ground, which they call the bounds of the bog, and which never fails to be worth the draining…".

Back-paludification and drain-blocking
Catotelm peat has an extremely low hydraulic conductivity – often more than 10,000 times lower than the conductivity in the acrotelm (Ingram 1983). Consequently it is extremely difficult to drain the catotelm. This is why, even when deep drains have been dug in a raised bog, the water content of the peat remains high and machinery can only move safely across the site if fitted with wide tracks or very large tyres.

Stewart & Lance (1983) examined the effect of agricultural drainage on peatland systems. They concluded that the main impact of drainage in such systems is that it "removes surface water more rapidly". More particularly, as Lindsay *et al.* (1988) point out, drainage specifically empties the acrotelm while leaving the catotelm still largely waterlogged. Figures 9 and 10 illustrate two areas that are being currently worked as peat-milling fields, with gradients specifically designed to shed water as quickly as possible. They show that even under these conditions, water can still usually be found standing in the slit drains. This is because it is very difficult to lower the water table more than a metre or so into the main body of peat (Boelter 1972). If this amount of visible water is found in the drains when the area is subject to active drainage and peat extraction, how much more water could be retained if the drainage system were to be blocked up? By installing dams in the drains, the water table is raised almost (but not quite) to the surface in an extensive area around the dam. This makes the exposed catotelm peat wetter, and potentially renders it sufficiently wet to provide conditions suitable for re-establishment of an acrotelm (*i.e.* generally some form of *Sphagnum* sward).

The primary function of drain blocking is thus to encourage surface conditions that are suitable for acrotelm re-establishment through paludification. Such suitable conditions may only occur in limited areas around the dams to begin with, but as acrotelm is formed over this area, this then widens the impact of the dams over a larger area of the bog surface through back-paludification. Eventually, separate areas of dam-influenced acrotelm begin to coalesce to form a more continuous acrotelm.

Most damaged sites have one or more drains cut through them, and commercially-worked sites have a whole network of largely regular drains. Each drain, if dammed, can form a linear focus for back-paludification. The main body of the drain becomes a zone of terrestrialisation, but the immediate margins of the drain become zones of paludification. As these become paludified, the process of back-paludification creates a gradual expansion of paludified conditions outwards and upslope from the drain, as water, then eventually bog vegetation, infill the ditch and


Lorne Gill

Figure 9: Commercial peat extraction, Letham Moss, Scotland. The slit-drains can be clearly seen, as can water ponded in the bottom of the slit drains, indicating that the water table remains high even under conditions of intensive drainage and extraction.


Lorne Gill

Figure 10: Commercial peat extraction, Whim Bog, Scotland. As with Figure 9, the water ponded in the ditches can be seen clearly.

Peatland Pictures

A GALLERY OF IMAGES OF RISLEY MOSS
compiled by John Moorcroft and Pat Waning

Album III - The End Results

Colonisation of woodland ground flora

Remnants of bog flora or areas of re-colonisation?

Colonisation of woodland ground flora

Remnants of bog flora or area of re-colonisation?

Recent *Sphagnum* growth

Polytrichium dying back

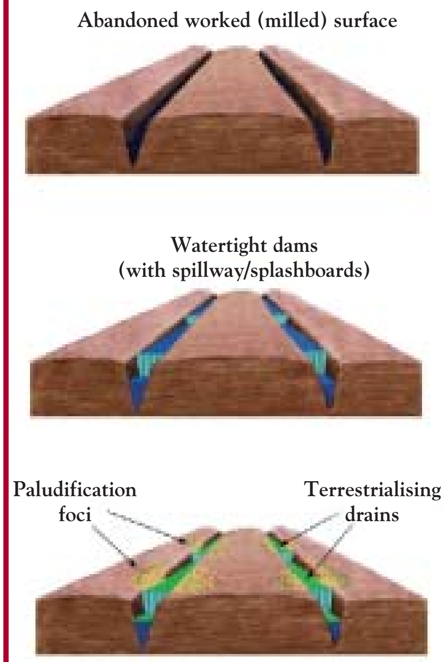


Figure 11: The combined process of terrestrialisation and paludification resulting from drain-blocking using waterproof dams. The top diagram shows the bog surface in its commercially-worked condition. The middle diagram shows the installation of dams and the resulting ponding of water within the drains. The bottom diagram shows the way in which the drains have become colonised through terrestrialisation, while areas around the choked drains are now forming expanding foci of colonisation through paludification.

cause surface water to pond back across the formerly dry bog surface. Using simple materials (as described in Brooks & Stoneman 1997) and relatively simple techniques, a dry, commercially worked milled peat area can in this way be converted into a network of paludification foci (see Figure 11).

With a general rise in local water tables caused by damming of the cutting hollows, increased paludification (in effect, elevated water tables) occurs within any associated upstanding baulks. Over time, as the flooded cutting-hollows become infilled with bog species through terrestrialisation, the influence of paludification on the adjoining baulks means that heath species become less competitive and are replaced by more typical bog species (though note the *caveat* made earlier about ensuring that precipitation is not intercepted by scrub or tree canopies).

Back-paludification - experience of ditch blocking/dams in Britain

Of the 43 sites listed in Appendix 6 of Wheeler & Shaw (1995), 26 of these had restoration management that involved ditch blocking (60%). At least some of these are described as producing the desired shift in vegetation toward peat-forming conditions. Concern has been expressed in the past that the result of ditch blocking in some sites has been disappointing. In some cases, the ditch-blocking has been carried out using peat rather than a truly waterproof material for the dams. Brooks and Stoneman (1997) set out a number of cautionary notes in relation to the use of peat dams, and it is likely that at least some of the problems encountered are because these points were not fully taken into account.

Brooks & Stoneman (1997) provide yet more examples of dam installation for both raised bogs and blanket bogs, the latter often having substantial gradients over quite short distances. The dams themselves have been made from a variety of materials, from simple peat to steel shuttering with inert coating. Many of these were originally described by Rowell (1988) and then subsequently, after more experience had been gained with the materials, by Brooks & Stoneman (1997).

A reasonably large number of raised bog and blanket bog sites now contain collections of dams installed in various and varied conditions.

As an example of this, Figure 12 illustrates two drains from an intensively drained area in Caithness, northern Scotland. Dams were installed about 5 years ago on an area with a fall of around 5 metres in 300 metres.

What is evident from the vegetation is that, while not all parts are benefitting from a high water table (because the dams do not

Richard Lindsay

Figure 12: Drain-blocking, Munsary, Caithness. The two drains illustrated were blocked, using plyboard dams, some five years prior to these photographs. The drains themselves show only limited colonisation by terrestrialisation, but the adjoining bog surface contains a relatively rich assemblage of 'terrestrial' *Sphagnum* species.

Richard Lindsay

Richard Lindsay

FIGURE 13: A close-up view of a corrugated sheet-metal dam installed at Blawhorne Moss, Scotland, some 6 or 7 years prior to this photograph. The top of the dam can just be seen (arrowed) after pulling back the upper layer of *Sphagnum*. The drain (and many like it on this site) has now largely infilled through terrestrialisation.

provide uniform re-wetting along the gradient), substantial parts do now have a high water table and the general response of the vegetation has been good.

Caithness is at a higher latitude than, for example, Cumbria and so there are substantial differences in terms of overall climate, but the rainfall in Caithness ranges from 650mm to 1000mm, which is not so very different from Cumbria.

Figure 13 illustrates another example of ditch-blocking, this time in the lowlands of Scotland. The site is Blawhorne Moss, a raised bog located south of Edinburgh, and the photograph illustrates the way in which the corrugated steel dam has become so overgrown by *Sphagnum* – in what was originally a clean, dry ditch – that it is necessary to dig down into the freshly-accumulated peat to find the top of the dam. The photograph was taken about 6 years after the dams had been installed across a sloping area that was intensively drained and which supported only a very dry, almost heath-like vegetation. The *Sphagnum* species in these ditches consist of *S. recurvum, S. tenellum, S. capillifolium* and even patches of *S. papillosum*.

More significantly, the *Sphagnum* sward from these ditches is spreading out across the intervening expanses of bog surface to re-establish a more typical bog vegetation through a process of paludification. Three species in particular play a major part in this expansion – *S. tenellum* (which is a species of wet heaths and can tolerate periods of wetting and drying), *S. capillifolium* (which is characteristic of hummock tops and can thus tolerate relatively low water levels, and *S. papillosum* which is the most vigorous of the typical bog *Sphagna*.

Back-paludification - dams and sloping bogs in Austria

Many bog restoration programmes involving ditch-blocking and damming are currently being carried out across the continent of Europe, but one example of particular relevance to the questions surrounding restoration of vegetation over sloping bog surfaces can be found in the Lower Tauern region of Austria, near Tamsweg. The climate here provides an annual rainfall of around 900mm. The site is listed in the Austrian Mire Conservation Catalogue (Steiner 1992) as the "bog south of Überlinghütte" [Moores südlich der Überlinghütte]. The site is only some 300 metres by 200 metres in size, but has a slope of more than 10 metres down its long axis. It had been intensively drained and consequently supported a relatively dry 'heath'-like vegetation.

Prior to any restoration management, continuous water-level records were obtained for the site using an electronic recorder. In September 2000, a series of dams was installed throughout the drainage system to encourage restoration through paludification (Steiner & Latzin 2001). The location of these on the drain lines can be seen as red dots in Figure 14. The response of the water table can be also seen in Figure 14. What is very striking about the water-level data is that within 1 month, the previously-fluctuating water table settles down to a stabe position just at the present ground surface. These are good conditions for encouraging the re-development of an active acrotelm through paludification.

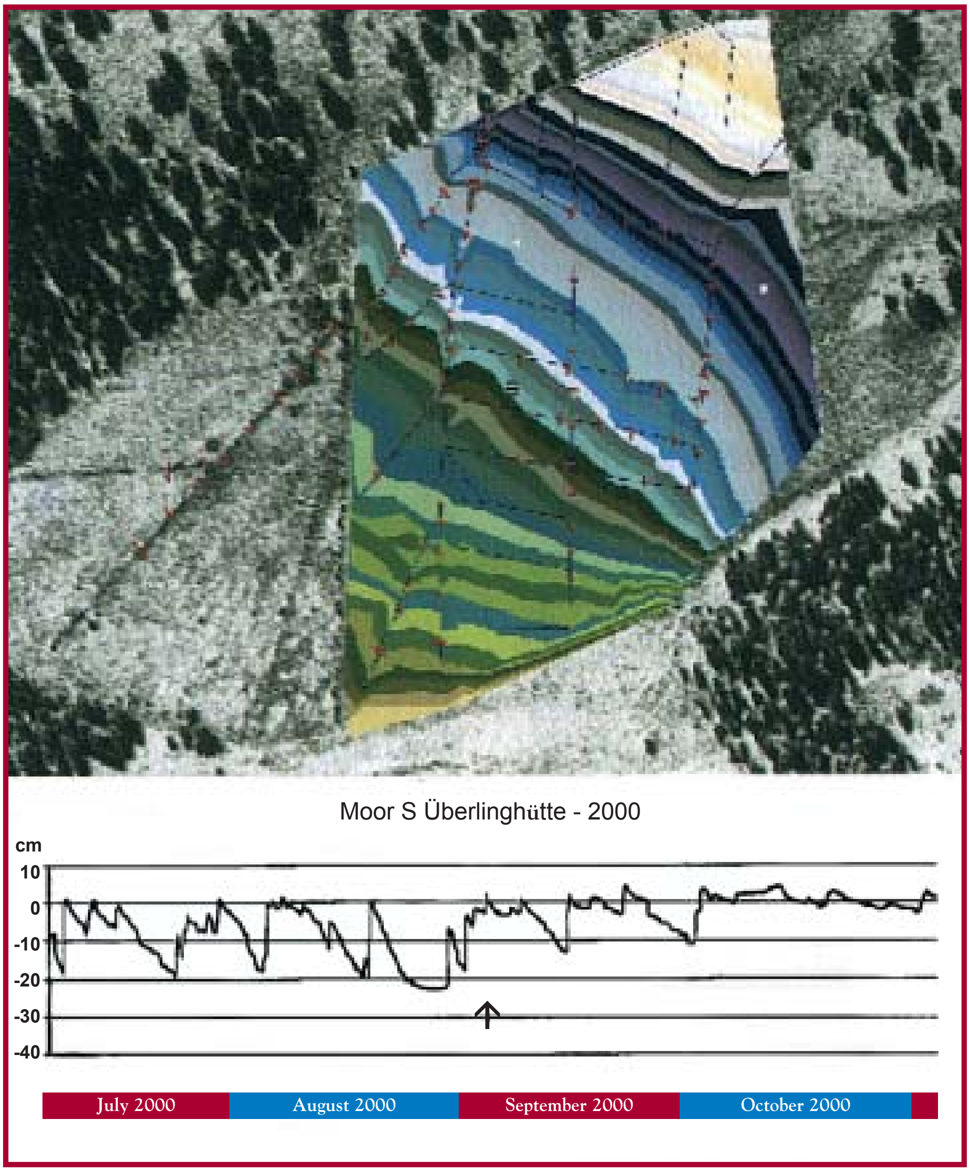
These data have particular relevance to the question of restoration and surface gradients because the site has a slope that matches or exceeds many of the most steeply-sloping parts of damaged raised bogs in Britain, yet the response of the water table is very clear. (Indeed Michael Steiner reports that the site actually has a fall of 20 metres, but this does not match with the illustration provided from Steiner & Latzin 2001, so the example may be even more dramatic than is presented here). The response of the water-table, as shown by the continuous recording trace, illustrates the extent to which back-paludification can give rise to a widespread response in the water table across a bog surface, even though management is only carried out on the drain lines. It is as yet too early to know how the peat-forming plants will respond to the raised water table.

Back-paludification - how to encourage vegetation colonisation ?

An abandoned milled surface is undoubtedly hostile, often with a pH as low as pH3, and the dark peat tends to absorb heat thus encouraging further water losses (Smart 1983). Nonetheless, as seen earlier, the water table itself is often quite close to the surface even in the most intensely drained milled fields. The problem for the catotelm is the lack of an acrotelm. The surface may be sufficiently wet to support *Sphagnum*, but the hostile temperatures and extreme acidity make colonisation difficult (see, for example, Grosvernier *et al.* 1995).

If an acrotelm can be re-established on areas surrounding blocked slit-drains, the process of restoration can be said to have begun. From that point onwards the natural interaction between acrotelm and catotelm will increasingly mimic the process of original bog hydrology and dynamics in these localised areas of paludification. In time, the acrotelm can be expected to expand. If conditions are dry on the site to begin with – perhaps because of steep gradients as a result of extraction – the model suggests that the acrotelm would tend to consist of *Sphagnum* species that are typical of drier climate phases or drier, more steeply-sloping parts of the bog such as the rand slopes. More specifically, the model suggests that *Sphagnum capillifolium* or *S. papillosum* would be a typical species for such conditions. Of course, opportunistic species such as *Pteridium aquilinum*, *Calluna vulgaris* or *Betula pubescens* frequently colonise and dominate the drier parts of abandoned peat workings, but scrub clearance and long-term paludification can be expected to encourage more typical bog species at the expense of such opportunists in the longer term.

The key question, therefore, is whether re-establishment of a *Sphagnum* cover is possible across such a hostile region within a relatively short time (30 years)? What if there appears to be no prospect of colonisation from surrounding refugia? Research carried out in Canada by the Canadian Peat Moss Association and the University of Laval has shown at least one way that might prove capable of encouraging a carpet of *Sphagnum* to become established on a milled surface. Building on the discovery that *Sphagnum* grows best when somewhat sheltered and if provided with a framework/ scaffolding structure to grow within, Boudreau & Rochefort (2000) have shown that covering a milled surface with a straw and *Sphagnum* mulch can result in development of a *Sphagnum* carpet within just 12 months. A regular re-covering may be required until the *Sphagnum* carpet becomes more fully established.



Michael Steiner

FIGURE 14: Plan view, superimposed on a monochrome vertical aerial photograph, of Überlinghütte Mire, Austria. The various colours indicate altitudinal differences in 20cm intervals. The bog slopes downwards from top-right to bottom-left, falling more than 10 metres in only 300 metres. Below the map is a continuous water-level record taken from close to the centre of the site. The left part of the water-level chart displays considerable fluctuations in water-table. In the centre of the chart is a vertical arrow; this indicates the date on which several dams were installed in the drainage ditches across the site. The resulting water-table to the right of the arrow displays much less fluctuation and remains consistently high. The location of the dams can be seen as red dots scattered across the site.

Propagule supply

There is evidence that spores and even fragments of *Sphagnum* are abundant in the atmosphere, and thus any surface with appropriate conditions can be colonised by *Sphagnum*. There are certainly recorded cases where bog surfaces that have lacked any trace of *Sphagnum* for more than 50 years have developed vigorous carpets within 12 months. For example, on removal of the dense cover of *Rhododendron* growing on the dome of Roudsea Mosses NNR in Cumbria, pockets of *Sphagnum* became established within months,

Richard Lindsay

FIGURE 15: This site in Switzerland had been drained decades ago, resulting in rapid colonisation by tree species. This picture shows the condition of the bog surface prior to restoration management, with no wetland byrophyte layer and a dark, dense forest cover.

and extensive carpets had formed within a year.

Figure 15 shows a site in Switzerland where dense mountain pine forest (*Pinus mugo*) had come to cover the whole area of a raised bog following intensive drainage. The same site is depicted in Figure 16, which shows the bog surface 12 months after tree clearance and ditch blocking, and it can be seen that the surface already has an extensive mixed *Sphagnum* carpet.

The recovery of these surfaces appears to due to three factors. Firstly and most obviously, the competitively aggressive tree canopy has been removed. Secondly, removal of the canopy has allowed more precipitation to reach the ground surface - effectively increasing paludification (or paludification-potential) of the ground surface. Thirdly, the increasingly favourable paludification and micro-climate conditions resulting from ditch blocking and tree clearance encourage colonisation by *Sphagnum* from spores or fragments borne on the winds.

It may be that use of a straw mulch can help with the establishment of naturally-existing propagules, but it would perhaps be more valuable first to carry out a review of restoration programmes already under way, and assess the extent to which paludification is giving good results without such additional (and somewhat un-natural) materials.

CONCLUSIONS AND POSSIBLE RESTORATION SCENARIOS

The evidence and issues set out in this paper are not intended as an argument for the sole use of paludification as the means by which peatland restoration can be achieved. They are presented in order to emphasise that most restoration work is actually a combination of terrestrialisation and paludification. It is, however, important to recognise that until now, theoretical and strategic planning for many of the larger bog sites now coming into conservation management have been concerned almost entirely with the potential use of terrestrialisation. Hopefully this paper has helped to clarify the parts played by both terresrialisation and paludification in peatland restoration, and raised awareness of the fact that more than one major pathway to restoration exists.

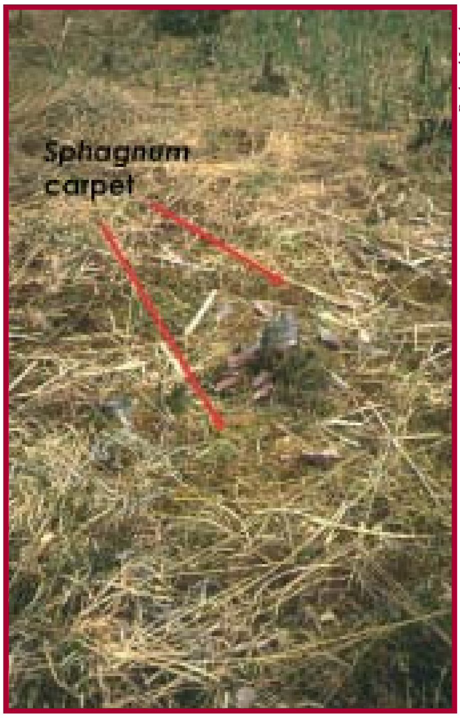
Of particular relevance is the way in which, by including paludification within the set of tools available for the restoration process, it is possible to offer alternative restoration scenarios to those based largely on terrestrialisation and large-scale engineering. Such an alternative scenario might consist of the following:

- Identification of all drains within the site.
- Identification of the outer bounds of the surviving peat-soil deposit.
- Identification of a potential lagg-fen zone.
- Insertion of entirely waterproof dams into all small-scale drains found within the site. This can be done sequentially, in response to what happens.
- Construction of waterproof dams on larger-scale drains, and sealing of any peat-cutting hollows.
- Removal of trees and scrub cover to maximise the proportion of precipitation that reaches the peat surface.
- Examination of raised baulks for evidence of cracks and severe slumping. Where present, consider re-profiling the edge (over as narrow a zone as possible) to provide more stability to the peat face. Re-profiling should aim to leave the maximum amount of dome untouched by the re-shaping process.
- Creation of a lagg fen either using dams in the lagg-fen ditch or by constructing pressure bunds along the outer edge of the peat boundary, or whatever boundary is realistic.

As for further research, it is strongly recommended that a comprehensive review be carried out into the wide range of bogland restoration activities currently being undertaken in Britain, Ireland, Austria, Switzerland, France, and the Nordic countries. In particular, the review would examine critically the relative contribution of terrestrialisation and paludification to the restoration process. It would also assess the relative degrees of success being achieved by the various practical restoration methods employed. Finally, it would set out an integrated framework for peatland restoration, combining the principles of terrestrialisation and paludification, together with the eco-hydrological model of the Ground Water Mound (in its most recent refinement), and the phasic model of acrotelm dynamics. It should also set out within this framework a range of appropriate monitoring methods that would enable judgements to be made about the ongoing success or failure of any restoration management programme.

ACKNOWLEDGEMENTS

I should like to acknowledge the generosity of Prof. Dr. G.M. Steiner, University of Vienna, in providing extensive information for, and illustrations of, regeneration work in Austria, and similar grateful thanks go to Andreas Grünig in Switzerland for his several guided tours of the mire management work being carried out in Switzerland. I am also grateful to Roger Meade for being able to provide photographs of Haaksbergerveen.



Richard Lindsay

FIGURE 16: The same bog surface as figure 16 one year after tree removal and blocking of drains with waterpoof dams. A reasonably continuous and vigorous cover of *Sphagnum* has developed over ground that was formerly almost devoid of vegetation.

REFERENCES

AGNEW, A.D.Q., RAPSON, G.L., SYKES, M.T. & BATSOW WILSON, J. (1993). *The functional ecology of Empodisma minus in New Zealand ombrotrophic mires*. New Phytologist, 124, 703-710.

BARBER, K.E. (1981). *Peat Stratigraphy and Climatic Change*. Rotterdam : Balkema.

BARBER, K.E., MADDY, D., ROSE, N., STEVENSON, A.C., STONEMAN, R.E. AND THOMPSON, R. (2000). *Replicated proxy-climate signals over the last 2000 years from two distant UK peat bogs: New evidence for regional palaeoclimate teleconnections*. Quaternary Science Reviews, 19, 481-487.

BELLAMY, D.J. & RIELEY, J.O. (1967). *Some ecological statistics of a "miniature bog"*. Oikos, 18, 33-40.

BELYEA, L. & CLYMO, R.S. (1998). *Do hollows control the rate of peat growth?* In: V. Standen, J.H. Tallis & R. Meade (Eds.) Patterned Mires and Mire Pools. Origin and Development; flora and fauna. (Proceedings of the Mires Research Group Conference, University of Durham, 6-7 April 1998.) London : British Ecological Society.

BENDELOW, V.C. & HARTNUP, R. (1980). *Climatic Classification of England & Wales*. (Technical Monograph 15.). Harpenden : Soil Survey of England & Wales.

BOATMAN, D.J. (1983). *The Silver Flowe National Nature Reserve, Galloway, Scotland*. Journal of Biogeography, 10, 163-274.

BOELTER, D.H. (1972). *Water table drawdown around an open ditch in organic soils*. Journal of Hydrology, 15, 329-340.

BRAGG, O.M. & STEINER, G.M.. (1995). *Applying groundwater mound theory to bog management on Puergschachenmoos in Austria*. In: A. Moen (Ed.) Regional variation and conservation of mire ecosystems. Gunneria, 70, 83-96.

BOUDREAU, S & ROCHEFORT, L. (2000). *The Use of Companion Species or Straw Mulch Cover : Microclimatic Conditions and Implications for Sphagnum Re-Establishment*. IPS Contributed Papers Session 150 (Part 1). Paper presented at Quebec 2000: Millennium Wetland Event.

BROOKS, S. & STONEMAN, R. (EDS.) (1997). *Conserving Bogs : The Management Handbook*. Edinburgh : The Stationery Office.

CAJANDER, A.K. (1913). *Studien uber die Moore Finnlands [Studies of Finnish Mires]*. Acta Forestalia Fennica, 2(3), 1-208.

CAMPBELL, E.O. (1983). *Mires in Australasia*. In: A.J.P. Gore (Ed.) Mires: Swamp, Bog, Fen and Moor. Regional Studies. Ecosystems of the World, 4B. pp. 95-152. Amsterdam : Elsevier.

CHARMAN, D.J. (1994). *Patterned fen development in northern Scotland: developing a hypothesis from palaeoecological data*. Journal of Quaternary Science, 9, 285-297.

CLEMENTS, F.E. (1916). *Plant succession. An analysis of the development of vegetation*. Washington : Carnegie Institute.

CLYMO, R.S. & HAYWARD, P.M.. (1982). *The ecology of Sphagnum*. In: A.J.E. Smith (Ed.) Bryophyte Ecology. 229-291. Newton Abbott : David & Charles.

DUPIEX, N. (1998). *La gestion conservatoire des tourbières de France : premiers éléments scientifiques et techniques*. Orléans : Espaces Naturels de France, programme Life "Tourbières de France".

FELDMAYER-CHRISTE, E. & MULHAUSER, G. (1994). *A moving mire – the burst bog of la Vraconnaz*. In: A. Grünig (Ed.) Mires and Man. Mire Conservation in a Densely Populated Country – the Swiss Experience. 181-186. Birmensdorf : Swiss federeal Institute for Forest, Snow & Landscape Research.

GIBSON, N. & KIRKPATRICK, J.B. (1992). *Dynamics of a Tasmanian cushion heath community*. Journal of Vegetation Science, 3, 647-654.

GODWIN, H., & CONWAY, V.M. (1939). *The ecology of a raised bog near Tregaron, Cardiganshire*. Journal of Ecology, 27, 313-363.

GOODE, D.A. (1973). *The significance of physical hydrology in the morphological classification of mires*. In: Proceedings of the International Peat Society Symposium, Glasgow, 1973. Classification of Peat and Peatlands, Paper 3.

GOODE, D.A. & RATCLIFFE, D.A. (1977). Peatlands. In: D.A. Ratcliffe (Ed.) A Nature Conservation Review. Vol.1, 249-287; Vol. 2, 206-244. Cambridge : Cambridge University Press.

GRANLUND, E. (1932). *De svenska högmossarnas geologie. [The geology of the Swedish Hochmoore]*. Sveriges Geologiska Undersökning. Afhandlingar och Uppsatser, 373, 1-193.

GROSVERNIER, P., MATTHEY, Y & BUTTLER, A. (1995). *Microclimate and Physical Properties of Peat: New Clues to the Understanding of Bog Restoration Processes*. In: B.D. Wheeler, S.C. Shaw, W.J. Fojt & R.A. Robertson (Eds.) Restoration of Temperate Wetlands. pp. 435-450. Chichester : John Wiley & Sons.

HEINSELMAN, M.L. (1963). *Forest sites, bog processes, and peatland types in the Glacial Lake Agassiz region, Minnesota*. Ecological Monographs, 33, 327-372.

HOBBS, N.B. (1986). *Mire morphology and the properties and behaviour of some British and foreign peats*. Quarterly Journal of Engineering Geology, 19, 7-80.

HULME, P.D. (1980). *The classification of Scottish peatlands*. Scottish Geographical Magazine, 96, 46-50.

HULME, P.D. (1986). *The origin and development of wet hollows and pools on Craigeazle Mire, south-west Scotland*. International Peat Journal, 1, 15-28.

INGRAM, H.A.P. (1967). *Problems of hydrology and plant distribution in mires*. Journal of Ecology, 55, 711-724.

INGRAM, H.A.P. (1982). *Size and shape in raised mire ecosystems: a geophysical model*. Nature, 297, 300-303.

INGRAM, H.A.P. (1983). *Hydrology*. In: A.J.P. Gore (Ed.) Mires: Swamp, Bog, Fen and Moor. General Studies. (Ecosystems of the World 4A.) pp. 67-158. Amsterdam : Elsevier Scientific.

INGRAM, H.A.P., & BRAGG, O.M. (1984). *The diplotelmic mire: some hydrological consequences reviewed*. In: Proceedings of the Seventh International Peat Congress, Dublin, 1984, 1, 220-234.

IVANOV, K.E. (1981). *Water Movement in Mirelands*. London : Academic Press.

KING, W. (1685). *On the bogs and loughs in Ireland*. Philosophical Transactions, 15, 948 *et seq*.

KLINGER, L. F. (1996). *The myth of the classic hydrosere model of bog succession*. Arctic & Alpine Research, 28, 1-9.

KULCZYNSKI, S. (1949). *Peat Bogs of Polesie*. Mémoirs de l'Académie Polonaise des Sciences et des Lettres, Série B., 15, 1-356.

LINDSAY, R.A. (1995). *Bogs: The Ecology, Classification and Conservation of Ombrotrophic Mires*. Perth : Scottish Natural Heritage.

LINDSAY, R.A., RIGGALL, J., & BURD, F. (1985). *The use of small-scale surface patterns in the classification of British peatlands*. Aquilo, Seria Botanica, 21, 69-79.

LINDSAY, R.A., CHARMAN, D.J., EVERINGHAM, F, O'REILLY, R.M., PALMER, M.A., ROWELL, T.A. AND STROUD, D.A. (1988). *The Flow Country : The peatlands of Caithness and Sutherland*. Peterborough : Nature Conservancy Council.

LINDSAY, R.A. AND IMMIRZI, C.P. (1996). *An inventory of lowland raised bogs in Great Britain*. Scottish Natural Heritage Research, Survey and Monitoring Report. No. 78. Perth : Scottish Natural Heritage.

MANNEVILLE, O., VERGNE, V. & VILLEPOUX, O. (1999). *Le Monde des tourbières et des marais*. Lausanne : Delachaux et Niestlé S.A.

MARK, A.F., JOHNSON, P.N., DICKINSON, K.J.M. & MCGLONE, M.S. (1995). *Southern hemisphere patterned mires, with emphasis on southern New Zealand*. Journal of the Royal Society of New Zealand, 25, 1, 23-54.

MOEN, A. (1999). *National Atlas of Norway : Vegetation*. Hønefoss : Norwegian Mapping Authority.

MOORE, P.D. & BELLAMY, J.D. (1974). *Peatlands*. London : Elek Science.

NATURE CONSERVANCY COUNCIL. (1986). *Nature Conservation and Afforestation*. Peterborough : Nature Conservancy Council.

NEWSOME,. M. (1985). *Forestry and water in the uplands of Britain: the background of hydrological research and options for harmonious land-use*. Quarterly Journal of Forestry, 79, 113-120.

OSVALD, H. (1923). *Die Vegetation de Hochmoores Komosse, Kap. 5 [The vegetation of the raised bogs of Komosse, Chapter 5]*. Svenska Växtsociologiska Sällskapets Handlingar, 1, 265-310.

PROCTOR, M.C.F. (1955). *A key to the British species of Sphagnum*. Transactions of the British Bryological Society, 2, 552-560.

PROCTOR, M.C.F. (1995). *The Ombrogenous Bog Environment*. In: B.D. Wheeler, S.C. Shaw, W.J. Fojt & R.A. Robertson (Eds.) Restoration of Temperate Wetlands. pp. 287-303. Chichester : John Wiley & Sons.

RATCLIFFE, D.A. (1964). *Mires and bogs*. In: J.H. Burnett (Ed.) The Vegetation of Scotland. 426-478. Edinburgh, Oliver and Boyd.

ROMÃO, C. (ED.) (1996). *Interpretation manual of European Union Habitats : Version EUR 15*. Brussells : Directorate General XI, D.2, European Commission.

ROWELL, T.A. (1988). *The peatland management handbook*. Research & Survey Report No.14. Peterborough : Nature Conservancy Council.

SCHNEEBELI, M. (1991). *Hydrologie und Dynamik der Hochmoorentwicklung. [Hydrology and Dynamics of Raised Mire Development.]* PhD Thesis. Zürich, ETH.

SJÖRS, H. (1948). *Myrvegetation i Bergslagen [Mire vegetation in Bergslagen, Sweden]*. Acta Phytogeographica Suecica, 21, 1-299. [English summary: 277-299.]

SMART, P.J. (1983). *The Plant ecology of re-vegetated peat cuttings in ombrotrophic mires, with special reference to Thorne Moors, South Yorkshire*. PhD thesis, University of Sheffield.

SMITH, L.T. (1910). *The Itinerary of John Leland in or about the Years 1535-1543*. Vol. 5 (Part IX). London : G. Bell and Sons.

STEINER, G.M. (1992). *Österreichischer Moorschutzkatalog [Austrian Mire Conservation Inventory]*. Wein : Bundesministerium für Umwelt, Jugend und Familie.

STEINER, G.M. & LAZIN, S. (2001). *Renaturierung und Management [Restoration and Management]*. Nature und Land, 1/2, 34-35.

STEWART, A.J.A., & LANCE, A.N. (1983). *Moor-draining: a review of impacts on land use*. Journal of Environmental Management, 17, 81-99.

TALLIS, J.H. (1964). *Studies on southern Pennine peats. I. The general pollen record*. Journal of Ecology, 52, 323-331.

TANSLEY, A.G. (1939). *The British Islands and their Vegetation*. Cambridge : Cambridge University Press.

VAN DER SCHAAF, S. (1999). *Analysis of the hydrology of raised bogs in the irish Midlands : A case study of Raheenmore Bog and Clara Bog*. PhD thesis. Wageningen : Wageningen Agricultural University.

VON GUNTEN, B. (1994). *How to rehabilitate a sloping bog – the Gamperfin site*. In: A. Grünig (Ed.) Mires and Man. Mire Conservation in a Densely Populated Country – the Swiss Experience. 246-253. Birmensdorf : Swiss federeal Institute for Forest, Snow & Landscape Research.

WEBER, C.A. (1902). *Über die Vegetation und Entstehung des Hochmoores von Augstumal im Memeldelta [On the Vegetation and development of the Aukštumala Raised Bog in the Memel Delta]*. Berlin.

WEBER, C.A. (1908). *Aufbau und Vegetation der Moore Norddeutschlands [Structure and vegetation in north German mires]*. Engler, Botanischen Jahrbüchern, 90, 19-34.

WHEELER, B.D. (1980). *Plant communities in rich-fen systems in England and Wales. I. Introduction. Tall sedge and reed communities*. Journal of Ecology, 68, 365-396.

WHEELER, B.D. & SHAW, S.C. (1995). *Restoration of Damaged Peatlands – with particular reference to lowland raised bogs affected by peat extraction*. London : HMSO.

WICKMAN, F.E. (1951). *The maximum height of raised bogs and a note on the motion of water in soligenous mires*. Geologiska Föreningens i Stockholm Förhandlingar, 73, 413-422.

WEB-SITE www.ex.ac.uk/geography/modules/GEO3208/session4.html