THE EFFECTS OF REHABILITATION MANAGEMENT ON THE VEGETATION OF FENN'S, WHIXALL AND BETTISFIELD MOSSES NATIONAL NATURE RESERVE – A CUT-OVER LOWLAND RAISED MIRE

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ABSTRACT

The relationship between vegetation change and rehabilitation management is investigated at a severely degraded cut-over lowland raised mire on the Wales/England border, managed by Natural England and The Countryside Council for Wales. Positive responses are confirmed 11 years after rehabilitation commenced, identifying trends towards raised mire as well as bog pool vegetation and water table thresholds associated with these trends have been established.

A landscape-scale vegetation survey was carried out three times over 9 years. Species abundance was correlated with average seasonal water table height, time since rehabilitation, cutting type and survey year. Key species maps for the time series confirmed positive vegetation response, but slower than stipulated in the site management plan. There was a clear increase in the target peat-forming species (*Sphagnum cuspidatum, Eriophorum angustifolium* and *E. vaginatum*) as a direct response to rehabilitation and correlating positively with a high water table.

Permanent quadrat vegetation monitoring was carried out three times at five-year intervals. Uncut areas and areas of recent commercial cuttings were rehabilitated earliest having significant increases in target mire species without the loss of other mire species from excess inundation. In the recent commercial cutting areas, a successional trend was identified, from a low water table to a fluctuating water table characterised by *Molinia caerulea*-rich vegetation, followed by a transition to stable, inundated conditions supporting *Sphagnum cuspidatum/Eriophorum* spp pool vegetation. A second successional trend, associated with the achievement of a near-surface, stable water table, saw the development of raised mire vegetation including *Sphagna* other than *S. cuspidatum*. This latter trend was primarily found in the uncut areas of the site but was also found to a lesser extent in recently cut-over areas where it was preceded by a fluctuating water table with a *Calluna vulgaris- Molinia caerulea* vegetation.

A new survey related water table residence time calculated from hydrology data with vegetation for each quadrat. Analysis identified a mire pool vegetation type correlated with shallow, above surface flooding. A diverse mire vegetation type was also found which correlated with the water table staying within the upper 10cm of peat. The minimum threshold for establishment of *Sphagnum* species was found to be an average water table level within the range of 5.1 to 10cm below the peat surface. Higher cover of *Sphagnum* species was related to shallow flooding – suggesting that these conditions would be most efficient in re-establishing mire vegetation.

A base-line vegetation monitoring survey on an area immediately following deforestation and damming identified a subtle but positive response of the mire vegetation to management within one year.

CONTENTS

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CHAPTER 1
INTRODUCTION

1.1 Introduction

The present study is an attempt to describe and assess the vegetation changes which are associated with the re-wetting of a highly cut-over lowland raised mire. The mire is Fenn's, Whixall & Bettisfield Mosses National Nature Reserve (NNR) which is located across the English-Welsh border in the counties of Shropshire and Wrexham.

The importance of lowland raised mires for conservation, science and natural history has received growing recognition. The visual character of the raised mire landscape, archaeology and palaeoecology interest, as well as flora and fauna communities are important features (Wheeler and Shaw, 1995).

1.2 Literature review

1.2.1 Mire systems

Mires are wetlands which span the high latitudes of the world and some areas of the tropics - covering approximately 3% of the world's land area (Brooks and Stoneman, 1997). The term *mire* describes any peat-forming ecosystem. They are commonly sub-divided into *bogs* or *fens* (according to nutrient status/ water source) and are known collectively as *peatlands*.

Mires develop where the accumulation of dead organic matter exceeds that lost by decay (Brooks and Stoneman, 1997). The conditions required for this accumulation (peat formation) are a humid climate where precipitation exceeds evapotranspiration. The high water table levels maintain anaerobic waterlogging, causing low levels of microbial activity in the soil (Päivänen, 1998).This leads to an accumulation of organic matter from plant debris (especially *Sphagnum* mosses which dominate the vegetation). Over a year, *Sphagnum* mosses grow in height by a few centimetres, but subsequent decomposition and compaction means the rate of accumulation of peat is approximately 0.5 to 1mm per year. Deep peat deposits therefore, represent thousands of years of plant debris accumulation (Quinty and Rochefort, 2003).

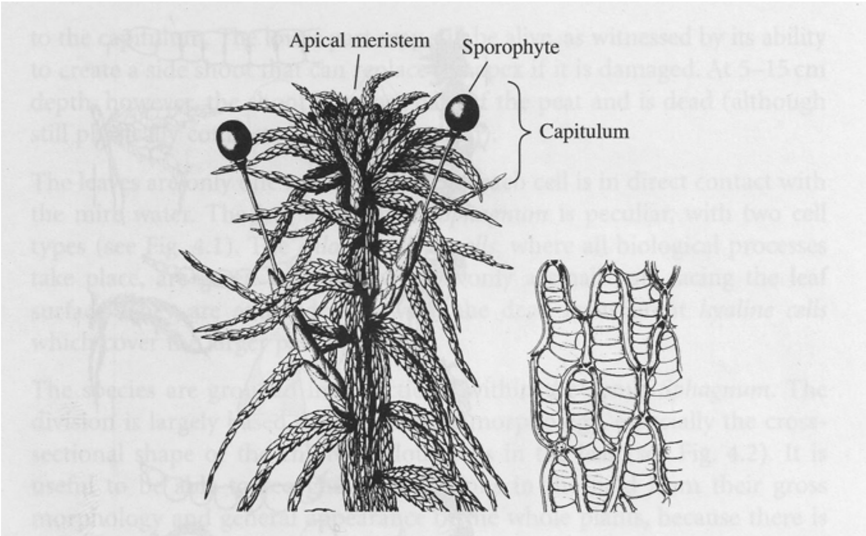
There are two processes by which mires develop: 1. terrestrialization (in-filling of shallow lakes; 2. paludification (formation of peat directly on poorly drained mineral ground) (Quinty and Rochefort, 2003).

Fen peat develops from vegetation receiving water and nutrients from surface run-off and/or groundwater, i.e. growing in minerotrophic conditions. This tends to be more nutrient rich and alkaline. Bog peat develops from vegetation receiving water and nutrients from the atmosphere only, i.e. growing in ombrotrophic conditions. This environment tends to be acidic and low in nutrients (Charman, 2002).

The dominant peat-forming plants are *Sphagnum* moss species with notable contribution also from the sedge family, *Cyperaceae,* grass family, *Poaceae* and rush family, *Juncaceae*. The morphology of the *Sphagnum* genus allows the plant to absorb and retain large quantities of water, preventing rapid drying out during periods of decreased humidity or falls in water level (Daniels and Eddy, 1985). *Sphagnum* is described by Berry *et al.* (1996) as being 'sponge-like' and capable of raising the water table due to its ability to hold water. Porley and Hodgetts (2005) describe the genus as being unique in that it has the ability to hold 20 times its own weight in water.

Sphagnum is capable of generating acid conditions which few other species can tolerate. It achieves these conditions through chemicals in the cell walls i.e. unesterified polyuronic compounds, which give up their hydrogen ions in exchange for mineral ions. The hydrogen ions are released into the surroundings and create the acidic conditions prevalent in mires. *Sphagnum* has an indeterminate growth pattern, where by individual shoots grow continually upward and die back below, to become peat (Porley and Hodgetts, 2005).

Figure 1.1 below shows the morphology of a *Sphagnum* shoot. A *Sphagnum* carpet has a density of 1-7 shoots cm^{-2} (Rydin and Jeglum, 2006).



A *Sphagnum palustre* shoot with sporophytes. The top meristem is embedded in the new, not yet fully developed branches. This cluster is called the capitulum. Below the capitulum the clearly distinguishable hanging (pendant) and spreading branches are seen. The close-up of the leaf shows the single layer of cells. The darker, narrow chlorophyllous cells are alive and perform photosynthesis. The larger hyaline cells with their fibres and pores are dead and normally filled with water. From Schimper (1858).

Figure 1.1 A *Sphagnum palustre* shoot.

Source: Rydin and Jeglum (2006).

Vascular plants have specific adaptations to the flooding and anoxic conditions of the peatland habitat. In order to transport oxygen to roots and rhizomes plants have widened intercellular spaces leading from the leaves and through the stem. These spaces are known as *aerenchyma* and also help with buoyancy (Rydin and Jeglum, 2006).

Vascular plants which are completely submerged have thin leaves with a large surface area. An example is *Utricularia* spp. which take up carbon dioxide and nutrients from the water into the leaves, in the way bryophytes do. Another adaptation seen is the formation of floating vegetation rafts i.e. *Carex* spp. and *Menyanthes trifoliata* hold together floating mats of *Sphagnum* in Schwingmoor or quaking mires (Rydin and Jeglum, 2006).

High tussock development in some sedge species means that these plants are able to endure a highly fluctuating water table and keep a large proportion of their leaves above the water table.

Vascular plants with shallow root systems colonize the hummocks of lowland raised mires. These species inhabit the aerated zone of microtopography, just above the upper limit of the water table. Some tree species and dwarf shrubs characteristically occupy this niche (Rydin and Jeglum, 2006).

Mire plants are mostly stress tolerators and have adapted to the nutrient-poor habitat by conserving nutrients. Conservation of nutrients is achieved by a long life span (with little production of seeds), long-lived leaves and recycling of nutrients (Grime, 2001).

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1.2.2 The little-disturbed lowland raised mire ecosystem

As the ice sheets retreated from northern Europe following the last ice age, large blocks of ice became detached from the edges of the ice sheets. The ice blocks were embedded in often impermeable glacial drift. The blocks gradually melted leaving water filled basins, forming lakes (Brooks and Stoneman, 1997).

The lowland raised mire progresses by continual natural developmental change (Figure 1.2), beginning most frequently as a water filled basin, developing into swamp, through fen, fen carr and eventually raised mire (Wheeler *et al.*, 1995). The swamp and fen vegetation stages of the transition primarily have a minerotrophic water source, rich in nutrients with pH values typically of neutral to alkaline.

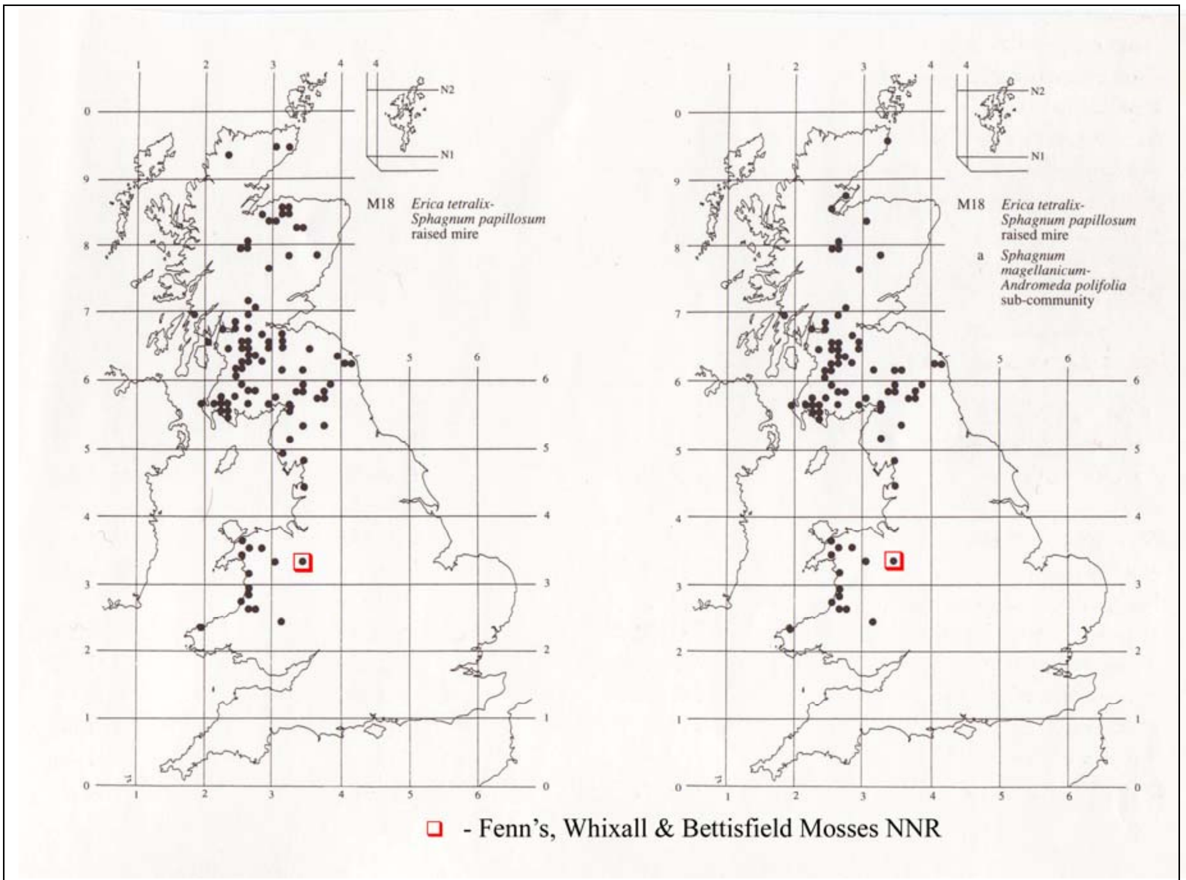


Figure 1.2 The distribution of UK lowland raised mires

The map on the left shows the distribution of the National Vegetation Classification (NVC) M18 *Erica tetralix-Sphagnum papillosum* raised and blanket mire community. The map on the right shows the distribution of the M18a *Sphagnum magellanicum-Andromeda polifolia* raised mire sub-community. The present study site is highlighted in red.

Source: Rodwell (1991).

As the basin becomes in-filled with fen peat, the central vegetation becomes isolated from nutrients incoming at the basin periphery. Conditions at the centre of the peat surface become nutrient poor (Brooks and Stoneman, 1997) and acidification of the fen peat surface occurs as it becomes independent of the ground water supply (Ratcliffe, 1977). The surface then becomes ombrogenous (dependent on the atmosphere for water and nutrients) with rain-fed inputs being low in nutrients. There is a transition in vegetation type, corresponding to the change in nutrient status. Sphagnum is able to exploit these oligotrophic conditions and further enhances acidic, anoxic, nutrient poor conditions, where it out-competes other plant species (Heathwaite and Göttlich, 1993). Figure 1.3 shows the development stages of lowland raised mires.

Sphagnum forms the upward growing dome of the lowland raised mire, and dominance of the genus, along with high peat water levels, is essential for continuing development. Runoff from water flowing from the mire and surrounding mineral soil forms a wet marginal fen zone to the dome, this is known as the *lagg* (Heathwaite and Göttlich, 1993). The lagg is shown in Figure 1.3 (diagram 5.).

The raised mire habitat supports a specialised assemblage of flora and fauna. Vegetation includes *Sphagnum* mosses, *Erica tetralix* and *Calluna vulgaris*, *Eriophorum vaginatum* and *E. angustifolium*, *Vaccinium oxycoccos* and *Drosera* spp. (Brooks and Stoneman, 1997).

In little-disturbed lowland raised mires, the peat profile has two layers; *catotelm* and *acrotelm.* The lower layer (catotelm) forms the greatest majority of the peat dome. The catotelm is permanently waterlogged and plant material is dead (Brooks and Stoneman, 1997). Anaerobic conditions result in low microbial activity and peat decomposition. Peat is relatively decomposed and compacted and water movement is slow (Quinty and Rochefort, 2003).

The upper layer (acrotelm) is where peat actively forms (Brooks and Stoneman, 1997). The acrotelm is an actively growing layer of plants approximately 50cm in thickness, predominantly comprising *Sphagnum* mosses (Ingram & Bragg, 1984). Individual stems of *Sphagnum* grow as a tightly packed carpet, with an undulating surface forming hummocks, lawns and pools. Water storage capacity in the acrotelm is high in intact mires. This provides a regulatory function, controlling water table fluctuations and maintaining surface-wet conditions (Bragg, 1989). It is only in the very driest of weather that the water level may fall below 10 – 20cm from the peat surface (Brooks and Stoneman, 1997). Anaerobic and aerobic conditions alternate periodically with the fluctuation of the water table and favour more rapid microbial activity than the catotelm (Quinty and Rochefort, 2003). Figure 1.4 shows the structure of the acrotelm and catotelm in undisturbed mires.

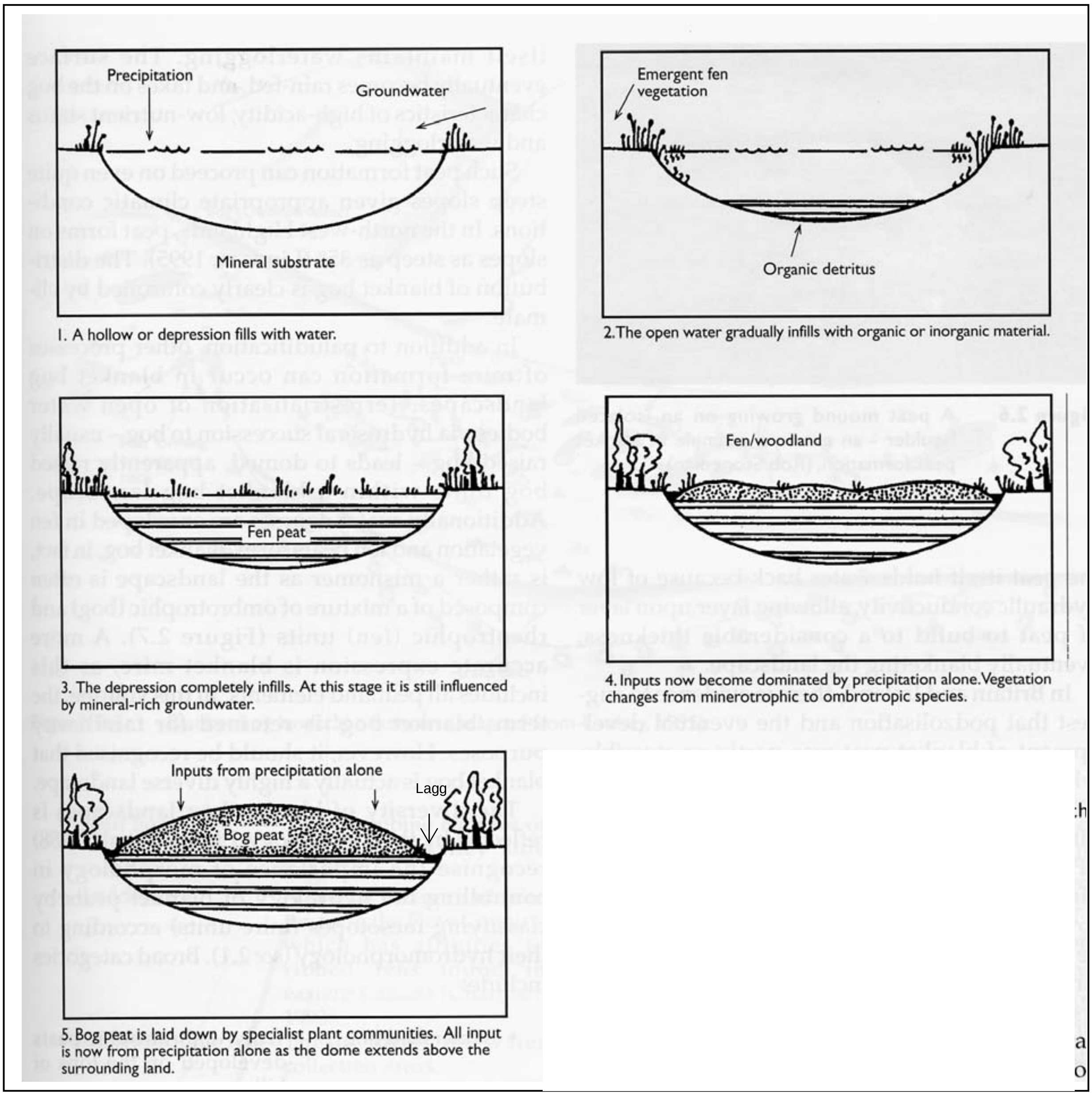


Figure 1.3 Hydroseral succession leading to the development of a lowland raised mire.

Source: Brooks and Stoneman (1997)

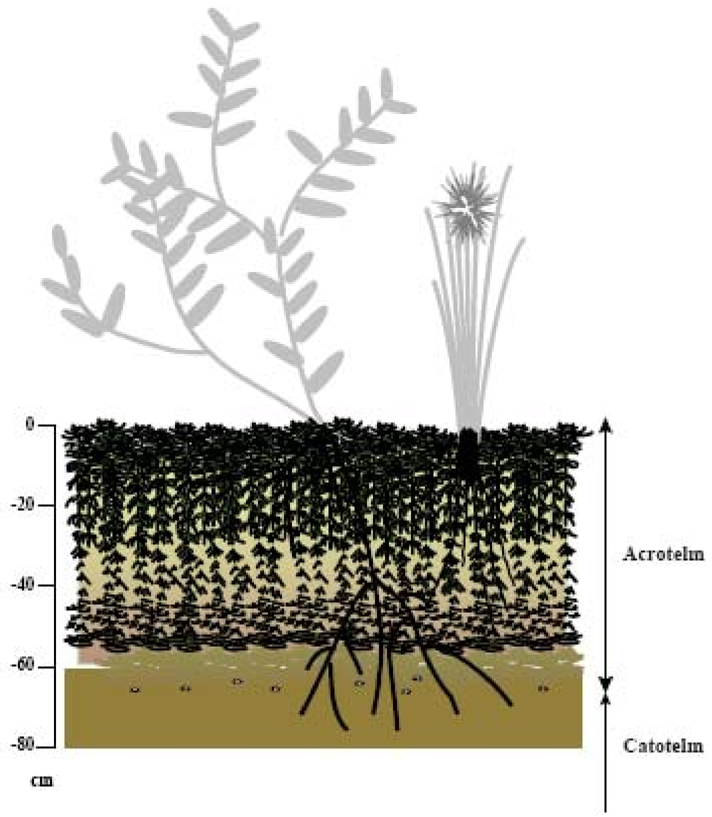


Figure 1.4 Diagram showing the structure of the acrotelm and catotelm

Source:,Quinty and Rochefort (2003)

Water content of peat in its natural state is 87-97%, dry matter is 2-10% and 1-7% is gas (Charman, 2002). The water table of the raised mire adopts a domed profile. Water reaching the dome surface is meteoric water and water leaves the mire system via evapotranspiration and seepage (vertically via the mire base and laterally via the sides). This process maintains the mire water balance (Brooks and Stoneman,1997). Figure 1.5 describes the hydraulic system which results in the formation of the dome which also known as the *ground water mound.*

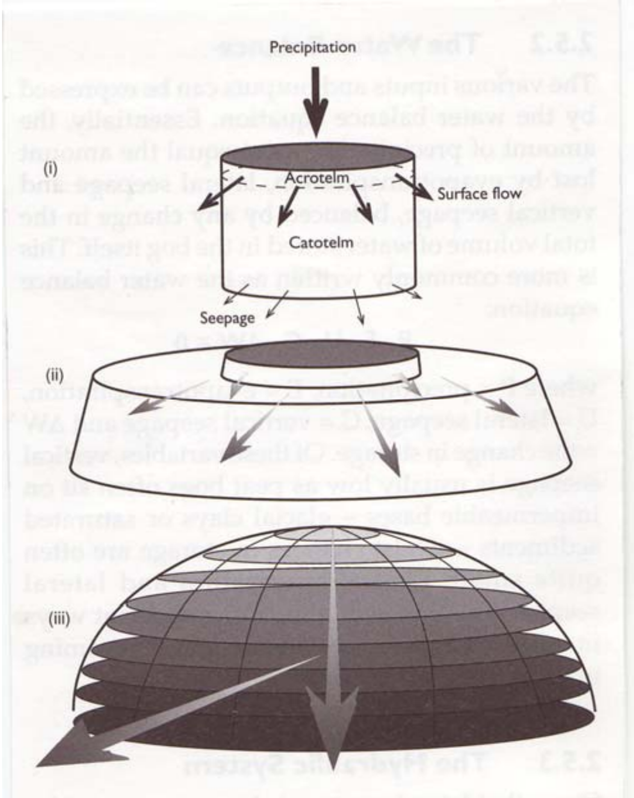


Figure 1.5 Lateral seepage in successive rings around the central core of the raised mire.

i). The centre of the mire receives meteoric water.

ii). The peat around the uppermost central area receives meteoric water and seepage.

iii). Each successive ring moving outwards away from the centre , receives progressively more water. To disperse the increasing volume of water, the slope of the water table has to increase, i.e. the water in the mire must take the form of a dome.

Source: Brooks and Stoneman (1997).

The continual development of the acrotelm surface is described by Tansley (1939) as a cyclic regeneration process, where the surface consists of alternating hummocks and hollows. Different plant species occupy the various microforms (Lindsay, 1995) of the hummock-hollow environment. Peat at the bottom of a hollow is built up by the remains of the vegetation occupying the hollow, until it rises above the adjacent hummock and replaces it as a new hummock. The former hummock therefore becomes a hollow and this process continues to be repeated (Tansley, 1939).

An alternative theory to the development of the mire surface is one of phasic growth (Heathwaite and Göttlich 1993) where the whole surface of the mire reacts in the same direction to climate oscillations.

1.2.3 Vegetation change – models of succession

The classic model of succession was described by Clements in 1916**.** Clement proposed that succession represented a unidirectional series of changes which could not be reversed. This definition was broadened in 1927 by Gleason who included all community changes including regeneration of the same vegetation type and minor fluctuations in community structure (Chapman and Reiss, 1992). Today succession falls between these two early views and is seen as a series of changes in community structure and species composition - the non-seasonal, directional and continuous pattern of colonisation and extinction on a site by species populations (Begon *et al.,* 1996).

The hydroseral succession of a post-glacial lake to a lowland raised mire is an example of *primary* succession, vegetation developing from a bare surface. *Secondary* succession is the sequence of vegetation developing on previously vegetated and disturbed ground (Chapman and Reiss, 1992).

The alternative to succession models is no model at all i.e. *chaos.* The chaos theory opposes the ordered, directional processes of succession. It states that the unpredictable processes external to ecosystems determine species change (Chapman and Reiss, 1992).

1.2.4 National Vegetation Classification

National Vegetation Classification (NVC) 'M18 *Erica tetralix* - *Sphagnum papillosum*' is recognised as the raised and blanket mire community (Rodwell, 1991). Blanket mire is similar vegetation which forms on slopes in the uplands under conditions of particularly high rainfall. The M18 sub-community M18a *Sphagnum magellanicum* - *Andromeda polifolia,* is the vegetation type believed to be most characteristic of little-damaged raised mires in the United Kingdom. Restoration goals would favour a return to such a vegetation type (Money, 1995).

M18a is dominated by an extensive bryophyte carpet of the family Sphagnaceae. *Sphagnum papillosum* and *S. magellanicum* form undulating lawns, accompanied to a lesser extent by *S. subnitens*, *S. tenellum* and *S. palustre*. *S. capillifolium* is associated with forming hummocks just above the water table, while *S. cuspidatum* and *S. auriculatum* colonize wetter hollows (Rodwell, 1991). The NVC M2 *Sphagnum cuspidatum/recurvum (fallax)* bog (mire) pool community is an integral part of M18a (see Figure 1.6).

Vascular plants play a subordinate role in the M18a community and include ericoid sub-shrubs (*Calluna vulgaris*, *Erica tetralix*, *Andromeda polifolia* and *Vaccinium oxycoccos*) and monocotyledons (*Eriophorum vaginatum* and *E. angustifolium*) forming a low and patchy canopy (Rodwell, 1991).

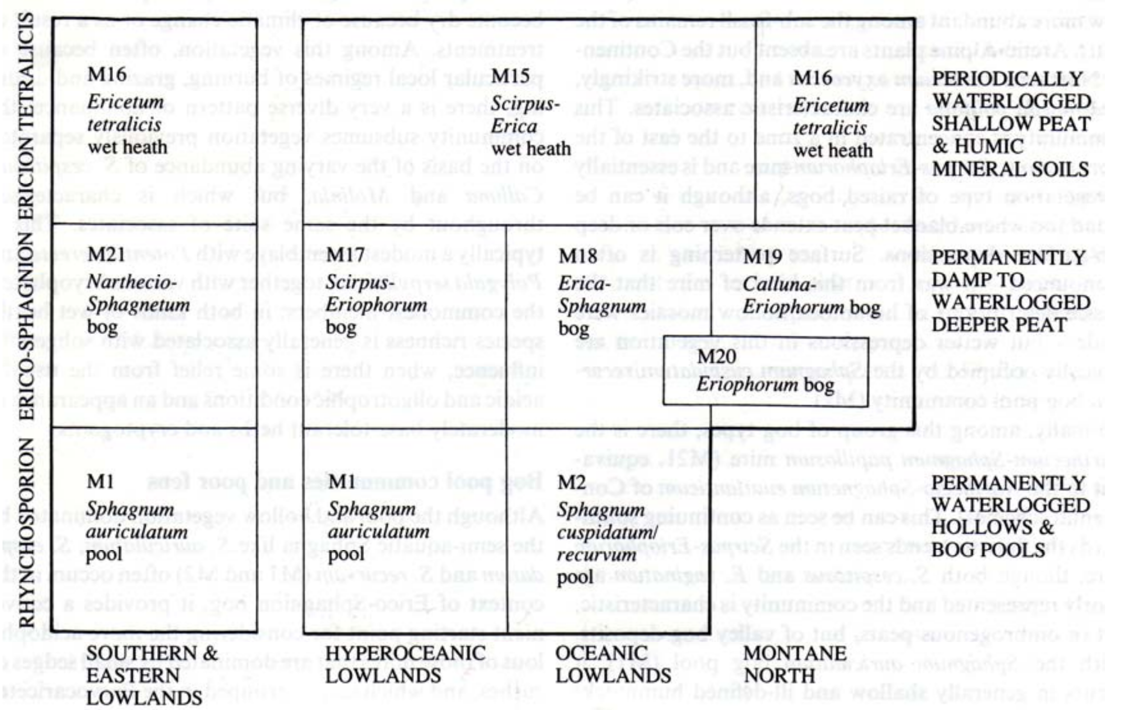


Figure 1.6 Mire and wet heath communities in relation to soils and climate.

Source: Rodwell (1991).

1.2.5 Fauna

Peatland fauna fall into three categories: aquatic (of open water pools), terrestrial confined to the peatland (including invertebrates living in peat) and terrestrial fauna which range beyond the remit of the peatland (Rydin and Jegum, 2006).

This is an important habitat for invertebrates. In a study of Finnish mires, more than a million individual invertebrates were found per square meter of peat (Rydin and Jegum, 2006). In the UK and mainland Europe, raised mires support populations of notable and rare insect and spider species (Wheeler and Shaw, 1995).

Significant populations of breeding birds are known to be of conservation importance in the raised mires of Britain. These include teal, red grouse, black grouse, nightjar, curlew, redshank and twite. Over-wintering species include pink-footed geese, greylag geese, Greenland white-fronted geese, merlin and hen harrier (Berry *et al.,* 1996).

1.2.6 Exploitation of Lowland Raised Mires

Wheeler and Shaw (1995) report that the ecological processes of every raised mire in Europe have been affected by anthropogenic impacts. For thousands of years peat has been cut by hand for use as domestic fuel and livestock bedding.

In agriculture there is a long history of drainage and burning of raised mires. This process dries the ground, improving the vegetation for livestock grazing. Fertilisation and ploughing of the peat have also created arable land (Brooks and Stoneman, 1997).

Drainage and fertilisation of peatlands has also been carried out to accommodate forest plantation. In conflict with mire conservation, this is the second most major claim on peatland in Britain (Heathwaite and Göttlich, 1993). Most commonly, non-native conifer species are grown. These conifers develop a closed canopy which intercepts sufficient rainwater to maintain soil dryness suitable for tree growth. The peat surface is bare, densely shaded and covered with dead conifer needles (Brooks and Stoneman, 1997).

The primary claim on peat extraction is from the horticultural industry. Commercial peat cutting to supply horticulture has caused a dramatic loss of lowland raised mires over the last thirty to forty years in particular (Heathwaite and Göttlich, 1993). Losses to this industry still continue.

1.2.7 Peat Extraction

Drainage is the first step in the process of peat extraction. This drying process makes access to and removal of peat easier. The living surface layer of vegetation is removed.

There are three main approaches to peat extraction/cutting: cutting peat blocks (or *sods*) by hand or machine, peat milling and sausage cutting (Charman, 2002).

Commercial peat extraction was originally carried out by hand (see Plate 1.1), but machines became operational (see Plate 1.2) before the First World War (Heathwaite and Göttlich, 1993). Mechanised block cutting became widespread practice until quite recently. A rectilinear pattern of drains dissect the mire into rectangular fields (Brooks and Stoneman, 1997). Blocks of peat are cut and stacked to dry before being removed from a site. The resulting peat profile is a series of hollows (peat cut) separated by upstanding ridges (baulks).

The most common present day method of commercial peat extraction is milling. Following drainage and removal of vegetation, the peat fields are rotavated (milled) and bulldozed into long ridges. Peat is then removed and bagged (Brooks and Stoneman, 1997).

Sausage cutting is replacing hand cutting in western Europe. This small-scale commercial fuel peat production uses tractor-towed extrusion machines. The peat is extruded from below surface, being drawn up through slits in the vegetation to produce lengths of peat with a sausage-like appearance. Once dried, they are cut into lengths for domestic fires (Charman, 2002).

1.2.8 The disturbed lowland raised mire ecosystem

Exploitation as described in section 1.2.4 is responsible for the degradation and in most cases, the removal of the acrotelm. Schouwenaars (1995) discussed water storage capacity of residual peats with no acrotelm layer as not being high enough to perform the same regulatory function. The situation is then worsened as the peat becomes colonized by the grass *Molinia caerulea* and tree species *Betula* spp. with further water loss resulting from evapotranspiration.

Drainage allows air into the peat profile, causing decay of the peat matrix (Daniels, 1998). Decomposition rate of the peat begins to accelerate, leading to consolidation and shrinkage, secondary compression and eventual wastage of the upper mire layers (Heathwaite and Göttlich, 1993).

Following abandonment, cut-over raised mires have no propagule bank and distance from propagule sources restricts plant colonisation from surrounding areas (Quinty and Rochefort, 2003).

1.2.9 Conservation status of lowland raised mires

The large scale damage caused by anthropogenic factors has led to this habitat type becoming increasingly more uncommon. In response to this, Government legislation has been developed to protect lowland raised mires.

Sites have been designated nationally as Sites of Special Scientific Interest (SSSIs), Special Areas of Conservation (SAC sites) and Internationally as Wetlands of International Importance under the RAMSAR Convention (Berry et al, 1996). Many sites are now owned or leased by nature conservation agencies. The management aim for these damaged sites is to restore actively growing raised mire.

Plate 1.1 Block cutting by hand. Source: Fenn's, Whixall & Bettisfield Mosses Site Archive.

Plate 1.2 Mechanised block cutting. Source: Fenn's, Whixall & Bettisfield Mosses Site Archive.

1.2.10 Restoration management of Cut-Over Lowland Raised Mires

Quinty and Rochefort (2003) suggest that natural recovery of damaged mires which returns them to peat-forming ecosystems is not possible without human intervention. They attribute this to the harsh hydrological and microclimatic conditions which are present following abandonment of peat cutting.

Mire restoration has been mostly implemented over the last twenty years. As a result of the short period encompassed by most schemes, research in this area appears to be limited in extent.

Restoration management focuses on raising and stabilising peat water levels. A great deal of work is therefore carried out to install dams which will block drains and ditches, in order to retain water on these sites. Ditch-filling, bunds, sluices and pumping are also methods utilised to improve hydrology and prevent peat erosion (Brooks and Stoneman, 1997).

Re-vegetation of bare peat surfaces by desirable raised mire species is dependent on several factors (Brooks and Stoneman, 1997):

- peat surface microclimate
- chemical and nutrient status
- hydrological characteristics
- distance from a refugium of mire species
- seed bank viability

Money (1995) investigated re-vegetation through the facilitation of *Sphagnum* colonisation on abandoned milled peat fields. The investigation found that applying *Sphagnum* inoculum within flooded peat pits encouraged raft establishment and recolonisation. Fragments of *Sphagnum* regenerated more effectively than whole plants. Optimal raft establishment is stated as being shallow water conditions, with the addition of brushwood for support.

1.2.11 Monitoring Ecology and Evaluating Restoration

Damaged mires are more frequently encountered than pristine, however they are rarely described (Brooks and Stoneman, 1997). Monitoring site vegetation and hydrology is essential to evaluate the effectiveness of management. Monitoring is a measurement tool to determine whether or not the aims and objectives of site management plans are being achieved and provides a detailed picture of change over time. Brooks and Stoneman (1997) stress the importance of monitoring before as well as after management works. Changes can then be demonstrated by a comparative analysis.

The most common method of collecting vegetation data is the use of *quadrats*. They are often marked in conservation management (known as *permanent quadrats*) in order to be resurveyed at regular time intervals – this allows a direct comparison of data sets (Charman, 2002). Quadrats are described in more detail in chapter 3.

Dipwells are the most frequently used measure of peat water table level and the frequency of recording dipwell data varies between sites. This method is described in chapter 3.

The literature explores whether waterlogged peat is better for *Sphagnum* establishment compared to conditions of complete inundation. Meade (1992) investigated early changes in vegetation following rewetting of a cut-over peat surface at Danes Moss, Cheshire. The study area was small (c. 200m x 150m), vegetation and hydrology data being examined separately and not undergoing statistical analysis. The vegetation were recorded in 1973 and repeated in 1987. Management was a rise in water level of 0.5m and the study used water level data from dipwell monitoring, carried out across the site in 1987 and 1989. It was found that complete inundation reduced the abundance of *Molinia caerulea* and *Betula* spp. and also brought about the death of *Sphagnum cuspidatum.* The most successful increase in the cover of *Sphagnum* was found in waterlogged conditions among tussocky vegetation. Management advice was to stabilise water levels where *Molinia* was dominant sufficient to maintain waterlogged conditions.

Rochefort and Gauthier (1995) also recommend a water level close to the surface for the regeneration of *Sphagnum.* In these conditions, *Eriophorum vaginatum* and *E.*

angustifolium were found to facilitate *Sphagnum* colonisation (under their leaves) in a re-introduction experiment in a cut-over mire. *E. vaginatum* was observed to be a typical dominant species in early post-management succession because of its ability to colonize bare peat surfaces (Quinty and Rochefort (2003).

In contrast to the recommendations of Meade (1992), Money (1995) suggests that raised mire vegetation can develop hydroserally as floating rafts. Optimal raft establishment is stated as being shallow water conditions, with the addition of brushwood for support. It was also found that applying *Sphagnum* inoculum within flooded peat pits encouraged raft establishment and recolonisation. Fragments of *Sphagnum* regenerated more effectively than whole plants.

The benefit of using Sphagnum diaspores is also supported by Rochefort *et al.,* (1995). The writers discuss the ability of *Sphagnum* to regenerate from almost any vegetative part of the plant.

Rochefort *et al.* (2002), examine two aspects of the effect of flooding on growth and development of *Sphagnum*. The first aspect was carried out as a laboratory experiment. The experiment monitored the production of innovations (growth buds and shoots) and capitula (head-like mass of crowded branches on the tip of a stem (Malcolm and Malcolm, 2000)) from plant fragments under continuous flooding conditions (8-10cm above ground level), intermittent flooding (-1 to +1cm) or non-flooding conditions. After one month of flooding (8-10cm), the number of innovations was the same as for intermittent and non-flooded conditions. Following a further period of growing on in a greenhouse environment for three months, the flooded fragments (8-10cm) produced more capitula than the non-flooded.

The second aspect of the Rochefort *et al.* (2002) investigation was carried out in the field, observing growth response of whole plants under long term continuous shallow flooding (+1cm above ground level). Most species were found to grow well, with several becoming etiolated. The writers advise that during drier events etiolation may render plants more prone to desiccation than plants with a regular growth form.

Large water table fluctuations characterise cut-over raised mires because of the low water storage capacity of exposed residual peat (Quinty and Rochefort, 2003). Studies by Mawby (1995) and Money (1995) highlight the fluctuating nature of water tables in cut-over peat. Both researchers suggest a relationship between instability of water tables and poor *Sphagnum* development. Mawby (1995) describes early management response, identifying that cut-over areas have a widely fluctuating water level with summer falls of at least 50cm. The nature of this fluctuation throughout the year was not described. A stable water table however, was identified in uncut areas of mire and these were associated with *Sphagnum* domination.

Natural England reports have quite recently analysed raised mire vegetation in three volumes entitled *'The effects of drainage and peat cutting on the vegetation of Wedholme Flow SSSI/cSAC*. Volume 1 (Dargie and Hulme, 2000) is entitled '*Numerical Analysis of Intact peat Vegetation'*. The objective of the study was to establish and describe spatial differences in vegetation and vegetation quality, attributing them to site conditions. Multivariate methods of ordination and classification were used for data analysis. Two trends were identified in the data - a successional gradient and a moisture gradient. The strong successional trend in the vegetation data was suggested to relate to past burning episodes over several decades. Species constancy and composition on the whole fall within the range of NVC M18a mire (Rodwell, 1991). The study did not use hydrology data, thus relationships between peat water table and plant species were not explored in detail. The study gives a very informative snap-shot in time of the current state of uncut peat vegetation at that site. Areas furthest away from active peat extraction were suggested to have had less impact and thus less hydrological change. These areas represented the closest likeness to the NVC M18a community.

Volume 2 (Dargie, 2001[1]) *Numerical Analysis of Vegetation in Rewetted Peat* Cuttings aimed to identify spatial differences in vegetation and vegetation quality. The floristic data set comprised 175 quadrats, and underwent numerical analysis using ordination methods. Three trends emerged in the data: - a strong moisture gradient and two successional gradients. Plant species significantly associated with the moisture gradient were described in relation to their ecological requirements - driest, intermediate and wettest.

Four successional directions were indicated:

1. Towards a vegetation similar to M18a *Sphagnum magellanicum - Andromeda polifolia* sub-community (with possibly little seasonal water table fluctuation).

2. Towards a vegetation similar to M19a *Calluna vulgaris - Eriophorum vaginatum* (with probable large seasonal water table fluctuations).

3. Towards a vegetation similar to M2 *Sphagnum cuspidatum /recurvum* bog pool with *S.cuspidatum* in the open water of deep cuttings.

4. Towards a vegetation similar to a second form of M2 (*S.recurvum - S.angustifolium* in tussocks of saturated *Eriophorum vaginatum).*

Strong spatial patterns were suggested in some successional groups. *Sphagnum* - rich vegetation showed success following rewetting nine years previously. Almost half of the samples had characteristics of NVC raised mire vegetation types. Management recommendations from Volume 2 warn of the risk of *Calluna vulgaris* and *Molinia caerulea* dominance, with loss of mire species if conditions become drier.

Volume 3 *Correlation of Vegetation and Hydrology Results in Rewetted Peat* Cuttings (Dargie, 2001[2]) related vegetation data from Volume 2 with hydrological findings from separate studies. The nature of the water table was suggested in the report to be the determining factor of vegetation type in rewetted peat cuttings. In 2001, 42% of the vegetation samples indicated an encouraging high cover of *Sphagnum* species.

1.3 Aims & objectives

The present study aims to evaluate the effect of nature conservation rehabilitation management on the vegetation of the cut-over lowland raised mire, 'Fenn's, Whixall & Bettisfield Mosses National Nature Reserve (NNR). In addition to identifying the nature of change in the vegetation, correlation with water table height will be used to identify hydrological thresholds for *Sphagnum* establishment.

A series of four inter-related ecological monitoring investigations were carried out which specifically aim to:

- elucidate plant species change (at ‘landscape level’ i.e. sub-compartment as opposed to quadrat level) in relation to rehabilitation management, seasonal water table height and previous peat cutting type.
- determine whether or not site management targets for percent cover of peat-forming species were being achieved.
- identify trends in vegetation change and vegetation types over time, at quadrat/ cutting profile level.
- establish key plant species losses and gains.
- distinguish between establishment of NVC M2 and trends towards development of NVC M18a vegetation.
- determine statistically significant change in key mire species over time.
- identify water table characteristics that support colonisation of *Sphagnum* species.
- explore the relationship between water table falls during summer on *Sphagnum* species.
- describe the initial change in vegetation composition following deforestation.

These aims have been achieved by a combination of analysis of archive data and the collection and comparative analysis of new vegetation and hydrological data at Fenn’s and Whixall Mosses. The present writer has also established a baseline vegetation monitoring system at Bettisfield Moss following deforestation management.

Multivariate statistical analysis has been applied to the data sets and plant species maps have been produced using Geographical Information Systems techniques. These methods are described in detail in chapter 3.

CHAPTER 2
SITE DESCRIPTION

2.1 Location and notification

Plate 2.1 View looking north across Compartment 3, Fenn’s Moss (2007)

Fenn’s, Whixall & Bettisfield Mosses National Nature Reserve (NNR) is a severely damaged lowland raised mire, which is part of a peat body known to be the third largest lowland raised mire site in Britain. It is the most southerly lowland raised mire in the UK (Jackson and McLeod, 2002). The peat body includes Fenn's, Whixall, Bettisfield, Cadney and Wem Mosses and lies across the English/Welsh border (GB Grid reference SJ 490365) 15 km south-west of Wrexham in Wales (MacAlister, 2001). Whixall Moss, the eastern part of Bettisfield Moss and Wem Moss are in Shropshire, England. Fenn’s Moss, the western part of Bettisfield Moss and Cadney Moss are in Wrexham, Wales (Daniels, 2004). Bettisfield Moss is separated from Fenn’s and Whixall Mosses by the Llangollen branch of the Shropshire Union Canal. Collectively the Mosses cover an area of 948 ha (Gilman, 2000).

Figure 1.1 in chapter 1 highlights the study site location in the UK (indicated by a red square). Figure 2.1 below, shows the site with neighbouring towns, counties and wetlands.

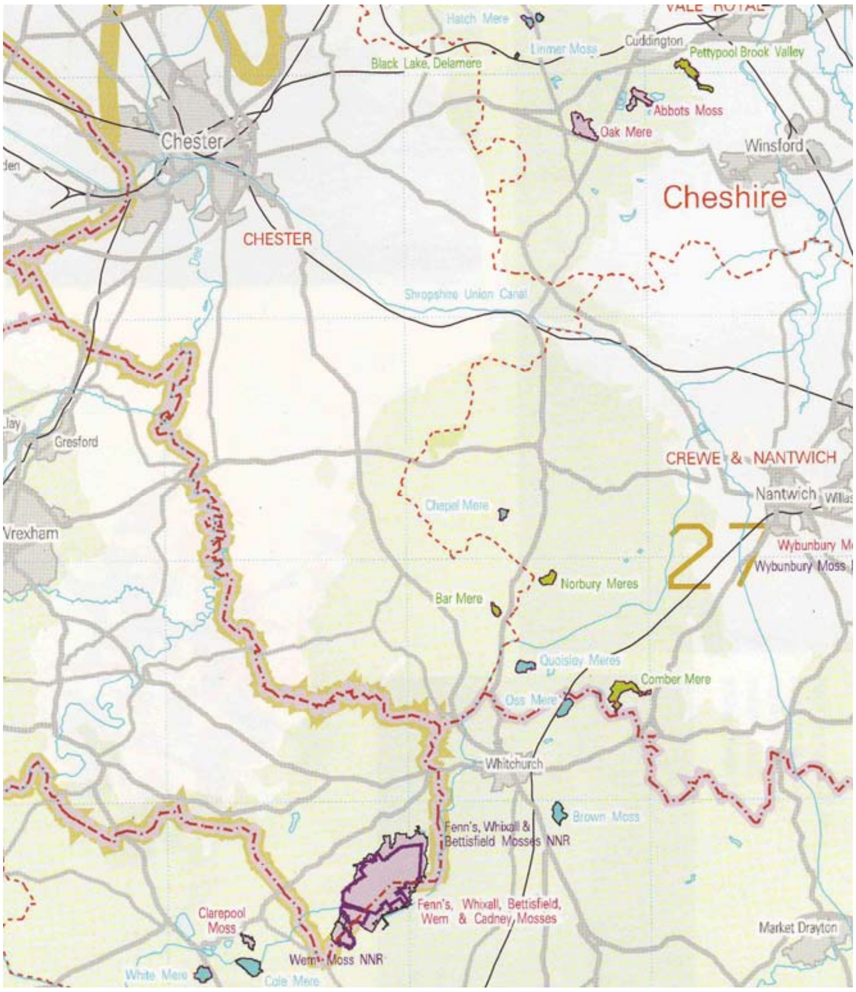


Figure 2.1 Location of Fenn's, Whixall & Bettisfield Mosses NNR

The study site is approximately central at the bottom of Figure 2.1 and outlined in purple.

Source: Brooks, S. (2003)

Plate 2.2 shows an aerial view of the SSSI and the names of the five mosses.

Fenn's and Whixall Mosses were notified as an SSSI for the first time in 1953, under the National Parks and Access to the Countryside Act of 1949. In 1983 the SSSI was re-notified to include Bettisfield Moss, under the 1981 Wildlife and Countryside Act. Wem Moss was initially notified as an SSSI in 1963 and subsequently re-notified in 1983 and 1985. The Mosses were collectively re-notified in 1994 as a single SSSI (Daniels, 2004).

In 1997 the SSSI was identified as a Wetland of International Importance as part of the Midland Meres and Mosses RAMSAR site. In 1997 it was also declared a candidate Special Area of Conservation under the European Habitats Directive Conservation Regulations of 1994, confirmed in 2001. Primary qualifying features for cSAC status are active raised mire and degraded raised mire capable of regeneration (Daniels, 2004).

Fenn's, Whixall & Bettisfield Mosses were declared a National Nature Reserve (NNR) in 1996, with an area of 576 hectares. Following further land acquisition by 2001, the NNR had a land area of 635.37 hectares (Daniels, 2004) (see Map 2.1 of the present chapter). The three Mosses of the NNR are three unequal sized units, separated by the border drain and the Llangollen Branch of the Shropshire Union Canal (Gilman, 2000). The NNR has public access and facilitates for education and research.

The investigational programme for the current thesis was carried out within Fenn's, Whixall & Bettisfield Mosses NNR and as such this area will be referred to collectively as 'the site' or 'the NNR' in subsequent text.

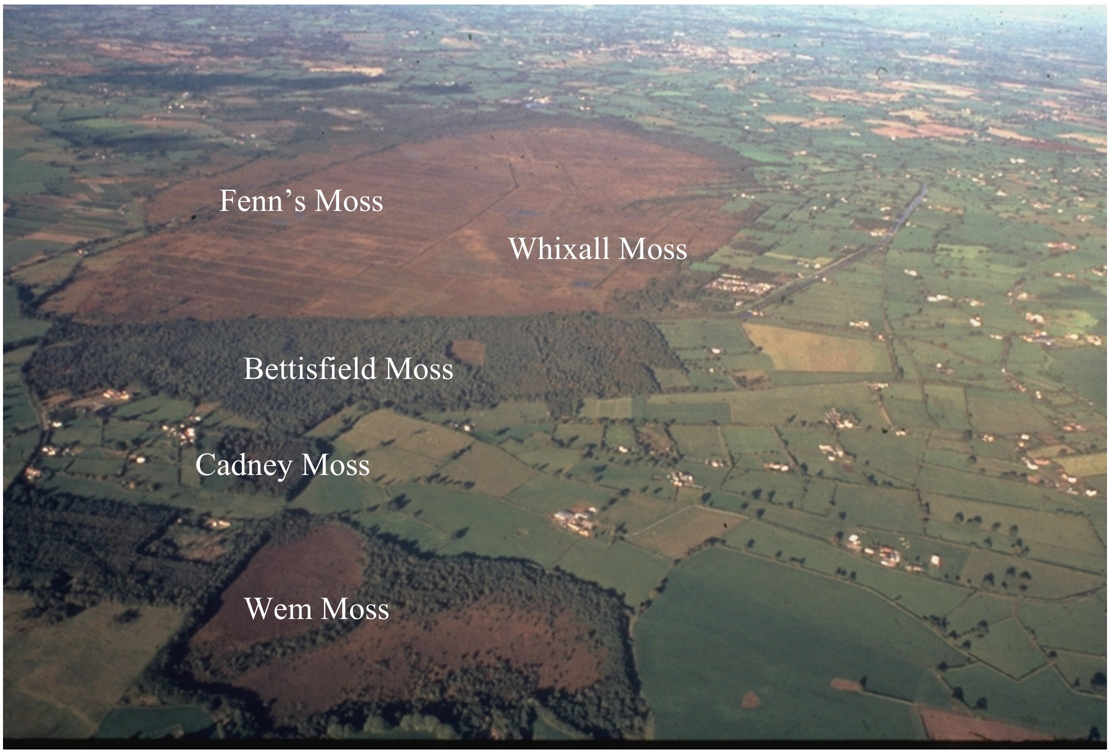


Plate 2.2 The study site
Aerial photograph of the five Mosses of the SSSI. This photograph shows the site surrounded by agricultural land. The photograph was taken prior to deforestation of Bettisfield Moss and demonstrates the closed tree canopy, with the exception of a small clearing on the east side.
Source: Fenn's, Whixall & Bettisfield Mosses Site Archive.

2.2 Tenure

In 1990 the site came under the ownership of the Nature Conservancy Council (Brooks and Stoneman, 1997). The freehold of Whixall and Bettisfield Mosses and the Manor House peat factory was purchased from the Land Improvement Group, operating on the Moss as Croxden's Horticultural Products and their lease of the area of Fenn's Moss with planning permission for peat extraction was also taken over. Since then more areas of the mire have been acquired and private landowners have entered into management agreements with the conservation agencies (Daniels, 2004).

A nature reserve office base has been established at the former peat factory site (N.G.R. SJ 505366) from where the NNR is managed on a joint funding basis by Natural England (NE) and The Countryside Council for Wales (CCW).

2.3 Geology and climate

The NNR forms part of the North Shropshire Meres and Mosses complex. Sinker (1962) describes the Meres and Mosses as 'a series of water or peat – filled hollows in the glacial drift which covers the Shropshire - Cheshire Plain'. The ice sheets of the last Pleistocene Ice Age covered the area 15,000 years ago (Daniels, 2004). The glaciers and ice sheets entered Shropshire from the north and west, meeting on the north Shropshire plain. This resulted in the burial of the older landscape by a great depth of glacial drift in the form of till (boulder clay), and sands and gravels (Sinker *et al.,* 1991). The glacial drift had been scoured from bedrock during the advance of the ice sheets and detached blocks of ice within the drift left steep-sided basins (kettle-holes) which filled with glacial melt water and rain at the end of this glacial period.

The resulting landscape seen today is one of rolling hills and depressions - a glacial moraine system with drift of up to 50m deep in places. Anon (1998) described the landscape as a series of diverse wetlands in a lowland area, interrupted by occasional sandstone ridges. The deep, steep-sided kettle-holes have remained as open water Meres (Berry *et al.,* 1996) while shallower Meres and Mosses (mires) are probably not formed from kettle-holes, but from the hollows of the hummocky landscape (Anon, 1998).

The NNR is a relatively shallow glacial basin with an undulating flat-floored base which slopes gently from north-east to south-west. Hardy (1939) in her work on peat cores in the west part of Bettisfield Moss, produced a basin profile of gentle slope with a maximum depth of 6m. Deposits which line the NNR basin (below the peat) are impermeable boulder clay (till) and lake clays below Bettisfield and lake clays below the southern part of Fenn's and Whixall Mosses. The remainder of the NNR has deposits of silt and sand (Gilman, 2000). The underlying bedrock was formed 200 million years ago during the Triassic period. Impermeable Upper Keuper Marls (fine red sand or silt) lie beneath Whixall Moss and the English side of Bettisfield Moss and Upper Keuper Saliniferous (salt) Beds lie below the remainder of Bettisfield Moss and Fenn's Moss (Berry *et al.*, 1996).

At the south-eastern limit for raised mire development in the UK, the site lies in the rain-shadow of the Welsh hills – a watershed valley feeding the River Dee to the north and River Severn to the south. The surface of the peat is approximately 90 m OD and rises towards the north (Gilman, 2000). The site receives an average 690mm of precipitation yearly, with an excess precipitation of 500mm per year (Daniels, 2004). These conditions are conducive to the accumulation of peat.

Due to evaporation there is a summer deficit of water causing a fall in the peat water table (Daniels, 2004). .

2.4 Lowland raised mire development at the NNR

Due to Whixall, central Fenn's and Bettisfield Mosses having either an impermeable drift layer of clays or layer of lake clays, a hydroseral succession from open water to fen and on to raised mire has occurred. Peat cores analysed for pollen and plant remains (Hardy, 1939) on Bettisfield Moss show a transition from organic lake mud to sedge-peat, then brushwood peat (acid carr or bog wood). This is followed by a considerable thickness of highly humified *Sphagnum* peat, above which is *Sphagnum* peat of varying humification and finally actively growing *Sphagnum* at the surface. However, there are areas of the NNR which do not follow this conventional process of development. Instead there is direct development from terrestrial soil at the basin base, upwards through brushwood and on to *Sphagnum* peat, with no lake sediments represented (Sinker, 1962), the process of paludification.

The base of the north-east area of Fenn's Moss is higher than the remainder of the site. This area appears to have begun peat formation at a later time point, as drainage to the south was impeded by peat development in Whixall Moss and central Fenn's Moss (Berry *et al*., 1996 and Jones, 1998).

The five Mosses of the SSSI were one connected peat body in their natural state, 5.6km long with a maximum width of 2.6km. Fenn's, Whixall and Bettisfield Mosses were connected to the smaller domes of Wem and Cadney Mosses by a narrow stretch of deep peat (Gilman, 2000). The remnants of two domes can be seen on Wem Moss, but it is not possible to say how many raised domes in total the mire complex would have had prior to anthropogenic interference (Berry *et al.,* 1996).

2.5 Anthropogenic factors

2.5.1 An overview

Archaeological remains indicate human settlement at the site since the Bronze Age, bringing forest clearance and cultivation to the land surrounding the peat body. Agricultural intensification since these early times has been the main source of eutrophication and pollution on the site (Anon, 1998). Records of domestic cutting of peat date back to 1550 and initial drainage of the periphery of the peat body by cutting through the surrounding moraines, appears to have commenced between 1750 and 1800 (Daniels, in MacAlister, 2001). The peat body is split between four parishes suggesting the likelihood of adjacent villages once having held turbary rights (the right to cut peat). Enclosure of peat land by neighbouring smallholders has caused a wide strip of the peat body margin to be brought under pasture and other cultivation. This has resulted in almost the complete loss of the original lagg, a small amount of drained lagg persisting round Wem Moss.

Peripheral fires have been accidental and deliberate. Fire has been deliberately used to remove vegetation and control adders. These early marginal activities of drainage, peat cutting and burning will have caused considerable downward shrinkage of the raised mire (Sinker, 1962).

The Shropshire Union Canal is carried across the peat on an embankment of boulder clay. Nutrient-enriched water percolating from the canal on to the NNR has led to the development of an adjacent strip of artificial lagg, dominated by alder (Sinker, 1962). The site is also subject to nutrient enrichment by drains carrying effluent from adjacent housing developments (Brookes and Stoneman, 1997).

Other factors resulting from human activity include the construction of the Oswestry, Ellesmere and Whitchurch railway line (now disused) across the north-west of Fenn's Moss (Berry *et al.,* 1996). The site was also used by the military during and prior to World War I for rifle ranges and as a bombing range during the Second World War (Sinker, 1962).

Hardy (1939) documents spruce and pine growing around the south-western side of Bettisfield Moss. She noted the flora of Bettisfield Moss as being dominated by *Calluna vulgaris* and a *Sphagnum* layer of mostly *Sphagnum papillosum*, with a few trees here and there. Drains associated with the canal have damaged its northern boundary. Peat cutting by hand occurred along its western and south-western boundary on the Welsh side and the English side was cut for peat across its entirety. Since Hardy's time, cessation of burning combined with the peat water table drawdown associated with all of the drainage led to the spread of self-sown pine and birch across the whole of Bettisfield Moss, as well as on many other disused areas of the study site.

2.5.2 The intensification of peat cutting

Without doubt, the activity of mire drainage to permit extraction of peat has had the most profound, damaging effect on the functioning of this ecosystem. Peat cutting activity has also been responsible for the removal of the vast majority of the acrotelm.

Deliberate drainage of the periphery of the peat body commenced around 1800. The drainage associated with the Enclosure awards of 1777 (Bronington) and 1823 (Whixall) permitted an expansion of peat cutting as well as agricultural conversion. Commercial interest in hand-cutting peat was initiated in 1851. Major works installing a network of drains across the site occurred in the 1920s. Hand cutting of peat for fuel, packaging and livestock bedding and feed continued into the 1950s. By the late 1950s peat was being cut for horticultural purposes, and when mechanised commercial cutting was introduced in 1968, the rate of peat extraction accelerated (MacAlister, 2001). Rental increases in the late 1980s led to a rapid acceleration in the rate and extent of mechanised cutting, leading to the conservation campaign to save the site.

2.6 Site features

This section describes the large scale variation across the site in topography, vegetation and water table height. These factors relate to various peat cutting methods and the length of time since the methods were abandoned. The complexity of the site is summarised in this section, along with a view of the vegetation existing at the time the NNR was taken over for conservation management, the effects of which are investigated in the present study.

The NNR is an open landscape with marginal scrub and woodland, surrounded by improved agriculture, woodland and forestry on the remainder of the SSSI. Despite being a severely cut-over site, most of the peat remains hydrologically connected (Berry *et al.,* 1996) with much variation in remaining peat depth. The English side of Bettisfield Moss has peat up to a depth of 3.5m and the Welsh side is up to 8m deep. Deep peats continue beneath the canal and on into Fenn's Moss where depths of just over 6m can be found in the uncut areas. The cut-over areas on Fenn's and Whixall Mosses have an average peat depth of approximately 3m. Peat cutting has exposed the underlying mineral ridges in some areas. Some peripheral areas have only 1-2m of remaining peat (Berry *et al.,* 1996).

The uncut areas of Fenn's and Whixall Mosses are up to 1.5m higher than the surrounding cut-over areas. Extensive peat cutting across the centre of Fenn's and Whixall Mosses has left a large depression. There is a further drop of 2-3m to the peripheral farmland (Berry *et al.,* 1996).

2.6.1 Compartments and sub-compartments

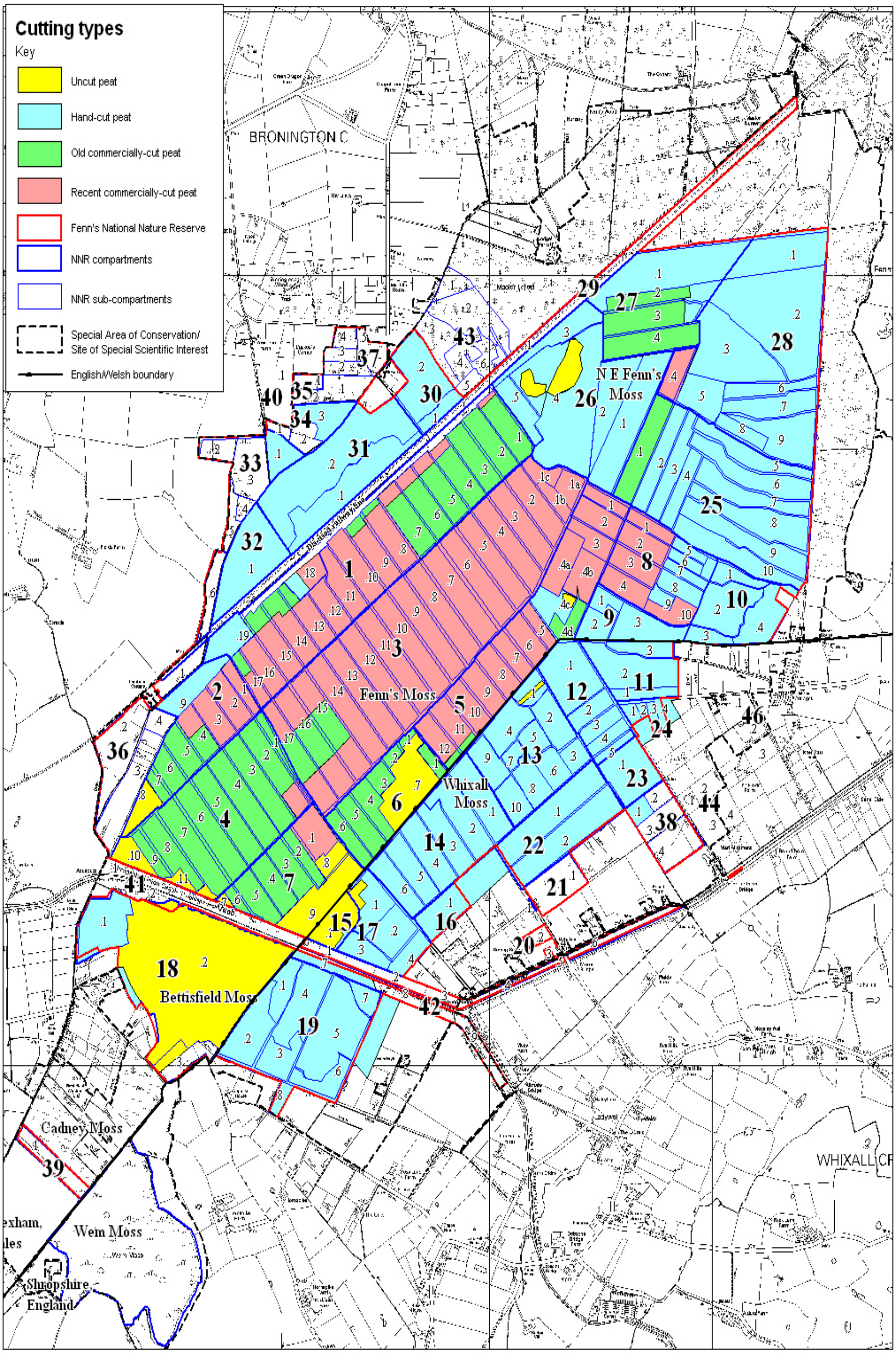
The Senior Reserve Manager at the site has allocated a number system to the NNR *compartments* for management purposes. The compartment numbers are the larger numbers on Map 2.1 and the compartment boundaries are shown as heavy blue lines. Within each compartment is a set of sub-compartments identified by the smaller numbers on this map. So, for example, compartment 14, located on Whixall Moss, has 6 sub-compartments which are known as sub-compartments 14.1-14.6. Each sub-compartment on the site was once an individual peat cutting *flat*. The fine blue lines on this map mark the sub-compartment boundaries and intervening tracks.

Map 2.2 includes hydrological information, showing the arterial drainage network as solid pink lines. The internal drains, individual to each sub-compartment, are shown by fine blue lines. Hydrological monitoring points (dipwells) are indicated by red solid circles and shown with their respective numbers. Dipwells are discussed in detail in chapter 3. Map 2.2 also shows the extent of rehabilitation management at the time work on the current study began. The rehabilitation area is outlined by a broken red line – all of the compartments within this area have undergone damming of drains and removal of birch.

The sub-compartment is the basic unit for rehabilitation management. It is bound by drainage channels and separated from adjacent sub-compartments by tracks or arterial drains on all four sides.

Map 2.1 - Fenn's, Whixall & Bettisfield Mosses National Nature Reserve

National Nature Reserve compartments, sub-compartments and areas of different peat cutting types.



Scale 1:15000   Map 2.1

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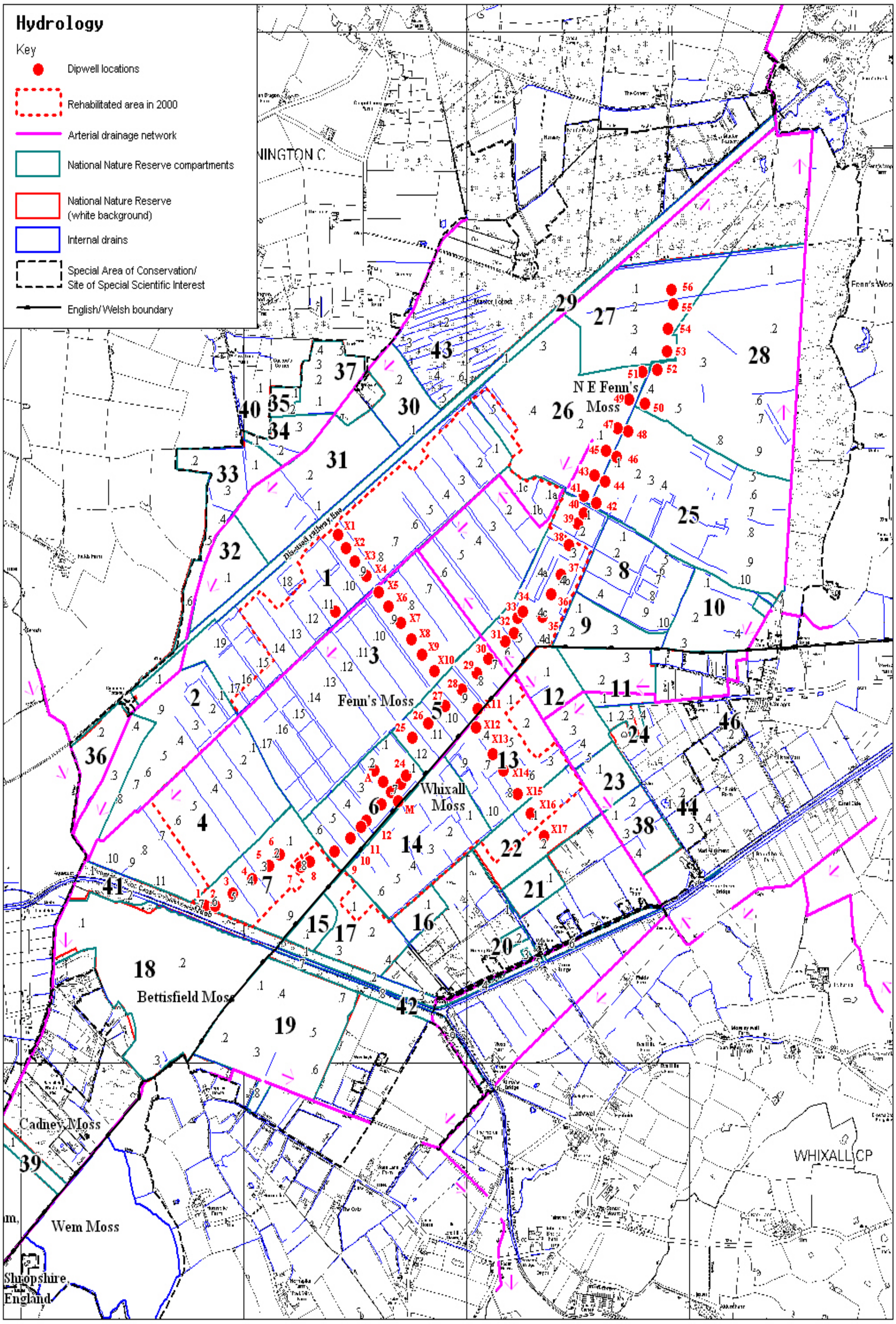
Map 2.2 - Fenn's, Whixall & Bettisfield Mosses National Nature Reserve

Locations of hydrological monitoring points, the arterial and internal drainage network, with direction of flow, and the extent of rehabilitation in 2000



Scale 1:15000
0 300 600 900m
0 250 500 750yd.

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2.6.2 Peat cutting and existing vegetation description

Map 2.1 displays a colour code which identifies the various peat-cutting types across the site. Across each sub-compartment is an artificial topography reflecting the peat-cutting method used. This has left repeating patterns at the peat surface (usually repeating at 10m intervals), resulting in a block profile of high, intermediate and low peat surfaces – all of differing distances from the peat water table. The highest peat surfaces (baulks) would have been where peat blocks were stacked to dry. Intermediate surfaces have been cut, peat extracted and sometimes vegetation dumped, and the lowest surfaces have been more severely cut for peat, often to create ditches/drainage within the sub-compartment. These varied surface levels with differing relationships to the water table have led to the development of different vegetation types across the profile. This means that the sub-compartments have a complex vegetation cover.

Hand cuttings

On Map 2.1 the compartments shaded in blue are the hand cut areas of the site – cut by local people for domestic purposes. Three methods of hand cutting have been used on the NNR, the first of which was used up until the 1920s and is the traditional, indigenous method of hand-cutting known as *Whixall Bible* cutting. This method was carried out on southern Whixall Moss, the English side of Bettisfield Moss, the north-east of Fenn's Moss and north of the Railway Line. According to the *Whixall Bible* method, blocks of peat were cut from worked pits 3-5m x 5-7m in size. Each individual peat block measured 22.5cm (9in) x 17.5cm (7in) x 10cm (4in) – the size of a bible at that time. There was little or no drainage of each pit, so the depth of cutting was dictated by the peat water table at the time. Once a pit had filled with water the peat worker would open another pit further upslope, draining the new pit into the old. Evidence of past cutting using this method can be seen today on north-east Fenn's Moss and Whixall Moss as square depressions, 0.5 – 1m deep. A few local peat workers continued this method until the 1960s, despite the new method of *Dutch* cutting which arrived in the 1920s (Berry *et al.,* (1996).

At the time the site was taken over by the Nature Conservancy Council, the bottoms of the cut-out pits of the *Whixall Bible* cuts were found to have developed mire pool and lawn plant communities. Species included *Sphagnum, Erica tetraix*, *Eriophorum* *vaginatum, Vaccinium oxycoccos* and *Drosera rotundifolia.* The higher peat surface surrounding the cut out pits supported a damp heath vegetation of *Calluna vulgaris, Erica tetralix, Eriophorum spp.,* with invading *Betula spp.* and *Pinus sylvestris* (Berry *et al.,* 1996).

The second of the domestic hand cutting methods was traditional *Linear* hand cut acres, carried out on central Whixall Moss, North-East Fenn's Moss and small areas of Fenn's Moss, copying the style of the Dutch commercial cuttings (see below). However each peat cutter only rented one or two 'acres' and cut this independently of the style and direction of surrounding cutters. Consequently this method left different orientations (not as regimented as the commercial methods) and differing depths. Each sub-compartment is 44 yards wide. The use of this method ceased at different areas of the site and at differing times over the last seventy years. Hydrological conditions were very varied at time of abandonment and since abandonment. In 1991, a range of plant species had established, from those of mire pools, lawns and bare peat in lower areas to those of dry heath and scrub on tracks and the higher surfaces of the cutting profile (Berry *et al.,* 1996).

The profile sections of the *Linear* peat cutting pattern are known as *baulk*, *flat* and *ditch*. This pattern was worked repeatedly across each sub-compartment, leaving a parallel block-like topography of three different heights of the peat surface. The baulks are the remnants of the original peat surface for that cutting round. They are the highest and driest surface, furthest away from the peat water table and were used to dry the stacked cut peat blocks and also as minor tracks to transport peat off the sub-compartment (Berry *et al.,* 1996). *Flat* within the peat cutting pattern is a lower surface compared to the baulk, where peat has been cut and removed and surface vegetation from adjacent cuts has been dumped. The ditch is the lowest peat surface, where peat was last cut from so did not have any vegetation dumped on it. The ditch also acts as a drain, carrying water from the central areas of a sub-compartment, out to its peripheral deeper drains. The ditches would have been the first to flood as peripheral drains collapsed when areas were abandoned. These conditions provided refugia for some mire plant species (Joan Daniels, *pers comm*). The baulks of the Linear peat cuttings were drier than those of the Whixall Bible, with much *Pteridium aquilinum, Betula spp.* and *Calluna vulgaris* (Berry *et al.,* 1996).

The third method of domestic hand cutting has formed the *Modern tractor extracted* areas. This method cuts large pits, producing large open pools with much bare ground. The wetter areas are colonized by *Eriophorum angustifolium* and *Sphagnum cuspidatum* (Berry *et al.,* 1996). This method is restricted to the north-east area of Whixall Moss and the south-east of north-east Fenn's Moss.

Old commercial cuttings

The green-shaded compartments in Map 2.1 are *old commercial* cuttings which would have been cut using the Dutch method. These were cut by hand, but on an industrial scale.

At this scale peat cutting established a series of deep arterial drains across the site (shown as solid pink lines on Map 2.2). These inter-connecting drainage channels cut in to the peat body, lowering the water table and diverting water off site. This enabled the cutter to stand in the base of the cutting. The Dutch method comprised a system of cutting fields (now known as sub-compartments) and drains, separated by caseys (tracks). Each cutting field was bounded by an edge drain and also had a drain running down the centre. The cutting field was divided into 10m (11 yard) wide strips, known as sides, set at right angles to the casey. One strip of cut peat blocks, taken from a side, was known as a bench – a single peat block measuring 6in x 6in x 16in. The surface vegetation was removed prior to peat cutting and thrown into the ditch created by the previously cut side or placed on the surface of the adjoining side, on the first cut in a new cutting field. Cut blocks of peat were lifted onto the peat surface to dry, adjacent to the bench being cut. The cut blocks were then transported off the site via the tracks between the cutting fields (Berry *et al.,* 1996).

In general, these sub-compartments are larger, more intensely drained and more uniform than the domestic hand cuts (*Linear, Whixall Bible* and *Modern tractor extracted)* discussed in the previous section. In 1991 these areas were drier than the domestic hand cuttings with more *Betula spp., Calluna vulgaris* and *Erica tetralix.* This cutting type was carried out on Fenn's Moss and was mostly abandoned over fifty years ago (Berry *et al.,* 1996), although some of the areas shown on Map 2.1 were still cut until 1968

(Joan Daniels, personal comment). The profile sections of the old commercial peat cutting pattern are known as baulk, flat and ditch.

Recent commercial cuttings

Recent commercial cuttings are shaded in pink (Map 2.1) and these compartments were worked intensively by machine from 1968-1990. In 1991 the surface was predominantly bare peat with strips of *Molinia caerulea.*.

The profile sections of the recent commercial peat cutting pattern are known as ditch, augered, *Molinia* and relict, and are generally 80m (88yards) long. The ditches are 1-2m wide and approximately 1m deep. Peat has been extracted from them and they lead to a 2-4m deep drain running down one side of the sub-compartment. Ditches were dry and devoid of vegetation when the Nature Conservancy Council took over management of the site. Adjacent to the ditch is the augered strip, a bare area where the vegetation was removed by machine. Next to the augered strip is the 3-4m wide *Molinia* strip, which has been damaged by the movement of tractors and excavators during peat extraction. This became dominated by *Molinia caerulea*. Immediately adjacent to the *Molinia* strip is the relict section – the remnant mire surface, degraded by drainage with the loss of the original mire plant species (Berry *et al.,* 1996).

Uncut areas

Uncut compartments are marked in yellow (Map 2.1) and are areas of the site which have suffered directly from vegetation burning and surrounding drainage, but have never been cut-over for peat extraction, although some trial ditches may have been cut into them. Sub-compartment 6.7 (known as Oaf's Orchard), compartment 15 (known as The Cranberry Beds), 5.4c (known as the Cowberry Patch) and the Welsh side of Bettisfield Moss are such areas and stand at approximately 1.5m above the surrounding cut-over compartments (Berry *et al.,* 1996).

Sub-compartment 6.7 supported damp heath communities in 1991, dominated by *Calluna vulgaris, Erica tetralix, Eriophorum spp.* and *Andromeda polifolia.* Small patches of *Sphagnum* species were found where drains had been cut in the past. The loss of *Sphagnum* cover and invasion by *Molinia caerulea* and *Betula spp.* is attributed to the surrounding effect of peat cutting (Berry *et al.,* 1996).

Compartment 15 escaped peat cutting due to its proximity to the canal and therefore being too wet to cut. Vegetation cover was a lawn of *Sphagnum* species and vascular plants of lowland raised mire. Indicators of the effects of nearby drainage were the spread of *Betula spp.* and *Pinus sylvestris* across the area (Berry *et al.,* 1996 and Joan Daniels, personal comment).

Sub-compartment 5.4c is unique to the site, having a dominant cover of *Vaccinium vitis-idaea.*

Prior to the deforestation of Bettisfield Moss which occurred between 2000 and 2002, dense *Pinus sylvestris* and *Betula spp.* had dried and shaded out much of the raised mire flora, with the exception of the wetter centre-north area. More marginal areas supported plant species of heathland and woodland (Joan Daniels, personal comment).

2.7 Conservation management

Since 1991 management work has focused on restoring the water level of the peat body, aiming to return it to surface, or near surface throughout the year. This work has been carried out on a large area of the site known as the *Rehabilitation Area*. The work commenced at the centre of the site (compartment 5), radiating outwards (Map 2.2). Rehabilitation work has included extensive tree and scrub removal, damming of drains and ditches and erosion prevention (Daniels, 1998).

The site management plan (Daniels, 1998) states that the goal for the Rehabilitation Area is to return "active raised mire formation". The target NVC peat forming communities

(Rodwell, 1991) stipulated in the plan were M18a (*Erica tetralix-Sphagnum papillosum* raised and blanket mire, *Sphagnum magellanicum-Andromeda polifolia* sub-community) and M2 (*Sphagnum cuspidatum/recurvum* bog pool community). Additional desirable communities were M18b (*Erica tetralix-Sphagnum papillosum* raised and blanket mire, *Empetrum nigrum-Cladonia* spp. sub-community), M20 (*Eriophorum vaginatum* blanket and raised mire) and M3 (*Eriophorum angustifolium* bog pool community). In developing and maintaining these communities it was expected that the combined cover of peat forming species i.e. *Sphagnum* and *Eriophorum* species should be in excess of 75% in each of the sub-compartments within the rehabilitation area within 5 years (Daniels, 1998).

In 1998 the extent of water levels sufficiently high for raised mire formation was limited to approximately 50% of the rehabilitation area (20% of the SSSI). Target water levels aimed to reside above or within the top 10cm of the general peat surface all year round. The only primary (uncut) area to be totally re-soaked was sub-compartment 6.7 (Daniels, 1998).

The management plan recognised a number of constraints on the rehabilitation process. The effects of drainage operating in the un-rehabilitated areas would continue to have a drawdown effect on adjacent rehabilitated areas. Tree and scrub development would continue to lower water levels through evapotranspiration and interception. The unmanaged areas would continue to degrade and decompose (Daniels, 1998).

2.8 Vegetation and hydrological monitoring

In order to assess management achievements, vegetation and hydrological monitoring was initiated. Base line vegetation surveys at the level of sub-compartment and 1m x 1m permanent quadrat began in 1991. The sub-compartment vegetation survey was repeated in 1998 and the permanent quadrat survey was repeated in 1996 (a rolling 5 yearly survey). Methodology for these surveys is explained in chapter 3.

Fortnightly hydrological monitoring along dipwell transects commenced in 1993. Measuring the position of the peat water table at dipwell stations is detailed in chapter 3. Summer and Winter ditch-water level surveys also commenced in 1993 and have been repeated every year.

The four investigations of the present study contribute to the vegetation monitoring of the NNR. Vegetation resurvey at sub-compartment and permanent quadrat level has been carried out. The addition of a new vegetation survey, recording each dipwell station, has provided data which can be directly correlated with water table height.

Baseline and resurvey of a new permanent quadrat monitoring regime on Bettisfield Moss is also part of the present study. The methodology for these surveys is described in detail in chapter 3.

CHAPTER 3
MATERIALS AND METHODS

3.1 Investigational and sampling design

Three approaches were designed to elucidate the relationship between vegetation change and site management. These were:

i) NNR sub-compartment surveys
ii) vegetation monitoring using permanent quadrats
iii) correlation of hydrological monitoring sites with vegetation change.

NNR sub-compartment surveys

The first approach was a monitoring exercise at the landscape (sub-compartment) level across the NNR. Vegetation surveys of the sub-compartments were carried out by Joy (1991) and Boardman (1998) and have been utilised for the present study. Seasonal average water table height for each sub-compartment was calculated using archive hydrology data from the site dipwell stations. The number of seasons since management practices of birch removal and drain/ditch damming was also calculated for each sub-compartment of those two survey years. These hydrology and management data were collated with the vegetation data as an Excel file.

The sub-compartment level survey (methodology described in section 3.2 of the present chapter) was also developed further as part of the present study. A vegetation survey compatible with those of Joy (1991) and Boardman (1998) was undertaken in 2000, covering 59 selected sub-compartments within the central rehabilitated area of the site. Seasonal average water table height immediately prior to this survey was calculated (using site archive hydrology data), along with number of seasons since birch removal and damming. These data were collated with those of the same sub-compartments from 1991 and 1998, to provide a separate multivariate analysis focusing on the rehabilitated area.

All of the vegetation data were explored using geographic information systems (GIS) computer software. Maps were generated using this technique, which provide a visual aid to the change in percent cover of key plant species over time (Maps 4.1 – 4.6 of chapter 4). Relationships between vegetation, hydrological and management data were examined using multivariate analysis computer applications.

Vegetation monitoring using permanent quadrats

A detailed comparative analysis of vegetation monitoring using 1m x 1m permanent quadrats formed the second approach. Natural England's site archive data from permanent quadrat vegetation surveys carried out in 1991 (part 1993) and 1996 were collated by the present writer. There are 528 permanent 1m x 1m vegetation quadrats across Fenn's and Whixall Mosses. The quadrats were resurveyed in 2001 as part of the present study. The data sets from the three survey years were collated and analysed using multivariate techniques as described in Section 3.7, in order to identify and examine, in detail, vegetation trends over time.

As part of the present study, the permanent quadrat approach was also applied to investigate the development of the vegetation of Bettisfield Moss following deforestation in 2002. A set of 1m x 1m quadrats was established and surveyed in 2002 and 2003. The present work therefore provides baseline vegetation data for the site. These data were analysed using multivariate techniques (Section 3.7.2 of the current chapter) to ascertain the initial vegetation response post - deforestation.

Correlation of hydrological monitoring sites with vegetation change

The third approach was specifically designed for the current study. In 2000 a vegetation survey of 1m x 1m quadrats was carried out, along existing hydrological monitoring transects which had previously been established for Fenn's and Whixall Mosses as a series of 91 dipwells. For the present study a 1m x 1m quadrat was recorded directly at each of the 91 dipwell stations. Direct water table measurements are therefore available for each quadrat. Orientation of the quadrats was documented during the survey, to provide the Senior Reserve Manager with a method which could be repeated in the future. These data were correlated with the seasonal average water table height, calculated for each dipwell from the preceding twelve months of hydrological readings. Residence time of the water table was calculated and related to percent cover of *Sphagnum*. Multivariate analysis has also been completed to identify relationships between plant species and peat water table height.

3.2 Sub-compartment botanical surveys

Within each sub-compartment percent cover was estimated for:

- each vascular plant species
- *Sphagnum cuspidatum*
- other *Sphagnum* species considered together
- non-*Sphagnum* bryophytes
- lichens
- bare ground
- surface water

Where cover was less than 1%, it was recorded as shown in Table 3.1 which incorporates a modified 'Domin' score (devised by the Senior Reserve Manager).

Score classification	Cover
< 1%	<1% but > 'Domin' 3
'Domin' 3	<1% with many plants but little cover
'Domin' 2	<1% with several plants but little cover
'Domin' 1	<1% with one or two plants

Table 3.1: Score classification for cover <1% in the sub-compartment vegetation surveys

The vegetation surveys were carried out by initially walking around the periphery of each sub-compartment and recording the main areas of different vegetation types on a sketch map. So for example, a sub-compartment might have two distinct areas of different vegetation types. The two areas could then be called 'A' and 'B' and 'A' may take up one third of the sub-compartment and 'B' the remaining two thirds. This information was documented on the sketch map. Each identified area within the sub-compartment was then assessed and recorded separately after closer survey, by walking across the sub-compartment at regular intervals. These data and the sketch map were used to calculate percent cover (or Domin score if applicable) for each species, bare ground and surface water, for the sub-compartment as a whole. This method of survey was designed by the Senior Reserve Manager.

Existing surveys of this nature carried out in 1991 (base line) and 1998 are held in the site data archives. The surveys recorded each sub-compartment within the remit of the NNR at that time. 1991 data were stored on paper record sheets and the 1998 data were stored as computer word processing files. During the present study, the writer collated these data into a single computer spreadsheet file using the application 'Excel'. For the purposes of multivariate analysis cover values below 1% were reclassified as 1% cover. This was felt to be justifiable due to the large size of the survey plots and the NNR in general. The analysis of vegetation change at landscape level seeks to identify large changes in the key plant species, highlighting major trends rather than very small changes. However for the purposes of GIS analysis, cover <1% and Domin scores 1, 2, and 3 (Table 3.1) were converted to 0.5, 0.1, 0.2, and 0.3 respectively. This was agreed with Natural England staff, so that the full detail of the surveys and additional future surveys would be maintained to the Senior Reserve Manager's specifications. Analysis of these data sets had not been carried out prior to the present investigation.

This survey method was applied by the present writer during 2000 to survey 59 sub-compartments within the rehabilitated area of the NNR. The sub-compartments were selected by the Senior Reserve Manager as 'representing the most typical response to management' in the rehabilitated area (Joan Daniels, *pers comm*). It was noted that this potentially brings a risk of introducing bias to the analysis. These data were collated with corresponding data from the previous two surveys. Species cover was treated as described in the paragraph above, for multivariate and GIS applications. This produced an Excel file for analysis of the rehabilitated area at three time points.

3.3 Permanent quadrat botanical surveys

With the exception of the first investigational approach using the sub-compartment as the individual sampling unit, all investigations in the present thesis use 1m x 1m quadrats.

The permanent quadrats on Fenn's, Whixall & Bettisfield Mosses NNR had all four corners marked by canes and location maps were provided by the Senior Reserve Manager. Species cover within a quadrat was carried out by looking down on the area and estimating the percentage cover occupied by each plant species, bare ground, litter, surface water and lichens.

The investigations of chapters 5 and 7 record cover as percentage, with the exception of cover <1% which adhered to the score classification devised by the Senior Reserve Manager. The previously gathered permanent quadrat data for chapter 5 (surveys 1991 and 1996) were collated with the re-survey of 2001, carried out by the present writer. An Excel spreadsheet was used to create the complete data file. Percent cover figures were retained and cover of <1% was converted to 1%. Domin scores 1, 2, and 3 were converted to 0.2, 0.5 and 0.8 respectively. The data file was then capable of being imported into multivariate analysis applications. This procedure was also followed for the Bettisfield Moss quadrat data (chapter 7).

The investigation of chapter 6 adhered to the 'standard' Domin Scale (Dahl & Hadac, 1941) when dealing with percent cover <4% in the field. This scale is shown in Table 3.2. Percent cover was converted entirely to Domin scores prior to recording this survey data in an Excel file. Domin data are pseudo-quantitative and considered as a pseudo-log transformation of percent cover estimation (Moore and Chapman, 1986).

Domin score	Cover
10	91–100%
9	76–90%
8	51–75%
7	34–50%
6	26–33%
5	11–25%
4	4–10%
3	< 4% with many individuals
2	< 4% with several individuals
1	< 4% with few individuals

Table 3.2: The standard Domin Scale (Dahl & Hadac, 1941)

The present writer carried out a complete site survey of the permanent quadrats of chapter 5 in 2001. Prior permanent quadrat surveys (1991 and 1996) were undertaken by various ecological consultants and volunteers. However, training and written instruction was given by the Senior Reserve Manager in each instance. Vascular plant species were identified in the field by the people carrying out the surveys. Voucher specimens of all bryophytes were obtained and their identification confirmed by Dr Martha Newton of Newton Biological Consultants.

For the purpose of the present study two target vegetation types are described. The first is referred to in the thesis as *peat-forming* and consists of NVC M2 (mire pool) – like vegetation, comprising three plant species i.e. *Sphagnum cuspidatum, Eriophorum vaginatum* and *Eriophorum angustifolium.* The second vegetation type is referred to as *target mire community* and consists of species characteristic of the NVC M18a (raised mire) –like vegetation.

3.4 Permanent quadrat locations

Maps 2.1 and 2.2 (chapter 2) clearly identify the site compartment and sub-compartment numbering system. All of the permanent quadrats are within the rehabilitation area and are surveyed every 5 years as part of site management. The quadrats are located on at least two replicate transects in each of the four peat cutting types (Tantram *et al.,* 2000). The number of quadrats in the various cutting types and initial site sampling method are detailed in Table 3.3 below.

3.4.1 **Fenn's and Whixall Mosses**

Sampling using the generation of random numbers and 10m intervals was employed in the uncut areas where the vegetation was fairly uniform. The remaining cutting types are complex due to the microtopes resulting from peat cutting practices. At each of the randomly generated points along the transects, the quadrat locations were chosen to be representative of each of the microtopes present i.e. surfaces of ditches, flat/'fey' (intermediate peat level where scraped off vegetation was thrown into peat cuttings) and baulks – in the hand-cut and old commercial areas. Microtopes present in the recent commercial cuttings represented the repeated surface pattern of ditch, augered (vegetation removed by machine), *Molinia* (tractor damaged) and relict (uncut degraded surface) (Tantram *et al.,* 2000).

Cutting type	**Sub-compartment**	**Sampling method**	**Number of quadrats**
Uncut	6.7	2 transects crossing at centre (A & B), random numbers used	60
Uncut	15.1	A grid using random numbers	30
Uncut	5.4c	2 transects crossing at centre (X & Y), 2 parallel transects (A & B), quadrats at 10m intervals	31
Old commercial	1.4	1 transect, representative sampling	42
Old commercial	4.4	1 transect, representative sampling	45
Recent commercial	3.3	1 transect, representative sampling	60
Recent commercial	3.9	1 transect, representative sampling	60
Recent commercial	3.13	1 transect, representative sampling	60
Recent commercial	5.9	1 transect, representative sampling	54
Hand cuts	14.6 & 16.1	1 transect, representative sampling	31
Hand cuts	13.4, 13.7 & 22.1	1 transect, representative sampling	55

Table 3.3: Permanent quadrat locations on Fenn's and Whixall Mosses

Representative sampling ensured that all sections of the cut-over surface were surveyed i.e. baulk, flat, ditch, *Molinia*, augered, and relict.

3.4.2 **Bettisfield Moss**

The location of the 106 permanent quadrats on Bettisfield Moss are shown in Map 7.1 (chapter 7) and are detailed in Table 3.4 below.

The vegetation across this area of the site was not uniform due to the influence of past peat cutting, disturbance and varying density and age of former tree cover. After tree clearance in 2001, Bettisfield Moss was divided by the Senior Reserve Manager into compartments based on the varying vegetation. A sub-sample of the compartments was chosen to be more closely monitored using permanent quadrats and initiated as part of the present study. These compartments represented the extremes of the variation on Bettisfield Moss. As such, permanent quadrat locations were chosen to be representative of the compartments and random sampling was therefore only used within the selected compartments.

Each quadrat was orientated 'north' and the south-west corner was marked with a painted wooden stake, showing the quadrat number.

Surface type	Compartment	Number of quadrats
Uncut Dense recent pine	12	15
Uncut Older pine	19	16
Uncut Last pine to colonize	20	15
Old hand cuttings Very old pine	31	15
Old hand cuttings Dense birch, pine, bracken	47	15
*Dynamited *Sphagnum* lawn	29	7
Dynamited *Sphagnum* lawn	30	8
Old hand cuttings Dense recent pine	33	6
Old hand cuttings Dense recent pine	35	9

Table 3.4: Permanent quadrat locations on Bettisfield Moss

* - this area was exploded using dynamite 40 years ago in an attempt to create a pool, by clearing a section of peat.

3.5 Hydrological survey – the dipwells

Dipwells are the most frequently used measure of peat water level. They are mostly 22mm diameter perforated plastic tubes pushed to the base of the peat, with ca 500mm of the tube length exposed above ground. A few 50mm diameter surface dipwells occur near to sub-peat hydrological monitoring points. To read the water level in the peat, a fine plastic tube is inserted into the dipwell and by blowing into it, bubbles are heard when the end touches the water. The fine tube can then be measured to establish the depth of the water table, by measuring and subtracting the height of the tube projecting above peat surface. (Brooks and Stoneman, 1997). Figure 3.1 provides an example of a dipwell.

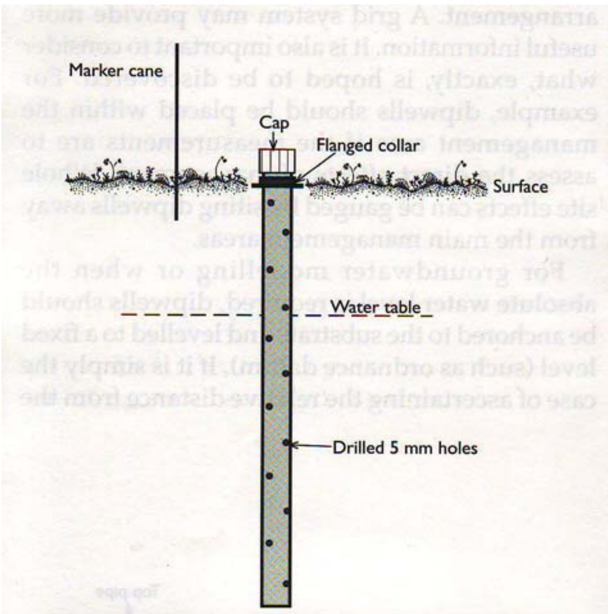

Figure 3.1 The dipwell

Source: (Brooks and Stoneman, 1997).

Figure 3.1 is not to scale, but demonstrates the use of 22mm diameter tubing drilled with 5mm holes.

The site dipwells on Fenn's and Whixall Mosses are positioned along two transect lines at right angles to each other and orientated along the main axes of the Moss. Their locations are marked on Map 2.2 (chapter 2). Water table depth for each of these dipwells was recorded fortnightly as part of the site management regime and added to the site hydrology data archives. The present study utilized water table measurements from this detailed archive.

3.6 Site management data

Rehabilitation management since 1991 involved clearance of pine and birch and damming of drains and ditches. The dates and details of the management works carried out on the sub-compartments have been documented by the Senior Reserve Manager. This information has been used in the present study to establish the length of time since damming and tree clearance – figures which are then treated as environmental variables in exploring/ explaining the vegetation data.

3.7 Data analysis

3.7.1 Geographic Information Systems (GIS) map formulation and analysis

The GIS computer application MapInfo (Version 8, 2005) was used to produce maps for the spatial analysis in chapter 4 and site description of chapter 2.

MapInfo provides a model of the landscape, which is built upon an underlying ordnance survey map. Overlying layers of digital information (e.g. alphanumerics, shapes, lines, and symbols) are added to the model and stored in tables within the software's data base. Labels can be applied to the shapes, e.g. compartment numbers. Data in Excel spreadsheets such as percentage cover data for each of the compartments, can then be linked via the label to the shapes on the mapping layers. The desired information for display or analysis is then chosen from within the database. Because the model is geo-referenced, it is possible to give exact grid references for any point on a generated map. MapInfo has a range of mathematical calculations which can be applied to the stored information. Individual layers of information are used to generate maps which can be compared and processed to enable the merging of data. Information can also be filtered to design maps showing a particular attribute e.g. the peat cutting types of a site.

The ordnance survey map covering the study site was digitised for use in the MapInfo program by Natural England headquarters staff. The present writer created a digitised map of the sub-compartments and tracks of the NNR, which was added to the GIS model. Percent cover data for all plant species of the three sub-compartment surveys (1991, 1998 and 2000) was also incorporated into the model as part of the current study. This enabled the production of detailed plant species thematic maps. Separate site maps for each of the three survey years has been produced on one page, showing the cover of individual key plant species. These maps provided a visual comparison of species cover change, from one survey year to the next. This technique facilitated qualitative and quantitative spatial interpretation of data.

The GIS model of the site was used to design and produce the site description maps of chapter 2.

3.7.2 Multivariate analyses

The present study utilises vegetation description and analysis in an applied sense to identify successional trends and vegetation change, through monitoring and evaluating the effects of management practices.

Kent and Coker (1992) describe plant community data as being multivariate in nature. Species and environmental data files produce the data matrices from which multivariate computer techniques will search for and summarise patterns of variation within the data.

In the present study, computer programmes TWINSPAN (Two-way indicator species analysis) (Hill and Smilauer, Version 2.3, 2005) which is a community classification method and CANOCO (Canonical correspondence analysis) (Ter Braak and Smilauer, Version 4, 1998) an ordination method, were used.

3.7.2.1 Classification

TWINSPAN is a divisive classification technique based on ordination and is widely used in vegetation science to classify species-by-sample data. The technique is a hierarchical divisive algorithm based on a correspondence analysis of the original (sample x species) data matrix. TWINSPAN summarises the major trends in the data and is also known as a dichotomised ordination analysis (Vaz, 2001).

Data are input as a species by sample matrix. The program subjects the data to an ordination analysis, where first of all it arranges the samples (quadrats) in order along the strongest axis of variation in relation to similarities and differences in the species which they contain. Samples at one end of the axis are different from those at the other end. The analysis output is a species x sample table of information about the data dichotomies.

The axis is then divided at its centre of gravity and a dichotomy made, with a group of samples on one side (the negative group) and a group of samples on the other side (the positive group). The negative group is characterised by one set of differential species and the positive group by a second set of differential species (Kent and Coker, 1992). These groups are plotted on to diagrams called *dendrograms* (presented in chapters 5 and 7) where the negative group of each division is positioned to the left and the positive group to the right. The initial division of the complete data set produces Group 0 on the left and Group 1 on the right. Group 0 is then ordinated separately, to form Groups 00 (negative) and 01 (positive). Similarly Group 1 is ordinated and divided to form Groups 10 (negative) and 11 (positive). This process is repeated for each group, providing a hierarchy of divisions until there are either too few samples or where the user considers there will be no further gain. At that point the final groups established are known as end groups.

During the first stage of the analysis the data are converted into *pseudospecies* levels which are derived from the species abundance scores and are defined by *cut levels*. These are illustrated by an example from chapter 7 where five cut levels were input at the start of the analysis to give pseudospecies scores 1 through to 5 representing species cover of 0-0.5%, >0.5-1%, >1-10%, >10-33% and >33% respectively. Pseudospecies which occur exclusively (or at higher frequency) on either side of a dichotomy are good *indicator species* which are important in differentiating one group from another. The indicator species for each group, along with preferential species (less well-marked associations), enable the investigator to characterise the groups ecologically. TWINSPAN incorporates sophisticated iterative secondary analyses to identify these indicator species for each dichotomy.

In chapter 5 the TWINSPAN end groups are presented as constancy tables. Frequency of each plant species in a group is summarised according to Roman numerals I to V (Table 3.5) and species abundance as average percent cover. Constancy tables further enhance characterization and interpretation of the vegetation types (end groups) identified by the TWINSPAN analysis.

Frequency class	**Percentage of samples**	**Class description**
I	1 – 20 %	Scarce species
II	21 – 40 %	Occasional species
III	41 – 60 %	Common / frequent species
IV	61 – 80 %	Constant species
V	81 - 100 %	Constant species

Table 3.5 Constancy table interpretation

Each frequency class (I to V) has a percentage range i.e. how many samples a particular species occurs in for a TWINSPAN end group.

Source: Rodwell (1991).

3.7.2.2 Ordination

The CANOCO (Canonical correspondence analysis) for Windows software comprises several programs (ter Braak and Smilauer, Version 4.5, 2002). Ordination is a method of gradient analysis which relates species composition of samples to environmental gradients (measured or hypothetical). Where classification creates distinct vegetation units, ordination reveals repeatable vegetation patterns and discontinuities in species composition (Lepš and Šmilauer, 2003). The data set for analysis can be imported into the computer program as an Excel spreadsheet. In the present study the primary data set (response variables) are the vegetation quadrats (samples) and the environmental variables (explanatory variables) include water table measurements, length of time since rehabilitation management, peat-cutting type and location, which apply to the individual samples.

Multivariate analyses identify the main trends in the data as axes. Four (theoretically) independent axes are identified of diminishing strength. This is achieved by identifying the strongest axes and then removing that part of the data which is associated with that axis before attempting to identify the next strongest axis. A measure of the strength of each axis is provided by its Eigenvalue. High Eigenvalues (up to 1.0) indicate a strong trend and those with a low Eigenvalue (close to 0.0) indicate a weak trend.

The central ordination methods of CANOCO are *linear* (Principal Components Analysis, PCA, and Redundancy Analysis, RDA) and *unimodal* (Correspondence Analysis, CA, Detrended Correspondence Analysis, DCA and Canonical Correspondence Analysis, CCA). The linear and unimodal models are used to establish species response to environmental gradients. Data determined to be unimodal assumes species have an optimum on the environmental gradient – the relationship being symmetrical around the species optimum (Lepš and Šmilauer, 2003). Data which is determined to be linear, tends to have species widely distributed in the samples and showing linear trends in abundance.

The appropriate model of analysis is determined by the length of gradient figure for axis 1, resulting from a preliminary DCA of the data set. Gradient length is expressed as standard deviation units of species turnover (SD). A gradient length > 4 SD demonstrates a unimodal species response along the gradient while < 3 SD demonstrates a linear response (ter Braak and Šmilauer, 2002).

3.7.2.2.1 Linear Models - Principal Component Analysis (PCA)

The linear response is fitted by the methods of (least squares) regression. Linear data sets are analysed using PCA which is an unconstrained ordination (indirect gradient analysis). This analysis is based on the covariance or correlation matrix. For species data the covariance matrix is used and for environmental data (measured on different scales) the correlation matrix (which standardises the data) is used (Maddy and Brew, 1995).

This method looks for the best pattern of variation amongst the species data. By calculating this ordination first, the main part of the variability in species composition is not missed (Lepš and Šmilauer, 1999).

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3.7.2.2.2 Linear Models - Redundancy Analysis (RDA)

Following on from the PCA a constrained ordination (direct gradient analysis) of species and environmental data uses RDA. Here the linear relation between primary and explanatory variables are considered simultaneously. The constrained ordination is a search for the best fit of the explanatory variables to the species data. This method focuses on the species composition variability which is explained by the measured environmental variables (ter Braak and Šmilauer, 2002).

3.7.2.2.3 Unimodal Models - Detrended Correspondence Analysis (DCA)

Unimodal data sets are analysed initially using the unconstrained DCA ordination. The unimodal response model estimates species optimum by calculating the weighted average of the environmental values where the species is found (Lepš and Šmilauer, 1999). Species optimum for a particular gradient is the average of all the values of the variable across the quadrats where the species occurred (ter Braak and Šmilauer, 2002).

3.7.2.2.4 Unimodal Models - Canonical Correspondence Analysis (CCA)

The DCA analysis is followed by the CCA to provide a constrained ordination which incorporates the environmental variables in to the analysis. As a result of reciprocal averaging of the sample scores, multiple regression is carried out on the environmental variables and used to modify the scores (Vaz, 2001). This process is repeated until the scores stabilise. The final ordination axes are restricted to be linear combinations of the species and environmental data (Maddy and Brew, 1995).

3.7.2.2.5 Monte Carlo permutation tests

During constrained ordination the statistical significance of each environmental variable's relationship to the species data can be tested using *Monte Carlo permutations*. An ordinary statistical test compares the value of the test statistic (calculated from the data) with the expected distribution under the null hypothesis. In the Monte Carlo permutation test, the reference distribution is simulated by repeatedly permuting the samples without the assumption of normality and without mathematical derivations (Vaz, 2001). The null hypothesis in the permutation test is that the response (species) is independent of the environmental variable. It therefore does not matter which set of explanatory variables is assigned to a particular sample, each permutation of the samples in the species data are equally likely (Lepš and Šmilauer, 1999).

The statistical significance of each explanatory variable is assessed individually by the Monte Carlo permutation test. Variables tested and found to be significant are added successively to the model in order of decreasing contribution (and often significance). This technique indicates where relationships between the environmental variables and trends in the vegetation identified by CANOCO have a less than 5% probability of being random. This allows the variables with a non-random relationship to be included in the analysis model and the rest to be excluded.

3.7.2.2.6 Ordination diagrams

Each quadrat (sample) and the species and environmental variables associated with it have numerical scores on each trend, it is therefore possible to plot the data using each trend as a distinct axis. The CANOCO software includes the program CANODRAW which displays the ordination results as diagrams (scatter plots/ bi-plots). Samples are represented as points (symbols) in the diagrams. In linear methods, species are represented by arrows (the direction in which the species abundance increases) and by points (symbols) in unimodal methods (estimates of the species optima). Continuous environmental variables are shown by arrows and nominal variables as points (symbols) (Lepš and Šmilauer, 2003).

CANOCO was used to examine all vegetation and environmental data in the present study.

CHAPTER 4
FENN'S AND WHIXALL MOSSES LANDSCAPE ASSESSMENT OF VEGETATION CHANGE

4.1 Introduction

The conditions prevailing on a raised mire prior to rehabilitation are not likely to be stable. Gaps in knowledge exist regarding the dynamics of damaged sites and how they respond to conservation management (Brooks, 2003). Each site is unique and management techniques will be influenced by issues including past land use, adjacent land use, existing species (flora and fauna), financial resources and local community needs (Ross and Cowan, 2003).

Limited or inconsistent site archive vegetation surveys were highlighted by Ross and Cowan (2003) as preventing quantitative analysis of vegetation change in UK mire sites.

Spatial differences in vegetation quality in relation to rehabilitation at any one specific time point are discussed in the literature. Such work includes reports on uncut raised mire (Dargie and Hulme, 2000) and rewetted peat cuttings (Dargie, 2001[2]) carried out at Wedholme Flow (an 800ha raised mire site on the South Solway Plain). The reports identified moisture and succession trends from the data analysis and provided an evaluation at one time point of the nature of the vegetation in relation to desirable mire communities.

Studies relating to the analysis of vegetation change at 'landscape' (sub-compartment) level are not well represented in the literature. Work of closest relevance to the current study is by Dargie (2000) who monitored the distribution and abundance of re-wetting indicator species on Thorne Moors (a damaged lowland raised mire in Yorkshire). The study was carried out at sub-compartment level by means of two vegetation surveys at a five year interval (survey years 1994 and 1999) and reported a strong *Sphagnum* response (increase of 13.9%). Dargie's (2000) findings highlighted that the strongest trend in vegetation change was related to re-wetting management which led to an increase in cover of *Sphagnum*. Significant declines in the range and abundance of *Andromeda polifolia* and *Vaccinium oxycoccus* were also found. Unexplained vegetation patterns were attributed to localised plant successions due to the rise in water table. Mire species in sub-compartments with a major increase in water table height (inundation) were slower to respond to management.

4.2 Aims of the investigation

The investigation described in this chapter aimed to elucidate plant species responses to site management (i.e. raising the water table by damming (rewetting) techniques and removing trees) at the sub-compartment level across the site. Management plan (Daniels, 1998) targets for percent cover development of target peat-forming species (*Sphagnum cuspidatum, Eriophorum vaginatum* and *E. angustifolium*) were used as a measure of success for the investigation.

An additional aim was to identify possible relationships between seasonal average water table level and plant species, as well as management treatments.

The present investigation drew together existing site monitoring data i.e. NNR vegetation surveys conducted in 1991 and 1998, utilising data from 140 vegetation sampling units (sub-compartments) from each of the two survey years. These data included sampling units from managed and unmanaged areas of the site. Multivariate analysis was carried out to explore species trends and relationships between species and management variables at the ‘landscape level’. Vegetation mapping was then undertaken using GIS. This technique provided a visual assessment of site-wide species cover for each survey year.

The existing surveys were expanded upon on as part of the present study, with a resurvey in 2000 of 59 sampling units within the central rehabilitated area of the site. These samples were analysed (along with the same samples recorded in 1991 and 1998) by means of multivariate and GIS techniques. The aim of this second data set analysis was to narrow the focus of assessment to the rehabilitated area.

It was hypothesised that rehabilitation management caused a rise in the peat water table which would establish conditions conducive to peat formation. The subsequent colonisation of peat forming species was also hypothesised. Management plan (Daniels, 1998) targets state that within 5 years of rehabilitation, *Sphagnum* and *Eriophorum* spp. should exceed a combined cover of 75% in each sub-compartment of the rehabilitated area.

The site sub-compartments had a varied topography due to the remaining peat cutting profile. Different depths of peat and subsequent variation in surface proximity to the peat water table occurred in each sub-compartment. There was much variation in vegetation types within the sampling units. Chapter 2 described the nature of the sub-compartments in detail.

4.3 Materials and methods

A detailed account is given in Chapter 3.

4.3.1 Botanical sampling method

During the summers of 1991 and 1998 sub-compartment vegetation surveys were carried out using methodology described in detail in chapter 3. The existing site method of sub-compartment vegetation survey was adopted for the current study when surveying the rehabilitated area in 2000. This practice ensured consistency between the data sets.

4.3.2 Environmental data

Each sub-compartment was assigned a set of environmental variables relating to site management practices. The number of seasons since damming and birch removal was calculated for each sub-compartment using the site management archive files. Management began at the centre of the site radiating outwards:
recent commercial cuttings in 1991-1994,
uncut in 1992 and 1995,
hand cuttings in 1995/1996,
old commercial cuttings in 1996/1997.

The nature of the peat-cut surface was recorded for each sub-compartment according to the history of peat cutting (i.e. cutting type). Percentage cover of bare peat was taken from the sub-compartment vegetation surveys and year was also included to provide a time sequence from the initial survey though subsequent surveys. These variables are listed in Table 4.1.

For the purpose of the present study, the Senior Reserve Manager suggested dipwell stations to represent each of the site sub-compartments. With her experience of the site, she was able to determine which dipwell measurements were generally typical of each sub-compartment. The appropriate dipwell data for the year prior to each vegetation survey (except for the 1991 survey, where 1993 dipwell data were used as this was the earliest available) were then used to calculate seasonal averages. Average water table depth was given as centimetres below (or above) the general peat surface.

4.3.3 Data analysis

Ordination by indirect and direct gradient analysis was performed. Plant species data were entered into the multivariate computer application as percentage cover and underwent log transformation for the analysis.

The Geographical Information Systems computer software MapInfo was used to digitise the site sub-compartments and species data from each of the surveys were imported into the programme. This facilitated the production of maps to demonstrate plant species cover at each survey time point.

Further explanation of the above methods is detailed in chapter 3.

In the present and subsequent chapters the words *waterlogged* and *inundated* have been used to describe the position of the peat water table. Waterlogged, refers to wet, saturated peat. Inundated, refers to areas of peat with an above surface water table.

4.4 Results

4.4.1 'Landscape' survey 1991 and 1998 - species ordination by indirect gradient analysis

The species/sub-compartment data matrix were analysed using ordination. The number of samples in this analysis was 280 and there were 43 species. Species names were abbreviated for the multivariate outputs and a key to these abbreviations is given in Appendix 1. A preliminary exploratory correspondence analysis de-trended by segment (DCA) resulted in a segment length on the first axis of 2.343 and an eigenvalue of 0.285. The linear method was most suited for analysis of data with this gradient and as such the data were re-analysed using Principal Component Analysis (PCA). The first two axes of the DCA explained 24% of the species variation and 32% of the species-environment relation. The PCA analysis, however, provided further information i.e. the first two axes explained 32.8% of the species variation and 59.6% of the species-environment relation. Eigenvalues for axes 1 and 2 were 0.197 and 0.132 respectively.

The species data were presented as a correlation scatter plot in Figure 4.1. Axis 1 (the horizontal axis) and Axis 2 (the vertical axis) displayed the two strongest trends in the vegetation data. Species which were most associated with these trends were shown by their extreme vector (arrow) lengths.

Axis 1 suggested a wet-dry gradient. Species to the extreme negative end of the axis (*Sphagnum cuspidatum, Eriophorum vaginatum* and *E. angustifolium*) were those of a high water table/ inundation. These species were target peat-formers. The opposite end of the axis 1 gradient depicted a low water table with the strong association of plant species of dry habit (*Pteridium aquilinum* and *Betula* spp. (1-3m and >3m in height)).

Species at the extremes of Axis 2 were *Molinia caerulea* which was negatively correlated with this axis and *Calluna vulgaris* and *Erica tetralix* which were positively correlated. This trend moved from undesirable species of fluctuating water table habit (*Molinia caerulea*) through to a cluster of more desirable species, including some lowland raised mire species characteristic of a more stable water table (*Vaccinium oxycoccos*, *Erica tetralix* and *Andromeda polifolia*) and then on to *Calluna vulgaris*, which indicated the dry conditions of a low water table.

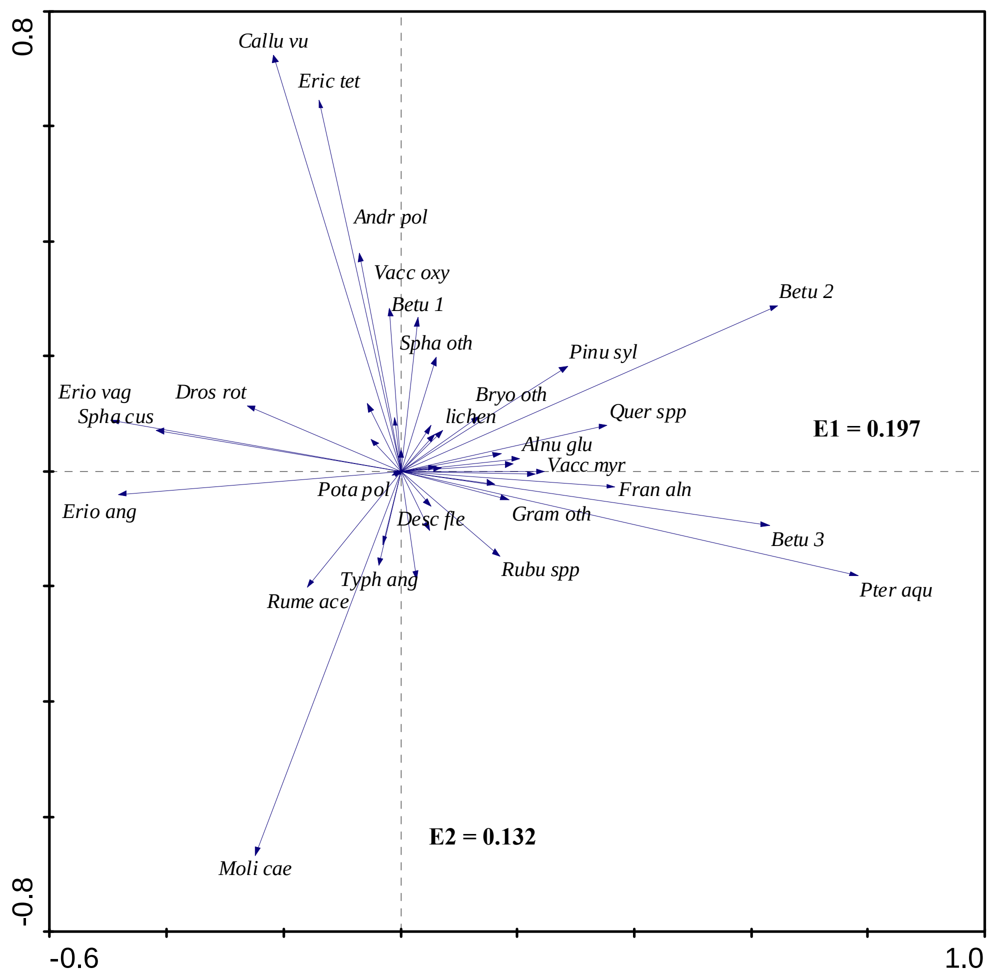

Figure 4.1 'Landscape' Investigation – survey years 1991 and 1998: PCA correlation scatter plot of plant species

The PCA is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focus on inter-species correlation and the scores are standardised after axes extraction to produce a correlation scatter plot where the length of the vector is a measure of fit with the ordination diagram. Eigenvalues for each axis are stated on the scatter plot as E1 and E2.

$\lambda 1$ = 19.7% of species variance; $\lambda 1 + \lambda 2$ = 32.8% of species variance (59.6% of the species/environment relationship)

4.4.2 'Landscape' survey 1991 and 1998 - species ordination by direct gradient analysis

To extrapolate patterns of association between species and environmental variables, ordination by direct gradient analysis was performed. The linear model required ordination using Redundancy Analysis (RDA). Eigenvalues for axes 1 and 2 were 0.106 and 0.047 respectively. Axis 1 explained 10.6% of the species variance and combined with axis 2 explained 15.3% of the species variance. This analysis also computed that 63.1% of the species/environment relationship was explained by the first two axes.

The significance of the explanatory variables (environmental variables) was tested in the RDA using Monte-Carlo permutations. The only non-significant variable ($p > 0.05$) was 'average spring water table depth' which was removed from the model. The summary statistics for the explanatory variables are listed in Table 4.1 and the RDA bi-plot is shown in Figure 4.2.

Order of inclusion	Variable code	Variable description	P value
1	Autumn	Average Autumn water table depth	0.0020
2	Rec com	Recent Commercially peat-cut areas	0.0020
3	Bir cut	Number of seasons since birch cutting	0.0020
4	Year	Increasing time – 1991 to 1998	0.0020
5	Hand cut	Hand Cut peat-cut areas	0.0020
6	Uncut	Uncut areas	0.0020
7	Bare	Bare peat surface	0.0020
8	Old com	Old Commercially peat-cut areas	0.0020
9	Summer	Average Summer water table depth	0.0080
10	Winter	Average Winter water table depth	0.0100
11	Dam	Number of seasons since damming	0.0220
*	Spring	Average Spring water table depth	0.6940

Table 4.1: 'Landscape' Samples: Summary statistics from Monte-Carlo permutations analysis of explanatory variables

* Excluded from the model – not significant

Although the spread of species vectors along axis 1 had rotated so that the species appeared reversed in the RDA, the general relationship between the species seen in the PCA analysis had been maintained. This was an indication that the strongest trends in the vegetation were well accounted for by the explanatory variables.

Axis 1 of the RDA maintained the strongest trend in the data as a wet-dry gradient. The strongest influences on this axis was the length of time since the application of the rehabilitation management treatments (damming and birch removal) which correlated with increases in the cover of the peat forming species *Eriophorum angustifolium,, E. vaginatum* and *Sphagnum cuspidatum.* Increases in seasonal water table depth appeared to relate to the dry end of the gradient on axis 1. This suggested that higher water tables were associated with peat-forming species and management effect. The analysis has not isolated one particular season as affecting particular species, effects of the seasons were correlated.

Poor management effect or no management effect (un-rehabilitated sub-compartments) was associated with the dry end of the gradient i.e. associated with *Pteridium aquilinum* and *Betula* spp.. This was confirmed by the location of un-rehabilitated samples at the positive end of axis 1 on viewing a bi-plot of samples and environmental variables.

Year appeared to influence both axes. In one respect increasing time correlated with increases in the three peat-forming species, but also related to the more diverse flora (including mire species of NVC M18a) which correlated with the uncut, hand and old commercial cutting types. This latter relationship was not correlated with management effect. This could be explained by the fact that these areas were rehabilitated at a later time compared to the recent commercial areas.

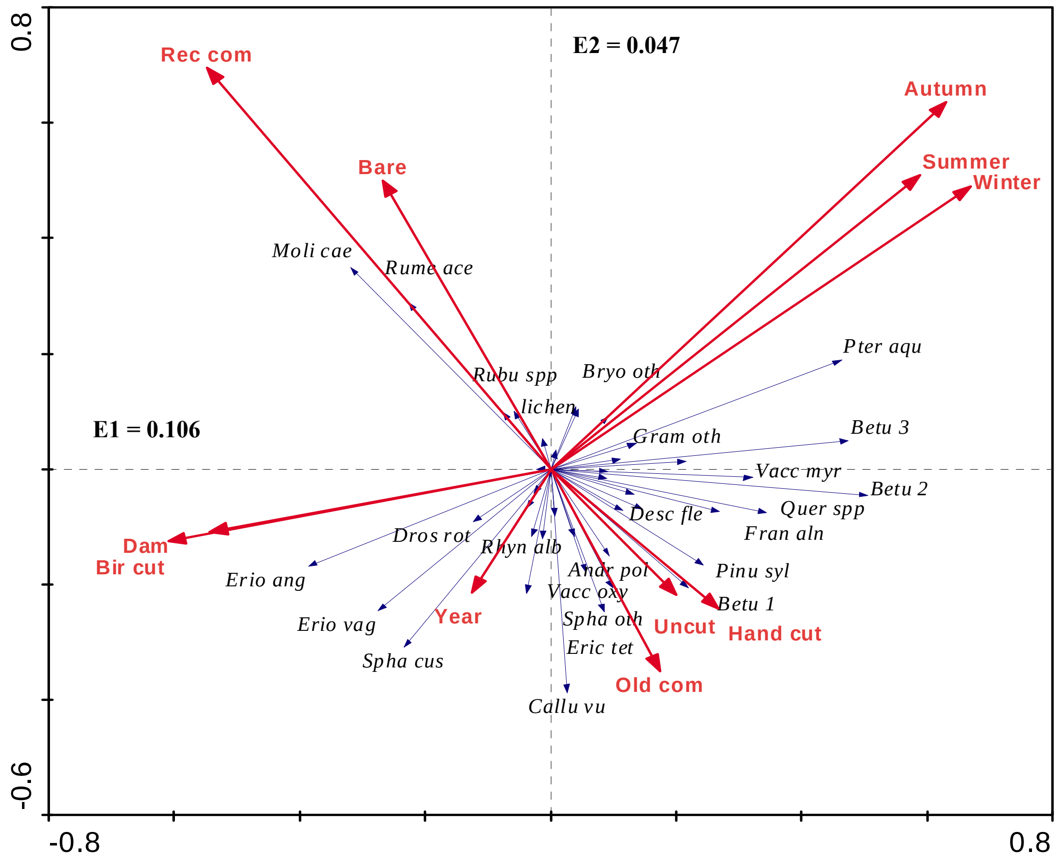

Figure 4.2 'Landscape' Investigation – survey years 1991 and 1998: RDA correlation bi-plot of plant species data constrained by significant environmental variables

The RDA analysis is based on the covariance matrix (species centred only, i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after the extraction of the axes to produce a correlation bi-plot where the length of vector is a measure of fit with the ordination diagram. Species names with very short vectors have been removed from the bi-plot to enhance clarity. Eigenvalues for each axis are stated on the scatter plot.

$\lambda 1$ = 10.6% of species variance; $\lambda 1 + \lambda 2$ = 15.3% of species variance (63.1% of the species/environment relationship)

All axes are significant and the sum of all canonical eigenvalues is 0.242

Autocorrelation detected for seasonal water table depth.

Axis 2 separated the recent commercial cutting type from the other three cutting types (which correlated with each other). Recent commercial areas were strongly correlated with higher cover of bare ground and *Molinia caerulea* and appeared to have a weak relationship with the wet end (management related) of axis 1.

The time interval between the two assessments (i.e. year) was most strongly correlated with increases in *Sphagnum cuspidatum* and its association with axis 1 was not strong. The slightly stronger association with the lower end of axis 2 may suggest that this axis reflected some change in the vegetation of the recent commercial cutting type away from *Molinia caerulea.*

4.4.3 Rehabilitated area surveys 1991, 1998 and 2000- species ordination by indirect gradient analysis

The number of samples in the analysis was 177 and there were 41 species. A preliminary exploratory DCA produced a segment size on the first axis of 1.566 and an eigenvalue of 0.128. As the length of gradient was < 3 the linear method of analysis was appropriate for the data and therefore re-analysis using PCA was performed. The first two axes of the DCA explained 16% of the species variation and 42% of the species-environment relation. The PCA provided further information i.e. the first two axes explained 39.7% of the species variation and 72.1% of the species-environment relation. Axis 1 had an eigenvalue of 0.236 and axis 2, 0.106.

PCA species correlation analysis output was produced as a scatter plot (Figure 4.3). Axis 1 and axis 2 displayed the two strongest trends in the vegetation data.

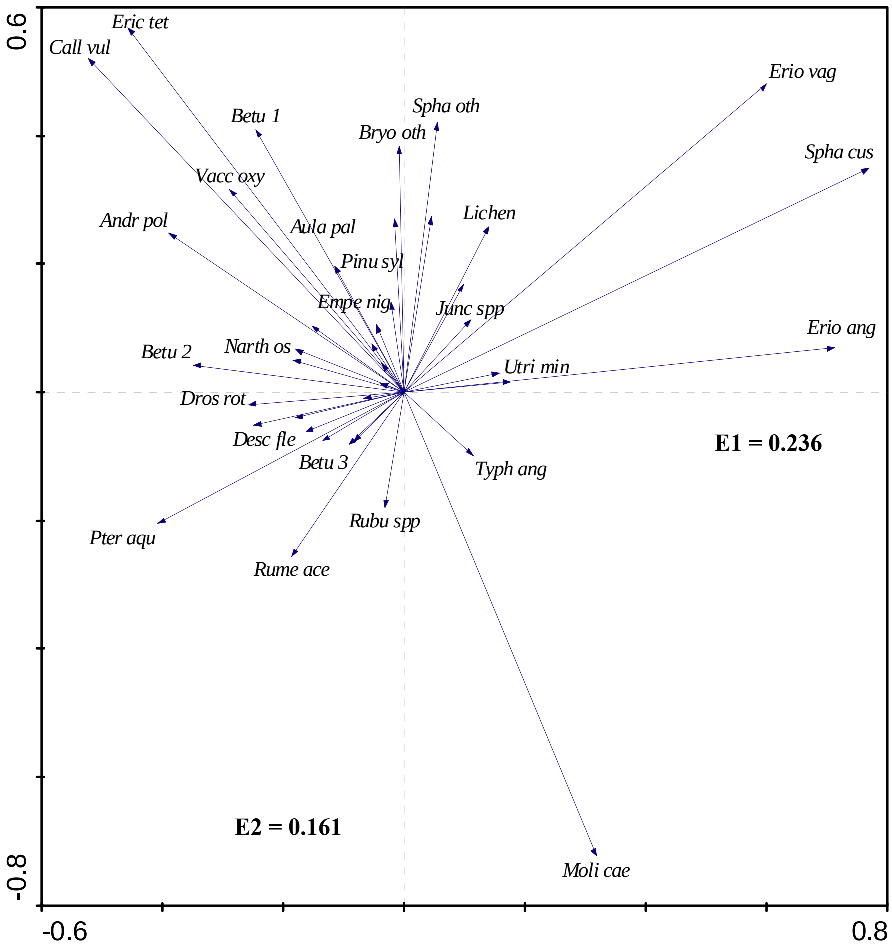

Figure 4.3 Rehabilitated Area Investigation – survey years 1991, 1998 and 2000: PCA correlation scatter plot of plant species

The PCA is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focus on inter-species correlation and the scores are standardised after axes extraction to produce a correlation scatter plot where the length of the vector (arrow) is a measure of fit with the ordination diagram. $\lambda1$ = 23.6% of species variance; $\lambda1 + \lambda2$ = 39.7% of species variance (72.1% of the species/environment relationship)

The strongest trend in the species data projected by axis 1 was a dry-inundated gradient. More extreme vector lengths associated with the three management target species and more reduced vector lengths at the dry end of the gradient (*Betula* spp. and *Pteridium aquilinum*) were seen compared to the ordination diagrams of the first data set. From left to right along axis 1, the species of dry ecological requirement quickly gave way to those of wet peat (*Drosera rotundifolia* and *Narthesium ossifragum*), leading across to species of inundation (*Eriophorum angustifolium). D. rotundifolia* and *N. ossifragum* oddly appeared on the drier side of axis 1 and were more closely associated with *Betula* spp., however their shorter vector lengths suggested less of an influence. There were a number of species with short vector lengths in Figure 4.3 and this central cluster of species with no strong relationship to either axis confirmed the complex nature of the site.

Axis 2 demonstrated the strong influence of *Molinia caerulea* on the data set. This axis suggested a trend of increasing diversity in a positive direction. Increases in *Sphagnum* species (other than *Sphagnum cuspidatum*) correlated with axis 2 at the diverse end of the gradient, where predominantly mire species were located.

4.4.4 Rehabilitated area surveys 1991, 1998 and 2000- species ordination by direct gradient analysis

Ordination by direct gradient analysis was performed according to the linear model using RDA. Axis 1 eigenvalue was 0.156 and for axis 2 was 0.080. Analysis output showed axis 1 explained 15.6% of the species variance and axis 1 and 2 combined explained 23.6% species variance and 76.1% of the species/environment relationship.

The significance of the explanatory variables was tested in the RDA using Monte-Carlo permutations. Non-significant variables ($p > 0.05$) were average spring and autumn water table depth. These variables were removed from the model. The summary statistics for the explanatory variables have been listed in Table 4.2 and the RDA bi-plot shown in Figure 4.4.

The species spread in the RDA bi-plot (Figure 4.4) was consistent with that of the PCA and appeared as a mirror image. The strongest trend identified (axis 1) was the dry-inundated gradient identified in the PCA. Inundation correlated with the management effect, time and the three target peat-forming plant species. The dry end of the gradient correlated with the lowest peat water table depth – most strongly related to average summer depth and species of dry habit e.g. *Deschampsia flexuosa.*

Axis 1 therefore suggested that a high water table correlates with rehabilitation management and an increase in the peat-forming species.

Order of inclusion	Variable code	Variable description	P value
1	Year	Increasing time – 1991 to 1998 to 2000	0.0020
2	Rec com	Recent Commercially peat-cut areas	0.0020
3	Hand cut	Hand Cut peat-cut areas	0.0020
4	Old com	Old Commercially peat-cut areas	0.0020
5	Uncut	Uncut areas	0.0020
6	Bare	Bare peat surface	0.0020
7	Bir cut	Number of seasons since birch cutting	0.0020
8	Summer	Average Summer water table depth	0.0020
9	Dam	Number of seasons since damming	0.0080
10	Winter	Average Winter water table depth	0.0220
*	Autumn	Average Autumn water table depth	0.1580
*	Spring	Average Spring water table depth	0.3660

Table 4.2: Rehabilitated Samples: Summary statistics from Monte-Carlo permutations analysis of explanatory variables

* Excluded from the model – not significant

Axis 2 related low species diversity to the recent commercial cutting type and increasing diversity with the other three cutting types. The strong presence of *Molinia caerulea* suggested a fluctuating water table within the dry-inundated gradient of axis 1. This species appeared to have some relationship with the effects of damming as well as bare ground. *M. caerulea* was negatively correlated with *Betula* spp. <0.5m in height as well as some desirable mire species. *M. caerulea* may therefore have the potential to be replaced by these species if the water table stabilised to a slightly drier direction. Alternatively it could be postulated that if the water table in the recent commercial areas is held above surface, *M. caerulea* may be replaced by the peat-formers.

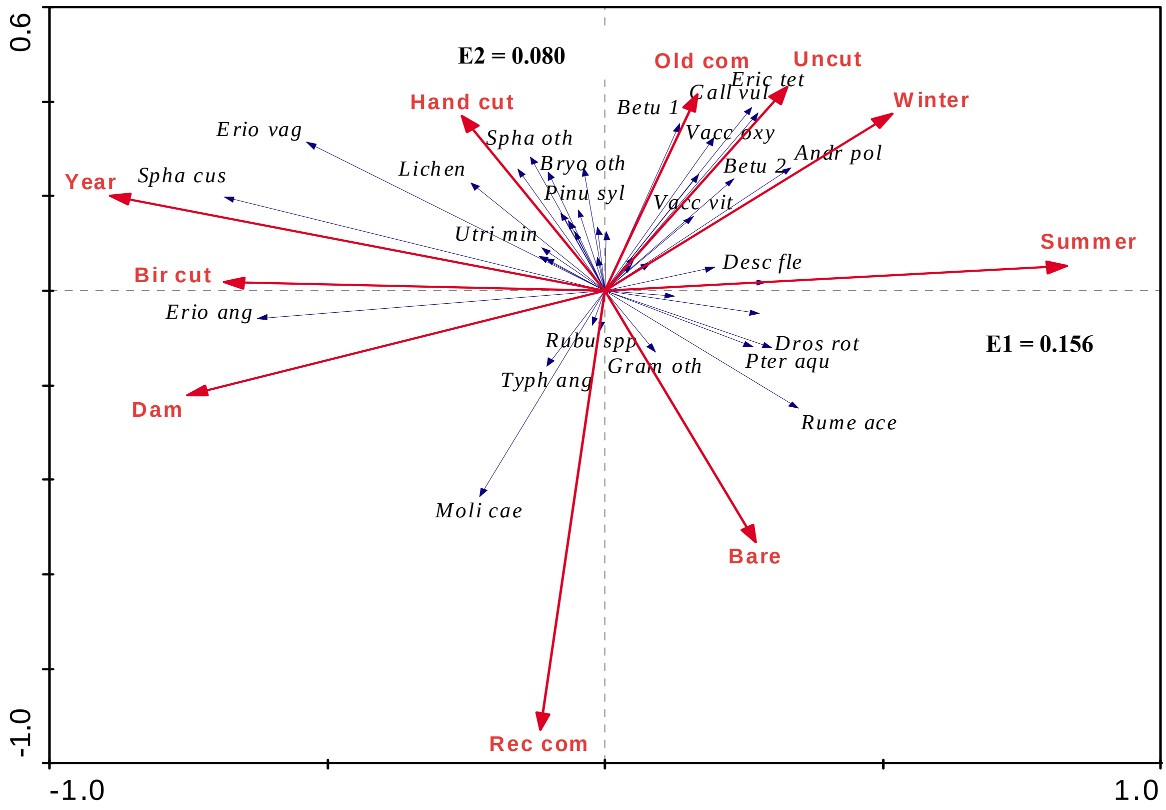

Figure 4.4 Rehabilitated Area Investigation – survey years 1991, 1998 and 2000: RDA correlation bi-plot of plant species data constrained by significant environmental variables

The RDA analysis is based on the covariance matrix (species centred only, i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after the extraction of the axes to produce a correlation bi-plot where the length of vector is a measure of fit with the ordination diagram. Species names with very short vectors have been removed from the bi-plot to enhance clarity. Eigenvalues are stated for each axis on the bi-plot.

$\lambda 1$ = 15.6% of species variance; $\lambda 1 + \lambda 2$ = 23.6% of species variance (76.1% of the species/environment relationship) All axes are significant and the sum of all canonical eigenvalues is 0.310

The recent commercial and hand cuttings were located on the left side of the bi-plot and thus indicated a possible weak relationship with the management variables.

A high summer water table correlated directly with increasing time since birch removal. This may indicate that the pre-management loss of precipitation to evapotranspiration is reduced post-management. This may be ameliorating peat water retention during the driest period of the year.

Increasing winter water table height correlated with increasing time (year) since damming (rewetting). This suggested that water was being retained in some sub-compartments (possibly recent commercial and hand cuttings which are located on the left side of the bi-plot i.e. the wetter side) and was not being lost to drainage.

The RDA analysis also highlighted that rewetting may cause the loss of NVC M18a species i.e. *Andromeda polifolia, Vaccinium oxycoccos, Drosera rotundifolia* and *Erica tetralix.* These species correlated with the uncut and old commercial cutting types and were likely to have been present it damper/ lower cut areas prior to rehabilitation. The effects of inundation in these areas may have a drowning effect on the species.

Analysis of this second data set confirmed the effect of rewetting on the plant community as being related to rehabilitation. There were fewer dry land species and an enhanced effect in peat-forming species was found.

4.4.5 'Landscape' assessment using geographical information systems computer software - vegetation surveys 1991, 1998 and 2000 (rehabilitated area only)

The following species cover maps were generated from the vegetation data sets:

- Map 4.1 – *Sphagnum cuspidatum*
- Map 4.2 – *Eriophorum vaginatum*
- Map 4.3 – *Eriophorum angustifolium*
- Map 4.4 – Combined percent cover for *Sphagnum cuspidatum, Eriophorum vaginatum* and *Eriophorum angustifolium*

- Map 4.5 – Sub-compartments achieving management plan targets
- Map 4.6 – *Calluna vulgaris*
- Map 4.7 – *Molinia caerulea*
- Map 4.8 - Bare peat

Maps 4.1 – 4.8 can be viewed in the Appendices of this thesis (Appendix 2).

The maps present a time series, showing percent species cover for each survey year. The 2000 survey was restricted to 59 sub-compartments within the rehabilitated area. Map 2.2, chapter 2 – shows the rehabilitated area of the site and Map 2.1, chapter 2 – identifies the different peat cutting types.

Sphagnum cuspidatum

This species is characteristic of ombrotrophic mire pools where it has a floating or submerged habit. It also occurs along pool margins and areas of partly submerged mire lawn (Daniels and Eddy, 1985).

Sphagnum cuspidatum (Map 4.1) prior to rehabilitation was generally either absent or at a very low percent cover (0-5%) across the sub-compartments. A few sub-compartments in the hand cut areas had cover of *Sphagnum cuspidatum* between 6 and 15%.

The 1998 survey showed an increase in cover within several sub-compartments (including all cutting types). These sub-compartments were located in the rehabilitated area. Further percent increase was seen in 2000, with highest cover in the hand cut and recent commercial areas. The greatest increase was seen in a hand cut sub-compartment which had no *Sphagnum cuspidatum* in 1991 and by 2000 had an approximately 50% cover. Another sub-compartment located in the recent commercial cuttings increased cover from none to 45% by 2000.

Eriophorum vaginatum

This species is commonly known as hare's tail cotton-grass/cotton-sedge and is a member of the *Cyperaceae* (sedge family). It is a tussock-forming species of wet acid peat, characteristic of waterlogged conditions and the ability to tolerate drier conditions during summer (Grime *et al.,* 1996).

In the present study Map 4.2 shows the percentage cover of *Eriophorum vaginatum*. Initial survey demonstrated only a few uncut and hand-cut sub-compartments with cover

>5%. The 1998 survey demonstrated an increase across many of the sub-compartments (all cutting types). The highest percent cover was seen in the hand cut and uncut areas. By 2000 further increases in cover were seen – notably in the old commercial cuttings.

Eriophorum angustifolium

This plant species is commonly known as common cotton-grass/cotton-sedge and is a member of the *Cyperaceae* (sedge family). This species is noted by Sinker *et al.* (1991) as one of wet hollows and bog pools and characteristically the first water plant to colonize peat cuttings.

Prior to rehabilitation at the NNR, *Eriophorum angustifolium* (Map 4.3) achieved its greatest percent cover (6-15%) within the hand cut areas. These areas showed a post-management increase in 1998 and this species developed in several recent commercial and a few old commercial sub-compartments. The 2000 survey demonstrated further increase where recent commercial and hand cuttings had the higher percent cover. By 2000 the species reached its highest cover of 60% in a recent commercial sub-compartment and also one of the hand cut compartments. These compartments had little or no cover of this species in 1991.

Combined peat-forming species cover

The site management plan target peat-forming species have been shown as combined cover in Map 4.4. Prior to rehabilitation, several sub-compartments had an existing low cover (6-10%) of these combined species (recent commercial and uncut areas). One sub-compartment in the hand cuttings had a 36-40% cover in 1991.

The 1998 survey demonstrated an increase in cover across the hand cut and recent commercial areas, as well as a few old commercial sub-compartments. A small number of sub-compartments adjacent to, but outside of the rehabilitation remit, showed a very low increase in cover. However, larger increases were seen within the rehabilitation area.

The 2000 survey highlighted further increases in cover, with several sub-compartments reaching 61-100% cover (in line with management plan targets). Both hand cuttings and recent commercial cuttings demonstrated increases over the study period. The difference appears to be that the recent commercial areas have taken longer to achieve the increased cover which is seen in 2000. The hand cuttings had already achieved similar cover by 1998, which was sustained and slightly enhanced by 2000.

Sub-compartments achieving management plan targets

Map 4.5 shows the sub-compartments which achieve management plan targets of $\geq$ 75% combined cover of *Sphagnum cuspidatum, Eriophorum vaginatum* and *Eriophorum angustifolium.* Only one sub-compartment achieved target by 1998 (sub-compartment 13.3 which is highlighted with a green star symbol on Map 4.5. Table 4.3 summarises the level of management plan target achievement.

Calluna vulgaris

Calluna vulgaris is a member of the *Ericaceae* (heath family) and common name is Ling (heather). This is a species of heath and moorland (Grime *et al.,* 1996) and a component of the NVC M18a community, colonising the drier aspects of hummock vegetation (Rodwell, 1991)

.

In the present study *Calluna vulgaris* demonstrated a strong relationship with axis 2 of the PCA of the first data set which indicated that this species was a dominant feature at the site relating to areas of dry peat. Map 4.6 was therefore included in the present section. By 1998 *C. vulgaris* had increased in percentage cover on the old commercial areas where it shows a subsequent decline in 2000.

Molinia caerulea

This species (of the *Gramineae,* grass family) is commonly known as purple moor-grass and is described by Grime *et al.*. (1996) as occupying the transition zone between wet and dry land. They also state that this species is replaced by *Eriophorum vaginatum* and *Juncus effusus* in waterlogged habitat.

The RDA ordination analysis of the first data set suggested a strong relationship between *M. caerulea* and the recent commercial cutting type, on axis 2 of the bi-plot. In Map 4.7 this species is seen to be widespread across the site (at varying levels of cover) prior to management.

It is evident that by 1998 *M. caerulea* cover increased and most profoundly so in the recent commercial areas. The 2000 survey then indicated a general reduction in percentage cover across the rehabilitated area, confirming levels of waterlogging had been achieved. However, a small number of sub-compartments in old commercial and hand cuttings continued to show an increase. This suggested subtle indications that rehabilitation has begun to affect the peat water table in these areas of later management, causing fluctuation of the water table.

Bare peat

Map 4.8 was included in the present section to clearly demonstrate the scale of bare peat in the recent commercial areas in the early stages of the rehabilitation process. In 1991 most of the sub-compartments in the recent commercial areas were 50-60% bare peat - this has decreased to 0-5% by 2000.

Cutting type	**Percent of sub-compartments**	**Achieved in < 5 years**	**Achieved at 5 years**	**Achieved in > 5 years**
Recent commercial cuttings	7			yes
Old commercial cuttings	8	yes		
Hand cuttings	12	yes		
NB. : None of the Uncut compartments achieve the target.				

Table 4.3: Summary table – rehabilitated area sub-compartments achieving management targets of ≥ 75% combined cover of *Eriophorum angustifolium, E. vaginatum* and *Sphagnum cuspidatum.*

Categories which are not applicable have been greyed-out.

4.5 Discussion

Fenn's Whixall and Bettisfield Mosses NNR is a huge site with a varied topography. Despite the complexity within each sampling unit, the multivariate analysis identified two trends in the data for individual sub-compartments.

The strongest trend was an inundated-dry gradient. This was characterised by the environmental variables of rehabilitation management, which correlated with increases in the three peat-forming species at the wettest end of the ecological gradient. Negatively correlated to the management effect were mire species of damp peat with dry land species such as *Betula* spp. and *Pteridium aquilinum* to the extreme of the dry end of the gradient. Analysis from the first data set confirmed that samples associated with the dry end of the gradient were those from unmanaged areas of the site.

The second strongest trend found in the analysis was characterised by differences between peat cutting types i.e. the difference between the recent commercial cuttings and the other cutting types. *Molinia caerulea* was correlated with the recent commercial cuttings while a more diverse flora of mire and drier species were related to the other three cutting types.

The second trend may also relate to increases in *M. caerulea* as a response to burning, carried out by the peat cutters to remove vegetation. The site has a long history of deliberate and accidental fire. The recent commercial areas would have been more recently affected by burning than the other cutting types. Also, *M. caerulea* had been deliberately sown across the site to strengthen and stabilise the network of track-ways within and between the sub-compartments (Berry *et al.,* 1996). An available seed source was therefore available to colonize the exposed peat surface.

The identified trends relate to work by Dargie (2000) who found the strongest data trend to be that of increasing *S. cuspidatum* associated with rewetting management. He discovered unexplained vegetation patterns which he attributed to localised plant successions. In light of the findings of the present investigation, these patterns may have related to variations in cutting types or time since rewetting.

The present investigation revealed some interesting differentiations relating to the improvement of summer water table height as a result of *Betula* spp. removal and winter water table height as a result of damming. Winter and summer were the only significant season variables in the final RDA. This suggested that a high water table during the wettest and driest periods of the year correlated with a positive peat-former response. It could therefore be postulated that a year round high water table is required to support peat-forming species.

The raised mire literature supports the positive effect on the peat water table following removal of *Betula* spp. (Gilman, 2000 and Lindsay, 1995). Significant improvement in summer water table height on Thorne Moors was found in plots where *Betula* spp. had been removed, compared with control plots (Meade, 2001). The final RDA of the present chapter discussed in the above paragraph was restricted to the rehabilitated area and as such did not include control samples. In order to determine actual causes of observed environmental change, control samples are of great importance.

An inference could also be made that there is a risk of mire species loss following rewetting in the old commercial, hand and uncut areas of the site. These locations negatively correlated with increasing time since damming, which suggested a reduction in species over time. These were the same species shown to decline at Thorne Moors as a result of management, by Dargie (2000).

Species mapping using GIS techniques provided a general view of existing vegetation composition prior to rehabilitation (in the case of recent commercial cuttings, the year management was initiated) and at two subsequent time points post- rehabilitation. *S. cuspidatum* (Map 4.1*)* and *E. angustifolium* (Map 4.3) had best percentage cover in the hand cuttings prior to management. Post management this cover increased most successfully in the hand cut and recent commercial areas. *E. vaginatum* (Map 4.2) was a low percent cover species of uncut and hand cuts before rehabilitation, after which it increased in cover within all the cutting types but achieved highest cover in the hand cut and uncut areas.

Calluna vulgaris (Map 4.6) was a major component of pre-rehabilitation vegetation of the uncut, hand cut and old commercial cutting types and characteristic of dry conditions. It demonstrated an increase in cover on both recent and old commercial cutting areas by 1998 and showed a reduction there by 2000 – a possible response to rewetting, which makes it more susceptible to attack by heather beetle (Joan Daniels, *pers comm*).

M. caerulea (Map 4.7) was seen to be widespread across the site (at varying levels of cover) before rehabilitation. By 1998 this species had increased in cover, most notably in the recent commercial cutting type. This may be related to the development of a fluctuating water table mid-study, in this earliest area to be rehabilitated. *M. caerulea* is tolerant of such fluctuation. By 2000 there was a general reduction in *M. caerulea* within the rehabilitated area, suggesting a possible stabilisation of the water table.

Both multivariate analysis and mapping of the species data supported the interpretation that practically all sub-compartments have shown the expected consistent and long-maintained increases in plant species associated with a higher water table. To this extent the analysis suggests that the management applied to the sub-compartments has been successful, and also demonstrated good levels of direct correlation between management application and timing and these desirable effects.

The effects on *Calluna vulgaris* and *Molinia caerulea* are more complex. *Calluna* initially showed an increase, which might be interpreted as the general process of revegetation, followed by a decrease, which may be a delayed negative response to rewetting. The multivariate analysis suggested that the main focus of *M. caerulea* initially was the recent commercial cuttings, but the mapping revealed that this species is widespread throughout the site. The initial trend for *M. caerulea* to increase probably reflects the wetting of areas originally too dry for *M. caerulea*. The later trend for *M. caerulea* to decrease probably reflects that inundation is now predominantly sufficiently well advanced, at least in the central area to suppress it.

Variation in the time of rehabilitation across the different cutting types complicates data analysis. Rehabilitation began with the recent commercial areas (1991), followed by the uncut and hand cuttings, then finally the old commercial areas (1996/1997).
The site also has complexity in cutting types and their ability to retain water following rewetting. The hand cut areas have been less severely drained and high tracks and baulks serve to enhance water retention. The old commercial areas however are influenced by

slope making them prone to through-drainage of water. Recent commercial areas have a general peat surface of similar height to surrounding tracks, limiting the height to which they can be inundated and rendering them susceptible to run-off (Daniels, 1998).

The present analysis has successfully demonstrated that there has been an increase in peat-forming species related to rehabilitation management. This has been achieved despite the fact that a rise in the peat water table may affect some areas within a sub-compartment, but not the sub-compartment as a whole. This complexity may explain why no particular cutting types were directly correlated with the management variables.

In addition to achieving the aims of this chapter, information on the nature of the peat water table have been revealed i.e. a high year round water table was needed to increase the cover of peat-forming species. Another factor revealed, was that following rewetting, a period of water table instability followed which then showed signs of stabilising over time.

The analysis results have also generated questions about rehabilitation effects. Are mire species being lost? Is *M. caerulea* being replaced by peat-formers? Is *C. vulgaris* reducing in cover? The present analysis suggested that this may be the case and these questions have been addressed in chapter 5 which provides a more detailed analysis of vegetation change on individual sections of the peat cutting profile (within each separate cutting type). Hydrological thresholds for *Sphagnum* development have been explored in chapter 6.

4.6 Conclusions

- The strongest trend in the multivariate analysis was an inundated-dry ecological gradient. Inundation was characterised by rehabilitation management treatment and increases in the three management target peat-forming species.
- High summer and winter average water table was related to management treatments.
- Rewetting may cause a decline in other existing mire species.
- 20% of the sub-compartments surveyed in the rehabilitated area achieved management target cover of peat-forming species within planned periods (5 years) and a further 7% of the sub-compartments achieved target cover after 5 years.
- Variation in existing plant species cover prior to rehabilitation management and their development following management was also related to different peat cutting types.
- Management effect caused an initial increase in *Molinia caerulea*, followed by a decrease - suggesting fluctuation and subsequent stabilisation of the peat water table.
- *Calluna vulgaris* reduced cover following rehabilitation management.

CHAPTER 5
PERMANENT QUADRAT ANALYSIS OF VEGETATION CHANGE ON FENN'S AND WHIXALL MOSSES

5.1 Introduction

When monitoring the effectiveness of management, it is important to monitor prior to, as well as following management so that a comparison can be made. Subsequent data must be comparable with previously collected data in order to provide reliable site evaluation (Brooks and Stoneman, 1997).

Quadrat sampling techniques provide quantitative data which can be statistically analysed to help explain changes in plant communities in a monitoring context. The quadrat provides a simple, repeatable method of recording species abundance (Murray, 2002). There is debate as to whether targeted (fixed/ permanent) location or random location of quadrats should be used in ecological monitoring and subsequent analysis. Random quadrat data are considered to be more statistically amenable by some researchers (Brooks and Stoneman, 1997) while others believe them to be subject to bias from the surveyor (Murray, 2002). Lindsay and Ross (1994) support the use of permanent plots for data analysis in order that it can be said with certainty that changes have occurred at particular locations. They state that random sample techniques only offer a statistical probability that changes have occurred.

There is a tendency in the UK to use targeted permanent quadrats for monitoring lowland raised mire and blanket mire (Brooks and Stoneman, 1997). Long term permanent quadrat research (covering a period of ≥ 10 years with > 2 survey points) however, is not evident in the raised mire rehabilitation literature. Other fields of ecology document long-term research using permanent quadrats e.g. weather and vegetation dynamics in road verges, a 38 year study with annual survey carried out by a single recorder (Dunnett, *et al.*, 1998); lake vegetation succession, a 13 year study with annual survey (Odland and del Moral, 2002); and spatial and temporal patterns in desert annuals, a 15 year study where summer and winter vegetation survey was carried out each year (Guo *et al.* 2000).

Many European raised mires came under nature conservation management between the late 1980s to mid- 1990s. Mire sites are therefore still in the early stages of rehabilitation and comprehensive monitoring systems have yet to be set up for some sites (Brooks and Stoneman, 1997). Previous lowland raised mire research using permanent quadrat data has been carried out by Meade (1992) and Mawby (1995).

Meade (1992) examined vegetation change at Danes Moss, Cheshire (a lowland raised mire) using a contiguous 2m x 2m quadrat survey repeated twice (1972 and 1987). The study area was flat, dissected by shallow drains and approximately 225m x 175m. Rewetting of the area was carried out in 1974. Results showed that *Sphagnum* mosses became most widely established among the tussocks of existing vegetation (*Molinia caerulea*, *Eriophorum vaginatum* and *Juncus effusus*) in waterlogged conditions rather than those of inundation. Meade recommended stabilising water levels in order to combat *Molinia* dominance.

Six years of permanent quadrat monitoring (the first 4 years on an annual basis with one final biennial survey) initiated soon after damming, were used by Mawby (1995) on Glasson Moss, Cumbria. The site supports uncut and cut-over peat. The investigation surveyed ten 0.5m² vegetation quadrats (5 on cut-over peat and the remaining 5 on uncut peat). Restoring *Sphagnum* to a damaged mire surface was found to be a slow process except where flooding or a high water table are maintained. *Sphagnum cuspidatum* colonized rapidly in constantly flooded conditions. Water table fluctuation was found to continue after damming and varied according to mire topography. Fluctuation was less where water was easily retained and greater in sloping areas where water was able to drain through the peat.

5.2 Aims and objectives

The investigation described in this chapter aims to identify trends in vegetation change within the four cutting types (uncut, recent commercial, old commercial and hand cuttings) found on Fenn's and Whixall Mosses. These cutting types are described in detail in chapter 2.

Environmental and vegetation information from 435 permanent vegetation quadrats, recorded on three occasions, 1991/93 (prior to management), 1996 (post-management) and 2001 (post-management), were investigated using multivariate analysis techniques.

Chi-squared analysis was applied to the quadrat data sets for each cutting type. The aim was to determine significant change over time in the presence of key plant species within the samples (quadrats).

Vegetation types across the NNR were determined using a TWINSPAN analysis of the complete data set and subsequent constancy tables were created to describe the TWINSPAN end groups and provide a comparison with the target NVC community. The TWINSPAN analysis uses only plant species data; however to enhance vegetation description, bare ground cover was included in the constancy tables. Further multivariate analysis was then carried out using CANOCO. For this analysis the complete data set was split into individual data sets for analysis. The individual data sets represented the three dates for each surface type (baulk, flat, ditch, augered, relict and *Molinia*) of the peat cutting profile, within each cutting type (recent commercial, old commercial, hand cut and uncut).

As well as elucidating the general trend in post-management vegetation change over time, these techniques aimed to provide detailed information to meet the following aims:

- Identify vegetation changes related to the four surface types of the peat cutting profile in the recent commercial areas (ditch, augered, relict, *Molinia*) and how they compare to the old commercial areas.
- Identify how the vegetation of the three surface types of the old commercial and hand cuttings (baulk, flat, ditch) developed.

- Identify differences between the uncut areas and how they change over time.
- Determine whether or not there is an increase in the site management plan target species - *Sphagnum cuspidatum, Eriophorum vaginatum* and *Eriophorum angustifolium.*
- Identify the response of *Molinia caerulea.*
- Determine whether management is a disadvantage to NVC M18a species.

5.3 Methods

5.3.1 Site description

The permanent quadrat survey of this chapter was located on Fenn's and Whixall Mosses within the rehabilitated area of the site.

The general topography of the site shows a downward slope towards the central recent commercial cuttings. The permanent quadrats are located within each cutting type, representing each surface of the peat cutting profile i.e. ditch, *Molinia,* augered and relict (recent commercial), ditch, flat and baulk (old commercial and hand cuttings). The uncut areas of the site also have permanent quadrats.

Chapter 2 provides a detailed site description.

5.3.2 Botanical assessment method

Permanent 1m x 1m vegetation quadrats were recorded following the existing site methodology as described in chapter 3. The surveys began in 1991 with the exception of the recent commercial cutting type surveys which commenced in 1993, as the surface was still undergoing management by augering piles of dead vegetation back into the drains until that time. The survey is repeated at 5 year intervals (during the summer) as part of site monitoring. The present investigation therefore utilised surveys from

1991/1993, 1996 and 2001 – the latter being carried out as a specific part of the present study.

Data from 435 permanent quadrats in each of the three years were collated into an Excel spreadsheet computer file for analysis. Quadrat data for recent commercial compartment 5 and uncut sub-compartment 5.4c were excluded from the analysis. Recent commercial compartment 5 was severely flooded following damming. Uncut sub-compartment 5.4c was dominated by *Vaccinium vitis-idaea,* a plant species only found on this particular sub-compartment within Fenn's and Whixall Mosses. It was believed that these attributes reduced comparability with the rest of the data. The influence of rare species or outlying plots risked reducing the clarity of the analysis.

5.3.3 Environmental data

Environmental data were used to complement the TWINSPAN analysis. These were added in the form of a Summary Table for each end group and provided details of applicable peat cutting surface type and the date of damming works. The dendrogram (Figure 5.1) of the TWINSPAN output also had the additional information of relevant year and cutting surface type.

The CANOCO analysis had a set of environmental variables for each sample (quadrat). These included:

- Number of seasons since damming
- Year of survey
- Transect number/ letter
- Sub-compartment number

5.3.4 Data analysis

To examine continuous distribution and significant change in the presence of plant species within the samples, Chi-square statistical analysis was used. Frequencies of particular species for each survey year were compared against the null hypothesis that there was no significant difference in frequency between survey years. If the number of samples for a particular year was ‘0’ then ‘1’ was added to the total number of samples for each year in that particular test. This provided an interpretation of which species changed significantly from one time to the next and the direction of change (an increase or decrease).

A TWINSPAN analysis was carried out on the complete vegetation data set (collated quadrats from all three survey years) in order to group quadrats and so identify types of vegetation. The ecological nature of these groups was interpreted from their indicator (and where applicable, preferential) species. The addition of species constancy tables aided interpretation of the groups. Available temporal, spatial and management information for the vegetation types further enhanced interpretation.

Species ordination by indirect gradient analysis using CANOCO was applied to the complete vegetation data set. This produced an unconstrained analysis of the plant species distribution for the site as a whole. The analysis output is displayed as an ordination diagram (bi-plot). Indirect gradient analysis was also applied to site specific data sets i.e. the complete data set was separated into the different peat cutting types and then into surface type within the cutting type. This provided individual data sets for each surface-type of the peat cutting profile. Due to the resulting large number of individual analyses, the indirect ordination diagrams are not included in the results section of the current chapter.

Appropriate direct gradient analysis followed on from the indirect analyses described above. Environmental data (explanatory variables) included the numerical variable (damming) and nominal variables (1991/1993, 1996, 2001, transect number/letter, sub-compartment number, surface type) were added to the species data in the analysis model. The environmental variables were submitted for significance ($p \leq 0.05$) testing by forward selection. Non-significant variables were removed from the model at this stage. Subsequent ordination diagrams were produced which included the significant environmental variables and demonstrated the best fit on the species data.

Vegetation data imported into TWINSPAN and CANOCO were in the form of percentage cover. During the CANOCO analysis these data were log transformed. Chapter 3 explains multivariate analysis in more detail than is given here.

5.4 Results

5.4.1 Chi – square significance testing of species change

The number of samples (quadrats) for 1991/93, 1996 and 2001 respectively and cover of key plant species are shown in Tables 5.1 to 5.6. These tables include Chi-square testing which has been applied to the data in order to establish the statistical significance of species change over time. All of the key species (with the exception of *Molinia caerulea*) are found in the NVC M18a community.

Key plant species were chosen to include the peat-builders and other desirable NVC M18a species. *Calluna vulgaris* and *Molinia caerulea* were also included due to these species being major features of the site vegetation, as demonstrated in chapter 4.

Table 5.1 examines the complete data set of 1,305 samples (435 samples replicated for each of the 3 survey years). This provides a very general view of the site data as a whole. With the exception of *Calluna vulgaris* (which decreases significantly from 1996 to 2001) species achieving statistical significance show an increase in presence within the samples. The ecological requirements of *C. vulgaris* for dryness suggest that rewetting has had a late effect on reducing the range of this species during the study period.

Sphagnum cuspidatum is the only species which increased significantly from each sampling to the next. Species which increased from 1991/93 to 2001 are *Andromeda polifolia, Eriophorum vaginatum, Sphagnum magellanicum, S. papillosum, S. capillifolium,* and *Vaccinium oxycoccos.* The latter two species also show significance from 1991/3 to 1996, suggesting a response early on in the study period. However, *Eriophorum angustifolium, E. vaginatum* and *S. magellanicum* increased their sample range from 1996 to 2001 – indicative of a later response.

Species	1991/93	1996	2001	Direction of change
Andromeda polifolia	53 [a]	60 [ab]	76 [b]	Increase from 1991/3 to 2001
Calluna vulgaris	286 [ab]	324 [b]	246 [a]	Decrease from 1996 to 2001
Drosera rotundifolia	29 [a]	16 [a]	28 [a]	n/a
Erica tetralix	247 [a]	281 [a]	289 [a]	n/a
Eriophorum angustifolium	220 [ab]	217 [a]	261 [b]	Increase from 1996 to 2001
Eriophorum vaginatum	216 [a]	200 [a]	322 [b]	increase from 1991/3 to 2001 and 1996 to 2001
Molinia caerulea	275 [a]	303 [a]	294 [a]	n/a
Odontoschisma sphagni	26 [a]	25 [a]	23 [a]	n/a
Sphagnum capillifolium	1 [a]	20 [b]	22 [b]	Increase from 1991/3 to 1996 and 1991/3 to 2001
Sphagnum cuspidatum	80 [a]	136 [b]	197 [c]	Increase from 1991/3 to 1996 and 1996 to 2001 and 1991/3 to 2001
Sphagnum magellanicum	1 [a]	1 [a]	9 [b]	Increase from 1991/3 to 2001 and 1996 to 2001
Sphagnum papillosum	18 [a]	25 [ab]	37 [b]	Increase from 1991/3 to 2001
Sphagnum tenellum	13 [a]	18 [a]	18 [a]	n/a
Vaccinium oxycoccos	51 [a]	74 [b]	92 [b]	Increase from 1991/3 to 1996 and 1991/3 to 2001

Table 5.1 Chi-squared analysis of the complete site data set of 1,305 samples (quadrats).

For each species, numbers of samples which are not significantly different at the 5% level in chi-squared tests have been given the same suffix. E.g. for *Eriophorum vaginatum* there is a significant change between 1991/93 and 2001, between 1996 and 2001, but not between 1991/93 and 1996. Chi-squared tests to investigate significant change in the number of permanent quadrats containing key species over the study period (1991/93, 1996 and 2001). Critical value at p=0.05 with 1 degree of freedom is 3.84.

Table 5.1 clearly demonstrated the presence of *Molinia caerulea* in a large number of samples from the first survey year, persisting through to the final year. There was no significant change in the range of this species however, when reviewing the entire set of site samples.

The permanent quadrat survey showed variation across the site related to peat cutting type, length of time since cessation of cutting and existing established vegetation at the start of the study period. Implementation of rehabilitation management has also occurred at varying time points. Change at local level i.e. within the different cutting types, will therefore be of greater value in clarifying the nature of vegetation change and relating that change to the time of management implementation. Chi-squared statistical testing specific to each cutting type was therefore explored below.

Uncut sub-compartment 6.7

This uncut sub-compartment (Table 5.2) underwent damming in 1992. All of the statistically significant species in Table 5.2 showed an increase in range from 1991 to 2001. *Andromeda polifolia* appeared to increase gradually over the study period, with the significant change identified from 1991 to 2001. *Odontoschisma sphagni* and *Vaccinium oxycoccos* also increased significantly from 1991 to 1996, suggesting that the greatest response had been early following management. *Sphagnum magellanicum* increased significantly from 1996 to 2001 (as well as 1991 to 2001) suggesting the most effective response was a late (post-management) one.

Sphagnum magellanicum is a peat building species of the *Sphagnaceae* and *Odontoschisma sphagni* is a liverwort (*Jungermanniineae)* associated with *Sphagnum* species and chiefly a plant of raised and valley mires (Watson, 1981).

Species	1991	1996	2001	Direction of change
Andromeda polifolia	16 [a]	24 [ab]	35 [b]	Increase from 1991 to 2001
Calluna vulgaris	58 [a]	57 [a]	42 [a]	n/a
Drosera rotundifolia	1 [a]	1 [a]	1 [a]	n/a
Erica tetralix	59 [a]	59 [a]	60 [a]	n/a
Eriophorum angustifolium	51 [a]	39 [a]	44 [a]	n/a
Eriophorum vaginatum	57 [a]	57 [a]	57 [a]	n/a
Molinia caerulea	17 [a]	15 [a]	20 [a]	n/a
Odontoschisma sphagni	4 [a]	13[b]	13[b]	Increase from 1991 to 1996 and 1991 to 2001
Sphagnum capillifolium	1 [a]	2 [a]	1 [a]	n/a
Sphagnum cuspidatum	6 [a]	7 [a]	8 [a]	n/a
Sphagnum magellanicum	1 [a]	1 [a]	8 [b]	Increase from 1991 to 2001 and 1996 to 2001
Sphagnum papillosum	4 [a]	5 [a]	10 [a]	n/a
Sphagnum tenellum	9 [a]	11 [a]	13 [a]	n/a
Vaccinium oxycoccos	7 [a]	27 [b]	32 [b]	Increase from 1991 to 1996 and 1991 to 2001

Table 5.2 Chi-squared analysis of the the uncut samples (180 quadrats) of sub-compartment 6.7 – number of samples containing each species.

For each species, numbers of samples which are not significantly different at the 5% level in chi-squared tests have been given the same suffix. E.g. for *Andromeda polifolia* there is a significant change between 1991 and 2001, but not between 1991 and 1996 or between 1996 and 2001. Chi-squared tests to investigate significant change in the number of permanent quadrats containing key species over the study period (1991, 1996 and 2001). Critical value at p=0.05 with 1 degree of freedom is 3.84.

Uncut compartment 15

Chi-squared analysis of compartment 15 is shown in Table 5.3. This area of the site escaped peat cutting as close proximity to the canal made it too wet for peat extraction (Berry *et al.,* 1996). Rehabilitation management commenced in 1991 with *Betula* spp. removal and this was followed in 1995 with peripheral damming.

Odontoschisma sphagni showed a decrease with statistical significance from 1991 to 1996 and 1991 to 2001. The greatest reduction appeared to be from 1991 to 1996. This was an interesting discovery as uncut sub-compartment 6.7 (Table 5.2) showed a significant increase in this species. This may be a random effect, but as this species is known to colonize mire hummock vegetation, it may indicate increasing wetness on compartment 15, reducing hummock forming species. On sub-compartment 6.7 the increase in this species may suggest the development of hummocks and a move towards the early vegetation of compartment 15.

The three species which have increased their range in compartment 15 are all *Sphagna* with greatest change occurring early following management.

Species	**1991**	**1996**	**2001**	**Direction of change**
Andromeda polifolia	24 [a]	21 [a]	25 [a]	n/a
Calluna vulgaris	29 [a]	27 [a]	22 [a]	n/a
Drosera rotundifolia	5 [a]	5 [a]	1 [a]	n/a
Erica tetralix	29 [a]	29 [a]	29 [a]	n/a
Eriophorum angustifolium	17 [a]	13 [a]	11 [a]	n/a
Eriophorum vaginatum	30 [a]	30 [a]	30 [a]	n/a
Molinia caerulea	4 [a]	3 [a]	2 [a]	n/a
Odontoschisma sphagni	21 [a]	10 [b]	9 [b]	Decrease from 1991 to 1996 and 1991 to 2001
Sphagnum capillifolium	1 [a]	19 [b]	22 [b]	Increase from 1991 to 1996 and 1991 to 2001
Sphagnum cuspidatum	1 [a]	2 [a]	3 [a]	n/a
Sphagnum magellanicum	1 [a]	1 [a]	2 [a]	n/a
Sphagnum papillosum	1 [a]	7 [b]	7 [b]	Increase from 1991 to 1996 and 1991 to 2001
Sphagnum tenellum	1 [a]	7 [b]	14 [b]	Increase from 1991 to 1996 and 1991 to 2001
Vaccinium oxycoccos	28 [a]	28 [a]	30 [a]	n/a

Table 5.3 Chi-squared analysis of the The uncut samples (90 quadrats) of compartment 15. – number of samples containing each species.

For each species, numbers of samples which are not significantly different at the 5% level in chi squared tests have been given the same suffix. E.g. for *Sphagnum capillifolium* there is a significant change between 1991 and 2001 and 1991 and 1996 but not between 1996 and 2001. Chi-squared tests to investigate significant change in the number of permanent quadrats containing key species over the study period (1991, 1996 and 2001). Critical value at p=0.05 with 1 degree of freedom is 3.84.

Recent commercial

The recent commercial samples were located on sub-compartments 3.3, 3.9 and 3.13 (Map 2.1 of chapter 2). Rewetting of these areas was implemented in 1991 and the first permanent quadrat survey of the recent commercial cuttings was carried out two years later in 1993. This was the only cutting type to have the initial vegetation survey carried out post- management.

Significant increases in most key species were seen in Table 5.4. *Sphagnum papillosum* increased sample range from 1993 to 2001. *Calluna vulgaris* and *Vaccinium oxycoccos* demonstrated their best increase early following rewetting and species with greatest increase late on were *Eriophorum vaginatum* and *Drosera rotundifolia.* The statistical increase of *Molinia caerulea* was restricted to the period 1993 to 1996.

Sphagnum cuspidatum, Eriophorum angustifolium and *Erica tetralix* all achieved significant increase from each time point to all subsequent time points.

Species	1993	1996	2001	Direction of change
Andromeda polifolia	1 [a]	2 [a]	3 [a]	n/a
Calluna vulgaris	61 [a]	107 [b]	92 [b]	increase from 1993 to 1996 and 1993 to 2001
Drosera rotundifolia	1 [a]	6 [a]	25 [b]	Increase from 1993 to 2001 and 1996 to 2001
Erica tetralix	21 [a]	57 [b]	90 [c]	Increase from 1993 to 1996, 1996 to 2001 and 1993 to 2001
Eriophorum angustifolium	31 [a]	54 [b]	103 [c]	Increase from 1993 to 1996, 1996 to 2001 and 1993 to 2001
Eriophorum vaginatum	13 [a]	7 [a]	109 [b]	Increase from 1993 to 2001 and 1996 to 2001
Molinia caerulea	120 [a]	161 [b]	151 [a b]	Increase from 1993 to 1996
Odontoschisma sphangi	1 [a]	2 [a]	1 [a]	n/a
Sphagnum capillifolium	1 [a]	1 [a]	1 [a]	n/a
Sphagnum cuspidatum	1 [a]	56 [b]	92 [c]	increase
Sphagnum magellanicum	1 [a]	1 [a]	1 [a]	n/a
Sphagnum papillosum	1 [a]	2 [ab]	8 [b]	Increase from 1993 to 2001
Sphagnum tenellum	1 [a]	1 [a]	1 [a]	n/a
Vaccinium oxycoccos	1 [a]	7 [b]	12 [b]	increase from 1993 to 1996 and 1993 to 2001

Table 5.4 Chi-squared analysis of the recent commercial samples (540 quadrats) – number of samples containing each species.

For each species, numbers of samples which are not significantly different at the 5% level in chi squared tests have been given the same suffix. E.g. for *Calluna vulgaris* there is a significant change between 1993 and 1996, between 1993 and 2001, but not between 1996 and 2001.Chi-squared tests to investigate significant change in the number of permanent quadrats containing key species over the study period (1991, 1996 and 2001). Critical value at p=0.05 with 1 degree of freedom is 3.84.

Old commercial

The old commercial samples were located on sub-compartments 1.4 and 4.4 (Map 2.1 of chapter 2) and were not rewetted until 1996 and 1997 respectively. Chi-squared results (Table 5.5) show that only two key species changed significantly and both decreased their range in the samples. *Calluna vulgaris* decreased from 1996 to 2001 and as such this may have been an early response to rewetting. *Drosera rotundifolia* however decreased from 1993 to 1996 i.e. prior to rewetting.

Species	1991	1996	2001	Direction of change
Andromeda polifolia	1[a]	5[a]	4[a]	n/a
Calluna vulgaris	61[ab]	83[a]	52[b]	decrease from 1996 to 2001
Drosera rotundifolia	13[a]	4[b]	3[b]	Decrease from 1991 to 1996 and 1991 to 2001
Erica tetralix	72[a]	72[a]	60[a]	n/a
Eriophorum angustifolium	59[a]	60[a]	54[a]	n/a
Eriophorum vaginatum	71[a]	65[a]	73[a]	n/a
Molinia caerulea	70[a]	63[a]	64[a]	n/a
Odontoschisma sphangi	1[a]	1[a]	2[a]	n/a
Sphagnum capillifolium	1[a]	1[a]	1[a]	n/a
Sphagnum cuspidatum	37[a]	39[a]	49[a]	n/a
Sphagnum magellanicum	1[a]	1[a]	1[a]	n/a
Sphagnum papillosum	7[a]	7[a]	7[a]	n/a
Sphagnum tenellum	3[a]	1[a]	2[a]	n/a
Vaccinium oxycoccos	8[a]	6[a]	11[a]	n/a

Table 5.5 Chi-squared analysis of the The old commercial samples (261 quadrats) – number of samples containing each species.

For each species, numbers of samples which are not significantly different at the 5% level in chi squared tests have been given the same suffix. Chi-squared tests to investigate significant change in the number of permanent quadrats containing key species over the study period (1991, 1996 and 2001). Critical value at p=0.05 with 1 degree of freedom is 3.84.

Hand cut

The hand cut samples were found on sub-compartments 14.6, 13.4, 13.7, 13.8 and 22.1. These areas did not undergo rewetting until 1995 to 1996. The only species with a significant change (Table 5.6) in this cutting type was *Drosera rotundifolia.* The direction of change was a decrease in presence which is most notable from 1991 to 1996. As damming of the hand cuttings was not carried out until late 1995, through to 1996, it appeared unlikely that the decrease in *Drosera rotundifolia* could be attributed to rehabilitation management.

Species	1991	1996	2001	Direction of change
Andromeda polifolia	12 [a]	9 [a]	10 [a]	n/a
Calluna vulgaris	57 [a]	50 [a]	38 [a]	n/a
Drosera rotundifolia	12 [a]	3[b]	1 [b]	Decrease from 1991 to 1996 and 1991 o 2001
Erica tetralix	66 [a]	64 [a]	50 [a]	n/a
Eriophorum angustifolium	62 [a]	51 [a]	49 [a]	n/a
Eriophorum vaginatum	45 [a]	41 [a]	53 [a]	n/a
Molinia caerulea	64 [a]	61 [a]	57 [a]	n/a
Odontoschisma sphangi	2 [a]	2 [a]	1 [a]	n/a
Sphagnum capillifolium	1 [a]	1 [a]	1 [a]	n/a
Sphagnum cuspidatum	36 [a]	33 [a]	46 [a]	n/a
Sphagnum magellanicum	1 [a]	1 [a]	1 [a]	n/a
Sphagnum papillosum	7 [a]	6 [a]	7 [a]	n/a
Sphagnum tenellum	2 [a]	1 [a]	1 [a]	n/a
Vaccinium oxycoccos	7 [a]	6 [a]	7 [a]	n/a

Table 5.6 Chi-squared analysis of the hand-cut samples (234 quadrats) – number of samples containing each species.

For each species, numbers of samples which are not significantly different at the 5% level in chi squared tests have been given the same suffix. Chi-squared tests to investigate significant change in the number of permanent quadrats containing key species over the study period (1991, 1996 and 2001). Critical value at p= 0.05 with 1 degree of freedom is 3.84.

Most of the key species in Table 5.6 occured as part of the existing vegetation in the hand cuttings, prior to rehabilitation management. These species persisted over the study period.

Chi-squared summary

To summarise, the chi-squared analysis has provided a view of species change (and the direction of change) specific to each peat cutting type of the site. Information about the time of rewetting allowed some inference of a relationship between species change and rehabilitation management. This inference is explored later in the present chapter using multivariate analysis.

Analysis of uncut area 6.7 revealed an increase in two ericoid sub-shrubs, one species of *Sphagna* and a liverwort characteristic of lowland raised mire. Uncut compartment 15 had an increase in three species of *Sphagna* and a decrease in the key liverwort (*Odontoschisma sphagni*).

Recent commercially cut areas showed the greatest level of species change, with most key species achieving significant increases across the survey period. Only *Molinia caerulea* had a restricted increase from 1993 to 1996. Increases in the site management plan target species (*Sphagnum cuspidatum, Eriophorum vaginatum* and *E. angustifolium)* which was expected following rewetting of the peat were most prolific. In addition to this however, were large increases in the presence of *Drosera rotundifolia* and *Erica tetralix* and small (but statistically significant) increases in the number of samples with *Sphagnum papillosum* and *Vaccinium oxycoccos.*

Little change was seen in the old commercial and hand cut samples, which underwent rehabilitation later than the aforementioned areas. Old commercial sub-compartments had only two significant species (*Calluna vulgaris* and *Drosera rotundifolia*) which both decreased their range. *C. vulgaris* appeared to decrease as an early response to rewetting and *D. rotundifolia* decreased its range prior to rewetting. The hand cut samples had only one significant species change which was a decrease in the presence of *Drosera rotundifolia* and not related to management as it was evident prior to rewetting.

5.4.2. The TWINSPAN Analysis

A TWINSPAN classification of the floristic data were computed using TWINSPAN for Windows (Hill *et al.* 2005) and the output has been displayed as a dendrogram (Figure 5.1). The species names were abbreviated and a key to these abbreviations presented in Appendix 1. In the dendrogram species names followed by pseudospecies level are located on the right side of each group. Pseudospecies levels are described in Table 5.7 below. Figure 5.1 also provides more detail on the TWINSPAN end groups i.e. peat cutting type/s along with relevant survey year and peat cutting surface type (baulk, flat, ditch, *Molinia*, augered, relict).

Pseudospecies level	% species cover
1	1 - 1.9
2	2.0 – 4.9
3	5.0 – 9.9
4	10.0 – 19.9
5	20.0 +

Table 5.7 TWINSPAN analysis pseudospecies levels.

This table shows percent species cover in relation to the pseudospecies levels (the five cut levels).

The complete data set of 1305 samples (quadrats) were entered into the analysis and 57 of these samples were omitted during the process. Omissions were samples with no species i.e. comprising bare ground/ surface water. There were 62 plant species (vascular plants and bryophytes) in the data. TWINSPAN methodology is described in chapter 3.

The TWINSPAN groups have been described further with the aid of species constancy tables. Here the cover of bare ground has been included with the vegetation data in order to clarify the nature of the site. Summary tables have also been designed for each TWINSPAN group. These tables provided information on the location of the vegetation groups across the site, timing of damming (rewetting) and statistically significant changes in the groups over time (chi-squared tests).

Division of the data set – 1248 samples

The first division had an eigenvalue of 0.351. This division separated the samples into negative **Group 0** (995 samples) and the positive **Group 1** (253 samples). Indicator species for **Group 0** were *Calluna vulgaris, Erica tetralix, Vaccinium oxycoccos* and *Campylopus introflexus.* The indicator species for **Group 1** were *Sphagnum cuspidatum* and *Eriophorum angustifolium.* These indicators suggested a non-inundated/inundated-based division.

Group 0 represented a large proportion of the total data. The varying ecological requirements of the indicator species for this group reflected the complexity in the nature of degraded lowland raised mire vegetation. With the exception of the bryophyte *Campylopus introflexus,* the indicator species were all constant species of the National Vegetation Classification (NVC) M18a (*Erica – Sphagnum* raised mire, *Sphagnum – Andromeda* sub-community) plant community. *Campylopus introflexus* is a recent introduction (of approximately 60 years) to the UK and more likely to be associated with baulks of the peat cutting profile (*pers comm* from Dr M. Newton). The indicator species for the positive side of this initial dichotomy (**Group 1**) suggested a narrower spectrum of environmental diversity. Here the indicator species were characteristic of the NVC M18a community at constancy scores of only II and V respectively. These species were also found at constancies of III and V respectively in the NVC M2 community (*Sphagnetum* pools) and generally suggested much wetter mire than the Group 0 indicators.

From **Group 0**, the next division identified is the negative **Group 00** (203 samples) and the positive **Group 01** (792 samples). The eigenvalue for the division was 0.337. **Group 00** had only one indicator species which is *Molinia caerulea* (pseudospecies level 2) and *Molinia caerulea* remains the single preferential for this group up to pseudospecies level 5. *M. caerulea* is characteristic of intermediate water levels between dry and wet land. **Group 01** showed greater species diversity. Indicator species (all of which were characteristic of the NVC M18a subcommunity) included *Calluna vulgaris* (pseudospecies level 3), *Erica tetralix* (2), *Vaccinium oxycoccos* (1), *Eriophorum vaginatum (*1) and *Eriophorum angustifolium* (1). This suggested a dichotomy on the basis of a distinction between reliably oligotrophic mire with a stable water table (**Group 01**) and a fluctuating water table, less reliably oligotrophic mire (**Group 00).**

Group 00 was the first end group of the analysis (Figure 5.1). Table 5.8 is the constancy table for the group. This vegetation type was one in which *M. caerulea* was a common and prominent feature. Bare ground was also a major feature, with 61-80% of the samples having bare ground at an average cover of 61%. **Group 00** was characterised by either a dry bare or a *Molinia* – type vegetation, probably with a seasonally fluctuating water table.

Close examination of the data set for this group (Table 5.9) revealed it to be an early pre-management vegetation type characteristic of the recent commercial cuttings. Table 5.9

also suggested that this group was disappearing over the study period and this was supported by the significant (chi-squared tested) decrease in number of samples at each time point for the recent commercial area.

GROUP 00	**constancy**	**mean % cover**		**constancy**	**mean % cover**
Molinia caerulea	V (II)	45.4	*Andromeda polifolia*	I (III)	5.0
Bare	IV	61.2	*Drosera rotundifolia*	I (IV)	0.5
Calluna vulgaris	III (V)	15.9	*Sphagnum fimbriatum*	I	0.8
Campylopus introflexus	II	5.0	*Dicranella cerviculata*	I	0.8
Erica tetralix	II (V)	2.0	*Cephalozia connivens*	I	0.2
Campylopus pyriformis	I	3.0	*Odontoschisma sphagni*	I (IV)	5.0
Pteridium aquilinum	I	19.4	*Kurzia* spp.	I	0.2
Rubus spp.	I	6.5	*Polytrichum juniperinum*	I	0.4
Eriophorum angustifolium	I (V)	2.3	*Pohlia nutans*	I (I)	1.8
Eriophorum vaginatum	I (IV)	3.5	*Vaccinium oxycoccos*	I (III)	2.8
Polytrichum commune	I (I)	26.7	*Quercus* spp.	I	2.6
Rumex acetosella	I	5.3	*Sphagnum cuspidatum*	I (II)	0.6
			Polytrichum alpestre	I	10.3

Table 5.8 Constancy table for Group 00

Constancies I-V denote the percentage of samples which contain a particular species i.e. I = 1-20%, II = 21-40%, III = 41-60%, IV = 61-80%, V = 81-100%. Mean % cover is the average percent cover of a species for the group of samples as a whole.

Constancy scores in brackets represent the NVC M18a community (Rodwell, 1991) score for that species.

Group 00: Open or *Molinia caerulea*-dominated grassland vegetation				
	Recent commercial	**Uncut**	**Old commercial**	**Hand cut**
Number of samples present for each survey year	1993 = 102[a] 1996 = 52[b] 2001 = 18[c]	1991 = 3[ab] 1996 = 1[a] 2001 = 9[b]	1991 = 1[a] 1996 = 3[a] 2001 = 2[a]	1991 = 3[a] 1996 = 6[a] 2001 = 6[a]
Surface type (section of the peat cutting profile)	Augered *Molinia* Relict	Uncut	Baulk	Baulk
Date of damming	Sub-compartment 3.3 - 1991/1992 Sub-compartment 3.9 – 1993/1994 Sub-compartment 3.13 – 1994/1995	Compartment 15 – 1995/1996 Sub-compartment 6.7 - 1992	Sub-compartment 1.4 – 1995/1996	Compartment 13 – 1995/1996 Compartment 14 – 1995/1996

Table 5.9 Summary of Group 00

A description of the general vegetation type, number of samples for each survey year and their location on the site. The surfaces of the peat profile applicable for the group are given. Compartments/ sub-compartments are stated as appropriate for the group with dates of rehabilitation management work.

For each cutting type, numbers of samples which are not significantly different at the 5% level in chi squared tests have been given the same suffix, e.g. for the uncut area there is a significant change between 1996 and 2001, but not between 1991 and 1996 or 1991 and 2001. Critical value at p=0.05 with 1 degree of freedom is 3.84. Where number of samples is 0, all years for that cutting type have had 1 added to their total.

Group 01 was not been treated as an end group in the analysis, however a constancy table has been included at this point to demonstrate the species diversity on this side of the dichotomy and the relationship of this large group to the NVC M18a community (Table 5.10). Species with IV and V constancy in the group matched M18a well, with the exception of *Molinia caerulea* which had a higher than desirable constancy. The M18a *Sphagnum* flora was present in **Group 01**, but at much lower constancy than is typical of M18a. The group had 27 of the 57 species present in NVC M18a community.

GROUP 01	constancy	mean % cover		constancy	mean % cover
Calluna vulgaris	V (V)	28.3	*Mylia anomalla*	I (III)	0.3
Erica tetralix	V (V)	17.4	*Pohlia nutans*	I (I)	0.4
Molinia caerulea	IV (II)	25.1	*Polytrichum juniperinum*	I	0.7
Eriophorum angustifolium	IV (V)	3.6	*Polytrichum alpestre*	I (I)	2.0
Eriophorum vaginatum	IV (IV)	20.6	*Cephalozia connivens*	I	1.2
Bare	III	12.1	*Odontoschisma sphagni*	I (IV)	0.5
Vaccinium oxycoccos	II (III)	6.0	*Kurzia pauciflora*	I (I)	0.6
Andromeda polifolia	II (III)	1.5	*Kurzia* spp.	I	0.5
Sphagnum cuspidatum	II (II)	10.6	*Sphagnum subnitens*	I (I)	0.1
Campylopus introflexus	II	2.2	*Calypogeia muellerana*	I (I)	0.2
Campylopus pyriformis	II	1.3	*Polytrichum commune*	I (I)	0.1
Pteridium aquilinum	I	0.5	*Sphagnum fallax*	I (I)	0.9
Rubus spp.	I	0.2	*Hypnum jutlandicum*	I (II)	0.1
Drosera rotundifolia	I (IV)	0.2	*Sphagnum magellanicum*	I (IV)	0.5
Empetrum nigrum	I (II)	0.6	*Aulacomnium palustre*	I (III)	2.9
Pinus sylvestris	I	0.1	*Sphagnum palustre*	I (I)	0.4
Sphagnum fimbriatum	I	0.3	*Sphagnum capillifolium*	I (IV)	1.6
Sphagnum papillosum	I (IV)	1.5	*Sphagnum angustifolium*	I	0.2
Sphagnum tenellum	I (IV)	0.7	*Campylopus paradoxus*	I (I)	0.5
Dicranella cerviculata	I	0.1			

Table 5.10 Constancy table for Group 01

Constancies I-V denote the percentage of samples which contain a particular species i.e. I = 1-20%, II = 21-40%, III = 41-60%, IV = 61-80%, V = 81-100%. Mean % cover is the average percent cover of a species for the group of samples as a whole.
Constancy scores in brackets represent the NVC M18a community (Rodwell, 1991) score for that species.

Group 01 sub-divided into negative **Group 010** (644 samples) and positive **Group 011** (148 samples). The eigenvalue at this division was 0.278. Negative **Group 010** was characterised by *Molinia caerulea* (pseudospecies level 2) and positive **Group 011** by lowland raised mire species *Vaccinium oxycoccos* and *Aulacomnium palustre* (both at pseudospecies level 1). This information suggested a division similar to that of the 00/01 dichotomy, implying that Group 010 was intermediate between Group 00 and Group 011. Group 011 is described later in this section.

Division of Group 010, the *Molinia*-rich side of this dichotomy, produced negative **Group 0100** (254 samples) and positive **Group 0101** (390 samples). The eigenvalue for this division was 0.191. **Group 0100** had one indicator species which was *Campylopus* *introflexus* (pseudospecies level 1) a characteristic colonizer of freshly cut, drained peat (Watson, 1981). **Group 0101** was characterised by *Eriophorum vaginatum* (pseudospecies level 3), *Erica tetralix* (pseudospecies level 4) and *Sphagnum cuspidatum* (pseudospecies level 1). The division at this point appeared to be of a dry/wet nature. Division of the dry side of the dichotomy i.e. **Group 0100** produced groups which have been treated as end groups in Fig. 5.1 - negative **Group 01000** (113 samples) and positive **Group 01001** (141)**.** The eigenvalue for the division was 0.229.

Vegetation of **Group 01000** was characterised by *Campylopus introflexus* (pseudospecies level 2) which suggested a pioneer vegetation of dry peat. **Group 01001** was characterised by *Molinia caerulea* (pseudospecies level 4) and additional species information from the constancy table suggested a relatively dry habit. **Groups 01000** and **01001** appeared to characterise different cutting types. This is demonstrated in Table 5.12 and Table 5.14 where **Group 01000** had most samples located in the old commercial baulk and flat surfaces and **Group 01001** samples were associated with the recent commercial augered, *Molinia* and relict surfaces.

The samples in **Group 01000** were represented in a constancy table (Table 5.11) and the distribution of the samples in **Group 01000** were shown in Table 5.12. This information depicted a vegetation type where bare ground, *Calluna vulgaris* and *Campylopus introflexus* were common and of the highest average percent cover. *Eriophorum vaginatum* had 61-80% constancy, but a lower average cover (8.5%). Table 5.12 showed that the group represented an early (pre-management) vegetation type, found mostly on the baulk and flat surfaces of the old commercial cuttings where it did not significantly change in frequency over time. A small number of samples were located on the relict and augered surfaces of the recent commercial areas where this vegetation type was also an early one, but showed a significant increase with time. It could be postulated that these recent commercial samples were following a similar successional trend to the old commercial baulks post- abandonment of peat cutting.

Comparing the **Group 01000** constancies with those for NVC sub-community M18a (in brackets – Table 5.11) the presence of a large number of target species (in the more intensively cut flat surfaces of the old commercial cuttings) was seen. On the whole the constancies tended to be much lower than in the target M18a community but demonstrated that this relatively unpromising vegetation may have the potential to develop into a more desirable one**. Group 01000** could be generally described as pre-management dry *Calluna vulgaris* - rich vegetation of old commercial baulks and flats which remained relatively unchanged over the study period.

GROUP 01000	**constancy**	**mean % cover**		**constancy**	**mean % cover**
Calluna vulgaris	V (V)	38.5	*Campylopus paradoxus*	I (I)	2.8
Bare	V	29.2	*Campyopus pyriformis*	I	3.2
Eriophorum vaginatum	IV (IV)	8.5	*Dicranella cerviculata*	I	2.6
Campylopus introflexus	IV	12.1	*Mylia anomala*	I (III)	1.6
Erica tetralix	III (V)	7.0	*Polytrichum juniperinum*	I	10.0
Molinia caerulea	III (II)	10.2	*Polytrichum alpestre*	I (I)	30.6
Eriophorum angusitfolium	III (V)	8.4	*Cephalozia connivens*	I	2.0
Lichen A	III	2.8	*Kurzia pauciflora*	I (I)	10.0
Pteridium aquilinum	II	6.6	*Kurzia* spp.	I	12.3
Pohlia nutans	II (I)	1.8	*Sphagnum subnitens*	I (I)	1.4
Vaccinium myrtilus	I (I)	2.0	*Calypogeia muelleriana*	I (I)	0.2
Vaccinium oxycoccos	I (III)	0.2	*Polytrichum commune*	I (I)	6.5
Andromeda polifolia	I (III)	0.7	*Cephaloziella* spp.	I	0.6
Rubus spp.	I	9.0	*Hypnum jutladicum*	I (II)	15.0
Drosera rotundifolia	I (IV)	0.5	*Orthodontium lineare*	I	8.0
Dryopteris dilatata	I	0.5	*Dicranium scoparium*	I (I)	0.8
Pinus sylvestris	I	10.8	*Sphagnum tenellum*	I (IV)	0.5
Sphagnum papillosum	I (IV)	0.9	*Sphagnum cuspidatum*	I (II)	0.2

Table 5.11 Constancy table for Group 01000

Constancies I-V denote the percentage of samples which contain a particular species i.e. I = 1-20%, II = 21-40%, III = 41-60%, IV = 61-80%, V = 81-100%. Mean % cover is the average percent cover of a species for the group of samples as a whole.

Constancy scores in brackets represent the NVC M18a community (Rodwell, 1991) score for that species.

Group 01000: A dry *Calluna*-rich vegetation				
	Recent commercial	**Uncut**	**Old commercial**	**Hand cut**
Number of samples present for each survey year	1993 = 5[a] 1996 = 8[ab] 2001 = 14[b]	1991 = 6[a] 1996 = 4[a] 2001 = 1[a]	1991 = 25[a] 1996 = 18[a] 2001 = 16[a]	1991 = 9[a] 1996 = 5[ab] 2001 = 2[b]
Surface type (section of the peat cutting profile)	Augered Relict	Uncut	Baulk Flat	Baulk Flat
Date of damming	Sub-compartment 3.3 -1991/1992 Sub-compartment 3.9 – 1993/1994 Sub-compartment 3.13 – 1994/1995	Sub-compartment 6.7 - 1992	Sub-compartment 1.4 – 1995/1996 Sub-compartment 4.4 - 1997	Compartment 13 – 1995/1996 Compartment 14 – 1995/1996

Table 5.12 Summary of Group 01000

A description of the general vegetation type, number of samples for each survey year and their location on the site. The surfaces of the peat profile applicable for the group are given. Compartments/ sub-compartments are stated as appropriate for the group with dates of rehabilitation management work.

For each cutting type, numbers of samples which are not significantly different at the 5% level in chi squared tests have been given the same suffix. Critical value at p=0.05 with 1 degree of freedom is 3.84.

The constancy table for **Group 01001** (Table 5.13) confirmed the highest average species cover was achieved by *Molinia caerulea* which also had the highest constancy (along with *Calluna vulgaris* and *Erica tetralix*). This group contained many of the NVC M18a species, however their percentage presence in the samples was much lower than is seen in M18a and of much lower constancy. Bare ground, *C. vulgaris* and *M. caerulea* are strong features of **Group 01001** which suggested a dry peat surface. Table 5.14 showed the spatial distribution of the samples in this group, which were found in small numbers on the baulk surfaces of the hand cuts (where *C. vulgaris* was common) and in larger numbers on the augered, *Molinia* and relict surfaces of the recent commercial areas (where *M. caerulea* was common). In the recent commercial cuttings, this vegetation type increased significantly from the first to the second survey year and then decreased significantly by the third survey year. In general this was an early *Molinia caerulea – Calluna vulgaris* vegetation type which developed to be a prominent mid-study feature of the recent commercial areas (post-management). The increase of *M. caerulea* cover mid-study, suggested a fluctuating water table at that time. The subsequent decrease suggested that a more stable water table was developing. This group may have been transitional with **Group 00**.

GROUP 01001	**constancy**	**mean % cover**		**constancy**	**mean % cover**
Calluna vulgaris	V (V)	33.6	*Dryopteris dilatata*	I	2.7
Erica tetralix	V (V)	7.2	*Pinus sylvestris*	I	2.8
Molinia caerulea	V (II)	40.4	*Sphagnum cuspidatum*	I (II)	2.2
Bare	IV	24.9	*Sphagnum fimbriatum*	I	2.7
Eriophorum angustifolium	III (V)	4.1	*Sphagnum papillosum*	I (IV)	2.9
Campylopus introflexus	III	1.3	*Campylopus paradoxus*	I (I)	1.2
Eriophorum vaginatum	II (IV)	5.2	*Dicranella cerviculata*	I	3.7
Campyopus pyriformis	II	5.1	*Mylia anomala*	I (III)	2.3
Vaccinium oxycoccos	I (III)	0.8	*Pohlia nutans*	I (I)	2.6
Andromeda polifolia	I (III)	0.8	*Polytrichum juniperinum*	I	12.1
Pteridium aquilinum	I	4.6	*Polytrichum alpestre*	I (I)	2.1
Rubus spp.	I	0.8	*Calypogeia fissa*	I	1.9
Drosera rotundifolia	I (IV)	1.1	*Cephalozia connivens*	I	2.3
Odontoschisma sphagni	I (IV)	7.6	*Hypnum jutlandicum*	I (II)	5.2
Kurzia pauciflora	I (I)	7.6	*Aulacomnium palustre*	I (III)	0.2
Kurzia spp.	I	1.4	*Sphagnum capillifolium*	I (IV)	0.2
Calypogeia muellerana	I (I)	1.6	*Cephaloziella divaricata*	I	0.2
Polytrichum commune	I (I)	3.4	*Polytrichum piliferum*	I	0.2
			Cephaloziella spp.	I	0.2

Table 5.13 Constancy table for Group 01001

Constancies I-V denote the percentage of samples which contain a particular species i.e. I = 1-20%, II = 21-40%, III = 41-60%, IV = 61-80%, V = 81-100%. Mean % cover is the average percent cover of a species for the group of samples as a whole.

Constancy scores in brackets represent the NVC M18a community (Rodwell, 1991) score for that species.

Group 01001: A dry *Molinia/ Calluna* vegetation				
	Recent commercial	**Uncut**	**Old commercial**	**Hand cut**
Number of samples present for each survey year	1993 = 21[a] 1996 = 43[b] 2001 = 18[a]	1991 = 5[a] 1996 = 2[a] 2001 = 2[a]	1991 = 6[a] 1996 = 8[a] 2001 = 8[a]	1991 = 10[a] 1996 = 13[a] 2001 = 5[a]
Surface type (section of the peat cutting profile)	Augered *Molinia* Relict	Uncut	Baulk Flat	Baulk Flat
Date of damming	Sub-compartment 3.3 -1991/1992 Sub-compartment 3.9 – 1993/1994 Sub-compartment 3.13 – 1994/1995	Sub-compartment 6.7 – 1992 Sub-compartment 15 – 1995/1996	Sub-compartment 1.4 – 1995/1996 Sub-compartment 4.4 - 1997	Compartment 13 – 1995/1996 Compartment 14 – 1995/1996

Table 5.14 Summary of Group 01001

A description of the general vegetation type, number of samples for each survey year and their location on the site. The surfaces of the peat profile applicable for the group are given. Compartments/ sub-compartments are stated as appropriate for the group with dates of rehabilitation management work.

For each cutting type, numbers of samples which are not significantly different at the 5% level in chi squared tests have been given the same suffix, e.g. for the uncut area there is a significant change between 1996 and 2001, but not between 1991 and 1996 or 1991 and 2001). Critical value at p=0.05 with 1 degree of freedom is 3.84.

Returning to the wet side of the **Group 010** dichotomy, further division of **Group 0101** was used to produce end groups: negative **Group 01010** (160 samples) and positive **Group 01011** (230 samples) with an eigenvalue of 0.163 for the division. Indicator species for **Group 01010** were *Sphagnum cuspidatum* (2) and *Eriophorum angustifolium* (2), clearly indicators of a high water table with inundation. **Group 01011** was characterised by *Campylopus pyriformis* (1) a bryophyte which colonizes wet peat exposed by cutting or clearing. This species is also found at the edges of bog pools during summer, colonising the peat exposed as the water recedes (Dr M Newton – *pers comm*). This suggested a division on the basis of wet/damp conditions.

Group 01010 was characterised by *Erica tetralix, Calluna vulgaris, Eriophorum spp.* and *Sphagnum cuspidatum* (Table 5.15). Most of the species with higher constancy scores were tolerant of a high water table with the exception of *C. vulgaris.* The majority of the samples were located on the ditch and flat surfaces of the old commercial and hand cut areas, as early (pre-management) vegetation. In the old commercial cuttings this vegetation significantly increased from 1991 to 1996 and then significantly reduced from 1996 to 2001 following management. In the hand cuttings no significant change was seen. *S. cuspidatum* was a common feature of the ditches and *C. vulgaris* and *E. tetralix* a feature of the flat surface. The high constancy score of *S. cuspidatum* suggested a high water table is maintained for much of the year i.e. the areas were holding water.

A small number of the samples appeared to be a late (post-management) damp-heath vegetation type of the relict and augered surfaces of the recent commercial cuttings (Table 5.16) where there was a significant increase from 1991 to 2001. This group was also an early and quickly disappearing *Calluna* - vegetation of uncut sub-compartment 6.7 and showed a significant decline following damming.

Over all **group 01010** was an early but declining vegetation type of flats and ditches in the old commercial cuttings and an early unchanging vegetation of the hand cuttings. The vegetation type showed a late increase in the recent commercial relict and augered surfaces.

The constancy table for **Group 01011** (Table 5.17) depicted a varied vegetation featuring *C. vulgaris, E. tetralix, E. vaginatum* and *M. caerulea.* This side of the dichotomy had a much lower cover of *S. cuspidatum.* Table 5.18 showed that this group was quite evenly distributed across all four cutting types. The vegetation was an early (pre-management) type and a persisting one (showing no significant change over time) of baulk and flat surfaces of old commercial and hand cuttings. *C. vulgaris* and *M. caerulea* were associated with the dry baulks while *E. tetralix* and *E. vaginatum* were associated with the damp flat surface (at closer proximity to the water table).

The same trend of persistence over the study period was also found in samples on uncut sub-compartment 6.7 where the two former species were found on drier raised areas and the latter species seen in damp hollows. **Group 01011** was also a late vegetation of the

GROUP 01010	**constancy**	**mean % cover**		**constancy**	**mean % cover**
Erica tetraix	V (V)	21.4	*Mylia anomala*	I (III)	0.2
Calluna vulgaris	V (V)	23.9	*Vaccinium oxycoccos*	I (III)	1.0
Eriophorum angustifolium	V (V)	5.9	*Drosera rotundifolia*	I (IV)	0.4
Eriophorum vaginatum	V (IV)	16.8	*Campylopus paradoxus*	I (I)	0.3
Molinia caerulea	IV (II)	16.2	*Campylopus introflexus*	I	0.1
Sphagnum cuspidatum	IV (II)	25.9	*Campylopus pyriformis*	I	0.1
Bare	III	6.1	*Sphagnum tenellum*	I (IV)	0.4
Kurzia spp.	I	0.3	*Kurzia pauiflora*	I (I)	0.4
Cephalozia connivens	I	0.1	*Dicranella cerviculata*	I	0.1
Andromeda polifolia	I (III)	0.7	*Sphagnum palustre*	I (I)	0.6
Sphagnum papillosum	I (IV)	2.7	*Polytrichum juniperinum*	I	0.1
			Polytrichum alpestre	I (I)	0.1

Table 5.15 Constancy table for Group 01010

Constancies I-V denote the percentage of samples which contain a particular species i.e. I = 1-20%, II = 21-40%, III = 41-60%, IV = 61-80%, V = 81-100%. Mean % cover is the average percent cover of a species for the group of samples as a whole.
Constancy scores in brackets represent the NVC M18a community (Rodwell, 1991) score for that species

augered and *Molinia* surfaces of the recent commercial areas where it increased significantly from each study time point to the next. These features have been summarised in Table 5.18.

The division of **Group 0101** described above can be further defined as a division separating wetter old commercial/ hand cut flats and ditches from drier old commercial/ hand cut flats and baulks.

Group 01011 may be transitional with **Group 00.** In the recent commercial areas Group 00 disappeared over time and Group 01011 appeared to have the potential to develop in place of it. This demonstrated a positive change with colonisation of NVC M18a species.

Group 01010: A damp *Calluna vulgaris/ Erica tetralix* heath and *Sphagnum cuspidatum* mire pool – type vegetation				
	Recent commercial	**Uncut**	**Old commercial**	**Hand cut**
Number of samples present for each survey year	1993 = 3[a] 1996 = 1[a] 2001 = 16[b]	1991 = 22 [a] 1996 = 4 [b] 2001 = 1 [b]	1991 = 20 [a] 1996 = 35 [b] 2001 = 17 [a]	1991 = 11 [a] 1996 = 18 [a] 2001 = 12 [a]
Surface type (section of the peat cutting profile)	Augered Relict	Uncut	Flat Ditch	Flat Ditch
Date of damming	Sub-compartment 3.3 -1991/1992 Sub-compartment 3.9 – 1993/1994	Sub-compartment 6.7 - 1992	Sub-compartment 1.4 – 1995/1996 Sub-compartment 4.4 - 1997	Compartment 13 – 1995/1996 Compartment 14 – 1995/1996

Table 5.16 Summary of Group 01010

A description of the general vegetation type, number of samples for each survey year and their location on the site. The surfaces of the peat profile applicable for the group are given. Compartments/ sub-compartments are stated as appropriate for the group with dates of rehabilitation management work.

For each cutting type, numbers of samples which are not significantly different at the 5% level in chi squared tests have been given the same suffix, e.g. for the uncut area there is a significant change between 1996 and 2001, but not between 1991 and 1996 or 1991 and 2001.Critical value at p=0.05 with 1 degree of freedom is 3.84.

GROUP 01011	constancy	mean % cover		constancy	mean % cover
Erica tetralix	V (V)	20.5	*Campylopus paradoxus*	I (I)	0.6
Calluna vulgaris	V (V)	29.4	*Mylia anomala*	I (III)	0.3
Eriophorum vaginatum	V (IV)	19.3	*Drosera rotundifolia*	I (IV)	0.1
Molinia caerulea	IV (II)	28.2	*Sphagnum papillosum*	I (IV)	0.3
Eriophorum angustifolium	IV (V)	0.7	*Campylopus introflexus*	I	0.1
Bare	III	7.1	*Calypogeia muelleriana*	I (I)	0.3
Campylopus pyriformis	II	1.0	*Kurzia pauciflora*	I (I)	0.6
Cephalozia connivens	II	1.6	*Polytrichum alpestre*	I (I)	0.3
Pohia nutans	I (I)	0.3	*Sphagnum fimbriatum*	I	0.1
Vaccinium oxycoccos	I (III)	1.2	*Odontoschisma sphagni*	I (IV)	0.1
Andromeda polifolia	I (III)	0.6	*Polytrichum juniperinum*	I	0.1
Sphagnum cuspdatum	I (II)	0.3	*Polytrichum formosum*	I	0.1
Kurzia spp.	I	0.4	*Sphagnum magellanicum*	I (IV)	0.1

Table 5.17 Constancy table for Group 01011

Constancies I-V denote the percentage of samples which contain a particular species i.e. I = 1-20%, II = 21-40%, III = 41-60%, IV = 61-80%, V = 81-100%. Mean % cover is the average percent cover of a species for the group of samples as a whole.

Constancy scores in brackets represent the NVC M18a community (Rodwell, 1991) score for that species.

Group 01011: A dry *C. vulgaris/ M. caerulea* and damp *Erica tetralix/ Eriophorum vaginatum* vegetation				
	Recent commercial	**Uncut areas**	**Old commercial**	**Hand cut**
Number of samples present for each survey year	1993 = 1[a] 1996 = 11[b] 2001 = 29[c]	1991 = 17[a] 1996 = 28[a] 2001 = 22[a]	1991 = 24[a] 1996 = 20[a] 2001 = 15[a]	1991 = 27[a] 1996 = 19[a] 2001 = 17[a]
Surface type (section of the peat cutting profile)	Augered *Molinia*	Uncut	Baulk Flat	Baulk Flat
Date of damming	Sub-compartment 3.3 - 1991/1992 Sub-compartment 3.9 – 1993/1994 Sub-compartment 3.13 – 1994/1995	Sub-compartment 6.7 - 1992	Sub-compartment 1.4 – 1995/1996 Sub-compartment 4.4 - 1997	Compartment 13 – 1995/1996 Compartment 14 – 1995/1996

Table 5.18 Summary of Group 01011

A description of the general vegetation type, number of samples for each survey year and their location on the site. The surfaces of the peat profile applicable for the group are given. Compartments/ sub-compartments are stated as appropriate for the group with dates of rehabilitation management work.

For each cutting type, numbers of samples which are not significantly different at the 5% level in chi squared tests have been given the same suffix, e.g. for the uncut area there is a significant change between 1996 and 2001, but not between 1991 and 1996 or 1991 and 2001. Critical value at p=0.05 with 1 degree of freedom is 3.84.

The **Group 011** constancy table (Table 5.19) showed the strong similarity this group had with M18a vegetation. Many of the component species were present but there was a notable lower cover of *Sphagna* compared to M18a. In Table 5.20 this vegetation type was seen to occur on uncut areas of the site where it was an early vegetation type in Compartment 15, remaining statistically unchanged throughout the study period. It was also present as an early vegetation type of sub-compartment 6.7 (to a lesser extent), where it showed a significant increase post-management (Table 5.20). This vegetation type suggested a near – surface water table.

The early-disappearing samples of Group 01010 originally present in uncut sub-compartment 6.7 may have been transitional with Group 011. This would relate to the development of a more stable near – surface water table. It could be postulated that over time sub-compartment 6.7 is becoming more like the uncut compartment 15.

GROUP 011	**constancy**	**mean % cover**		**constancy**	**mean % cover**
Erica tetralix	V (V)	20.8	*Drosera rotundifolia*	I (IV)	0.3
Eriophorum vaginatum	V (IV)	37.0	*Calypogeia muelleriana*	I (I)	2.7
Vaccinium oxycoccos	V (III)	19.8	*Nardia scalaris*	I	0.4
Calluna vulgaris	V (V)	17.9	*Mylia anomala*	I (III)	0.4
Andromeda polifolia	IV (III)	4.9	*Kurzia* spp.	I	3.2
Eriophorum angustifolium	IV (V)	2.8	*Sphagnum magellanicum*	I (IV)	27.1
Aulacomnium palustre	III (III)	16.6	*Pinus sylvestris*	I	0.5
Odontoschisma sphagni	III (IV)	2.8	*Campylopus introflexus*	I	1.2
Sphagnum capillifolium	II (IV)	17.5	*Dicranella heteromalla*	I	1.4
Campylopus pyriformis	II	3.3	*Sphagnum palustre*	I (I)	10.8
Pohlia nutans	II (I)	0.7	*Dicranella* spp	I	0.4
Polyrichum alpestre	II (I)	11.0	*Pteridium aquilinum*	I	0.3
Sphagnum tenellum	II (IV)	7.1	*Campylopus paradoxus*	I (I)	1.5
Sphagnum papillosum	I (IV)	5.8	*Dryopteris dilatata*	I	0.2
Cephalozia connivens	I	3.8	*Polytrichum commune*	I (I)	0.5
Sphagnum cuspidatum	I (II)	10.5	*Sphagnum angustifolium*	I	38.5
Sphagnum fallax	I (I)	23.4	*Pleurozium schreberi*	I (II)	4.0
Sphagnum fimbriatum	I	5.5	*Kurzia pauciflora*	I (I)	1.0
Empetrum nigrum	I (II)	24.8	*Sphagnum subnitens*	I (I)	5.0
Polytrichum juniperinum	I	1.1	*Cephaloziella rubella*	I	0.2
Cephalozia bicuspidate	I (I)	0.2	*Sphagnum flexuosum*	I	10.0
Molinia caerulea	I (II)	0.7	*Calypogeia neesiana*	I	1.0
			Bare	I	5.7

Table 5.19 Constancy table for Group 011

Constancies I-V denote the percentage of samples which contain a particular species i.e. I = 1-20%, II = 21-40%, III = 41-60%, IV = 61-80%, V = 81-100%. Mean % cover is the average percent cover of a species for the group of samples as a whole.

Constancy scores in brackets represent the NVC M18a community (Rodwell, 1991) score for that species.

Group 011: A mire type vegetation	
	Uncut
Number of samples present for each survey year	Compartment 15: 1991 = 28 [a] 1996 = 29 [a] 2001 = 29 [a] Sub-compartment 6.7: 1991 = 9 [a] 1996 = 23[b] 2001 = 27[b]
Surface type (section of the peat cutting profile)	Uncut
Date of damming	Compartment 15 – 1995/1996 Sub-compartment 6.7 - 1992

Table 5.20 Summary of Group 011

A description of the general vegetation type, number of samples for each survey year and their location on the site. The surfaces of the peat profile applicable for the group are given. Compartments/ sub-compartments are stated as appropriate for the group with dates of rehabilitation management work.

For each cutting type, numbers of samples which are not significantly different at the 5% level in chi squared tests have been given the same suffix. Critical value at p=0.05 with 1 degree of freedom is 3.84.

Returning to **Group 1**, which included the vegetation most strongly associated with wet, inundated conditions, it divided into negative **Group 10** (196 samples) and positive **Group 11** (57 samples) with eigenvalue 0.393. **Group 10** had indicators *Eriophorum angustifolium* (pseudospecies level 1), *E. vaginatum* (pseudospecies level 1) and *Erica tetralix* (pseudospecies level 1) which were typical of a high water table. **Group 11** was characterised by *Campylopus pyriformis* (pseudospecies level 1) which indicated early colonisation of bare wet peat and *Molinia caerulea* (pseudospecies level 3) which in wet conditions suggested a fluctuating water table. On the basis of the indicator species the division at this point appeared to be based on a stable/fluctuating water table.

The end group, **Group 10** constancy table (Table 5.21) had fewer species than previously described tables. The vegetation was dominated by *Sphagnum cuspidatum* and *Eriophorum vaginatum* was common.

Molinia caerulea and *E. angustifolium* occured in 61-80% of the samples at low average percentage (13.9% and 12.4% respectively). This vegetation type had one of the lower average percent covers for *M. caerulea.* **Group 10** was mostly a late (post-management) vegetation of the recent commercial cuts (augered, *Molinia,* relict and ditch) – increasing slightly from the first to second survey year and prolifically from second to third survey year (see Table 5.22). This change was statistically significant from each time point to the subsequent one. The group was found as an early vegetation of flat and ditch surfaces on old commercial and hand cut areas, where it persisted as small numbers of samples from first to second survey and then showed a significant increase by the third year (following management). In summary, this was a post-management *Sphagnum* vegetation type suggestive of a stable high water table with inundation.

GROUP 10	constancy	mean % cover
Sphagnum cuspidatum	V (II)	68.8
Molinia caerulea	IV (II)	13.9
Eriophorum angustifolium	IV (V)	12.4
Eriophorum vaginatum	IV (V)	23.9
Erica tetralix	II (V)	2.6
Bare	II	9.8
Calluna vulgaris	I (V)	1.7
Sphagnum fimbriatum	I	0.2
Sphagnum papillosum	I (IV)	0.3
Dicranella cerviculata	I	0.1
Pohlia nutans	I (I)	0.1
Sphagnum fallax	I (I)	0.4

Table 5.21 Constancy table for Group 10

Constancies I-V denote the percentage of samples which contain a particular species i.e. I = 1-20%, II = 21-40%, III = 41-60%, IV = 61-80%, V = 81-100%. Mean % cover is the average percent cover of a species for the group of samples as a whole.

Constancy scores in brackets represent the NVC M18a community (Rodwell, 1991) score for that species.

Group 10: A *Sphagnum cuspidatum* inundated vegetation			
	Recent commercial	**Old commercial**	**Hand cut**
Number of samples present for each survey year	1993 = 5 [a] 1996 = 16 [b] 2001 = 67 [c]	1991 = 9 [a] 1996 = 4 [a] 2001 = 29 [b]	1991 = 18 [a] 1996 = 17 [a] 2001 = 31 [b]
Surface type (section of the peat cutting profile)	Augered *Molinia* Relict Ditch	Flat Ditch	Flat Ditch
Date of damming	Sub-compartment 3.3 - 1991/1992 Sub-compartment 3.9 – 1993/1994 Sub-compartment 3.13 – 1994/1995	Sub-compartment 1.4 – 1995/1996 Sub-compartment 4.4 - 1997	Compartment 13 – 1995/1996 Compartment 14 – 1995/1996

Table 5.22 Summary of Group 10

A description of the general vegetation type, number of samples for each survey year and their location on the site. The surfaces of the peat profile applicable for the group are given. Compartments/ sub-compartments are stated as appropriate for the group with dates of rehabilitation management work.

For each cutting type, numbers of samples which are not significantly different at the 5% level in chi squared tests have been given the same suffix. Critical value at p=0.05 with 1 degree of freedom is 3.84.

Group 11 was characterised by high constancies and cover-abundances of *M. caerulea, S. cuspidatum* and *C. pyriformis* (Table 5.23). The species with the highest constancy (Table 5.23) and average percent cover were *M. caerulea* and *S. cuspidatum.* The bryophyte *C. pyriformis* along with bare ground were common features of this vegetation type. This suggested a succession from wet bare ground colonized by *C. pyriformis* to a fluctuating peat water table where *M. caerulea* and *S. cuspidatum* became established. This group was found exclusively in the recent commercial areas (all surfaces of the cutting profile) where it had established by 1996 (post-management) and then by 2001 was declining (Table 5.24). The increase in this group from 1993 to 1996 and subsequent decrease from 1996 to 2001 were statistically significant. It is postulated that this group was transitional with **Group 10** – as the water table became more stable, the decrease in *M. caerulea* and increase in *S. cuspidatum* and *E. vaginatum* transfered **Group 11** samples to **Group 10**.

GROUP 11	**constancy**	**mean % cover**
Molinia caerulea	V (II)	33.7
Sphagnum cuspidatum	V (II)	35.4
Campylopus pyriformis	IV	28.4
Bare	IV	33.5
Calluna vulgaris	I (V)	2.6
Eriophorum angustifolium	I (V)	5.4
Eriophorum vaginatum	I (IV)	5.1
Pteridium aquilinum	I	0.5
Campylopus introflexus	I	20.0

Table 5.23 Constancy table for Group 11

Constancies I-V denote the percentage of samples which contain a particular species i.e. I = 1-20%, II = 21-40%, III = 41-60%, IV = 61-80%, V = 81-100%. Mean % cover is the average percent cover of a species for the group of samples as a whole.

Constancy scores in brackets represent the NVC M18a community (Rodwell, 1991) score for that species.

Group 11: A wet *Molinia/ Sphagnum* vegetation	
	Recent commercial
Number of samples present for each survey year	1993 = 1[a] 1996 = 47[c] 2001 = 12[b]
Surface type (section of the peat cutting profile)	Augered *Molinia* Relict Ditch
Date of damming	Sub-compartment 3.3 - 1991/1992 Sub-compartment 3.9 – 1993/1994 Sub-compartment 3.13 – 1994/1995

Table 5.24 Summary of Group 11

A description of the general vegetation type, number of samples for each survey year and their location on the site. The surfaces of the peat profile applicable for the group are given. Compartments/ sub-compartments are stated as appropriate for the group with dates of rehabilitation management work.

For each cutting type, numbers of samples which are not significantly different at the 5% level in chi squared tests have been given the same suffix. Critical value at p=0.05 with 1 degree of freedom is 3.84.

Summary of the TWINSPAN analysis

The results of the TWINSPAN analysis highlighted several factors relating to vegetation change across the site. At the driest end of the ecological gradient was **group 00**, an open - *Molinia* vegetation, typical of the recent commercial areas. It was present as established pre-management vegetation which declined following management.

Another dry vegetation type of old commercial baulks and flats was the *Calluna*-rich **group 01000**. This group persisted unchanged in the old commercial areas, however it was found to a lesser extent in the recent commercial cuttings where it significantly increased from 1993 to 2001.

The recent commercial areas also supported a dry *Molinia-Calluna* vegetation (**group 01001**) which appeared to be an early post-management response showing a significant decline from 1996 to 2001. This suggested a fluctuating water table by 1996.

Damp and dry heath-type vegetation were seen in **groups 01010** (old commercial & hand cut flat and ditches) and **01011** (old commercial & hand cut flat and baulks) respectively. The samples for these groups identified them as existing vegetation types prior to management, which persisted relatively unchanged in abundance across all three survey years. This suggested that these areas of the site had not been affected by management. This may be due to height above the water table (e.g. in the case of baulk surfaces). Other possible explanations are that it was too early post-management to establish data trends or it may have been that damming was ineffective.

Compartment 15 (uncut) was a mire-type vegetation and the only area on the site to resemble NVC M18a. The TWINSPAN analysis suggested that this vegetation type (**group 011**) was present prior to management and persisted following management. Samples from this group were also found as a late vegetation type of uncut sub-compartment 6.7, suggesting the sub-compartment was becoming more like compartment 15 i.e. developing a near-surface, stable water table. This was supported by the chi-squared analysis, where raised mire species significantly increased their range in the uncut samples. This suggested a post-management improvement to sub-compartments 6.7 and compartment 15.

A fluctuating water table was identified again in the recent commercial areas of the site by 1996 (**group 11**). This was shown as a post-management development of a wet *Molinia caerulea- Sphagnum cuspidatum* vegetation which declined significantly by the final survey year. This indicated fluctuation in the water table mid-study, followed by a more stable, high water table by the final survey year. This was confirmed in the analysis results by the characteristics of **group 10** which appeared to be transitional with **group 11**. **Group 10** was a *Sphagnum cuspidatum* vegetation type of the recent commercial areas which showed a dramatic increase from the second to the third survey year. This group was also located (to a lesser extent) on flat and ditch surfaces of the old commercial and hand cuttings. Here too it demonstrated a significant increase from the second to the third survey year (post-management).

The TWINSPAN results suggested little vegetation change in the old commercial and hand cuttings. Areas demonstrating change were the uncut and recent commercial cuttings. These findings concur with the earlier chi-squared analysis.

Following rehabilitation management, a large proportion of the samples showed vegetation change as a move away from dominance by dry-land species. This process goes through a fluctuating water table phase and on to a stable, high water table with *Sphagnum* – type vegetation. This was seen clearly in the recent commercial areas where the *Molinia-Sphagnum cuspidatum* vegetation (**group 11**) present mid-study was replaced by the *Sphagnum cuspidatum* vegetation (**group 10**) at the final survey. This resulting vegetation (**group 10**) was characterised by *Sphagnum cuspidatum* and cover of *Eriophorum vaginatum* was now greater than *Molinia caerulea* and *Eriophorum angustifolium*. It was very interesting to see that this group showed colonisation at very low percent cover of *Sphagnum papillosum* and *Sphagnum fallax*. These species were not present in this cutting type when rehabilitation began, they had been lost to extensive peat cutting practices. They appeared to now be colonising the *Sphagnum cuspidatum* mats which suggested even at this early stage that development of the NVC M18a community was a possibility.

5.4.3 The CANOCO analysis

The species data were analysed using ordination techniques. Species names were abbreviated in the multivariate outputs and a key to the abbreviations is presented in Appendix 1.

Initial indirect and direct analyses were carried out on the entire permanent quadrat data set, in order to provide a general overview. Due to the complexity of the site, separate direct gradient analyses were then carried out for each cutting profile surface within each of the cutting types. The uncut areas of the site (compartments 15 and sub-compartments 6.7) were also treated individually.

Analysis of the hand cut and old commercial cuttings did not produce strong axes or correlation with rehabilitation. This confirmed the chi-squared and TWINSPAN analyses which found little change in these areas. The CANOCO results for these two cutting types has therefore not been included in the present chapter.

The complete data set - species ordination by indirect and direct gradient analysis

A preliminary exploratory correspondence analysis detrended by segments (DCA) was carried out on the complete data set. This produced a gradient length of 5.797, suggesting the unimodal model of analysis was appropriate for the data. Therefore indirect gradient analysis utilised DCA and direct gradient analysis used CCA.

The DCA output was shown as an ordination diagram - a species scatter diagram (Figure 5.2). Axis 1 appeared to demonstrate vegetation composition according to cutting type which was identified by the TWINSPAN analysis. To the left of Axis 1 the diverse mire vegetation of the uncut areas was seen. Species included *Vaccinium oxycoccos*, *Empetrum nigrum, Odontoschisma sphagni* and several species of *Sphagna*.

To the centre of Axis 1, species typical of the baulk and flat surfaces of old commercial and hand cuttings were seen – e.g. *Erica tetralix* and *Calluna vulgaris.* Finally, to the right of Axis 1 species typical of the recent commercial cuttings were seen i.e. *Molinia caerulea* and *Campylopus pyriformis.* Axis 2 suggested of a wet-dry gradient with species associated with a high water table/ inundation at the positive end of Axis 2 and those of a low water table at the negative end of this axis.

The CCA constrained the plant species according to significant environmental variables (significance determined by Monte Carlo permutation tests) and was shown as Figure 5.3. The general species spread of the DCA was well maintained by the CCA (which appeared as a mirror image of the DCA). This suggested that the environmental variables explained a considerable proportion of the two main trends in the unconstrained analysis. There was more definition between the species assemblages on Axis 1 and the relationship with cutting types was confirmed.

Axis 2 maintained the wet-dry gradient, where increasing time (year) and increasing number of seasons since damming (rewetting) correlated with the wet end of the gradient. The peat cutting surfaces also followed this gradient. The baulks were associated with the lower water table, the flat, *Molinia,* augered and relict surfaces related to an intermediate water table and the ditches to a high water table.

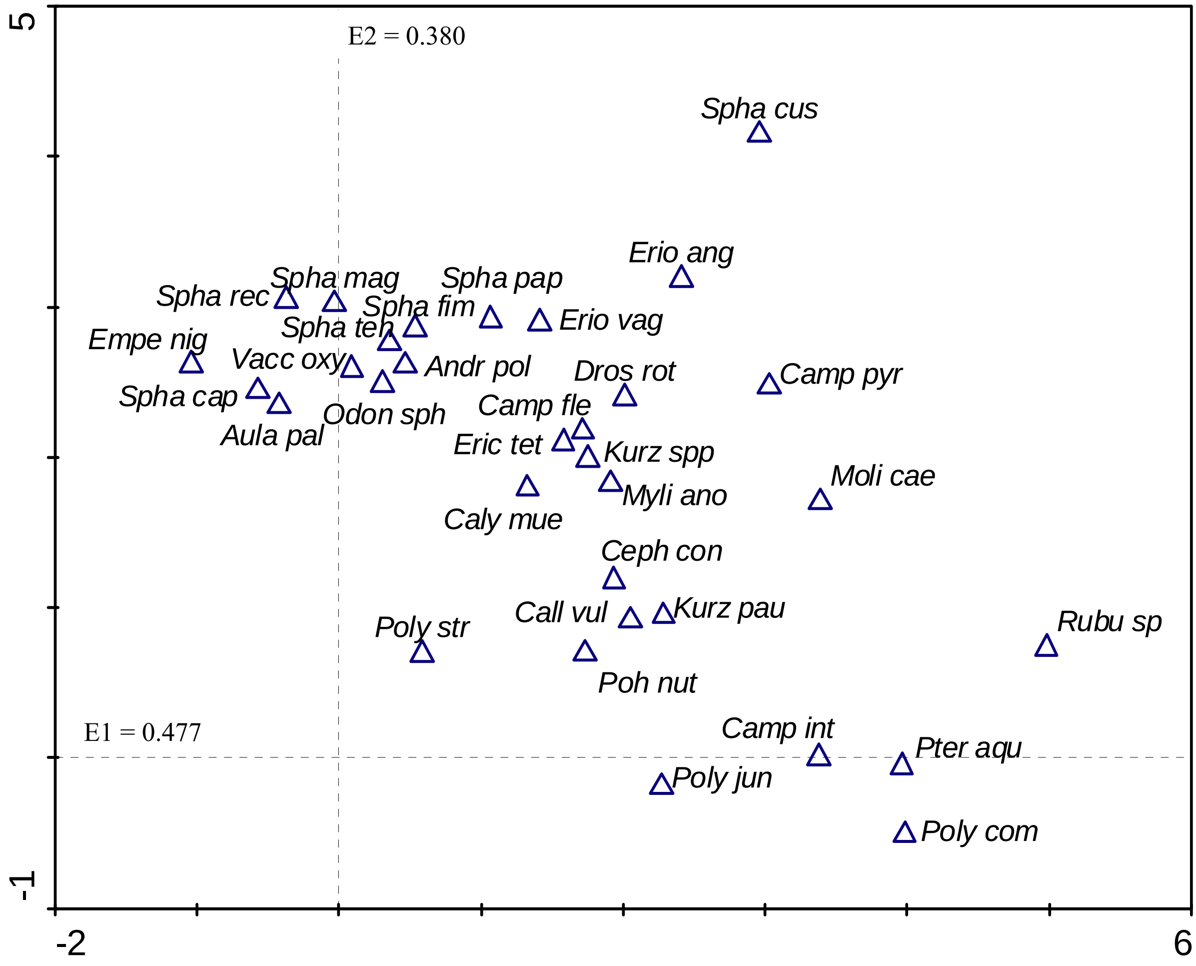

Figure 5.2 Indirect gradient analysis of all samples (quadrats) Permanent Quadrat Investigation (survey years 1991, 1996 and 2001): DCA correlation scatter diagram of plant species

The DCA (unconstrained) was performed on 1,248 samples. The DCA is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after axes extraction to produce a correlation scatter plot where the position of the species symbol (triangle) is a measure of fit with the ordination diagram.

$\lambda 1$ = 6.4% of species variance; $\lambda 1 + \lambda 2$ = 11.5% of species variance (61.6% of the species/environment relationship). Eigenvalues for each axis are given (E1 and E2).

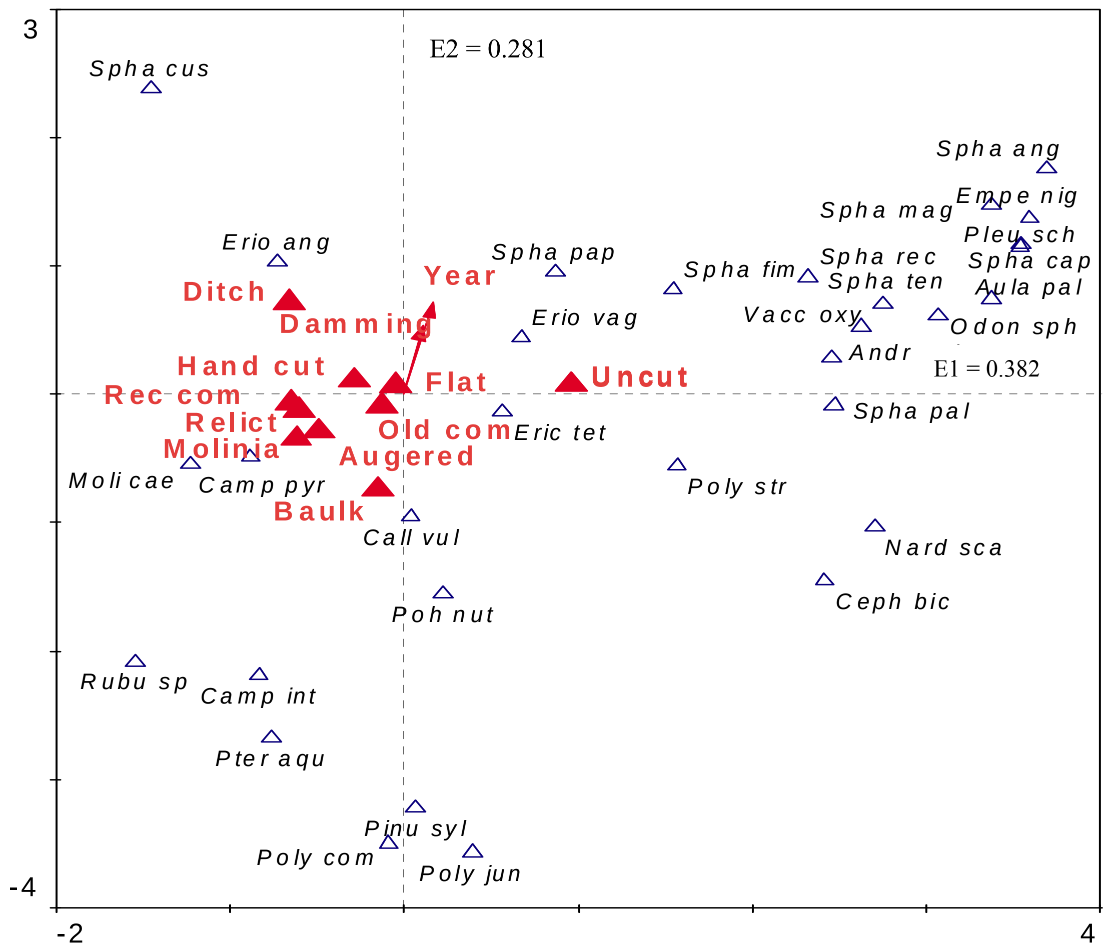

Figure 5.3 Direct analysis of all samples (quadrats) - Permanent Quadrat Investigation (survey years 1991, 1996 and 2001): CCA correlation biplot on vegetation data constrained by significant environmental variables.

The CCA was performed on 1,248 samples. It is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after axes extraction to produce a correlation biplot where the position of the species/ environmental variable symbol (triangle) and length of vector (arrow) is a measure of fit with the ordination diagram.

$\lambda 1$ = 4.1% of species variance; $\lambda 1 + \lambda 2$ = 7.1% of species variance (67.0% of the species/environment relationship).

Uncut compartment 15 - species ordination by direct gradient analysis

The preliminary DCA analysis of this data set produced a gradient length of 2.498 and as such was further analysed with the constrained RDA model (Figure 5.4).

Axis 1 of Figure 5.4 suggested a wet-dry gradient with the management effect of damming correlating with the species of wetter ecological requirements (*Eriophorum vaginatum* and *Sphagnum* species). The negative correlation of management effect with *Calluna vulgaris* and *Odontoschisma sphagni* suggested a decline in these species, brought about by damming. This inference was supported by the chi-squared analysis of compartment 15 (significant increases in species of *Sphagna* and decrease in *O. sphagni*). Raising the water table had positively affected the mature target mire species (NVC M18a species).

Axis 2 appeared to separate 1996 from the other two survey years. This suggested that the major trend in this data set was between 1991 and 2001. This would appear to be logical, as damming was undertaken in 1995 and one year on to the 1996 survey may not have been long enough for a vegetation response.

Uncut sub-compartment 6.7 - species ordination by direct gradient analysis

Initial exploratory DCA resulted in a gradient length of 3.165. Constrained ordination was therefore carried out using RDA and shown as Figure 5.5.

Axis 1 depicted a trend of time from 1991 through 1996 and on to 2001. Increasing time and seasons since damming related to target mire species, including *Vaccinium oxycoccos, Eriophorum vaginatum, Andromeda polifolia* and *Sphagnum magellanicum.* This suggested a positive response to rehabilitation. Axis 2 appeared to suggest a difference between the two recording transects. The early management of this sub-compartment (1992) had resulted in a continuing trend over the study period. This was shown in the chi-squared analysis with significant increases in mire species.

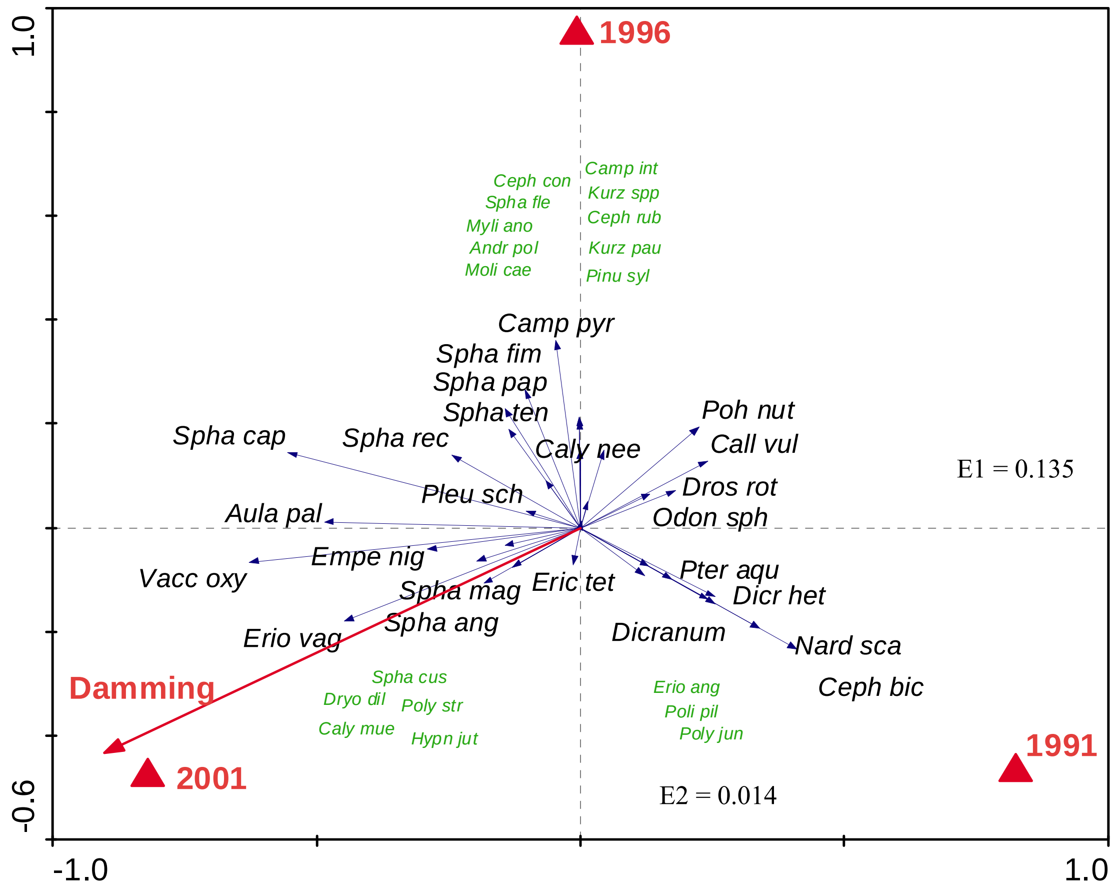

Figure 5.4 Direct gradient analysis of uncut compartment 15 samples (quadrats) - Permanent Quadrat Investigation (survey years 1991, 1996 and 2001): RDA correlation biplot on vegetation data constrained by significant environmental variables.

The RDA was performed on 90 samples. It is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after axes extraction to produce a correlation biplot where the length of arrow is a measure of fit with the ordination diagram. Species with very short vectors are listed in green.

$\lambda 1$ = 13.5% of species variance; $\lambda 1 + \lambda 2$ = 14.9% of species variance (100**%** of the species/environment relationship)

Data were log transformed during this analysis. Collinearity was detected when fitting environmental variables *1996* and *2001* (this is inevitable since all stands belong to the three year groups).

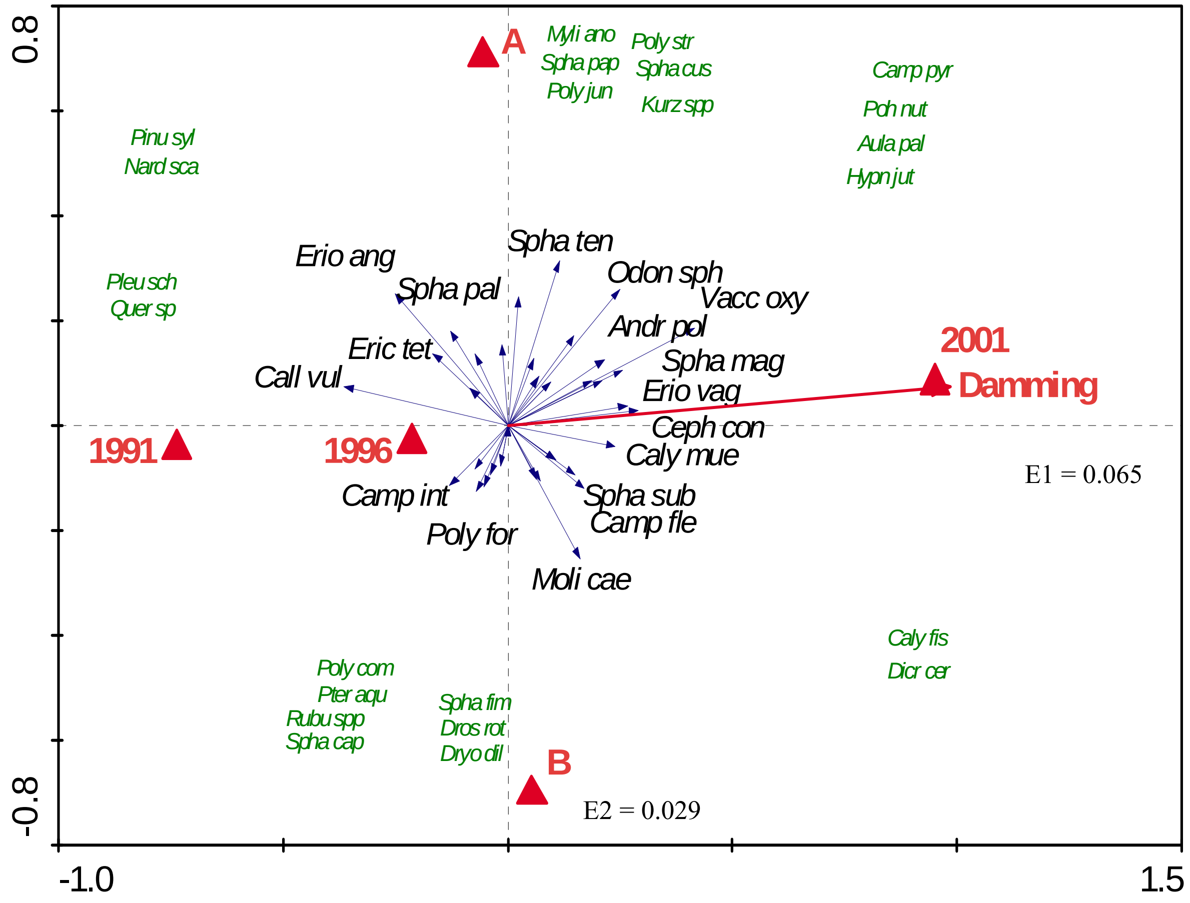

Figure 5.5 Direct gradient analysis of uncut sub-compartment 6.7 samples (quadrats) - Permanent Quadrat Investigation (survey years 1991, 1996 and 2001): RDA correlation biplot on vegetation data constrained by significant environmental variables.

The RDA was performed on 180 samples. It is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after axes extraction to produce a correlation biplot where the length of arrow is a measure of fit with the ordination diagram. Species with very short vectors are listed in green.

λ1 = 6.5% of species variance; λ1 + λ2 = 9.3% of species variance **(**87**%** of the species/environment relationship)

Data were log transformed during this analysis. Collinearity was detected when fitting environmental variables *1991*, *2001* and transect *B*.

Recent commercial cuttings- *Ditches* - species ordination by direct gradient analysis

Of the total 135 samples, 110 were accepted for analysis by the CANOCO programme. A preliminary DCA produced a gradient length of 4.489 and thus constrained analysis used CCA.

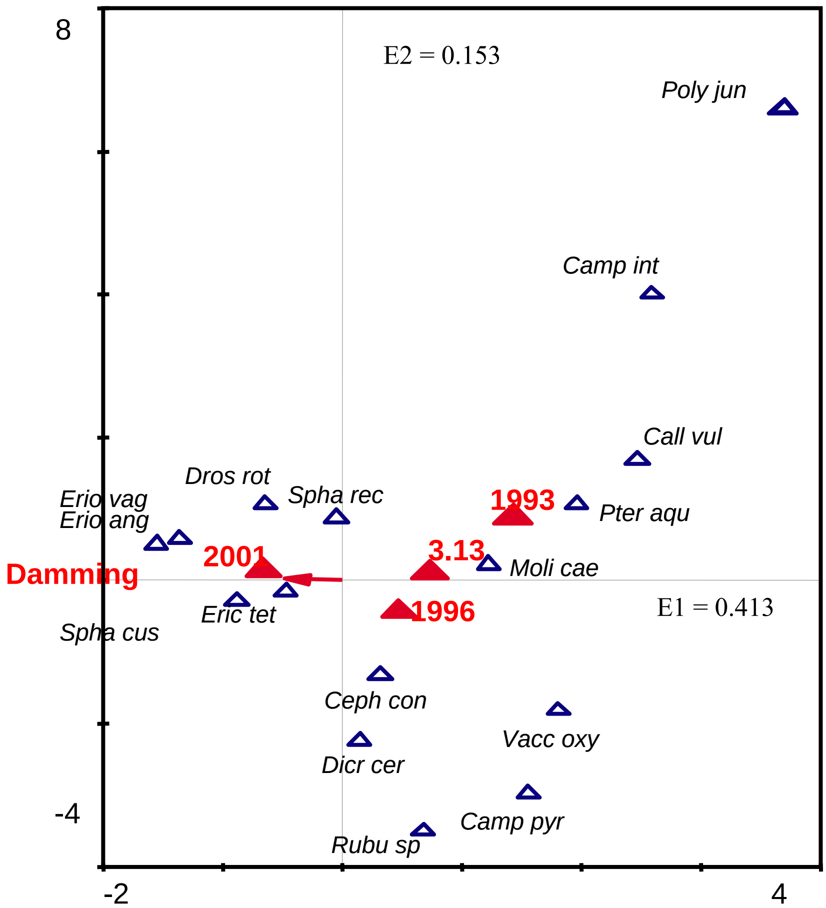

Figure 5.6 Direct gradient analysis of recent commercial *Ditch* samples (quadrats) - Permanent Quadrat Investigation (survey years 1991, 1996 and 2001): CCA correlation biplot on vegetation data constrained by significant environmental variables.

The CCA was performed on 110 samples. It is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after axes extraction to produce a correlation biplot where location of species (triangle) and environmental variables (triangle location and length of vector) is a measure of fit with the ordination diagram.

$\lambda 1$ = 12.9% of species variance; $\lambda 1 + \lambda 2$ = 17.7% of species variance **(**82.8**%** of the species/environment relationship). Data were log transformed during this analysis. Collinearity was detected when fitting environmental variable,*2001*.

Axis 1 of Figure 5.6 suggested of a wet-dry trend, where increasing time and seasons since damming correlated with the management plan target species. These species indicated inundation of the ditches. The location of *Molinia caerulea* between 1993 and 1996 was seen in the TWINSPAN analysis – where this species showed an increase at this time interval which was followed by a decrease by 2001.

Axis 2 suggested succession from bare ground to colonisation of lower and upper land species in a positive direction on the biplot.

Recent commercial cuttings- *Augered* - species ordination by direct gradient analysis

Of the 135 samples of this data set, 132 were accepted in the CANOCO analysis. An initial gradient length of 3.067 led to the RDA displayed as Figure 5.7.

The augered surfaces were devoid of vegetation when the site was taken over for nature conservation. The CANOCO analysis output revealed two successional trends in the augered data. The strongest seen on axis 1 showed a time line across each of the three survey years. Colonisation of bare peat by the bryophyte *Campylopous pyriformis* was followed by the establishment of NVC M18a species i.e. *Erica tetralix, Andromeda polifolia, Drosera rotundifolia* and *Sphagnum papillosum.* These species suggested a near surface water table and correlated with damming. They appeared to be most characteristic of sub-compartment 3.3.

Axis 2 demonstrated the second successional trend which followed a time line from 1996 to 2001, suggesting that this trend was a later post-management response. Succession from bare, disturbed ground was suggested by the presence of *Rubus* spp. which developed in to mire pool species (*S. cuspidatum, S. fallax* and *Eriophorum* vaginatum) and suggested an above surface water table. This trend was also related to damming.

Molinia caerulea correlated with increasing time since damming, but was not a dominant species in the bi-plot.

Rehabilitation management has clearly resulted in two processes on the augered surfaces. The management plan target peat-formers have developed in inundated areas and additionally, where the water table has achieved a near surface level, M18a species are colonising the surface directly (without going through a hydroseral succession from mire pool). These M18a species were also revealed in the constancy tables of the recent commercial TWINSPAN groups.

Recent commercial cuttings- *Molinia* - species ordination by direct gradient analysis

120 of the 135 samples in the data set were accepted by the CANOCO analysis and the RDA output shown as Figure 5.8.

Axis 1 separated the different sub-compartments from each other (as seen in the *Augered* surface biplot). Axis 2 followed a damp-inundated trend which related to increasing time and increasing number of seasons since damming. Environmental variable 1993 was located further away from axis 2 than the other two years. It appeared that the time period from 1996 to 2001 was related to the management effect.

Molinia caerulea correlated with increasing time since damming lying between 1996 and 2001. Species which appearred to be more closely related to 2001 were *Eriophorum vaginatum* and *Sphagnum cuspidatum.* Axis 2 appeared to reproduce the TWINSPAN environmental gradient of a move from dry, low water table conditions, through fluctuating water table and finally on to a stable high water table.

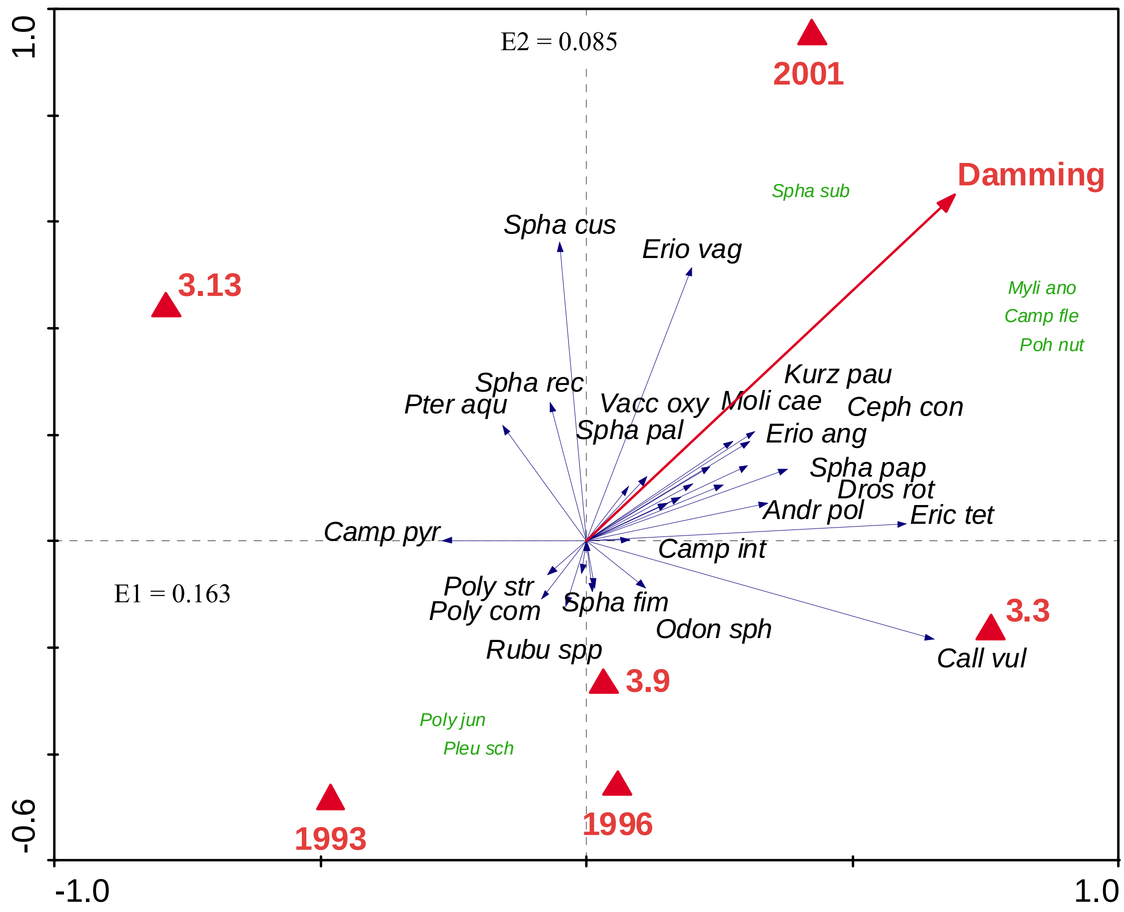

Figure 5.7 Direct gradient analysis of recent commercial *Augered* samples (quadrats) - Permanent Quadrat Investigation (survey years 1991, 1996 and 2001): RDA correlation biplot on vegetation data constrained by significant environmental variables.

The RDA was performed on 132 samples. It is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after axes extraction to produce a correlation biplot where length of vector is a measure of fit with the ordination diagram. Species with the shortest vectors are listed in green.

$\lambda 1$ = 16.3% of species variance; $\lambda 1 + \lambda 2$ = 24.8% of species variance (80.4% of the species/environment relationship)

Data were log transformed during this analysis. Collinearity was detected when fitting environmental variables *2001* and sub-compartment number *3.13*.

Recent commercial cuttings- *Relict* - species ordination by direct gradient analysis

The initial DCA was followed by CCA on the basis of a gradient length of 4.134. 126 samples were included by the CANOCO application during analysis.

Figure 5.9 was the resulting CCA biplot where Axis 1 separated the three sub-compartments. Axis 2 appeared to be related to a dry-wet trend which followed increasing time and number of seasons since damming. The positive end of Axis 2 showed species with dry habitat requirements (*Rubus* spp and *Calluna vulgaris)* associated with 1993. Further towards the centre of this axis a fluctuating water table was suggested by the presence of *Molinia caerulea* which correlated with 1996. Continuing to the negative side of axis 2 damming and the year 2001 related to target raised mire species. A close relationship between management effect and *Eriophorum angustifolium, E. vaginatum, Erica tetralix* and *Andromeda polifolia* was seen – the relationship with *Sphagnum cuspidatum* on this surface type however was not as direct. These findings suggested that some of the relict samples develop to a *S. cuspidatum* vegetation of inundation, however direct colonisation of the peat surface by more diverse target mire community species was more characteristic. This suggested development towards a similar vegetation type to the early uncut sub-compartment 6.7. The relict surfaces were remnants of the original mire surface which have not been cut for peat. These areas had undergone more disturbance and more intensive drainage and degradation compared to sub-compartment 6.7 and compartment 15.

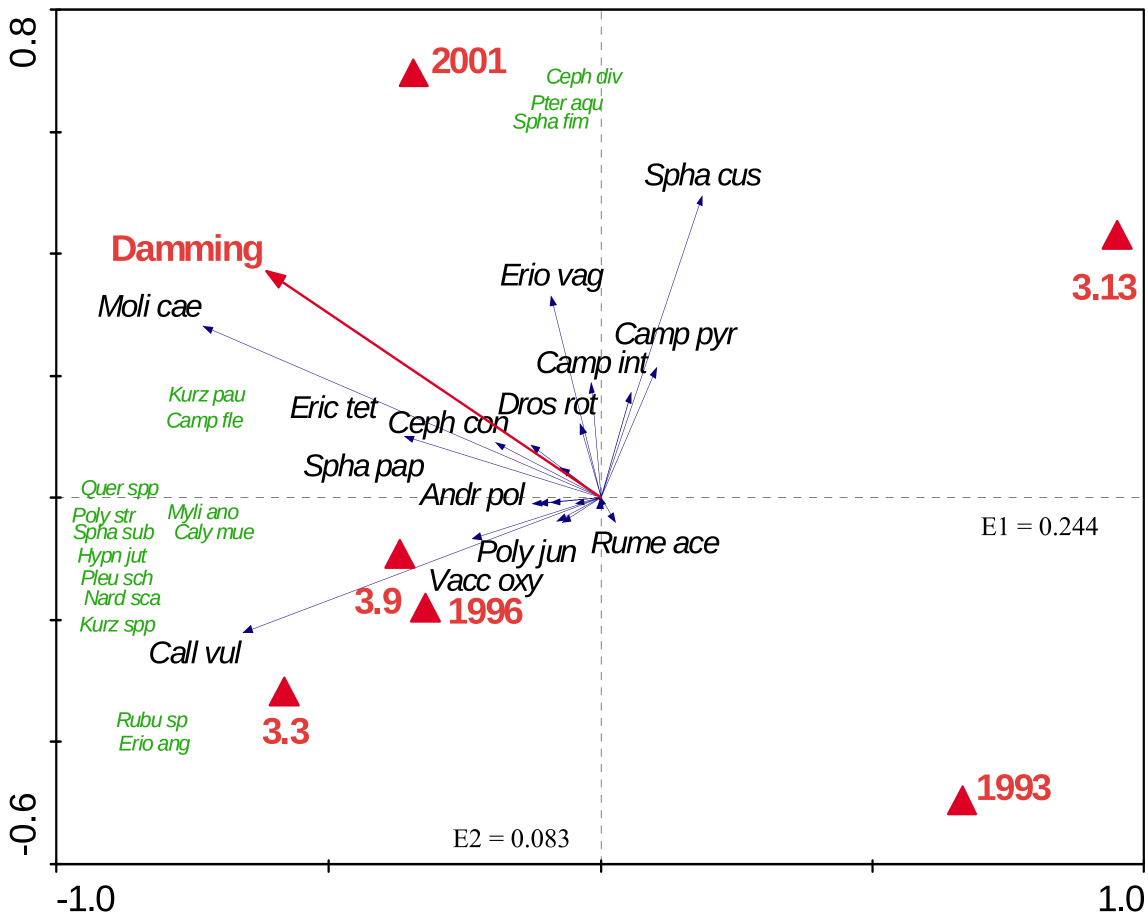

Figure 5.8 Direct gradient analysis of recent commercial *Molinia* samples (quadrats) - Permanent Quadrat Investigation (survey years 1991, 1996 and 2001): RDA correlation biplot on vegetation data constrained by significant environmental variables.

The RDA was performed on 120 samples. It is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after axes extraction to produce a correlation biplot where length of arrow is a measure of fit with the ordination diagram. Species with the shortest vectors are listed in green.

$\lambda 1$ = 24.4% of species variance; $\lambda 1 + \lambda 2$ = 32.7% of species variance (84.6% of the species/environment relationship)

Data were log transformed during this analysis. Collinearity was detected when fitting environmental variables *2001* and sub-compartment number *3.13*.

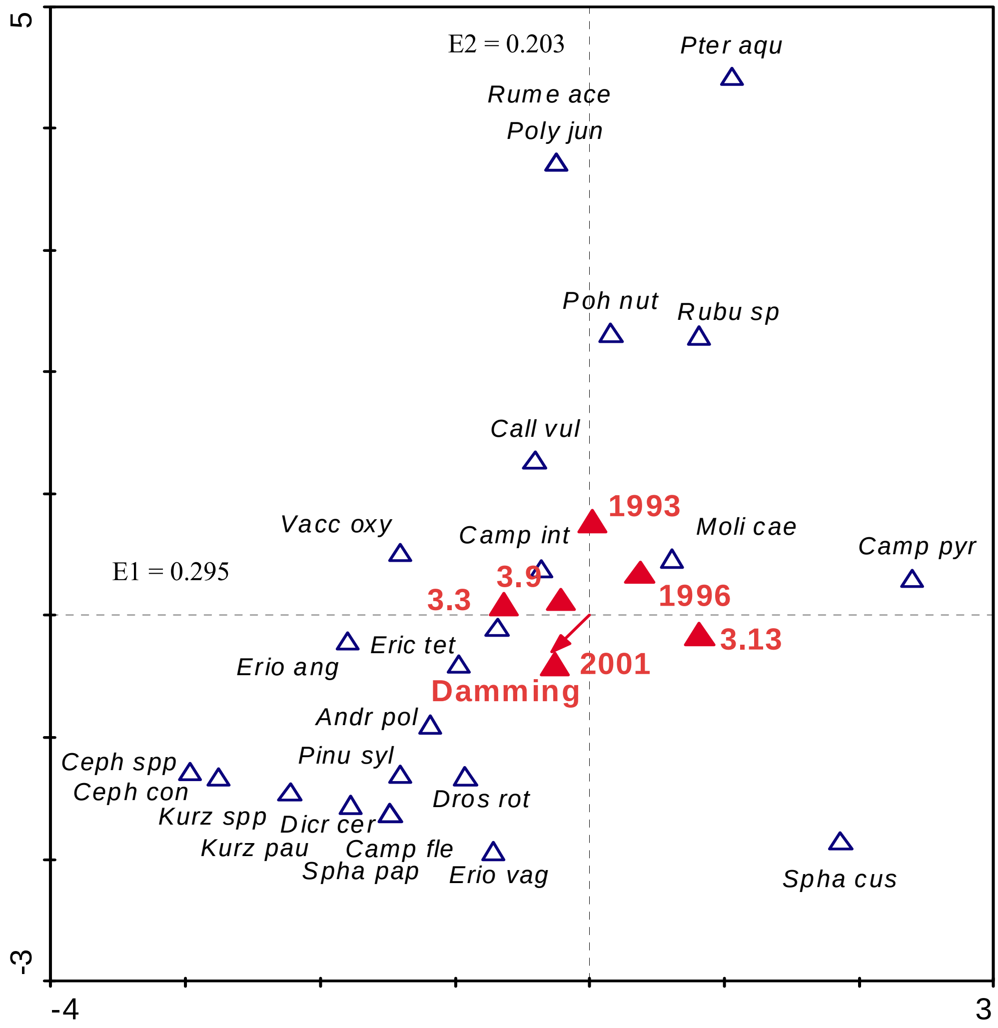

Figure 5.9 Direct gradient analysis of recent commercial *Relict* samples (quadrats) - Permanent Quadrat Investigation (survey years 1991, 1996 and 2001): CCA correlation biplot on vegetation data constrained by significant environmental variables.

The CCA was performed on 126 samples. It is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after axes extraction to produce a correlation biplot where location of species and environmental variable symbols (triangles and arrow length) are a measure of fit with the ordination diagram.

$\lambda1$ = 9.1% of species variance; $\lambda1 + \lambda2$ = 15.4% of species variance (73.8**%** of the species/environment relationship)

Data were log transformed during this analysis. Collinearity was detected when fitting environmental variables *2001* and sub-compartment number *3.13*.

5.5 Discussion

The present investigation established major trends in the complete permanent quadrat data set. The primary trend related to cutting type and separated the uncut areas as being different from the rest of the cutting types. The secondary trend was a dry-inundated vegetation trend. In order to establish the effects of rewetting on the vegetation of this complex site, each cutting type was explored individually for vegetation change.

Uncut areas of peat showed increases in the spread of *Sphagnum* species following rewetting. The vegetation of uncut compartment 15 showed the closest resemblance to species composition of NVC M18a of the whole site. It was a pre-management vegetation type which persisted and improved following management. Sub-compartment 6.7 developed into the early compartment 15 vegetation type following management. This was seen as an increase in *Sphagna* and also target mire community vascular plant species.

Recent commercial cuttings demonstrated the largest numbers of species which increased their range following management. These areas also showed the most prolific increases in the three management plan target species. Significant increases in *Sphagnum papillosum, Vaccinium oxycoccos, Drosera rotundifolia* and *Erica tetralix* were seen. *Molinia caerulea* increased in range from 1993 to 1996.

The early vegetation type of the recent commercial cuttings immediately after damming, was open *Molinia caerulea* grassland with much bare peat. This vegetation decreased in cover over the study period. Some of the augered and relict surfaces showed a post-management change towards a *Calluna*-rich vegetation, typical of old commercial baulk and flats. This vegetation persisted over time. There was also an indication that some damper (rather than inundated) augered and relict surfaces were developing towards an M18a-like vegetation. The vast majority of the recent commercial samples showed a mid-study change to a wet *Molinia*-*Sphagnum cuspidatum* vegetation, found on all surfaces types. This vegetation type suffered a loss by 2001 and appeared to be replaced by a *Sphagnum cuspidatum*-inundated vegetation type. This suggested a mid-study (post-management) fluctuating water table which then late-study, stabilised causing the further increase of *S. cuspidatum* and loss of *M. caerulea.*

Constancy tables for the recent commercial areas indicated that the mid-study fluctuating water table vegetation (*Molinia-Sphagnum)* did not support *Sphagnum* species other than *S. cuspidatum.* However, the late vegetation type of inundated-*Sphagnum cuspidatum (*suggestive of water table stability) demonstrated the colonisation of other species of *Sphagna* at very low percent cover. This suggested the possibility of development towards target M18a mire community.

The importance of water table stability in combating *M. caerulea* dominance was highlighted by Meade (1992). This was well reflected in the recent commercial areas of the present study. *Molinia caerulea* may have ameliorated the development of *Sphagnum cuspidatum* initially, by acting as a nurse crop. The final loss of *M. caerulea* with water table stability and inundation provided conditions to further enhance the development of *S. cuspidatum*. Mawby (1995) recommended constant flooding conditions for rapid colonisation by *S. cuspidatum.* At the present study site the peat surface type most closely affected early in the rehabilitation process by persistent flooding was the ditch, where *S. cuspidatum* had colonized by mid-study. As this surface type is lower lying than the other three surfaces of the recent commercial areas, it would be less affected by water table fluctuation and sheltered by the adjacent sections of the peat cutting profile. Stabilisation of the water table by the final survey year was reflected by surface wet and inundation conditions to surface types other than the ditches.

Old commercial cuttings showed an early decrease in *Calluna vulgaris* following rewetting and a decrease in *Drosera rotundifolia* prior to management. In the chi-squared analysis of the entire site data set the decrease in *Calluna vulgaris* was described as a late response as it was seen in the final survey year. Detailed analysis however has identified that this decrease was most significant to the old commercial areas which were later to be rehabilitated. As such the decrease in this species was an early management response.

The old commercial baulks and some of the flat surface samples supported a dry-*Calluna vulgaris* vegetation type. This was a pre-management vegetation which persisted following damming. Flat and ditch surface types had a *Calluna-Erica* vegetation prior to management which increased from first to second survey year. However, following damming (which occurred later than the uncut and recent commercial cuttings) this vegetation type began to decline. The early post-management vegetation type developing on the old commercial flat and ditch surfaces appeared to be a *Sphagnum cuspidatum* type (this was postulated by the CANOCO analysis).

Constancy tables of old commercial vegetation types show that some of the flat surfaces supporting *Sphagna* other than *S. cuspidatum* declined in range and others persisted over time. This suggested that there may be some losses in *Sphagnum* species on these areas. However the late development of other *Sphagnum* species seen in the recent commercial areas tends to suggest that any losses may be in the short-term only.

Hand cuttings showed a pre-management decrease in *Drosera rotundifolia*. The baulk surface type of the hand cut areas supported a dry vegetation characterised by *Calluna vulgaris* and *Molinia caerulea,* while some of the flat surfaces had a damper *Erica tetralix-Eriophorum vaginatum* vegetation. Other flat surface type samples were seen as a damp *Calluna-Erica* vegetation. Ditches supported a *Sphagnum*-rich vegetation. Although this cutting type was later to undergo management, these vegetation types were present prior to management and persisted in spite of it. A small number of samples appeared to develop into an inundated-*Sphagnum cuspidatum* vegetation type following management (this was seen in the CANOCO analysis also), suggesting that these areas were getting wetter following management. The low percent cover of *Sphagna*, other than *S. cuspidatum*, in the hand cuttings appeared to be a pre-management and continuing post-management element of the vegetation.

It is important to mention the varying topography of the site and the effects that this may have had on management. Recent commercial cuttings had surrounding tracks which were of similar height to the general cut-over surface, making it difficult to retain water. The hand cuttings had higher tracks which made inundation more effective. Old commercial areas had higher surrounding tracks but were affected by slope, making water levels more difficult to control (J Daniels, *pers comm*). These problems were discussed by Mawby (1995) who found that water table fluctuation was less where water was easily retained, but greater in sloping areas where water could drain through the peat.

5.6 Conclusions

Significant plant species change following rehabilitation management indicated an increase in the development of target mire species. This trend was most evident in the uncut and recent commercial areas of the site. These were the earliest areas to undergo rehabilitation.

The most prolific increases in mire species were seen in the recent commercial areas. Here a trend from a low water table, through a fluctuating water table and on to a stable high water table was evident over time.

As well as the significant increase in the three peat-forming management plan target species, significant increases in other target mire community species were seen.

Other than a significant early response following management, seen as the reduction in the range of the dry land species *Calluna vulgaris* (old commercial areas) – the hand and old commercial cuttings showed little change following rehabilitation. This may relate to the knowledge that these areas were rehabilitated later and as such were at an early post-management stage.

Significant increases have been found in the range of other *Sphagnum* species in addition to *Sphagnum cuspidatum*.

CHAPTER 6
THE RELATIONSHIP BETWEEN THE VEGETATION AND HYDROLOGY AT HYDROLOGICAL MONITORING LOCATIONS ON FENN'S AND WHIXALL MOSSES

6.1 Introduction

One of the main factors affecting recolonisation by different plant species on cut-over lowland raised mires is the hydrological regime (Wheeler and Shaw, 1995). The success of raised mire rehabilitation relates to hydrology and vegetation response - factors which are inextricably linked. Brookes and Stoneman (1997) state that vegetation response alone is too slow to guide management and advise that hydrological monitoring be integrated with vegetation monitoring to assess the effect on the site.

Rooting and rafting are the two mechanisms for colonisation of raised mire species on cut-over sites recommended by Wheeler and Shaw (1995). Rooting requires a sub-surface/ shallow flooding water level for establishment of mire species *Eriophorum* spp., *Erica tetralix* and *Sphagnum* spp. The problem of strong water table fluctuation following rewetting may delay colonisation by rooting, as dry periods at the peat surface may facilitate the colonisation of non-mire species, in particular *Molinia caerulea.* The effects of water table fluctuation are much stronger when the water table is close to the surface. Because Molinia caerulea is a surface-rooting plant, it may not be an increase in fluctuation but increase in effects. Rafting requires persistent inundation with a depth of approximately 50cm (Wheeler and Shaw, 1995) to facilitate colonisation of species capable of developing as floating rafts e.g. *Menyanthes trifoliata, Eriophorum angustifolium* and aquatic *Sphagna.* This level of inundation may destroy some existing mire species which are not tolerant of flooding, but may also destroy or prevent establishment of *M. caerulea.* Rafting is described as fundamental in regenerating an acrotelm-like structure.

Rochefort *et al.* (2002) investigated regeneration and growth of *Sphagnum* in relation to shallow flooding (8-10cm above surface) and non-flooding conditions (0 to 3cm below surface). Their experiments were carried out both in the field and laboratory using aquatic and hummock forming *Sphagnum* species. The results suggested that all of the species benefited from shallow flooding, particularly long-term (3 months). Some hummock species displayed etiolation which may result in an increased risk of desiccation as lower water levels develop during the summer.

Sphagnum re-establishment by raft formation on cut-over raised mires was the subject of experiments over a 30-month period by Money (1995). Peat trenches (4m² and 1m deep) were created to provide surface wet, shallow water (30-50cm deep) and deep water (>50cm) conditions. Water table fluctuation was also monitored. *Sphagnum* inocula as whole plants or fragments were introduced to the trenches. Water table fluctuation inhibited *Sphagnum* regeneration. Whole plants of *Sphagnum* regenerated successfully across all but the deep water table level, however the regeneration of fragments was more prolific and included the deepest water level. Species which were most successful were *S. cuspidatum* and *S. fallax*.

The present investigation on Fenn's and Whixall Mosses provides an insight into the effects of rewetting on colonisation by *Sphagnum* and other species.

6.2 Aims and objectives

In chapter 4 of the present thesis, multivariate analysis suggested that a high, year round water table correlated with an increase in peat-forming species. The investigation of the current chapter therefore aimed to determine the hydrological threshold for colonisation by *Sphagnum* species. This was achieved by identifying water table characteristics which supported the colonisation of *Sphagnum* species by correlating water table residence time with percent cover of *Sphagnum.*

Multivariate analysis was carried out on the hydrology and vegetation data at all of the site dipwell stations. This method aimed to elucidate species trends in relation to direct water table measurements. The present investigation covered one year of hydrological data.

6.3 Methods

6.3.1 Site description

Peat water level data are collected on a fortnightly basis from a network of 91 dipwell stations spanning Fenn's and Whixall Mosses. This work is carried out by site staff and volunteers and the data is added to the hydrology database which commenced in 1993. This detailed monitoring informs the Senior Reserve Manager of the effectiveness of rehabilitation on the peat water table.

The dipwells are arranged as transects across the site and span all cutting types within rehabilitated and un-rehabilitated areas. The dipwells are distributed relatively equally between recent commercial, uncut and hand cut areas. Only 8 dipwells are on old commercial cuttings. The locations of the dipwell stations are shown in chapter 2 (Map 2.2) and a description of the practicalities of dipwells can be found in chapter 3.

The balance between rainfall and evapotranspiration at the site is very close. Meteorological data for the area showed an average annual rainfall of 686 mm and evapotranspiration of 611 mm from 1980-1998. Climate variation from year to year can swing the imbalance either way. Evaporation loss exceeds rainfall every summer causing falls in the peat water table. In a natural undisturbed state these events would have a limited effect on the site. However the highly damaged and cut surface which exists experiences resulting episodes of drought (Gilman, 2000).

6.3.2 Investigational design

To study vegetation-hydrology relation it was essential to choose a strategy which would directly relate plant species cover-abundance to peat water table level. It was important to obtain as much precision as possible in the field, which would take this investigation to a further stage compared to the representative water table averages used in chapter 4.

The present investigation recorded vegetation survey of a 1m x 1m quadrat at each of 91 pre-existing dipwell stations during the summer of 2000. The dipwell was incorporated within the quadrat which was also positioned to avoid areas of trampling. Vegetation data were then collated with detailed hydrological readings from the site archives for the year prior to the vegetation survey. Although this may appear as if the vegetation is being assessed as a function of only one years' previous hydrology, this was believed to be the most effective method. One growing season would have been completed since the hydrology data was collected, allowing some response time by the vegetation to that particular hydrological regime.

Residence time was calculated i.e. percent of the year that the water table resided at a series of 10cm intervals/categories ranging from above to below the peat surface. Residence intervals were shown in Table 6.2.

6.3.3 Sampling methods and data analysis

The vegetation quadrats were surveyed for percentage species cover. This was later converted to DOMIN scores (the standard DOMIN scale, as described in chapter 3). The practice of data conversion to DOMIN scores was not essential as the CANOCO software (ter Braak and Šmilauer, 1998) has the facility to log transform data entered as percentages. Residence time of the water table was calculated and collated with the vegetation data as an Excel spread sheet computer file. These data were then used to carry out multivariate analysis techniques using the computer programme CANOCO for Windows (ter Braak and Šmilauer, 1998).

6.4 Results

6.4.1 Average water table depth

Table 6.1 presents various average water table categories (for the entire year prior to the vegetation survey of the present chapter) and associated average percent cover of *Sphagnum* species.

Mean depth (cm)	Mean percent cover *Sphagnum* spp.	n	SD
> +5	75.00	1	-
0 to +5	15.40	5	33.32
-0.1 to -5	12.26	19	29.47
-5.1 to -10	1.06	17	2.51
-10.1 to -15	0	10	-
-15.1 to -20	0	13	-
> -20	0	26	-

Table 6.1 Average water table depth relating to average percent cover *Sphagnum* species

Average water table depth for the year prior to the vegetation survey was given in centimetres for the various depth categories (from greater than 5cm above peat surface to greater than 20cm below peat surface). Corresponding *Sphagnum* cover was given as average percent and *n* is the number of samples in each category. *SD* denotes standard deviation for the *Sphagnum* figures.

These data (Table 6.1) suggested that for *Sphagnum* to be present, the average water table depth must be at least within 5.1 to 10cm below the peat surface. Increasing average percent cover of *Sphagnum* related to near surface and above surface water levels. The highest cover of *Sphagnum* (75%) was achieved by one of the samples which had the highest above surface water table of the data set - an average water table height of 6.2cm.

6.4.2 The multivariate analysis

Species and environmental data for the complete set of 91 samples were entered in to the CANOCO computer program. Species data were entered as Domin scores (the standard Domin scale, as described in chapter 3) and as such did not require data transformation. In the CANOCO output, species names were abbreviated – full species names have been provided in Appendix 1. Environmental data were entered in to the program as percent residence time of the water table at 10cm intervals and shown in Table 6.2.

Name of variable	Description
> + 10cm	Increasing percent of the year that water table resides at greater than 10 cm above the peat surface
0 to + 10cm	Increasing percent of the year that water table resides between 0.1 cm and 10 cm above the peat surface
0 to - 10cm	Increasing percent of the year that water table resides between the peat surface and 10 cm below surface
- 10 to -20cm	Increasing percent of the year that water table resides between 10.1cm and 20cm below the peat surface
- 20 to -30cm	Increasing percent of the year that water table resides between 20.1cm and 30cm below the peat surface
>30cm	Increasing percent of the year that water table resides at greater than 30cm below the peat surface

Table 6.2 Description of environmental variables

A preliminary exploratory unconstrained DCA highlighted an outlier (sample number 39, located in an uncut area of the site) which caused an extreme separation of the species *Vaccinium myrtillus* from the remaining species. On viewing the data set this sample was found to be the only one with cover of this species. The sample was therefore removed and the analysis re-run with 90 samples, 42 species and 6 environmental variables.

The DCA analysis generated a gradient length of 4.233 which fulfilled the criteria for unimodal analysis at the lower end of the range. This meant that an initial unconstrained DCA followed by a constrained CCA was appropriate. On exploring the DCA analysis, strong eigenvalues were accompanied by a low percent explanation of species variance (Figure 6.1). As the gradient length was quite marginal, a PCA (linear model) was also carried out which yielded slightly lower eigenvalues, however improved percent variance of the species data. Both unimodal and linear models of analysis have therefore been carried out on this data.

Unimodal analysis

The strongest trend in the vegetation on axis 1 of the PCA (Figure 6.1) appeared to relate to a moisture gradient. The vegetation associated with the far left of the axis was that of raised mire, with a stable near surface water table. The vegetation to the right of axis 1 suggested a low water table, with dry land species (*Calluna vulgaris*, *Pteridium aquilinum* and *Dryopteris dilatata*).

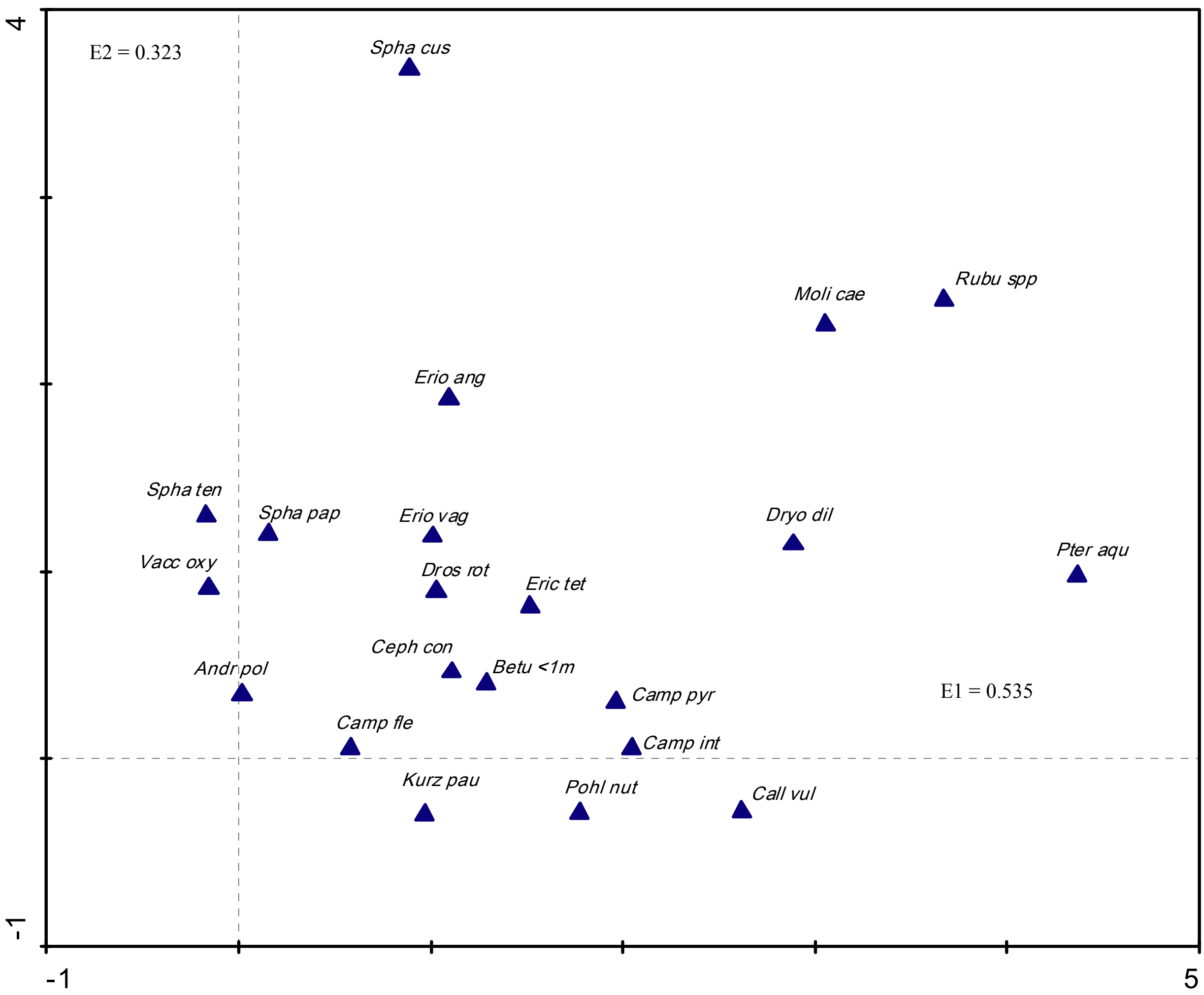

Figure 6.1 Indirect gradient analysis of all samples (quadrats) – Vegetation and hydrology investigation (vegetation survey 2000, hydrology data: 1999/2000): DCA correlation scatter diagram of plant species

The DCA (unconstrained) was performed on 90 samples. The DCA is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after axes extraction to produce a correlation scatter plot where the position of the species symbol (triangle) is a measure of fit with the ordination diagram.

$\lambda 1$ = 11.9% of species variance; $\lambda 1 + \lambda 2$ = 19% of species variance (54% of the species/environment relationship). Eigenvalues (E) for axes 1 and 2 are 0.535 and 0.323 respectively.

Species with less than 2% fit to the axes have been omitted in order to enhance clarity.

Axis 2 suggested the second strongest trend in the data appeared to be a separation of mire lawn/hummock-type vegetation (*Sphagnum tenellum, Sphagnum papillosum, Vaccinium oxycoccos*, *Drosera rotundifolia, Erica tetralix* and *Eriophorum vaginatum*) and that of mire pools (*Eriophorum angustifolium* and *Sphagnum cuspidatum*).

CCA analysis

Figure 6.2 below, represents the constrained unimodal analysis using CCA. The environmental variables were tested for significance in the analysis model using Monte Carlo permutation tests. Only variables which achieved significance at the 5% level were included in the constrained analysis out-put (Figure 6.2).

Species spread appeared similar to the DCA which suggested that the environmental variables had a genuine relationship with the main trends in the species/sample matrix. The species appeared a little more closely related to axis 1 when constrained by the environmental variables.

Axis 1 was clearly a trend related to increasing water table height in a positive direction along the axis. This axis made a clear differentiation between increasing residence time at greater than 30cm below surface and the other three significant levels i.e. between very dry and wet conditions. Increasing time where the water table resided at greater than 30cm below peat surface, related to a dry scrub vegetation of *Pteridium aquilinum* and *Rubus* spp..

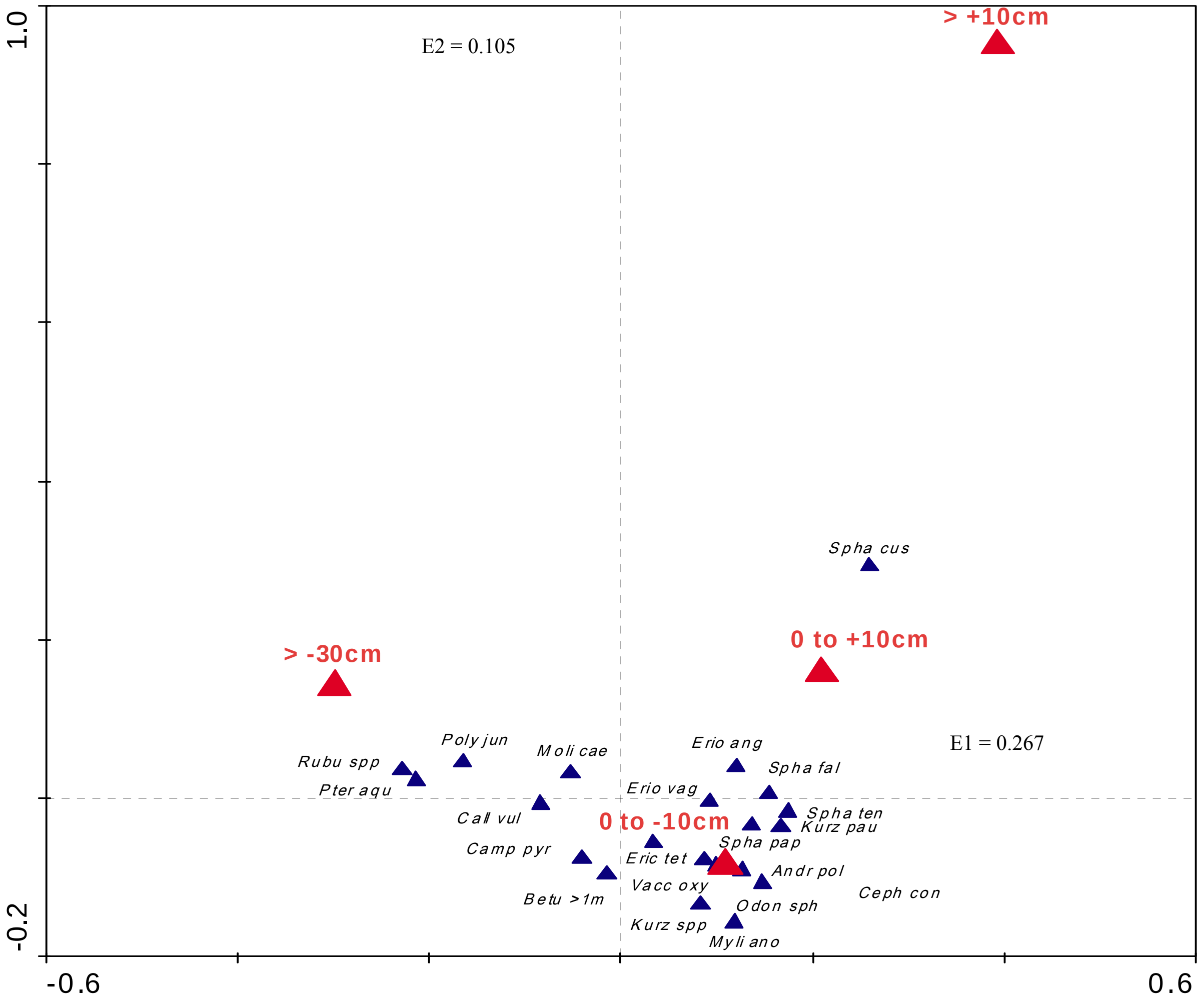

Figure 6.2 Direct gradient analysis of all samples (quadrats) - Vegetation and hydrology investigation (vegetation survey 2000, hydrology data: 1999/2000): CCA correlation biplot on vegetation data constrained by significant environmental variables.

The CCA was performed on 90 samples. It was based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after axes extraction to produce a correlation biplot where the position of the species/ environmental variable symbol (triangle) is a measure of fit with the ordination diagram.

$\lambda 1$ = 5.9% of species variance; $\lambda 1 + \lambda 2$ = 8.2% of species variance (75.1**%** of the species/environment relationship).

Species with less than 2% fit to the axes have been omitted in order to enhance clarity.

Axis 2 depicted a trend in the water table from near surface to above surface in a positive direction on the diagram. Residence time at surface to 10cm below surface was characterised by the most diverse cluster of species. These were raised mire species and included species of *Sphagna.* In chapter 5 this vegetation type was found to be of closest comparison to the NVC M18a community on the site. The vegetation type was associated with the uncut areas of the NNR.

Above surface (inundation) residence time i.e. surface to 10cm above and greater than 10cm above peat surface was characterised by mire pool type vegetation of *Sphagnum cuspidatum* and *Eriophorum angustifolium*.

Molinia caerulea was central along axis 1 which suggested an intermediate fluctuating water table.

These results confirmed the various water table heights required to facilitate colonisation of the vegetation types described above.

Linear analysis

PCA analysis

The output of the unconstrained PCA was shown as Figure 6.3. The strongest trend in the data (axis 1) was a separation of increasing *M. caerulea* from increasing *Calluna vulgaris* and *Eriophorum vaginatum*. *E. vaginatum* correlated with other characteristic raised mire species (including *Sphagna*) which formed a species rich assemblage in the upper left quartile of the ordination diagram.

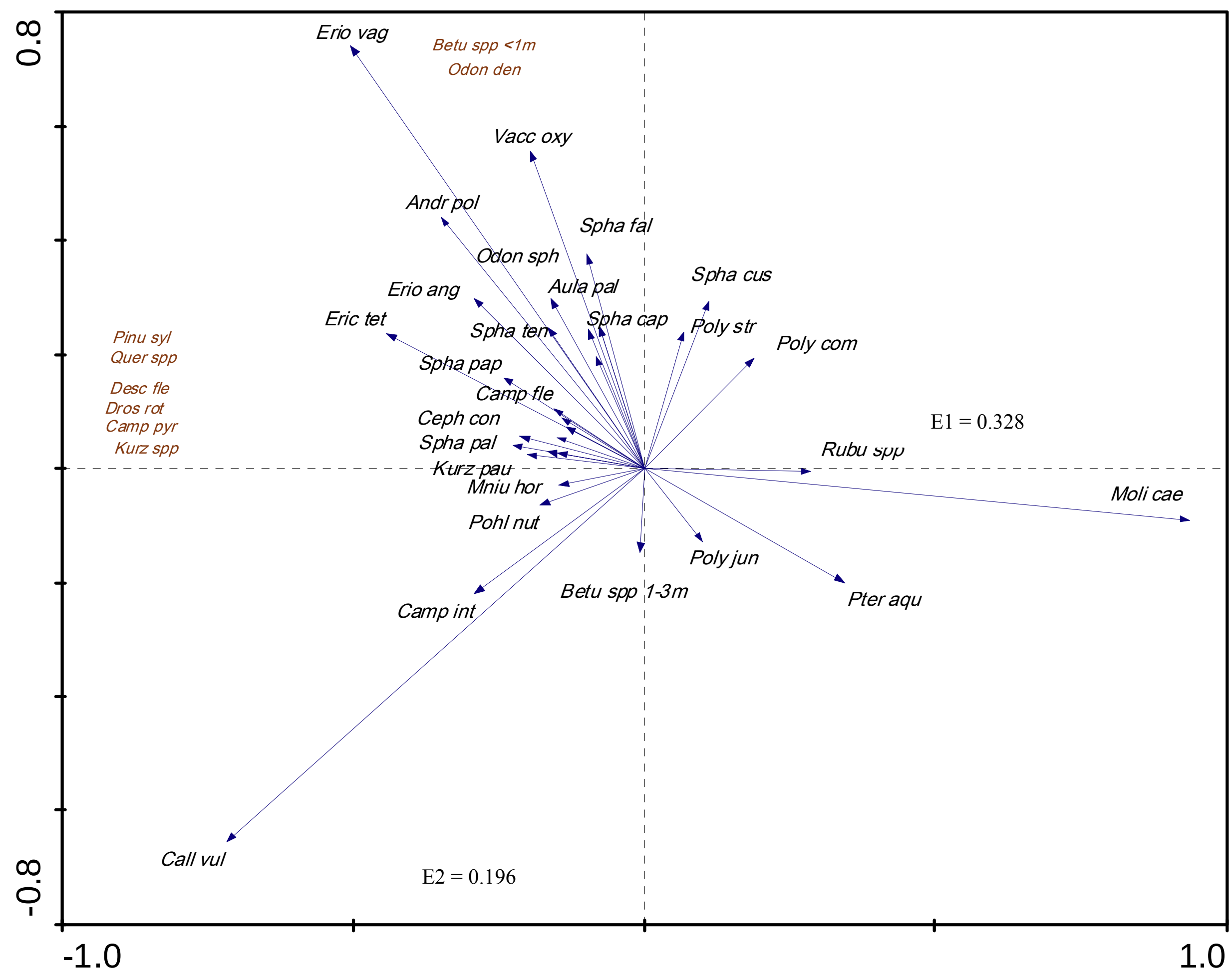

Figure 6.3 Indirect gradient analysis of all samples (quadrats) – Vegetation and hydrology investigation (vegetation survey 2000, hydrology data: 1999/2000): PCA correlation scatter diagram of plant species

The PCA is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after axes extraction to produce a correlation scatter plot where the length of the vector is a measure of fit with the ordination diagram. Eigenvalues for each axis are stated on the scatter plot as E1 and E2.

$\lambda 1$ = 32.8% of species variance; $\lambda 1 + \lambda 2$ = 52.4% of species variance (67.9% of the species/environment relationship).

Species with short vectors are shown in brown font.

Species with less than 2% fit to the axes have been omitted in order to enhance clarity.

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The plant species which correlated with axis 2 were suggestive of a dry-wet trend which became wetter in a positive direction.

The species spread and ecological trends in the PCA scatter diagram were identified previously in the results of chapters 4 and 5. The characteristic pattern on axis 1 related to cutting types. *Molinia caerulea* was associated with species poor recent commercial cuttings which were distinctly different and as such separated from the species characteristic of the other cutting types.

RDA analysis

A constrained analysis using RDA was carried out and significance of environmental variables assessed using Monte Carlo permutations. Significant environmental variables included in the analysis model were water table residence time at:

- surface to 10cm below surface
- surface to 10cm above surface
- greater than 10cm above surface

Species spread in this analysis was similar to that seen in the PCA, however the species appeared to have rotated. This had placed the dry-wet trend on axis 1 and axis 2 separated species of inundation (*S. cuspidatum* and *Eriophorum angustifolium*) and fluctuating water tables (*Molinia caerulea*) in the upper section of axis 2, from those of a stable near surface water table (M18 species) and greater species diversity, in the lower section.

A near surface (0 to -10cm) water table correlated with NVC M18a lawn and hummock species which included *Andromeda polifolia, Erica tetralix, Vaccinium oxycoccos, Sphagnum tenellum* and *S. papillosum.* It could be postulated that increased residence time at this level causes the retreat of species of lower water table requirements i.e. *Calluna vulgaris* (located intermediate to axes 1 and 2). Therefore if the water table were to become lower, this species could increase in cover.

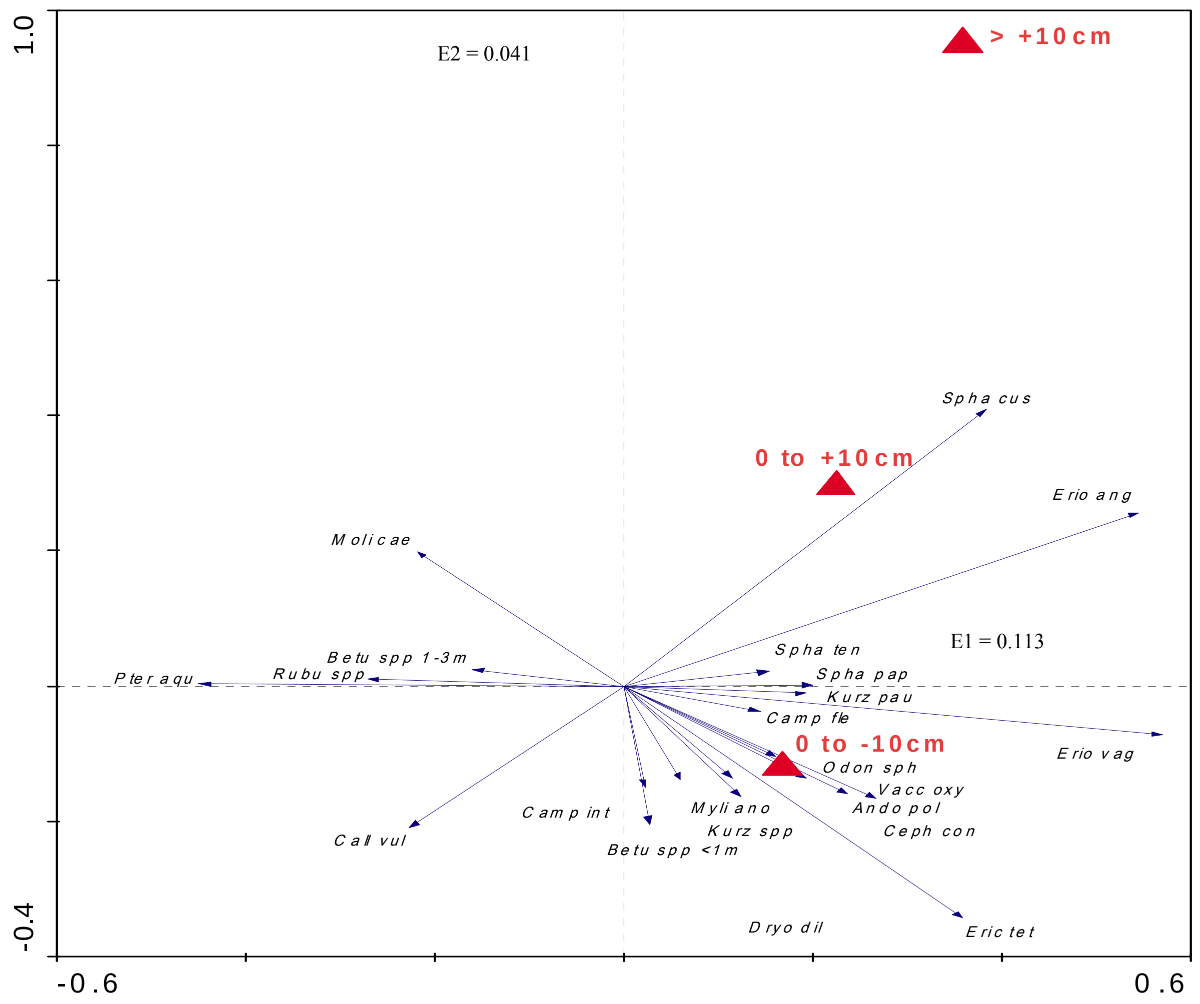


Figure 6.4 Direct gradient analysis of all samples (quadrats) – Vegetation and hydrology investigation (vegetation survey 2000, hydrology data: 1999/2000): RDA correlation bi-plot of plant species data constrained by significant environmental variables

The RDA analysis is based on the covariance matrix (species centred only, i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after the extraction of the axes to produce a correlation bi-plot where the length of vector is a measure of fit with the ordination diagram. Species names with very short vectors have been removed from the bi-plot to enhance clarity. Eigenvalues for each axis are stated on the scatter plot.

$\lambda 1$ = 11.3% of species variance; $\lambda 1 + \lambda 2$ = 15.4% of species variance (94.2% of the species/environment relationship).

Species with less than 2% fit to the axes have been omitted in order to enhance clarity.

An above surface water table (0 to +10cm and >+10cm) correlated with increasing *S.cuspidatum* and *E. angustifolium*. The location of *M. caerulea* on the ordination diagram suggested that this species may decline as a result of a maintained above surface water table. This suggested that the conditions of inundation were stable and enhancing *Sphagnum* development while causing a decline in *M. caerulea*. If the water table were to lower or undergo fluctuation, conditions suitable for re-establishment of *M. caerulea* and loss of *Sphagnum cuspidatum* would occur.

The present analysis has clearly identified a raised mire-type vegetation characteristic of the uncut areas of the site. The investigation of chapter 5 determined that the positive changes in this cutting type were not strongly related to site management effect. Most prolific responses to management were found to be occurring in the recent commercial cuttings. The present chapter therefore continued by focusing on the cut-over samples of the data set and the uncut samples have been removed.

Unimodal analysis of cut-over samples

DCA analysis of cut-over samples

A preliminary DCA of the 58 samples (34 species) was carried out and resulted in a gradient length of 3.653. Due to the intermediate nature of the gradient length, both unimodal and linear methods of analysis were used.

Axis 1 of the DCA species scatter plot (Figure 6.5) demonstrated vegetation along an inundated-dry gradient, with *Sphagnum cuspidatum* at the wettest extreme and *Pteridium aquilinum* at the driest. The passive position of the environmental variables confirmed this trend, with above surface residence time leading through to increasingly lower water table level in a positive direction along axis 1. The vegetation along axis 1 started with the mire pool vegetation (*S. cuspidatum* and *E. angustifolium*) followed by the raised mire lawn/ hummock vegetation (*E. vaginatum, Drosera rotundifolia, Erica tetralix*) of a stable, near-surface water table. This led on to vegetation suggestive of water table fluctuation (*M. caerulea*) and finally to vegetation of a low water table (*Pteridium aquilinum, Rubus* spp and *Betula* spp).

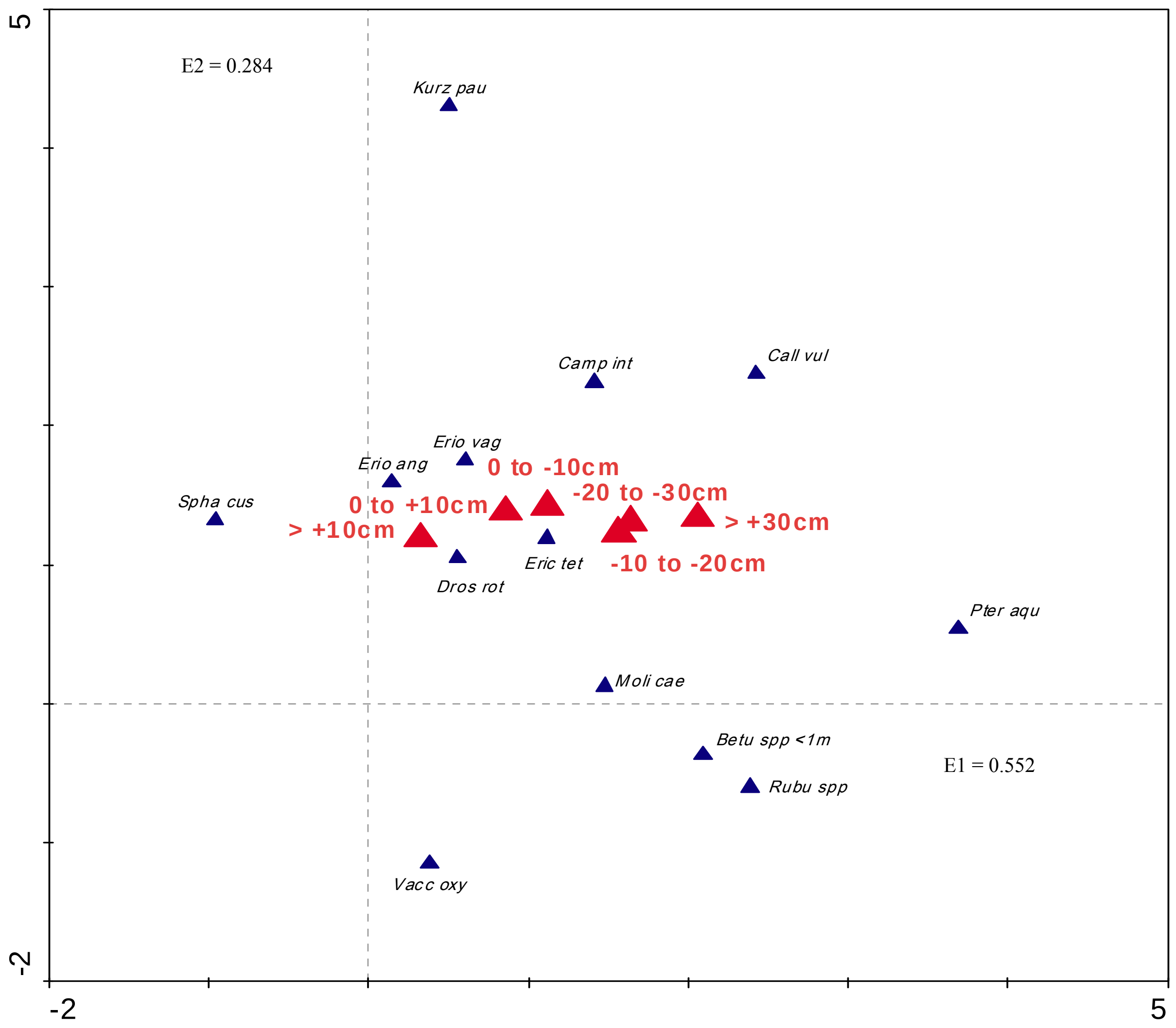


Figure 6.5 Indirect gradient analysis of cut-over samples (quadrats) – Vegetation and hydrology investigation (vegetation survey 2000, hydrology data: 1999/2000): DCA correlation scatter diagram of plant species

The DCA (unconstrained) was performed on 58 samples. The DCA is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after axes extraction to produce a correlation scatter plot where the position of the species symbol (triangle) is a measure of fit with the ordination diagram. Environmental variables are superimposed.

$\lambda 1$ = 15.8% of species variance; $\lambda 1 + \lambda 2$ = 24% of species variance (46.1% of the species/environment relationship). Eigenvalues (E) for axes 1 and 2 are 0.552 and 0.284 respectively.

Species with less than 2% fit to the axes have been omitted in order to enhance clarity.

The second strongest trend in the data (axis 2) is less clearly defined. It may represent a separation of mire lawn (above) and hummock vegetation (below), however this is not clear. Other factors which may affect the site (and are not included as environmental variables) are past burning, surrounding land use and nutrient flow.

CCA analysis of cut-over samples

A constrained analysis using CCA resulted in two significant environmental variables by using Monte Carlo permutation tests. These were shown in Figure 6.6, the CCA output in the form of a bi-plot. Shallow flooding (above peat surface residence of up to + 10cm) and the lowest residence level (greater than 30cm below surface) were significant environmental variables.

Axis 1 maintained the inundated-dry trend identified in the DCA. There appears to be three distinct vegetation types associated with axis 1. The first is mire pool vegetation which appeared to include *M. caerulea* and is characterised by a water table residing from surface to 10cm above surface. This vegetation included 2 species of *Sphagna* (the aquatic *S. cuspidatum* and lawn species, *S. papillosum*). *Kurzia pauciflora* is a bryophyte commonly found among *Sphagnum* species on raised mire (Watson, 1981). The position of *M. caerulea* in Figure 6.6 suggested that this species was becoming less characteristic of this vegetation.

The second vegetation type included target mire community species e.g. *Andromeda polifolia, Erica tetralix, Vaccinium oxycoccos* and *Odontoschisma sphagni,* as well as scrub species e.g. *Betula* spp..The third vegetation type was of a dry nature and included *Rubus* spp. and *Pteridium aquilinum*, with a water table residing at greater than 30cm below surface.

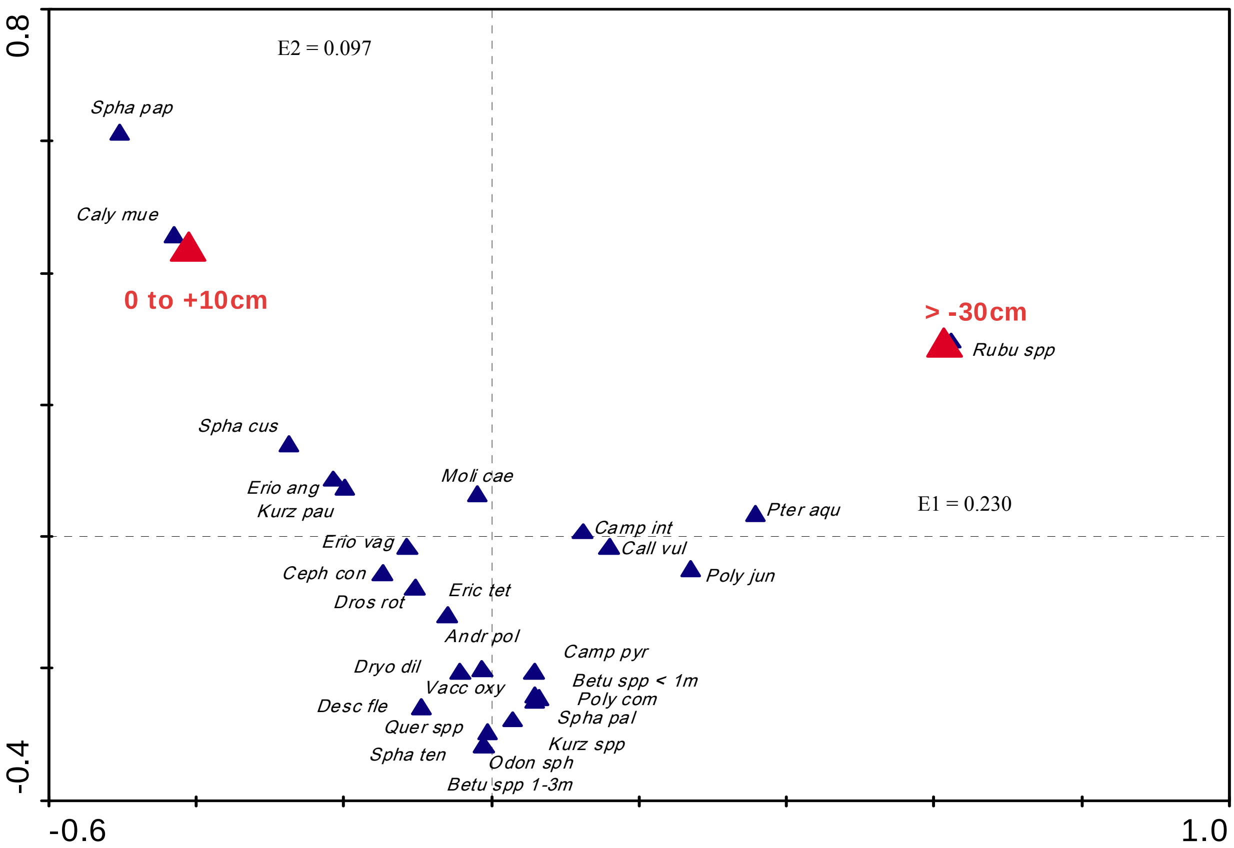


Figure 6.6 Direct gradient analysis of cut-over samples (quadrats) - Vegetation and hydrology investigation (vegetation survey 2000, hydrology data: 1999/2000): CCA correlation biplot on vegetation data constrained by significant environmental variables.

The CCA was performed on 58 samples. It is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after axes extraction to produce a correlation biplot where the position of the species/ environmental variable symbol (triangle) is a measure of fit with the ordination diagram.

$\lambda 1$ = 6.6% of species variance; $\lambda 1 + \lambda 2$ = 9.4% of species variance (100**%** of the species/environment relationship).

Species with less than 1% fit to the axes have been omitted in order to enhance clarity.

Axis 2 of the CCA appeared to separate the inundated and dry vegetation types from the more diverse vegetation which was a combination of scrub and raised mire species (including *Sphagna*). This was suggestive of baulks and the floors of cuttings which had not been flooded – the cutting floors being damp enough to support raised mire species.

Linear analysis of cut-over samples

PCA of cut-over samples

Figure 6.7 - the PCA scatter plot of species with environmental variables passively superimposed.

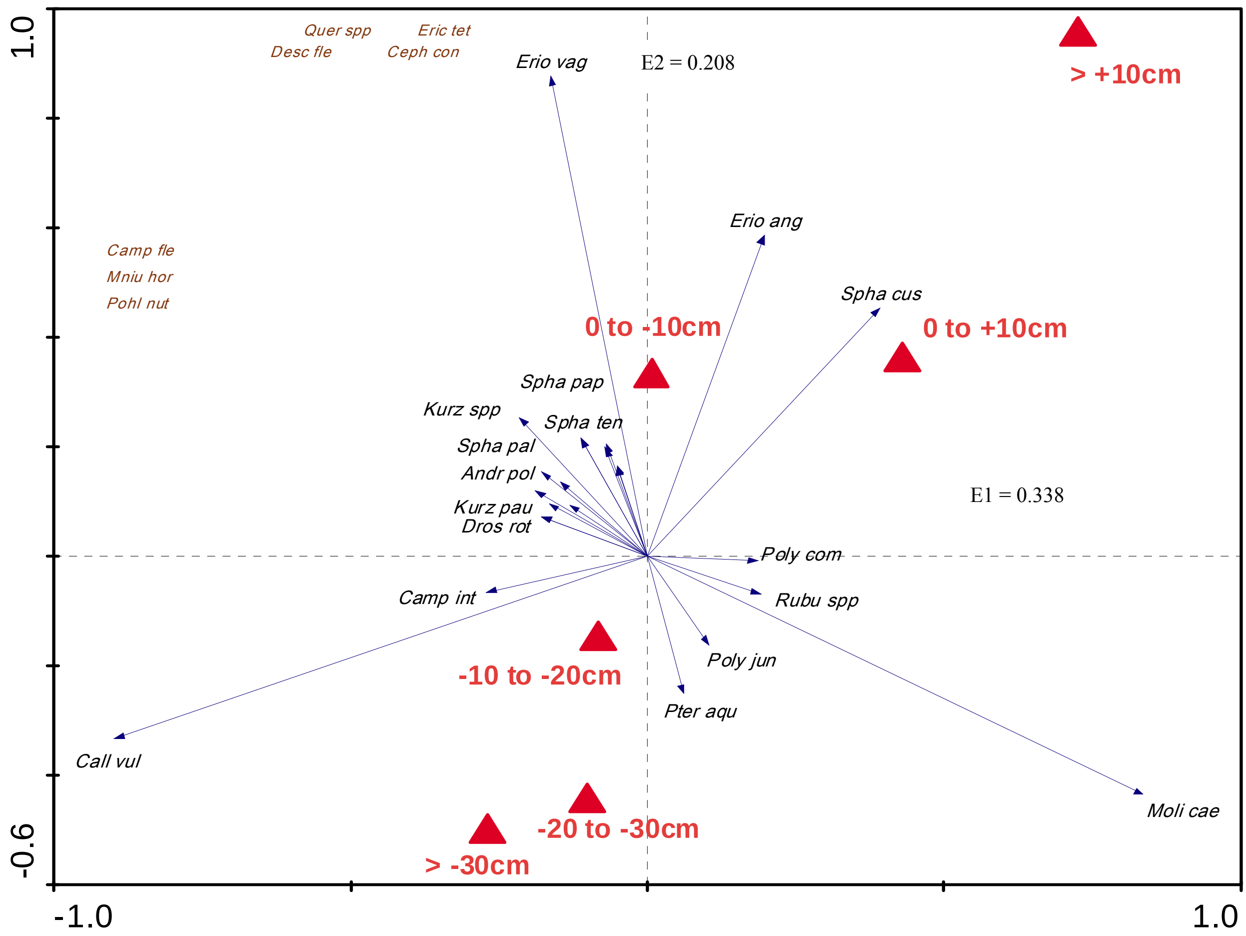


Figure 6.7 Indirect gradient analysis of cut-over samples (quadrats) – Vegetation and hydrology investigation (vegetation survey 2000, hydrology data: 1999/2000): PCA correlation scatter diagram of plant species

The PCA is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after axes extraction to produce a correlation scatter plot where the length of the vector is a measure of fit with the ordination diagram. Eigenvalues for each axis are stated on the scatter plot as E1 and E2.

$\lambda 1$ = 33.8% of species variance; $\lambda 1 + \lambda 2$ = 54.7% of species variance (66% of the species/environment relationship).

Species with short vectors are shown in brown font.

Species with less than 1% fit to the axes have been omitted in order to enhance clarity.

Axis 1 highlighted the difference between *Molinia caerulea* and *Calluna vulgaris.* The second strongest trend in the present analysis, was of a wet-dry nature in a negative direction on axis 2. The passive environmental variables reflected the trend of inundation through to residence time at the lowest level below surface.

RDA analysis of cut-over samples

The output of this constrained analysis was shown as Figure 6.8. Monte Carlo permutation tests established significance for three environmental variables. These variables were added to the analysis model i.e. increasing residence time within the upper 10cm of peat and also the two above-surface residence categories.

Species spread was similar to that seen in the PCA however it has rotated, so that the wet-dry trend was now seen on axis 1. Axis 2 appeared to suggest a trend of increasing species diversity in a negative direction.

Above surface residence time of the water table correlated with increases in *Sphagnum cuspidatum* and *Eriophorum angustifolium.* This also appeared to apply to *S. papillosum* and *M caerulea* to a lesser extent.

The present investigation showed a weak relationship between *Molinia caerulea* and shallow flooding. This may well indicate the retreat of *M. caerulea* in response to more stable conditions of inundation.

Figure 6.8 showed a correlation of NVC M18a species (including 2 of *Sphagna*) with residence time of the water table within the upper 10cm of peat. The most characteristic species of this residence level were *Eriophorum. vaginatum* and *Erica tetralix*. It was encouraging to see evidence of these species in the cut-over areas of the site as they were characteristic of the uncut areas. This confirmed the finding which suggested areas of cut-over peat could develop the more mature M18a vegetation, without going through the successional process from mire pools (NVC M2) which flooding created.

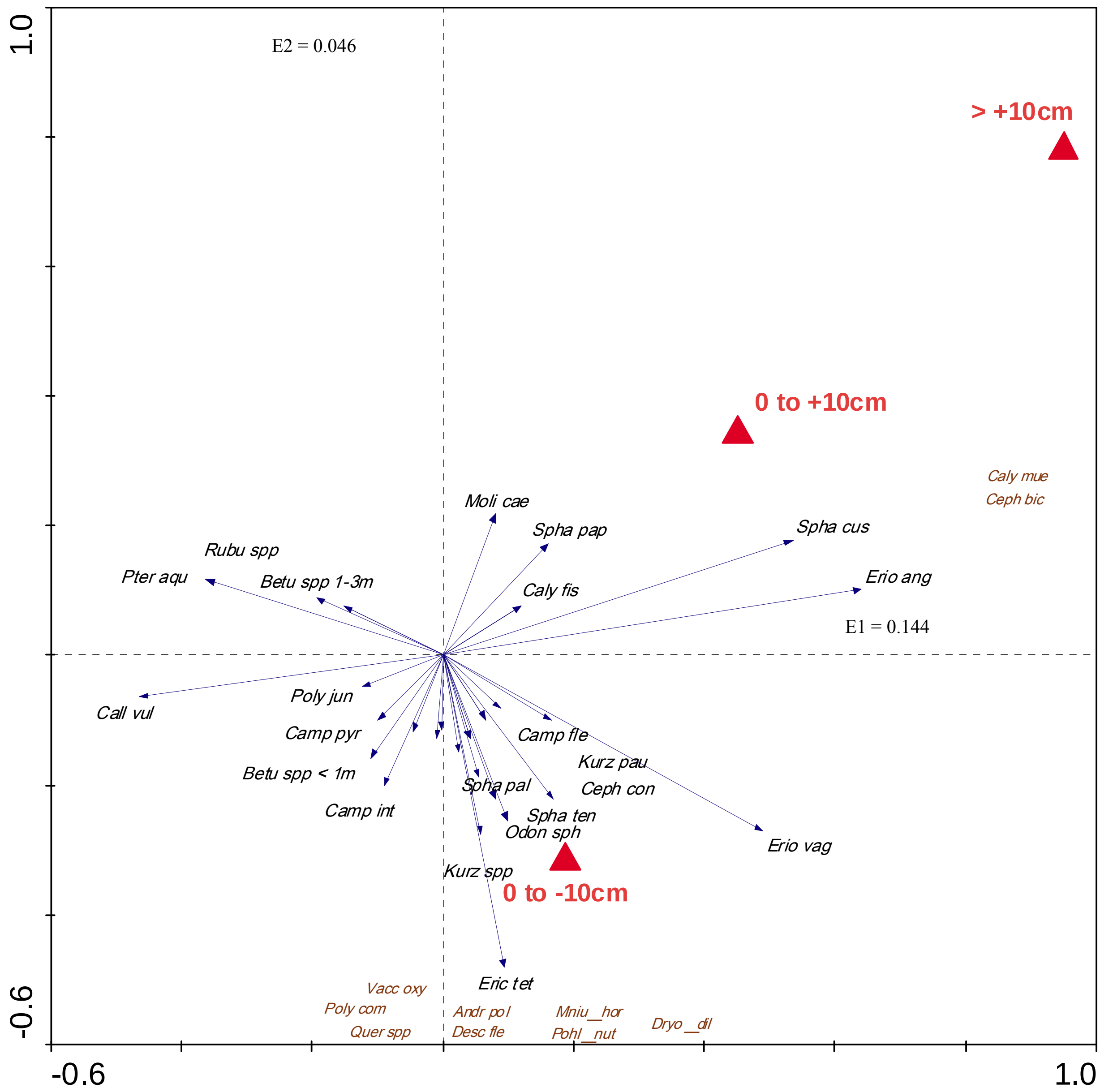


Figure 6.8 Direct gradient analysis of cut-over samples (quadrats) – Vegetation and hydrology investigation (vegetation survey 2000, hydrology data: 1999/2000): RDA correlation bi-plot of plant species data constrained by significant environmental variables

The RDA analysis is based on the covariance matrix (species centred only, i.e. weighted by their variance). The scaling focuses on inter-species correlation and the scores are standardised after the extraction of the axes to produce a correlation bi-plot where the length of vector is a measure of fit with the ordination diagram. Species names with very short vectors have been removed from the bi-plot to enhance clarity. Eigenvalues for each axis are stated on the scatter plot.

$\lambda 1$ = 14.4% of species variance; $\lambda 1 + \lambda 2$ = 19% of species variance (91.6% of the species/environment relationship).

Species with less than 1% fit to the axes have been omitted in order to enhance clarity.

6.5 Discussion

Two vegetation types which support *Sphagnum* species have been revealed by the multivariate analysis. The first was a mire pool vegetation of *Sphagnum cuspidatum* and *Eriophorum angustifolium*, with some cover of *S. papillosum* and resembles the NVC M2 (*Sphagnum cuspidatum/recurvum* bog pool) M3 (*Eriophorum angustifolium* bog pool) communities. This vegetation correlated with long water table residence time above peat surface. Conditions were those of shallow flooding with a maximum average water table height above surface of 6.3cm.

The second vegetation type comprised raised mire species (including species of *Sphagna* other than *S. cuspidatum*) which are components of the NVC M18a. This vegetation has been confirmed in the analysis as being present in the uncut areas and to a lesser extent the cut-over areas. The characteristic hydrology was increasing residence time near surface i.e. surface to 10cm below surface.

In the cut-over areas this second vegetation type was not present at such high cover as that of mire pools. The permanent quadrat analysis (chapter 5) placed this vegetation in non-inundated areas i.e. on flat and ditch surfaces of the old commercial cuttings, flat surfaces of the hand cuttings and relict and augered surfaces of the recent commercial cuttings. The hand and old commercial cuttings have been more recently rehabilitated compared to the recent commercial. They may therefore not yet have been fully affected by the flooding conditions rehabilitation brings to cut-over areas. The old commercial areas are also affected by slope and therefore prone to the effects of drainage. The CANOCO analyses of the present chapter showed a negative correlation of inundation and diverse mire species. The constancy tables of chapter 5 showed very subtle losses and gains of *Sphagnum* species (other than *S. cuspidatum*) but no statistically significant declines were found. The evidence from analyses carried out in the current study has suggested that species losses may be a future risk to the site.

The RDA analysis of the cut-over areas (Figure 6.8) showed a weak positive relationship between *Molinia caerulea* and shallow flooding. Chapter 5 of the present thesis has shown *M. caerulea* to be an early prominent feature of the recent commercial cuttings which reduced in cover following rehabilitation and eventual stabilisation of the peat water table. Figure 6.8 of the present chapter demonstrated the relationship it had with the recent commercial cuttings and that it was reducing in that area. Shallow flooding appeared to be reducing the effect of *Molinia caerulea* on the vegetation associated with mire pools.

The present analysis has determined the threshold for *Sphagnum* establishment as being an average water table level of at least 5.1cm to 10cm below the peat surface. This level facilitated a very low cover of *Sphagnum* while the inclusion of above surface water levels, resulted in greater percentage cover. The conclusion of the present study that the successful effect of shallow flooding of this nature on Sphagnum development is supported by findings of Rochefort *et al.* (2002).

6.6 Conclusions

- The water table threshold for *Sphagnum* species establishment is an average level of 5.1cm to 10cm below surface.
- Higher percentage cover of *Sphagnum cuspidatum* is related to shallow flooding.
- Shallow flooding appears to result in a retreat of *Molinia caerulea*.
- Shallow flooding is characterised by mire pool like vegetation which includes *Sphagnum cuspidatum* and *Sphagnum papillosum*.
- A near-surface water table is characterised by raised mire species including *Sphagnum* other than *Sphagnum cuspidatum*.
- There may be a risk of a reduction in some established mire species as a result of flooding, which leads to the cyclical transition between NVC M2 and M18a communities.

CHAPTER 7

PERMANENT QUADRAT ANALYSIS OF VEGETATION CHANGE ON BETTISFIELD MOSS

7.1 Introduction

Afforestation of lowland raised mire and upland blanket mire with conifer species is the result of forestry plantation practices developed in the early 20th century (Anderson, 1997). The ecohydrological impacts of commercial planting on deep peats are summarised in Table 7.1.

Process	Response
Ploughing	Destroys the acrotelm. Creates a dry mound inhospitable to mire vegetation. Encourages non-mire species. Exposes bare furrows acting as drains.
Drainage	Increases water-table drawdown. Increases moisture deficits and lowers summer water-table. Increases mineralisation of peat. Increases in the availability of plant nutrients.
Canopy closure	Increases interception and evaporation. Increases transpiration. Induces cracking. Root development and cracking create new pathways for water flow. Needle fall and canopy shade out most vegetation. Peat compaction.
Fertiliser application	Favours competitive species. Increases microbial activity.

Table 7.1 Ecohydrological impacts of afforestation (Brooks and Stoneman, 1997)

Post-forestry mire restoration projects in Europe have been undertaken too recently to be conclusively assessed for effectiveness. Anderson (2001) recommends long term monitoring, with a minimum term of 10 years to allow the direction of vegetation succession to become clear. Initial vegetation growth following clearance of conifer plantation has however indicated the formation of large mono-specific stands of *Sphagnum* within 2 years.

A blanket mire site in Sutherland was described as recovering well 6 years following deforestation. Increases in cover of mire species and decreases in *Calluna* indicated a move towards wetter conditions (Robinson, 2005).

Successes and failures in raising water-tables in mire recovery following deforestation have been documented in the literature. A Finnish study restoring an ombrotrophic mire by tree removal, blocking side drains and completely infilling main drains, saw a mean summer below surface water-table rise from 31-36cm to 11-16cm (Komulainen *et al.*, 1998). Similar restoration management carried out by Vasander *et al.* (1992) was not as successful and only raised the water-table by a few centimetres.

These examples demonstrate that there is a need for detailed and persistent monitoring of mires following deforestation with a view to identifying the processes which take place. During the present study the opportunity to initiate such a monitoring exercise occurred and the results have been presented below.

Deforestation of Bettisfield Moss (Map 2.1, chapter 2 and Map 7.1 of the present chapter) by cable crane commenced during winter 2001/2002 and was completed in May 2002. This was immediately followed by damming of drains and ditches across the site.

The nature of the vegetation present prior to these management techniques, is described in chapter 2 and described further in section 7.3 below.

7.2 Aims and experimental design

The investigation described in this chapter aimed to identify the initial change in vegetation composition on Bettisfield Moss, following deforestation and ditch damming procedures. This investigation hypothesised that one year following deforestation there would be evidence of vegetation change and the direction of that change.

The specific aims at Bettisfield were to establish a monitoring scheme to begin to describe the effects of deforestation on the vegetation and to relate these changes to measured environmental features.

These aims were achieved by collecting vegetation information from permanent quadrats established and recorded during late June 2002 immediately after deforestation and ditch damming. This survey was repeated during July 2003. These two datasets were collated and analysed using multivariate techniques.

Environmental factors were recorded for each quadrat and included in the analysis as possible explanatory variables for trends in the vegetation.

The exercise was intended to be continued by future surveyors to provide a long-term appraisal of the results of deforestation.

7.3 Site Description

Bettisfield Moss is the southernmost of the three Mosses (chapter 2, Map 2.1) being investigated in the present study. It is situated adjacent to the Shropshire Union Canal and lies across the Welsh-English border (O.S. Grid. Ref. SJ 476355) with an area of 65 hectares.

Prior to deforestation in May 2002, the physical environment of Bettisfield Moss can be generally described as a dense pine forest. The under-storey was heavily shaded by the tree canopy and densely littered with pine-needles. Forest bryophyte and vascular plant species dominated the ground flora and remnants of mire species were found across the site in damper depressions.

Pine trees had colonized in a northerly direction across the site, eliminating mire plant species. The peat cutters regularly burned the site until approximately thirty-five years ago at which point only marginal and scattered large pine had survived (Broad, 2003). From that time up until deforestation in 2002, there had been rapid infill of the site with self-sown pine and birch trees.

Map 7.1 shows the current compartment boundaries and numbering. Compartments are also highlighted to show permanent quadrat location. Note that the site maps of chapter 2 show pre-deforestation compartment boundaries and numbering.

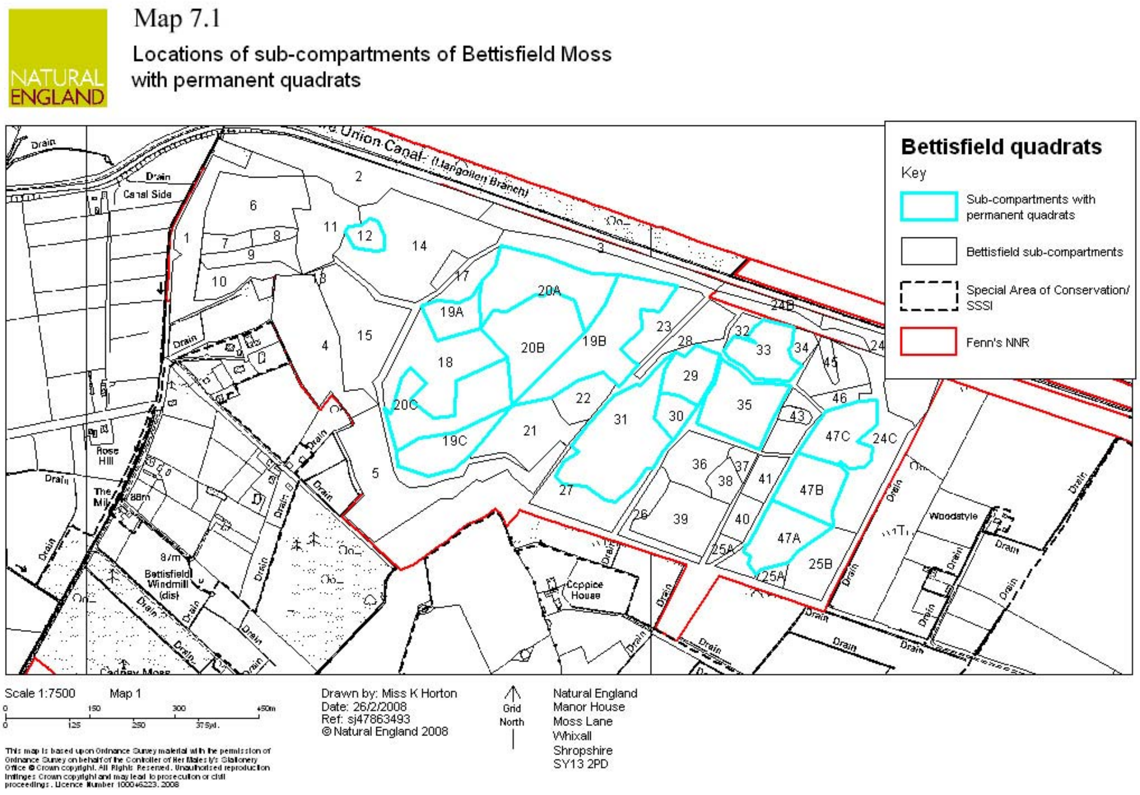
The English side of the site was hand cut for peat until approximately 50 years ago. The eastern half of the English side (compartments 47A, 47B and 47C) has been less intensively cut than those in the western half (compartments 33, 35 and 31) (Dr J Daniels, personal communication). Vegetation monitoring compartments 29 and 30 have an unusual history in that they were blown up with dynamite approximately 40 years ago. The intention was to create an open pool for water fowl shooting, but the result was blockage of surrounding drains and the development of this area into an expanse of floating *Sphagnum* (Broad, 2003).

The Welsh side of the site has a history of hand cutting confined to compartments 1-10. The majority of the area however remains uncut (compartments 11-23) with a peat depth in excess of 8m. The uncut area was the part most successful in retaining a low cover of raised mire vascular and lower land plant species (Broad, 2003).

7.4 Existing post-deforestation vegetation survey

In May 2002 the Senior Reserve Manager identified vegetation 'compartments' (Map 7.1). The boundaries of the compartments were drawn where it appeared that there was a change in vegetation type. Some compartments are delimited by tracks left after peat cutting and brash tracks left following timber clearance (Broad, 2003). During early June 2002 Natural England staff mapped the compartments (numbered 1-38, in a westerly direction) using GPS. The data was transferred to GIS computer software (MapInfo) for the creation of site monitoring maps. Towards the end of 2002 the compartments underwent redefinition and renumbering by the Senior Reserve Manager. Compartments were renumbered as 1-47 in an easterly direction.

The site compartments underwent a baseline subjective vegetation survey by Natural England staff during early June 2002, using the same methodology as the sub-compartment surveys of Fenn's and Whixall Mosses (chapter 3). Maps were then



Map 7.1 Locations of sub-compartments of Bettisfield Moss with permanent quadrats

produced (Broad 2003) using MapInfo to illustrate percentage cover of major plant species. These maps demonstrated a general vegetation of low percentage cover forest bryophyte and vascular plants species, across the site. Target mire species were also found across the site, at mostly less than 1% in each compartment. The exception to this was the uncut area in Wales, where target mire species achieved better percentage cover and compartments 29 and 30 where there was a 100% cover for *Sphagnum*.

7.5 Sampling methods and data analyses

The vegetation survey of 106 1m x 1m quadrats was designed and initiated in June 2002 in consultation with the Senior Reserve Manager. This survey was then repeated in July

2003. Compartments and the location of permanent quadrats within them were chosen in order that all differences in vegetation type and cutting type were represented.

The method for recording permanent vegetation quadrats is described in chapter 3 (section 3.3). Quadrat locations are shown in Map 7.1 and described in Table 3.4 of chapter 3.

Environmental features recorded at the quadrat level for this investigation include *bare peat*, *litter*, *above peat surface water* and *lichens*. These features were measured as percentage cover for each of the vegetation samples (quadrats). Additional environmental measurements (variables) for each sample were recorded i.e. *year*, *compartment number* and whether the sample was in an area with a history of *peat cutting*.

Vegetation and environmental data were collated into an Excel file for importing into the computer programmes TWINSPAN and CANOCO for analysis.

7.6 Results

7.6.1 TWINSPAN Classification

A TWINSPAN classification of the two sets of vegetation samples was computed using the software application 'TWINSPAN for Windows version 2.3' (Hill and Smilauer, 2005). The output was shown as a dendrogram (Fig. 7.2). The species names shown were indicators for the groups and have been abbreviated (see Appendix 1 for key to abbreviations). The numbers after species names represented the relevant pseudospecies levels. The pseudospecies cut-off levels were given in Table 7.2. The dendrogram also summarised the site compartment numbers and recording years of the samples (quadrats) included in each TWINSPAN group. In addition, the balance of *uncut* and *cut-over* status relating to the quadrats was stipulated for each group.

The total number of samples for analysis from the two years of field survey was 200. This would have been 212 samples, if survey difficulties had not been encountered during the 2003 survey. Prior to this survey (and following the 2002 survey) the compartments and permanent quadrats had been renumbered by Natural England staff. Re-orientation of the site quadrats to ensure the data matched with those of the previous year took extra time to accomplish. With different numbering and in the absence of GPS equipment it was not possible to locate 6 of the quadrats within the central uncut area with complete certainty. Due to time constraints this problem was not resolved and the 6 quadrats were not recorded.

Of the total 200 samples, 197 were included in the TWINSPAN analysis. The 3 samples excluded were sample numbers 27, 143 and 173. The TWINSPAN programme omitted these samples by regarding them as empty as they contained no species data.

Pseudospecies level	Percent cover of the species
1	0 – 0.5 %
2	> 0.5 – 1 %
3	> 1 – 10 %
4	> 10 – 33 %
5	> 33 %

Table 7.2 Cover level relevant to the analysis shown in Fig. 7.2

The initial division of the 197 quadrats produced the negative **Group 0** which comprised 120 samples and the positive **Group 1** comprising 77 samples. The eigenvalue for this division was 0.426, inferring that a large proportion of the variation in the data could be explained at that point. Indicators for **Group 0** were vascular plants of lowland raised mire and for **Group 1** was a bryophyte of bare ground which also has some tolerance to dense conifer plantation. This suggested that the primary division separated samples which have adequately wetted substrates with mire vegetation (**Group 0**) from samples of drier situations still in the early stages of colonisation following deforestation (**Group 1**).

Group 0 had indicator species characteristic of lowland raised mire. *Eriophorum vaginatum* with a pseudospecies level 2 - a plant of mire and wet heath. *Empetrum nigrum* was also an indicator at pseudospecies level 2 and indicative of upland heath and lowland raised mire on damp to dry peat. *Vaccinium oxycoccos* was the final indicator species of this group (at pseudospecies level 1) and associated with very wet, spongy acidic mire (Trueman *et al.*, 1995).

All of the site compartments were represented in **Group 0** with the exception of compartments 31 and 47. Quadrats from both recording years were widespread in this group, suggesting no obvious change in the vegetation type from one recording year to the next. Both uncut and cut-over sample areas were included in the group.

Group 0 then divided into the negative **Group 00** and positive **Group 01** with an eigenvalue of 0.388 at that point.

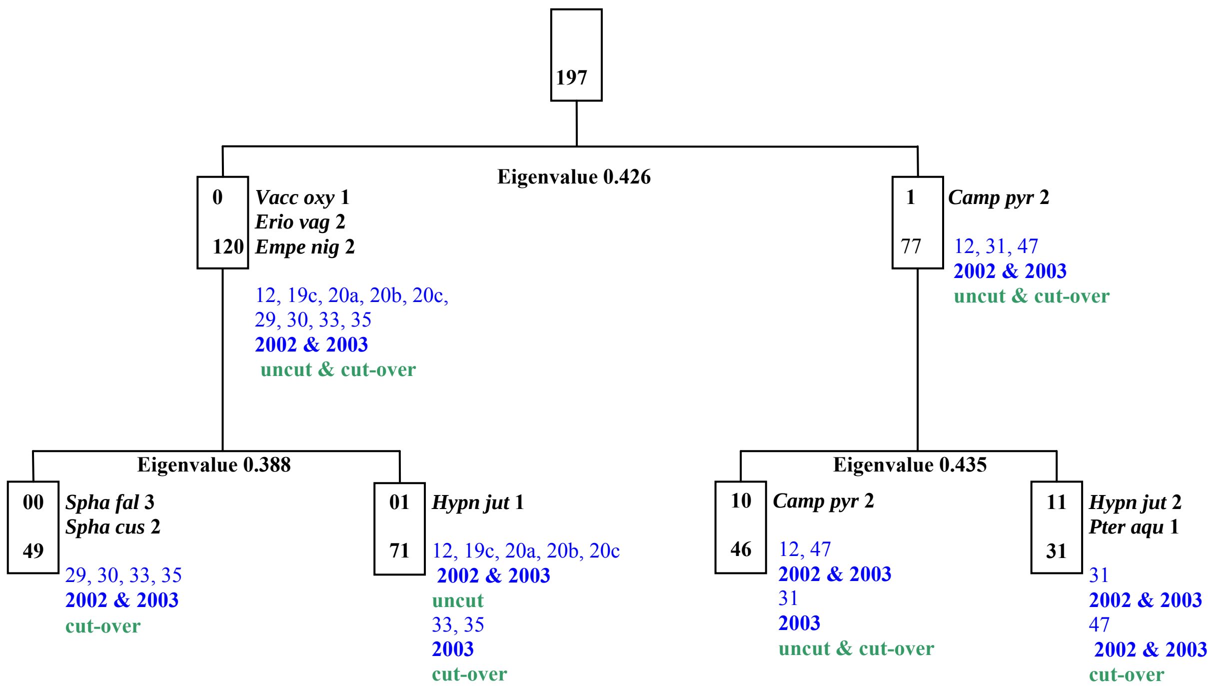


Figure 7.1 Dendrogram – TWINSPAN Sample Classification for the permanent quadrat vegetation surveys of 2002 & 2003 at Bettisfield Moss
The information to the right hand side of each TWINSPAN group (in italic, blue and green print) is explained in section 7.6.1 (first paragraph) of the present Chapter.

Group 00 had 49 samples and both indicator species were lower land plants of the family *Sphagnaceae*. *Sphagnum fallax* dominated this group with a pseudospecies level of 3 and is typical of mire pool margins. *Sphagnum cuspidatum* had a pseudospecies level 2 and is characteristic of bog pools.

Group 00 occurred only in the cut-over compartments and represented the wettest end of the ecological gradient in this analysis. Most samples were found in compartments 29 and 30, which comprised the unique area of floating *Sphagna.* The samples remained present in both recording years, indicating no change in vegetation composition over one year. This reflected the stable nature of this area of the site. **Group 00** also contained samples 141-158 (compartment 35) and samples 159-170 (compartment 33) for both years, thus also showing no change over time. These samples were distinct in having some *Sphagnum* cover in the first survey year and this persisted through to the second survey year. Compartment 35 is adjacent to compartment 29 and compartment 33 is immediately south of the Shropshire Union Canal and adjacent to compartment 35. These compartments are the older, more intensively hand-cut lower lying areas on Bettisfield Moss.

Group 01 had 71 samples and the lower land plant *Hypnum jutlandicum* as indicator species (pseudospecies level 1). *Hypnum jutlandicum* is a bryophyte of acid soil found on heath, moor and conifer plantation. Despite this, the preferential species for the group included higher plants and lower land plants of lowland raised mire. **Group 01** was found to be consistent in both recording years in the uncut compartments 12, 19 and 20. *Hypnum jutlandicum* iwas constant throughout the samples in compartment 12, but *Eriophorum vaginatum* and *Erica tetralix* were present in several of the samples. Compartments 19 and 20 also had *Hypnum jutlandicum* as a constant presence, but many of the samples also recorded combinations of *Sphagnum capillifolium, S. papillosum, Empetrum nigrum, Erica tetralix* and *Eriophorum vaginatum.* Interestingly 2 samples from each of compartments 33 and 35 (cut-over) were present in this group only in 2003. The changes in these four samples were an increase in *Calluna vulgaris* and *Eriophorum vaginatum* and the appearance in 2003 of *Sphagnum papillosum, S. fallax* and *Vaccinium oxycoccos*.

Group 01 appeared to demonstrate the extensive plantation bryophyte cover which remained following deforestation, with remnant mire species persisting in the uncut areas of the site. This suggested the areas in this group were acidic but damp rather than wet. The few samples in cut-over compartments 33 and 35 which were showing a change towards a vegetation of mire species indicated that this old hand-cut area of the site was getting wetter.

Returning to the first division, **Group 1** had *Campylopus pyriformis* as the indicator species with a pseudospecies level of 2. This species is a colonizer of bare peat and is also shade tolerant. **Group 1** was represented in both field survey years and occurred on uncut compartment 12 and cut-over compartments 31 and 47. This group represented drier areas in the early stages of colonisation post-deforestation. The eigenvalue for the division of **Group 1** was 0.435 and producesd the negative **Group 10** and positive **Group 11**.

Group 10 had 46 samples from the uncut compartment 12 and the cut-over compartment 47 which have remained unchanged over the time of monitoring. In 2003 **Group 10** samples were also found in cut-over compartment 31. As in **Group 1** the indicator species was *Campylopus pyriformis* with pseudospecies level 2. Negative preferentials included *Sphagnum fimbriatum, Eriophorum vaginatum* and *Betula* spp.
The majority of samples in this group were located in compartment 47 which had the least intensive hand-cutting history of the cut-over compartments. The vegetation type had the constant presence of *Campylopus pyriformis,* frequent cover of *Deschampsia flexuosa* and the woodland bryophyte *Sphagnum fimbriatum*. A very low cover of *Erica tetralix* and *Eriophorum vaginatum* was evident.

In the analysis, eleven samples from compartment 31 which were allocated to **Group 11** in 2002 were allocated to **Group 10** in 2003. The changes in plant species which brought about this move were the appearance of *Eriophorum vaginatum* and *C. pyriformis* and the loss of *Rubus* spp. and *Pteridium aquilinum.*

The indicator species for the 31 samples in **Group 11** were *Hypnum jutlandicum* (pseudospecies level 2) and *Pteridium aquilinum* (pseudospecies level 1). Both species are characteristic of dry to damp, well drained scrub and woodland. **Group 11** was found at the very driest end of the analysis gradient. Most of the samples were located in compartment 31 during 2002. These samples were predominantly 100% litter-covered with very low percentage cover of *Pteridium aquilinum, Rubus* spp. and *Hypnum jutlandicum.* As described above, 11 samples of compartment 31 changed species composition sufficiently to be included in the negative **Group 10** in 2003. This demonstrated a move away from the very driest of the site conditions, with the loss of *Pteridium aquilinum* and *Rubus* spp. and a gain of low percentage cover for *Eriophorum vaginatum.*

TWINSPAN Group	Vegetation type	Compartment	Year	Surface
00	*Sphagna*	29, 30, 33, 35	2002 & 2003	- cut-over
01	Hypnum jutlandicum / Eriophorum vaginatum - Empetrum nigrum	12, 19a, 19b,19c, 20a, 20b, 20c 33, 35	2002 & 2003 2003	-uncut - cut-over
10	Campylopus pyriformis / Eriophorum vaginatum	12, 47 31	2002 & 2003 2003	- uncut & cut-over - cut-over
11	Hypnum jutlandicum / Pteridium aquilinum	31, 47	2002 & 2003	- cut-over

Table 7.3 TWINSPAN summary table of the main vegetation types

To summarise, the TWINSPAN analysis identified a wet-dry ecological gradient in the Bettisfield Moss vegetation data. The wettest end of this gradient was represented by **group 00**, a vegetation type of bog-pool *Sphagna* characteristic of compartments 29 and 30, with a small number of samples also found in cut-over compartments 33 and 35.

Group 01 though dominated by a woodland bryophyte, supported a low percentage cover of NVC M18 species suggestive of damp peat with a near surface water table. This group was characteristic of the uncut compartments.

Further along the ecological gradient was **group 10 -** characteristic of cut-over compartment 47. The vegetation was characterised by woodland bryophytes and the grass, *Deschampsia flexuosa.* Slight depressions in the peat surface topography showed very low cover of *Erica tetralix* and *Eriophorum vaginatum*.

The driest end of the analysis gradient was represented in **group 11** which was located in cut-over compartments 31 and 47. This group was characterised by a very high cover of leaf/pine needle litter and low percentage cover of well drained scrub and woodland species i.e. *Hypnum jutlandicum, Pteridium aquilinum* and *Rubus* spp.. This suggested that the topography of compartment 47 varies to support this group at higher levels of peat compared to **group 10.** Compartment 31 had the highest cover of mature pine trees until deforestation in 2002. This suggested that water table draw-down may have been most profound in compartment 31.

Vegetation change from first to second survey year was quite subtle and appeared to affect only a small number of samples. The changes to samples in **group 00** demonstrated colonization of mire-building *Sphagnum* species and vascular plants of lowland raised mire. This suggested succession from mire-pool vegetation (found in cut-over areas of the site) towards lawn and hummock vegetation (**group 01**) found as low cover in uncut areas of Bettisfield Moss.

A small number of samples in **group 11** also indicated change over the survey period. These samples demonstrated the loss of dry scrub and woodland species and as such the samples were relocated to **group 10** in 2003. This was a clear demonstration of change towards damper conditions, suggesting that one year on the site was becoming wetter.

The samples demonstrating these changes were located in the cut-over areas of the site.

7.6.2 Species ordination by indirect gradient analysis

An exploratory preliminary correspondence analysis, detrended by segment (DCA) revealed that the largest gradient length was 5.526. Therefore, the vegetation data were analysed using unimodal methods of ordination. This meant that DCA was appropriate to extrapolate the initial species relation. Plant species names were abbreviated for this analysis (key to the abbreviations is given in Appendix 1)**.** Figure 7.2 is a bi-plot of the variable scores in the plane of the first two principal axes of the DCA analysis, displaying the distribution of the variables in relation to each other and the numerical explanatory variables (surface water, bare peat and litter) and the nominal explanatory variables (survey year 2002 (O2) and 2003 (O3), compartment number, whether cut-over or not (cut) and lichens). In this bi-plot the explanatory variables were represented passively and did not constrain the axes.

The ecological gradient uncovered by the TWINSPAN classification was confirmed by this analysis. The strongest trend in the data (Axis 1) from left to right, displayed species indicative of a wet-dry gradient. Again from left to right along Axis 1, the passive representation of the compartment numbers reflected the TWINSPAN end groups shown in Figure 7.1 – compartment numbers 29 and 30 (**Group 00**), moving across to compartments 19, 20, 33 and 35 (**Group 01**), on to compartments 12 and 47 (**Group 10**) and finally to the driest compartment (number 31, **Group 11**).

The second strongest trend (Axis 2) of the DCA appeared to separate the cut and uncut peat surfaces, as this was reflected in the species trend. The lower half of the bi-plot shows species exclusively located in uncut compartments 19 and 20 i.e. *Empetrum nigrum* and *Narthecium ossifragum.*

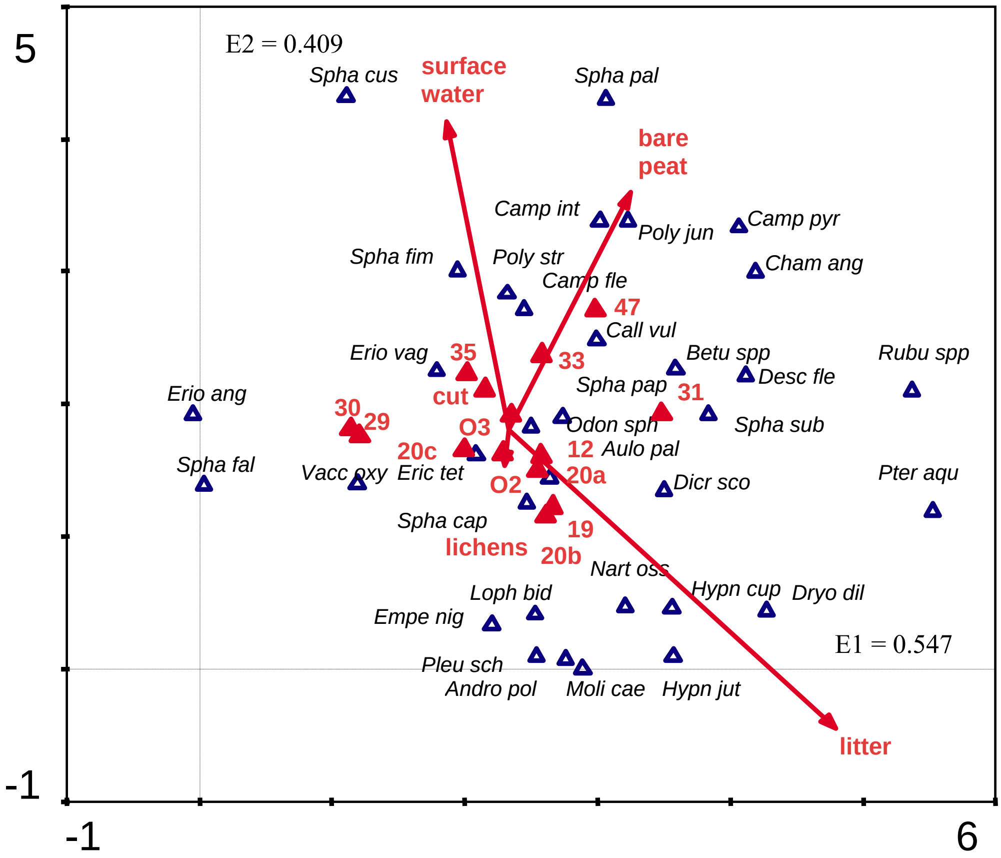


Figure 7.2 Bettisfield Moss: Indirect gradient analysis of the complete data set of permanent quadrat samples (survey years 2002 and 2003) DCA correlation bi-plot on vegetation.
Unconstrained inter-species correlation.

The DCA (unconstrained) was performed on 200 samples with 54 active species. The DCA is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focus on inter-species correlation and the scores are standardised after axes extraction to produce a correlation scatter plot where the position of the species symbol (blue triangle) is a measure of fit with the ordination diagram.

Passive representation of environmental variables are shown as vectors for numerical variables (red arrows) and centroids (red triangles) for nominal variables.

Eigenvalue for Axis 1: 0.547. Length of gradient for Axis 1: 5.526.

$\lambda 1$ = 8.5% of species variance; $\lambda 1 + \lambda 2$ = 14.9% of species variance (38.1% of the species/environment relationship). Eigenvalues for each axis are given (E1 and E2).

Compartment numbers 29 and 30 (the floating *Sphagnum* mat) have long comprised a stable peat-forming area. These compartments were free from conifer encroachment and thus escaped the closed tree canopy that the remainder of the site endured. As such the floating *Sphagnum* vegetation was not representative of the site as a whole. Figure 7.2 demonstrated this vegetation type separated to the far left of the bi-plot (species: *S. fallax, Eriophorum angustifolium, Vaccinium oxycoccos)* with *S. cuspidatum* also strongly associated with this end of the gradient. As the present investigation focused on the immediate vegetation response following deforestation, it was decided to re-analyse the DCA without the samples from compartments 29 and 30 (sample numbers 81 – 110). These compartments were identified as **group 00** (the wettest vegetation type) in the TWINSPAN analysis. Reanalysis allowed more clarity in elucidating the possible response of mire species across the site.

7.6.3 Species ordination by indirect gradient analysis – minus compartment 29 and 30 samples

The DCA re-analysis revealed a gradient length of 4.189 and the analysis output was represented as biplot, Figure 7.3. Axis 2 this time depicted the wet-dry gradient, which became drier in a positive direction. *Rubus* spp. and *Pteridium aquilinum* were represented at the dry end of the trend. Axis 2 also showed the passive representation of the compartment numbers following the same pattern as their related TWINSPAN end groups (as seen on Axis 1 of the first DCA).

There was increased species spread across both axes compared to the first DCA analysis. By removing the data for compartments 29 and 30, a clear separation of species associated with the uncut compartments from those of cut-over areas has been achieved. The strongest trend in the data (Axis 1) was the difference between the plant species relating to whether they are in uncut or cut-over site compartments. Species related to the uncut compartments were located to the far left of Axis 1 (e.g. *Narthecium ossifragum, Empetrum nigrum* and *Andromeda polifolia*). The position of *S. cuspidatum* to the far right of Axis 1 suggested it had a strong relationship with the cut-over samples.

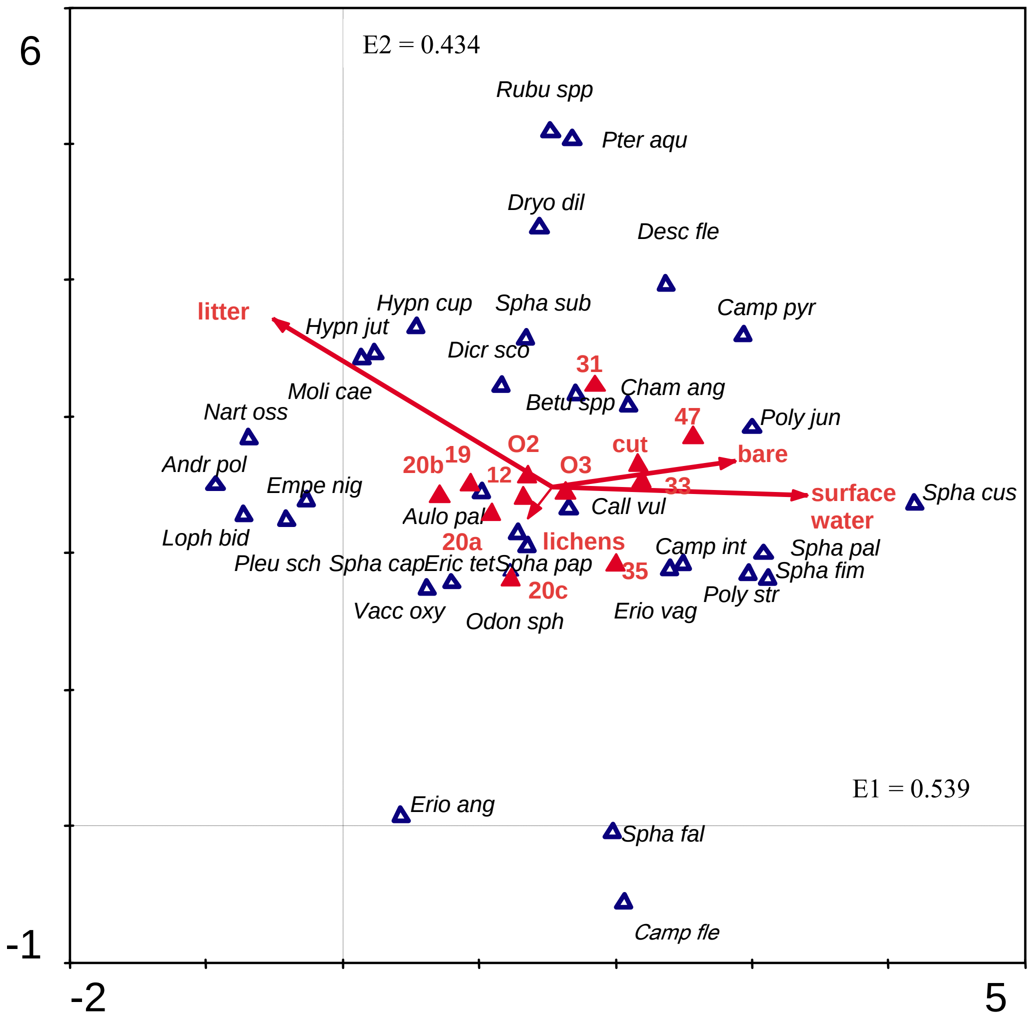


Figure 7.3 Bettisfield Moss – Indirect gradient analysis minus compartments 29 and 30: DCA correlation bi-plot on vegetation. Unconstrained inter-species correlation.

The DCA (unconstrained) was performed on 170 samples (167 of which were accepted by the analysis model) with 53 active species. The DCA is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focus on inter-species correlation and the scores are standardised after axes extraction to produce a correlation scatter plot where the position of the species symbol (blue triangle) is a measure of fit with the ordination diagram.

Passive representation of environmental variables are shown as vectors for numerical variables (red arrows) and centroids (red triangles) for nominal variables.

Eigenvalue for Axis 1: 0.539. Length of gradient for Axis 1: 4.189

$\lambda 1$ = 8.2% of species variance; $\lambda 1 + \lambda 2$ = 14.8% of species variance (38.6% of the species/environment relationship). Eigenvalues for each axis are given (E1 and E2).

Passive representation of the environmental variables allowed certain inferences to be made on the data. Higher covers of litter appeared to be related to the uncut areas and higher cover surface water and bare peat were associated with the cut-over areas and the bryophyte *Sphagnum cuspidatum* in particular.

7.6.4 Species ordination with direct gradient analysis – minus compartment 29 and 30 data

CCA was performed to constrain the relationship between the species and environment data. Monte-Carlo permutation tests were utilised in the analysis model to measure the significance of the environmental variables in relation to the species trends identified. Only two variables were found to be significant: *cut-over* which showed a probability of 0.0020 and *year*, with a probability of 0.0020. Non-significant variables were removed from the model and a final analysis included only the significant environmental variables (shown as biplot, Figure 7.4).

The species spread in the CCA was similar to that of the DCA with a difference being the species on the right ride of the bi-plot are more closely clustered around the zero value on axis 1. The significant environmental variables maintained the positions they held in the DCA. The strongest trend in the data remained that of the differentiation between uncut and cut-over areas. The environmental variable for cutting type (cut) confirms that the right side of Axis 1 correlated with species of cut-over peat and the left side with species of uncut peat.

Axis 2 maintained a wet-dry gradient, though not as clearly as in the DCA. Species of driest habit appeared intermediate between the upper end of Axis 2 and the right side of Axis 1. This confirmed the strong relationship between the driest species and the cut-over compartments (**group 11** of the TWINSPAN analysis). The clear progression from wet to dry species may also have been affected by peat surface topography – e.g. a sample in the uncut areas could contain hummock species such as *Calluna vulgaris*

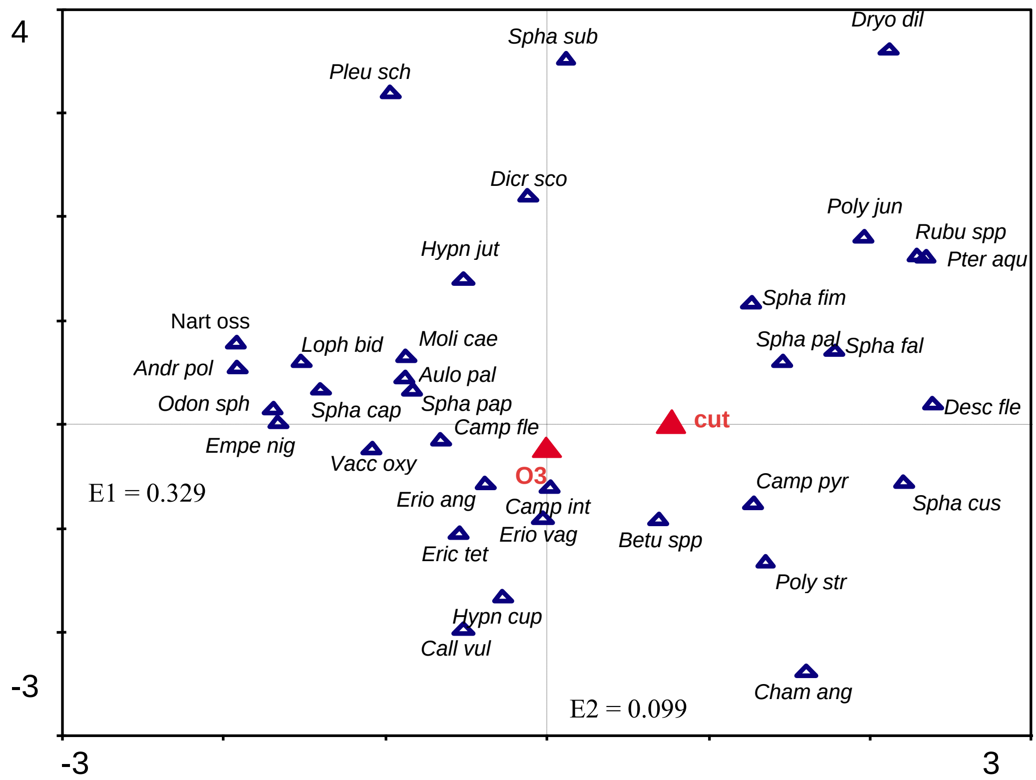


Figure 7.4 Bettisfield Moss – Direct gradient analysis minus compartments 29 and 30 : CCA correlation bi-plot on vegetation data constrained by significant environmental variables.

The CCA was performed on 170 samples (167 of which were accepted by the analysis model) with 53 active species. The CCA is based on a covariance matrix (species are centred only i.e. weighted by their variance). The scaling focus on inter-species correlation and the scores are standardised after axes extraction to produce a correlation scatter plot where the position of the species symbol (blue triangle) is a measure of fit with the ordination diagram.

Significant environmental variables are shown as centroids (red triangles).

Eigenvalue for Axis 1: 0.329.

$\lambda 1$ = 5.0% of species variance; $\lambda 1 + \lambda 2$ = 6.5% of species variance (100% of the species/environment relationship). Eigenvalues for each axis are given (E1 and E2).

which is adjacent to flatter, lower lying peat where *Erica tetralix* with damper requirements is found. Both of these ecological niches therefore occurred in the same sample. This combination of species was seen at the lower end of Axis 2.

The year 2003 (O3) was located fairly centrally in the ordination bi-plot, suggesting a relationship with both trends in the data, but no specific correlation direction. This was not surprising as the vegetation changes highlighted by the TWINSPAN analysis were subtle and of small scale. In the CCA 2003 appeared to correlate most closely with the species *Eriophorum vaginatum, E. angustifolium, Erica tetralix* and *Campylopus introflexus*. This effect appeared to have no particular bias towards cut-over or uncut compartments.

In general, time appeared to correlate with species of higher water table requirements, suggesting that site conditions were getting wetter.

7.7 Discussion

Four distinct vegetation types have been identified on Bettisfield Moss. They range from the wettest *Sphagnum* dominated, to the driest litter dominated type with the presence of woodland and scrub plant species.

Changes in species composition was very subtle in the analysis with only a small number of samples (15) demonstrating change. The trends represented by these changes were consistent – species which increased in cover were those of raised mire i.e. *Calluna vulgaris* and *Eriophorum vaginatum.* Species which appeared by the second year of field survey were *Campylopus pyriformis, Sphagnum papillosum, Sphagnum fallax* and *Vaccinium oxycoccos.* Species losses were *Rubus* spp. and *Pteridium aquilinum* – suggesting the retreat of non-mire vascular plant species.

These results in part reflect the outcomes of work by Robinson (2005). She found that 6 years following peatland deforestation and damming, there were statistically significant increases in cover of *Eriophorum vaginatum, E. angustifoium* and *Sphagnum* species.

In the present investigation samples showing vegetation change were located in the cut-over areas of the site. It could be postulated that damming of cut-over areas is initially more successful than and less prone to run-off than the uncut areas.

Colonisation of *Sphagnum fallax* may indicate areas more affected by nutrient release post-deforestation, as it is a mesotrophic species (Stoneman and Brooks, 1994).

Despite only a one year interval between vegetation surveys, the current analysis has identified a successional trend in the direction of increasing site wetness. *Sphagnum* species have increased which may indicate that the widespread stands of *Sphagna* reported by (Anderson, 2001) at 2 years post-deforestation may not be unrealistic for Bettisfield Moss. Establishment of peat water table monitoring across Bettisfield Moss will be essential to guide future management in providing prompt information on water table falls which could cause a trend reversal and subsequently the increase of dry scrub species.

7.8 Conclusions

- One year following deforestation and ditch damming, has seen only small scale, subtle changes to the site vegetation.

- Plant species which have shown increases in cover or which have colonized over the one year period are mire species. Those which have been lost or reduced are species of dry scrub. This suggests that the site is becoming wetter.

CHAPTER 8
SYNTHESIS AND DISCUSSION

Environmental issues provoke many controversies in a densely populated country, where conservation has rarely been well supported politically. There are differences about what areas should be conserved and how they should be managed, what the targets for management should be and whether maintenance of what are mostly the products of forms of traditional agriculture, is a sensible goal in the 21st century. Raised mires are minority habitats, largely poorly accessible and damaged not only by past peat cutting and drainage, but also by changes in rain chemistry consequent on pollution of the air by nitrogen oxides from vehicles, and ammonia from stock keeping. Some of these issues are discussed below, together with an appraisal of the results obtained.

8.1 Nature Conservation

With a dense population, there is considerable pressure on available land in the United Kingdom. Agricultural intensification began earlier here than elsewhere in Europe, as did industrialisation and urbanisation. As a result nature conservation has long been an important political issue (Bromley, 1997). Its priority when it comes to Government policy-making however, is open to much debate.

The present study site is jointly managed by Natural England and the Countryside Council for Wales (who advise the government on nature conservation issues) as a National Nature Reserve (NNR). In the UK site designation as an NNR protects natural heritage through statute. NNRs encompass some of the most important natural and semi-natural coastal and terrestrial ecosystems in the UK. NNRs are managed to conserve their habitats and to provide opportunity for scientific study of the habitat communities and species represented within them. The statutory country conservation agencies declare sites as NNRs under the National Parks and Access to the Countryside Act (1949) and the Wildlife and Countryside Act 1981 (Joint Nature Conservation Committee, 2009). Conservation action strategies have two broad divisions; management of individual sites, or groups of sites and influencing policy (English Nature, 1998). Lowland raised mires are just one of many habitats with which they are concerned, but they are particularly vulnerable.

The value of rehabilitating lowland raised mires in general is great. These habitats are important for carbon storage, water regulation, biodiversity (genetic as well as species) and education and research (Bragg and Lindsay, 2003). The study site of the present thesis is of particular interest also due to its location as the most southerly raised mire formation in the UK as well as being one of the larger sites in the UK.

If the site had not undergone conservation management it would have continued to lose water and gain nutrients due to the effects of over-exploitation which had been placed on the system. Active management appears to have been the right pathway to follow. The possibility of non-interventional recovery of cut-over raised mires was discussed in an investigation in Canada (Lavoie *et al.*, 2005) which assessed a raised mire (which had been cut-over using a method similar to milling) 5 years and 20 years following abandonment with no management. After 5 years the water table was continually lower than 40cm beneath the surface with no sign of re-colonisation by mire species. This remained the case after 20 years. Spontaneous re-vegetation by mire plants in abandoned block-cut mires was described by Lavoie *et al.* (2003) and attributed to the use of less intensive drainage during peat cutting compared with other methods of cutting. Their investigation however did not compare the effectiveness of re-colonisation with a similar (control) site which had undergone rewetting management. Natural re-colonisation of some mire species prior to rewetting was seen at the present study site, but was restricted to the ditch bottoms of the hand cut and old commercial areas.

A huge amount of effort and expense has gone into the rehabilitation and monitoring of the study site. This raises the question – could all this effort at monitoring be better directed at solving other problems? I feel that although it is laborious to record and detect change on such a large site, it is worthwhile as will be shown in the following discussion. The findings are important on a national and global level, for what continues to be an increasingly rare habitat, in order to inform future management and rehabilitation of cut-over mires.

Natural England, the site managers, though are susceptible to changes in approach directed by fashions in government policy. Presently, the trend is towards “nature for people” which could be interpreted in terms of reducing naturalness. The present study site has specific maintained tracks for safe public access and welcomes visitors. The periphery of the peat body lies under what is now agricultural land. In general funding for conservation has been very low compared with other demands on the public purse and conservation may have suffered. Future changes in policy probably need to elevate the nature conservation outcomes over commercial outcomes in a far wider context than at present. This may cause conflict and need for compensation, but it is now realized that natural habitats are not optional adjuncts to human societies but essential through the goods and services they provide for maintenance of human societies. The value of a small site such as Whixall Moss is minuscule in absolute terms but restoration of it supports an approach and attitude that is urgently needed globally for much bigger systems.

8.2 The National Vegetation Classification

Natural England places great emphasis on targets for restoration based on the categories of the National Vegetation Classification (NVC) (Rodwell, 1991). This scheme has been used in the present study to compare vegetation types identified in the study analysis with recognized plant communities. The NVC provides floristic models which may eventually impede our understanding because they are static and difficult to modify once accepted and may be are facts of the immediate past management that are only of ephemeral significance. It does however provide information about the dynamic nature of vegetation by allowing comparisons and identifying trends between the different vegetation types in a wide range of ecological situations. Since it is country-wide and summative, it is bound to be a crude approximation at any one site and the analysis in the present study of changes in individual species is probably giving a more subtle appreciation of the changes occurring.

The NVC does however seem to be a quite useful model for explaining the trends uncovered in the present study and provides a nationally recognisable context for understanding and communicating those trends. For historical reasons, the present study has focused on data collection at sub-compartment and one-metre quadrat scales, which makes the investigation difficult to use to improve or advance the NVC.

8.3 Site Management Plans for Nature Conservation

The need for management of remaining areas of semi-natural habitat if their conservation value was to be maintained was highlighted by the Nature Conservancy Council (now divided into Natural England, Scottish Natural Heritage and the Countryside Council for Wales). No British habitat is pristine; all are severely altered not least in loss of the large fauna that has been shown to be instrumental in the resilience and functioning of truly pristine habitats. To maintain features of what remains, traditional management seems to be required, but can often be haphazard if not controlled. Traditional management in the mediaeval and later periods prior to the twentieth century was quite deliberate for on it depended the sustainable provision of services and goods such as grazing and timber. Current management plans provide a guide for site managers but the structure and format of plans has been standardised (Nature Conservancy Council, 1983 and 1988), which may be convenient bureaucratically, but nonetheless may inhibit experiment and more creative approaches. The standard format was originally produced specifically for National Nature Reserves and aimed to ensure:

- sites are properly described
- that importance is assessed against recognized standards
- that clear objectives are made
- that relevant work is prescribed, planned and executed
- that the effects of work are monitored

The standard format was designed to ensure that there is continuity and stability of management. Without an effective management plan, sites are at risk of inconsistent management which could lead to a waste of resources and the loss of the sites special interest (Nature Conservancy Council, 1988). It may also result in much waste of effort and resources in promoting activities that give little real return, especially where the management is not backed by clear, controlled experimental evidence. Much countryside management is based on solid experience, but equally much appears to be based on opinion and prejudice.

Management plans are usually designed by site managers who determine what must be done to maintain or enhance the important site features. The management prescription is based entirely on the evaluation of nature conservation interest, with the constraints operating being used only to modify the desired outcomes. Most modern variants of the management plan lose objectivity by focusing on the prescription rather than the evaluation. The evaluation process ensures that any problems which are detrimental to a site are picked up and rectified in order to prevent further damage.

In the present study, whether or not management targets were being met was investigated. The desired vegetation cover after five years was not being achieved in all rehabilitated sub-compartments. The analysis showed that vegetation was changing in a positive direction but suggested that target time intervals were too short. This information will be useful to other UK sites at earlier stages (or at the beginning) of management.

The aim of management at the site was not to return it to a particular stage in its development at a particular historical period. The main aims were to raise the water table sufficiently to establish a mire pool vegetation which would then develop into a closed *Sphagnum* carpet and thus a self –regulating acrotelm. The formation of a closed *Sphagnum* carpet or acrotelm was seen as the main indicator of successful rehabilitation (Pfadenhauer and Klötzli 1996, Money and Wheeler 1999). The results of the present study clearly demonstrate that this process has started and continues through natural processes. This suggests that in the future active management should be reduced with development of the site becoming more natural when human influences have been ameliorated. This may in turn strengthen the resilience of the site to the potentially damaging effects of climate change, though the indicators are not favourable. Mire sites are dependent on ample rainfall, but precipitation is predicted to be much reduced in the UK in the critical summer growth period.

There is an argument against conservation management which relates to the possible effects of climate change being detrimental to conservation efforts. As the effects of climate change are not known with absolute certainty, the present writer believes that action to protect such important sites should be maintained. Hindsight may show however that some alternative habitat will have proved more stable.

8.4 Vegetation Change at the Study Site

The present work revealed clear trends in the data which related to a wet-dry gradient and also one which differentiated between cutting types. Measured management variables were found to cause an increase in peat-forming mire pool species. Other influences on the vegetation of the site that were not measured include past burning episodes and leaf litter from *Betula* trees/ scrub. *Molinia caerulea* is known to respond to fire, but its increase in the recent commercial areas (which were mostly bare) following rewetting of this severely dehydrated surface is more likely to be the result of the peat becoming sufficiently wet to support it. By the final survey year this species started to decline in the presence of an above surface stable water table, and did not prevent the development of *Sphagnum*.

The processes of succession described in Chapter 1 and the NVC model of succession between mire pool (NVC M2) and hummock/lawn (M18a) appear to give a useful model for the vegetation changes actually occurring at the site. The first successional trend identified in the data was characteristic of the recent commercial cuttings and followed a change from dry conditions (bare), through a fluctuating water table (*Molinia/ Sphagnum cuspidatum*) and on to stable shallow inundation (*Sphagnum cuspidatum*/ *Eriophorum* spp.). This is clearly the development of mire pools envisaged in the management plan

This vegetation type also showed evidence (to a lesser degree) of further development of the mire pools to include colonization of hummock-forming species of *Sphagnum*. Dargie (2001) warned that the unnatural nature of a peat cutting pool is too wet to be conducive to development of M18 vegetation on the M2 surface. He stated that at Wedholme Flow, eleven years following rewetting there was no sign that the *Sphagnum cuspidatum* carpet was diversifying with hummock forming species in quantity. The present study at Fenn's, Whixall and Bettisfield Mosses NNR has shown colonization of *Sphagnum cuspidatum* carpets by *Sphagnum papillosum* and *Sphagnum tenellum* 10 years following rewetting. This has been identified on the '*Molinia*' and 'ditch' surfaces of the recent commercial cuttings. These results give confidence that the site has the potential to go on to develop the full range of species typical of a raised mire.

The second trend of succession expected in the management plan was the development of hummock/lawn mire species. This was primarily found on uncut areas of the site (sub-compartment 6.7 and compartment 15). In addition these species were found to be developing in a small number of samples in the recent commercial cuttings (the 'relict' and 'augered' surfaces). They were characteristic of a near surface water table rather than shallow flooding, colonizing directly on the peat surface. This development in cut-over peat was unexpected and suggests that rehabilitation is effective even after intensive exploitation.

Rodwell (1991) described M2 vegetation as "pools and wet lawns on ombrogenous mire" and considered that it readily colonized shallow-flooded peat cuttings. He also noted that the cyclical pattern of hummock-hollow complexes in the raised mire community suggested that replacement of mire pools by hummocks is probably a slow process occurring over centuries. As the present study spanned a relatively short period (11 years) mire pool to hummock succession was not found. However, hummock vegetation was found to have developed as a management response amongst vegetation of the uncut areas and also by the process of paludification in the recent commercial areas. This suggests that the development of a pool-hummock profile may well be achieved in less than the time suggested by Rodwell (1991).

The trends of vegetation change described above as succession could be random or chaotic. However, as the expected outcome of mire pool vegetation following rewetting occurred, this does not seem to meet with chaos theory, though there may be an element of chaos in the specific species that developed as part of the gross structural change. The centre of the site (not included in the data analysis) where flooding has left deep pools, is a deviation from desired management which is also not obviously chaotic. It is a response to the fact that so much peat has been lost that the profile is concave i.e. dish shaped rather than mound shape. This area of deep water attracts water fowl which generate more mesotrophic and disturbed conditions with no *Sphagnum* development. This could be interpreted as a chaotic trend.

During its development the NNR has undergone past climate influence, causing flooding. This was seen in historical evidence from the peat stratigraphy at Fenn's, Whixall and Bettisfield Mosses which confirmed a period of flooding with abundant *Eriophorum* species ca. 3,400 years before present (Grant, 1994). The resulting mire pool vegetation returned to a characteristic lowland raised mire plant community over time. This information can be used as a comparison with the current condition of the site which has essentially undergone artificial flooding and has developed mire pool vegetation and more recently the colonization of hummock/lawn species too. The study site shows signs of moving towards natural development.

An evaluation was made of apparent ecological differences between the cotton-sedge species *Eriophorum angustifolium* and *Eriophorum vaginatum*. *Eriophorum angustifolium* was found mainly in the hand cuttings prior to management and increased in abundance as well as range (colonizing the recent commercial cuttings) post-management. This species persisted over time and indicated deeper water and colonization of bare peat (Grime *et al.,* 1996) quite rapidly in the recent commercial cuttings, by rhizome spread. *Eriophorum vaginatum* was established in the hand cut and uncut areas prior to rewetting. Following rewetting *Eriophorum vaginatum* increased generally (particularly on the old commercial cuttings), with higher cover seen in uncut and hand cut areas. In the hand cuttings the water table had remained relatively high on the flat and ditch surfaces. *Eriophorum vaginatum* showed a late post-rehabilitation increase as part of the relict/augered M18a –like vegetation type. On the *Molinia* surface of the recent commercial cutting type, *Eriophorum vaginatum* increased from 1996 to 2001, but *Eriophorum angustifolium* did not. This may be related to the *Molinia* surface having no bare ground to colonize. Both *Eriophorum* species showed a late post-rehabilitation increase as part of the *Sphagnum cuspidatum* mire pool vegetation (all recent commercial surfaces and ditches of hand and old commercial cuttings). Here they replaced *Molinia caerulea.*

The distinction between the two *Eriophorum* species appeared to be that *Eriophorum angustifolium* can colonise bare ground by rhizomatous spread and tolerates deeper inundation. *Eriophorum vaginatum* appeared to colonise peat with a near-surface water table, colonizing areas of deeper water by establishing on the surface of floating *Sphagnum* mats (field observation). *Eriophorum vaginatum* is a tussock-forming species (Grime *et al.,* 1996). Both species significantly increased their range on the site from 1996 to 2001.

Much of the analysis depends on multivariate statistics because several variables were simultaneously changing and many species were involved. Such data are inherently messy compared with those derived from controlled experiments. Interpretation of multivariate bi-plots is not without risk of subjectivity and bias. Care was taken to follow guidelines from the CANOCO user manual (ter Braak and Šmilauer, 2002) in order to make reliable inferences about ecological relationships and trends in the data output. Bias and surveyor error was also considered during the present study. With the exception of the investigations of Chapters 6 and 7, surveys were included which had been carried out by different surveyors. The site manager provided guidelines/instruction on carrying out the surveys correctly in order to maintain consistency. This practice allows the most reliable possible data collection given that using the same surveyor each time was not possible. The alternative of not using the data on the basis of risk would mean that knowledge about the progress of sites would never be made.

While collating previous vegetation data for Chapter 5 (permanent 1m x 1m quadrats) an inconsistency in surveyor was found. Data from a small number of quadrats were being viewed by the present writer as a computer file and did not appear logical. This was discussed with the Senior Reserve Manager and resolved by looking at the field survey record sheets for the samples. This revealed that the surveyor had not followed instructions, but had devised his own method of recording. His field survey sheets were then used in the present study to correct the data for these particular samples in order to make them comparable with the rest of the data. This incident highlighted the importance of following site management instruction and the usefulness of seeing previous field survey recording sheets prior to carrying out surveys.

Ecosystems are not entirely composed of plants. There is a greater diversity in general of animals and microorganisms, but plants are obvious and thus lend themselves to descriptions of change. The relatively narrow plant orientation of the present work was necessary. I could have included invertebrate, bird or chemical responses to rewetting, but as my expertise was botanical that was the focus taken. In any case this was most fitting as the purpose of the investigation was to ascertain response in the mire vegetation to nature conservation management.

The different components of the present thesis i.e. site sub-compartments, 1m quadrats of Fenn's and Whixall Mosses and the 1m quadrats of Bettisfield, provided analysis which did not necessarily have to give parallel results. However, the results do support parallel conclusions about vegetation change. The common trend towards development of raised mire species is clearly seen. This provides further evidence that we are looking at quite well defined trends rather than random interactions.

Since the site surveys were carried out by the present writer, some have been repeated by students as part of investigations for university courses. The sub-compartment survey was repeated and investigated in 2005 and results continued to demonstrate a positive trend in the vegetation which related to rehabilitation management (Pedreira, 2005 and Elustond, 2005). Further work on Bettisfield Moss (Hargreaves, 2005) confirmed successful regeneration of raised mire plant species which significantly increased in abundance since 2002. The permanent 1m x 1m quadrats on Fenn's and Whixall Mosses have not been resurveyed. However, rapid acceleration of raised mire species/conditions has been seen on Fenn's and Whixall Mosses since 2001 (J. Daniels, *personal comment*).

8.5 Future Work and Recommendations

Fenn's, Whixall and Bettisfield Mosses NNR comprise a very large and complex site with variations in general as well as localized topography, cutting methods and length of time since abandonment as well as variation in time of rehabilitation. Despite the inevitable limitations imposed by these complex factors, a very clear assessment of vegetation change has emerged. The results are sufficiently encouraging to suggest that raised mire rehabilitation would be worth attempting on any cut-over raised mire. In the UK there are other cut-over, damaged mire sites with similar histories to the present study site. The results are therefore very relevant to UK sites and sites worldwide. Outside of the UK, mire sites are influenced by different peat cutting methods and climatic conditions, but the present results demonstrate that rehabilitation of severely damaged raised mires is worthwhile.

The peat-cutting history of the present study site bears most similarity to that of the South Solway Mosses (Glasson Moss and Wedholme Flow), North Cumbria. These sites have been damaged by peat cutting, drainage and past burning, but do contain some of the best examples of intact raised mire in England (Brooks and Stoneman, 1997).

Management began 4 years earlier than it did at the study site of the present thesis. Uncut areas at Wedholme Flow were described as having the closest likeness to NVC M18a (Dargie and Hulme, 2000). The investigation at Wedholme Flow looked at one data set only i.e. did not investigate change over time. The present study can therefore inform this site that rehabilitation management does have a continuing positive effect on uncut raised mire as long as the average water table remains near the surface.

The problems of slope/ hydrological gradient at the present study site were considered in Chapters 4 and 5. Retaining a high water table in the peripheral site compartments is difficult to achieve. Findings at Cors Caron, a raised mire in Dyfed showed a steep hydrological gradient of an opposite nature to that of the present study site. Cors Caron has a domed uncut centre which drops steeply to the surrounding cut-over peat. The rewetted peat cuttings supported *Molinia caerulea* while the difficult to rewet uncut dome had a vegetation rich in ericaceous species (Brookes and Stoneman, 1997). The use of ‘bunds’ to retain water was found to be successful, though expensive at Cors Caron. The construction of bunds at the present study site could also be trialed to ameliorate water retention.

Advice for other UK sites where management plans are being drawn up would include details of the need for longer time-frames when it comes to vegetation targets. Alternatively the addition of *Sphagnum* inoculum is advised. The use of *Sphagnum* inoculum may help to speed up the process in areas of shallow flooding as well as areas with a near-surface water table (Campeau and Rochefort, 1996, Rochefort *et al.* 2002). It may be preferable to revise management plan targets and acknowledge that *Sphagna* other than *Sphagnum cuspidatum* will take longer to establish in inundated areas.

I would also advise managers of other sites that *Molinia caerulea* appears to act as a nurse species in supporting the development of *Sphagnum* and that the species begins to decline when shallow flooding conditions are achieved. At this point it is replaced by *Eriophorum* spp. and increased *Sphagnum* is also seen.

Minimum average water table range for *Sphagnum* development was found to be 5.1 – 10cm below the peat surface at the site. Above-surface shallow flooding correlated with higher cover of *Sphagnum* species. These findings have contributed to an existing debate on raised mire rehabilitation i.e. supported work by Mawby (1995) and confirmed that the most effective development of *Sphagna* related to conditions of shallow flooding and not just surface wetness.

In an investigation correlating hydrology and vegetation response in cut-over peat at Wedholme Flow, Dargie (2001[2]) found the determining factor of vegetation type was the water table. The findings of the present thesis provide detailed water table requirements of relevance to Wedholme Flow. These findings will inform site managers of the need for hydrological monitoring and care in achieving and maintaining shallow water above surface.

A huge baseline vegetation data set for the sub-compartments and permanent quadrats of Fenn's and Whixall Mosses was made available for this thesis by the Senior Reserve Manager. Some constraints were therefore inevitable on the present study methodology. In order to contribute to the site archive data, the use of existing site methods was maintained and as such resurvey of existing 1m x 1m permanent quadrats and sub-compartments was carried out. On initiating the baseline survey of Bettisfield Moss the use of 1m x 1m permanent quadrats was adopted in line with continuing site management requirements.

The present study identified that it would be useful to take the permanent quadrat analysis further by including a fourth survey 5 years on from the third. This would confirm whether the lack of significant vegetation change found in the hand and old commercial cuttings was due to their undergoing later management than the other two cutting types and would also determine how *Sphagna* other than *Sphagnum cuspidatum* were faring. This would also confirm or otherwise the significance of the various trends towards the *Sphagnum magellanicum – Andromeda polifolia* subcommunity of the M18 *Erica tetralix – Sphagnum papillosum* raised mire community detected in the present study.

A repeat of the "landscape scale" assessment would be beneficial as the production of comparable site species maps for each successive survey would provide visual evidence of species change. The time spent on the landscape surveys could be reduced and made less laborious by recording only key species (*Sphagnum cuspidatum, Eriophorum angustifolium, Eriophorum vaginatum, Molinia caerulea* and *Calluna vulgaris*) instead of all species. To limit the difference between surveyors and thus produce reliable species maps, as far as possible the same surveyor should be used. If this is not possible, on-site training in survey methodology for each individual will help to maintain consistency.

Further survey and analysis of the permanent quadrat vegetation on Bettisfield Moss is recommended. Bettisfield Moss provides an exciting opportunity to compare the rehabilitation of deforested mire previously under a closed tree canopy, with that taking place on the cut-over but un-forested mires of Fenn's and Whixall Mosses.

The influence of slope and general concavity of Fenn's and Whixall Mosses was discussed earlier. A study to investigate the relationship between slope and vegetation/hydrological change, in order to identify areas of the site which are not retaining water sufficiently would be valuable. This information could then be utilized to direct remedial site management.

Further, the development of vegetation in the deeper pools of the centre of the site would be worthwhile. This would involve attempts at creating a Schwingmoor-type vegetation by use of *Sphagnum* inoculum and a raft species such as *Menyanthes trifoliata* for support, compared with *Sphagnum* inoculum only, and compared with control pools with no intervention at all.

8.6 Conclusions

1. Rehabilitation management has successfully resulted in an increase in raised mire plant species even on such a highly damaged and cut-over mire as this. It is possible to produce significant positive rehabilitation in a relatively short time.

2. Successional trends related to rehabilitation were seen as development to mire pool and mire lawn/hummock vegetation.

3. Water table fluctuation was found to stabilize by the end of the study period. This may have been due to more even rainfall but also to vegetation development. It was seen in the most severely damaged areas of the site, which also demonstrated the most significant response to management.

4. The direct development of NVC M18a species in surface-wet areas (uncut areas and augered/relict surfaces of the recent commercial cuttings) was not previously anticipated and has contributed new information on the site.

5. Conditions of fairly stable inundation were necessary to cause the decline of *Molinia caerulea* which resulted in further increases in the cover of peat-forming species.

6. *Calluna vulgaris* was a dominant feature of the vegetation of baulk and flat surfaces on the hand and old commercial cuttings and some recent commercial surfaces. This species declined significantly following rewetting.

7. Constancy tables suggested that target raised mire community species (NVC M18a) were not suffering widespread loss to inundation following management.

8. Minimum average water table range for *Sphagnum* development was 5.1 – 10cm below the peat surface. Above-surface shallow flooding correlated with higher cover of *Sphagnum* species.

9. The recent commercial and uncut areas showed clear and significant positive vegetation change. The effect of the water table in these areas was quite uniform. Vegetation of the old commercial and hand cuts remained little changed - these areas had a more complex topography and had been rehabilitated at a later time than the recent commercial and uncut areas. It was probably too soon to have seen significant change.

10. More time was needed than anticipated to achieve management plan targets for combined cover of peat-forming species.

11. Small positive changes were detected on Bettisfield Moss one year following deforestation.

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APPENDIX 1
KEY TO ALL INVESTIGATION PLANT SPECIES NAME ABBREVIATIONS

VASCUAR PLANT SPECIES NAME (LATIN)	VASCUAR PLANT SPECIES NAME (ENGLISH)	SPECIES ABBREVIATION USED IN RESULTS FIGURES
Alnus glutinosa	Alder	*Alnu glu*
Andromeda polifolia	Bog rosemary	*Andr pol*
Betula spp. <1m in height	Birch	*Betu* 1
Betula spp. 1m-3m in height	Birch	*Betu 2*
Betula spp. >3m in height	Birch	*Betu* 3
Calluna vulgaris	Heather	*Call vul*
Chamerion angustifolium	Rosebay Willowherb	*Cham ang*
Deschampsia flexuosa	Wavy-hair Grass	*Desc fle*
Drosera rotundifolia	Round-leaved Sundew	*Dros rot*
Dryopteris dilatata	Broad Buckler-fern	*Dryo dil*
Empetrum nigrum	Crowberry	*Empe nig*
Erica tetralix	Cross-leaved Heath	*Eric tet*
Eriophorum angustifolium	Common Cottongrass	*Erio ang*
Eriophorum vaginatum	Hare's-tail Cottongrass	*Erio vag*
Frangula alnus	Alder Buckthorn	*Fran aln*
Fraxinus excelsior	Ash	*Frax exc*
Gramineae (other)	Grasses	*Gram* oth
Ilex aquifolium	Holly	*Ilex aqu*
Juncus spp.	Rushes	*Junc spp.*
Lonicera peryclymenum	Honeysuckle	*Loni per*
Molinia caerulea	Purple Moor-grass	*Moli cae*
Narthecium ossifragum	Bog Asphodel	*Nart oss*
Pinus sylvestris	Scots Pine	*Pinu syl*
Potamogeton polygonifolius	Bog Pondweed	*Pota pol*
Pteridium aquilinum	Bracken	*Pter aqu*
Quercus spp.	Oak	*Quer spp*
Ranunculus repens	Creeping Buttercup	*Ranu rep*
Rhododendron ponticum	Rhododendron	*Rhod pon*
Rhynchospora alba	White Beak-sedge	*Rhyn alb*
Rubus spp	Bramble	*Rubu spp*
Rumex acetosella	Sheep's Sorrel	*Rume ace*
Salix spp	Willow	*Sali spp*
Sorbus aucuparia	Rowan	*Sorb auc*
Typha angustifolia	Lesser Bulrush	*Typh ang*
Utricularia minor	Lesser Bladderwort	*Utri min*
Vaccinium myrtillus	Bilberry	*Vacc myr*
Vaccinium oxycoccos	Cranberry	*Vacc oxy*
Vaccinium vitis-idaea	Cowberry	*Vacc vit*

Full Latin and English plant names after Stace (1999).

BRYOPHYTE SPECIES NAME	SPECIES ABBREVIATION USED IN RESULTS FIGURES
Aulacomnium palustre	*Aula pal*
Brachythecium rutabulum	*Brac rut*
Bryophytes (other)	*Bryo oth*
Calypogeia fissa	*Caly fis*
Calypogeia muelleriana	*Caly mue*
Campylopus flexuosus	*Camp fle*
Campylopus introflexus	*Camp int*
Campylopus pyriformis	*Camp pyr*
Cephalozia connivens	*Ceph con*
Cephaloziella spp.	*Ceph spp*
Dicranella cerviculata	*Dicr cer*
Dicranella spp	*Dicr spp*
Dicranum scoparium	*Dicr sco*
Drepanocladus fluitans	*Drep flu*
Eurhynchium praelongum	*Eurh pra*
Hypnum cupressiforme	*Hypn cup*
Hypnum jutlandicum	*Hypn jut*
Hypnum lacunosum	*Hypn lac*
Kurzia pauciflora	*Kurz pau*
Kurzia spp	*Kurz spp*
Lophocolea bidentata	*Loph bid*
Lophozia ventricosa	*Loph ven*
Mnium hornum	*Mniu hor*
Mylia anomala	*Myli ano*
Odontoschisma sphagni	*Odon sph*
Orthodontium lineare	*Orth lin*
Pleurozium schreberi	*Pleu sch*
Pohlia nutans	*Pohl nut*
Polytrichum commune	*Poly com*
Polytrichum juniperinum	*Poly jun*
Polytrichum strictum	*Poly str*
Polytrichum spp	*Poly spp*
Sphagnum capillifolium	*Spha cap*
Sphagnum cuspidatum	*Spha cus*
Sphagnum fallax (recurvum)	*Spha fal*
Sphagnum fimbriatum	*Spha fim*
Sphagnum recurvum (fallax)	*Spha rec*
Sphagnum subnitens	*Spha sub*
Sphagnum tenellum	*Spha ten*
Sphagnum (other)	*Spha oth*

Full Latin plant names after Watson (1981).

NB: Lichens have not been identified as species, there presence is recorded as follows:

Lichen spp.	*Lichen*

APPENDIX 2

SPECIES COVER MAPS

4.1 – 4.8

Map 4.1 Fenn's, Whixall & Bettisfield Mosses National Nature Reserve

Percentage Cover of Sphagnum cuspidatum

Not to scale

Compiled by: Karen Horton Date: November 2005

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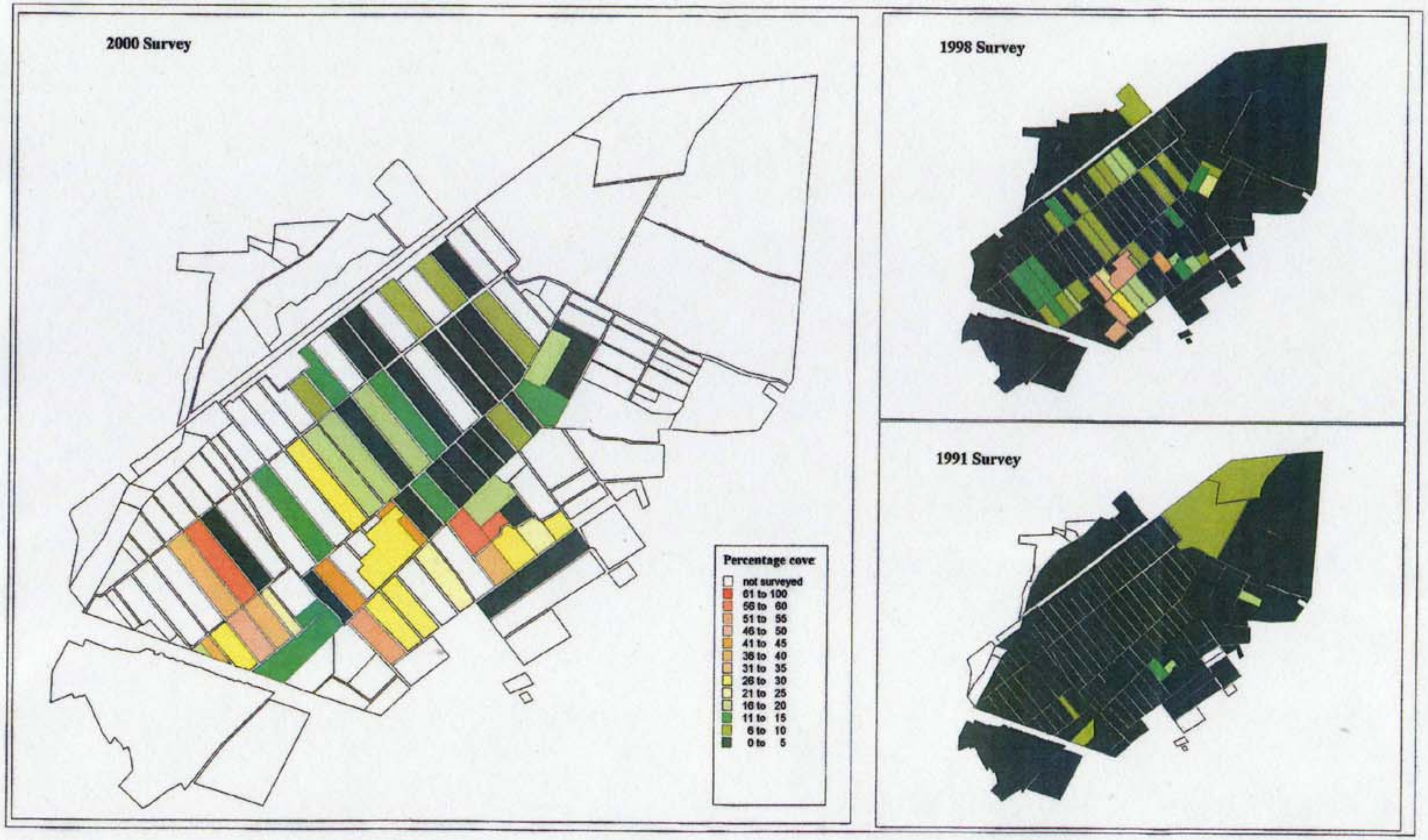
Map 4.2 Fenn's, Whixall & Bettisfield Mosses National Nature Reserve

Percentage Cover of Eriophorum vaginatum



Not to scale

Compiled by: Karen Horton Date: November 2005

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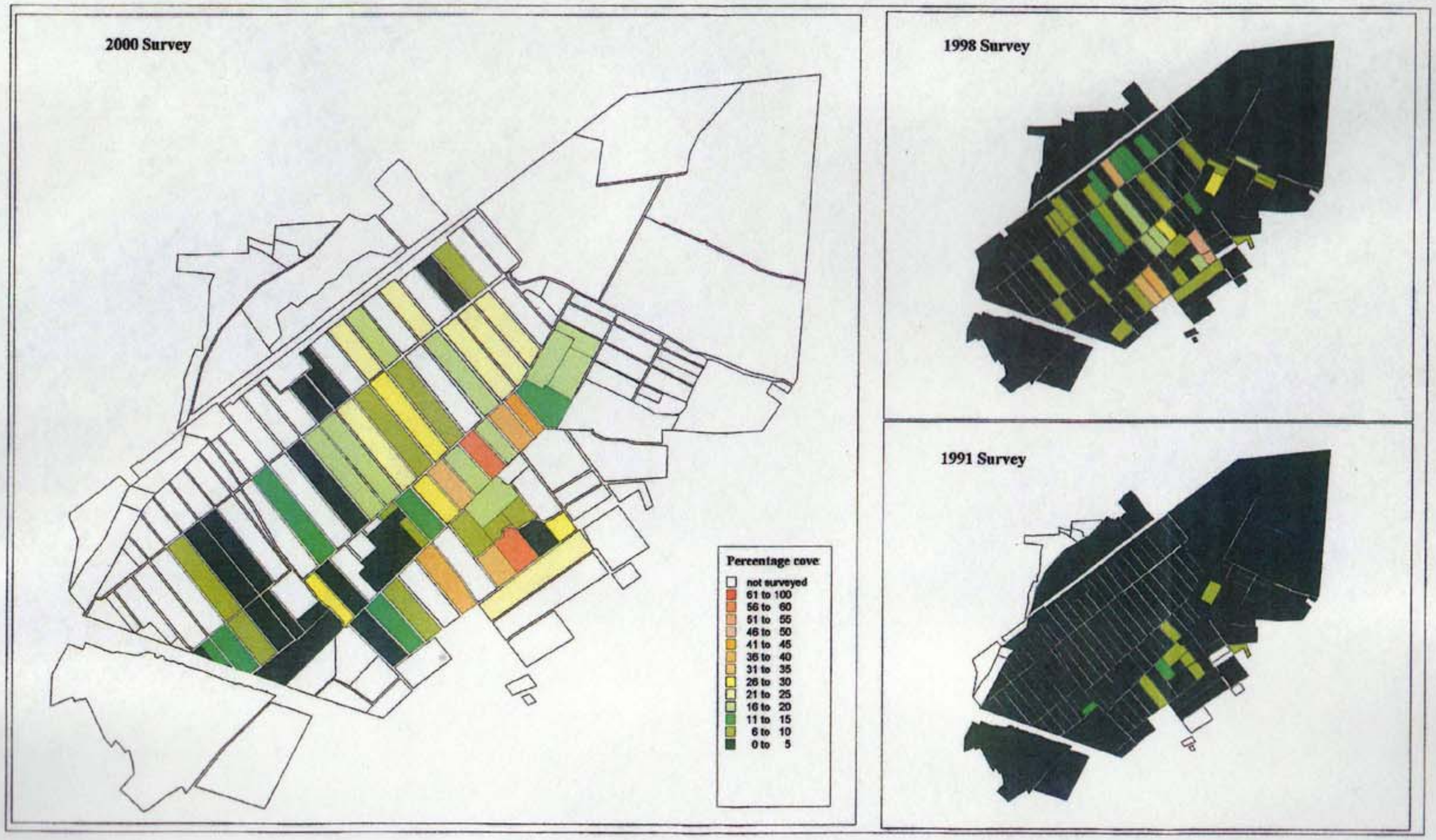
University of Wolverhampton

Map 4.3 Fenn's, Whixall & Bettisfield Mosses National Nature Reserve

Percentage Cover of Eriophorum angustifolium



Not to scale

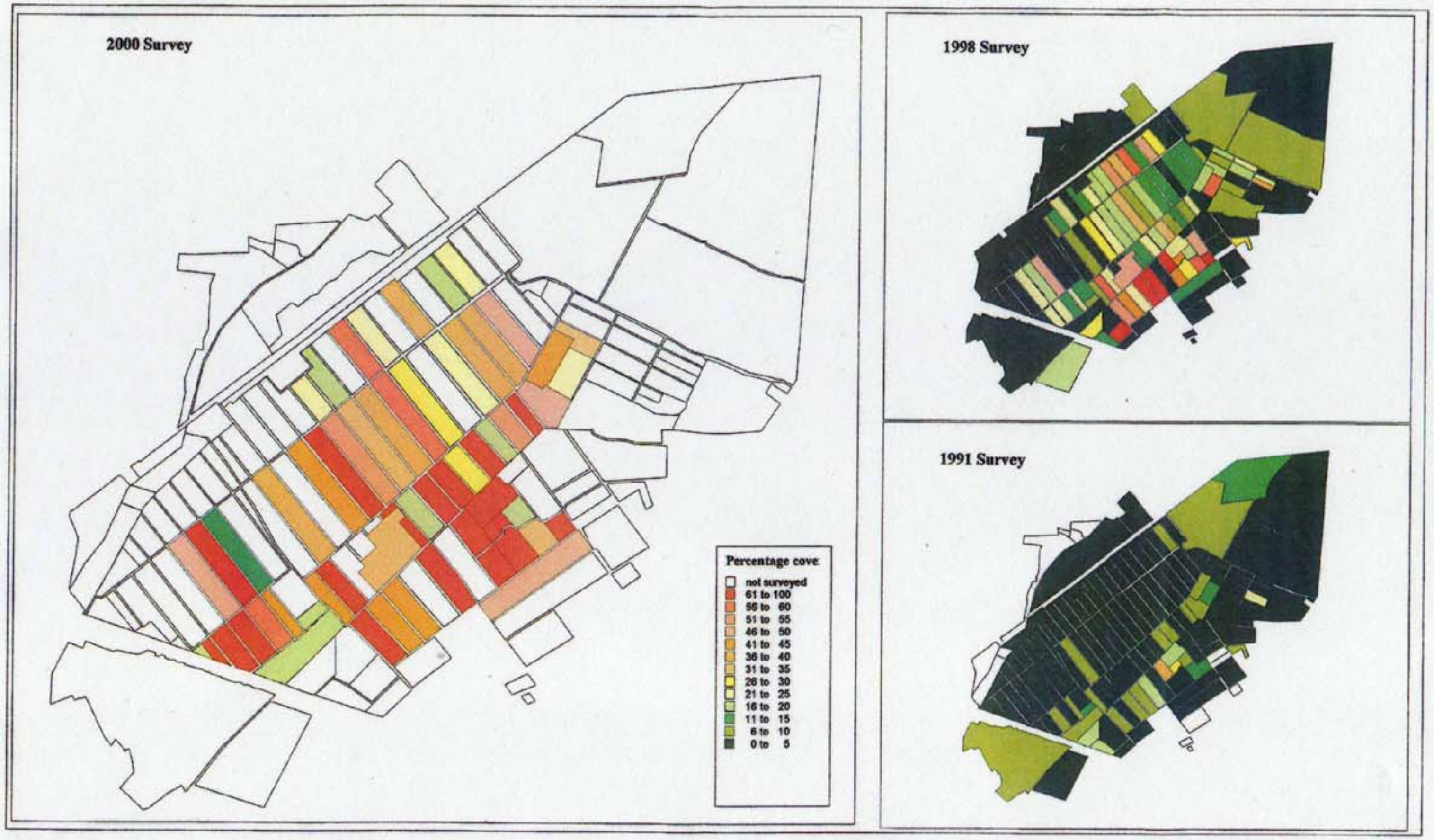
K Horton

School of Applied Science
University of Wolverhampton

Compiled by: Karen Horton Date: November 2005

Map 4.4 Fenn's, Whixall & Bettisfield Mosses National Nature Reserve

Percentage Cover of Combined Sphagnum cuspidatum, Eriophorum vaginatum & Eriophorum angustifolium



Not to scale

Compiled by: Karen Horton Date: November 2005

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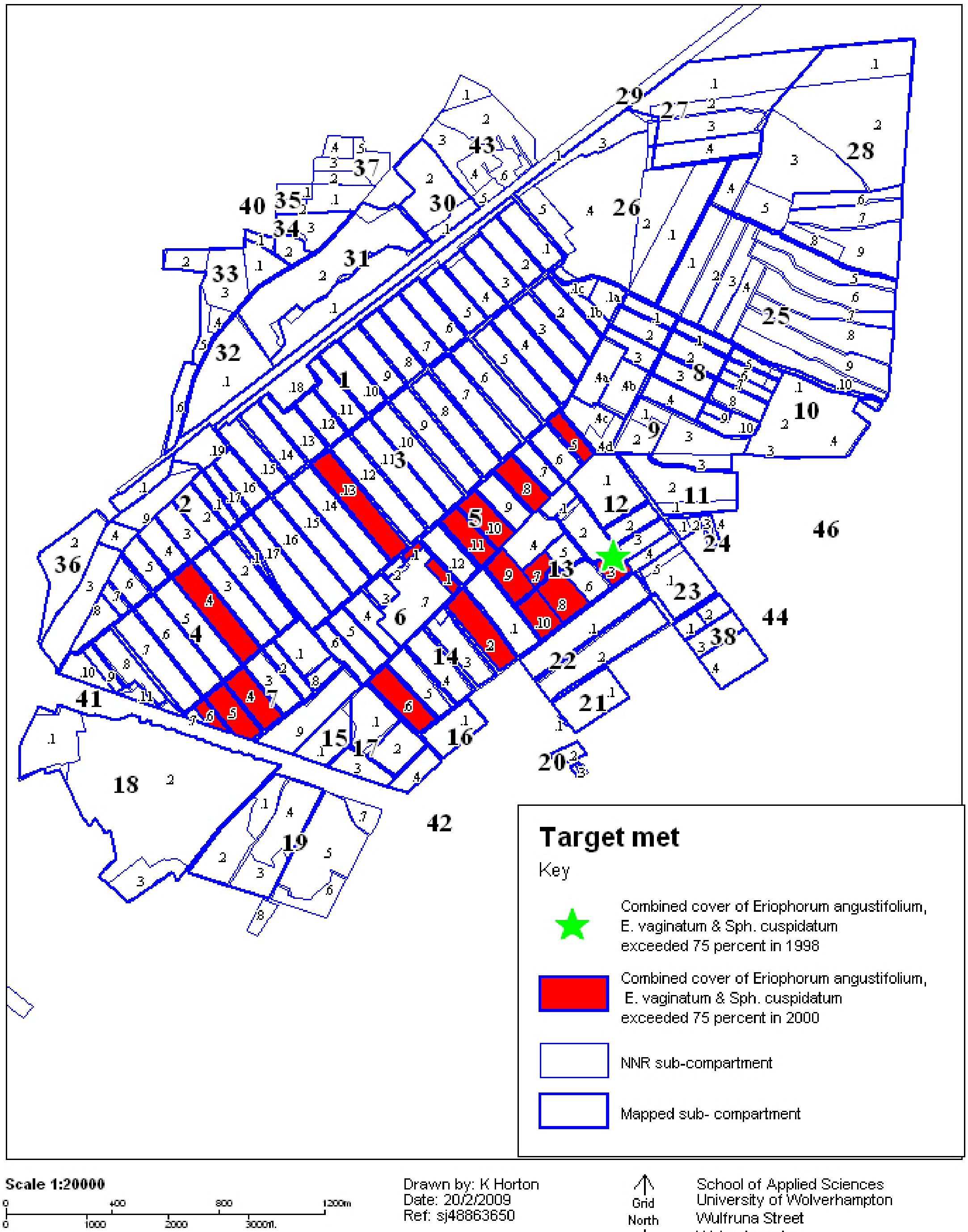
University of Wolverhampton

Map 4.5 Fenn's, Whixall & Bettisfield Mosses National Nature Reserve

Mapped Sub-compartments achieving Management Plan Targets



Drawn by: K Horton
Date: 20/2/2009
Ref: sj48863650

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Map 4.6 Fenn's, Whixall & Bettisfield Mosses National Nature Reserve

Percentage Cover of Calluna vulgaris

Not to scale

Compiled by: Karen Horton Date: November 2005

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Map 4.7 Fenn's, Whixall & Bettisfield Mosses National Nature Reserve

Percentage Cover of Molinia caerulea

Not to scale

Compiled by: Karen Horton Date: November 2005

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Map 4.8 Fenn's, Whixall & Bettisfield Mosses National Nature Reserve

Percentage Cover of Bare Peat

Not to scale

Compiled by: Karen Horton Date: November 2005

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