Sphagnum in the Peak District Current Status and Potential for Restoration

Moors for the Future Report No 16

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Moors for the Future Partnership

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Literature Survey

Loss of *Sphagnum* from the Peak District blanket bogs is likely to be due to a number of factors, including inappropriate land-use, burning, grazing, drainage and climate change.

The high levels of sulphur dioxide and associated sulphur and acid deposition over the last 100 years are however considered to be the major factor. These levels have now fallen dramatically, but nitrogen deposition remains high.

Sphagnum species and bryophytes generally are now returning to the Peak District but recovery is slow and conditions may still not be suitable for many species.

Intact Ombrotrophic Mires

A key feature of blanket bog is the occurrence of ombrogenous peat on hill slopes (>10 ^{o}) with rainfall > 1200mm a^{-1} and 160 wet days per year. Acrotelm is defined as the active functional horizon, containing living and dead plant remains. It is a largely aerobic layer, with strong microbial activity usually <50cms in depth, with water moving freely through it. A high and stable water table within the acrotelm is usually given as the condition for successfully functioning bog.

Intact ombrotrophic bogs are mainly rainwater fed and the soil solution chemistry should generally approximate to the rainfall with some concentration due to evaporation. pH values of around 4 are typical. Sulphate concentrations are generally lower, but sometimes higher than would be expected from rainfall input. Ammonium ions are present in substantial concentrations in rainwater, but at much lower or undetectable levels in ombrotrophic bog surface waters. Bog water nitrate concentrations should rarely be above 62 µg l^{-1} in unpolluted systems.

Conditions in Polluted Mires

Conditions in polluted mires are often very different. Ammonium (NH_4^+), nitrate (NO_3^-) and sulphate (SO_4^{2-}) ionic concentrations in bog water at Holme Moss in 2005 were still much higher than those from cleaner areas in Wales. Higher concentrations were also obtained for a range of other ions. Current SO_4^{2-} concentrations are however well below toxic levels as defined by Ferguson and Lee (1978) for toxic effects on *Sphagnum* growth.

The deposition of large quantities of sulphuric acid leads to acidification and displaces calcium, magnesium and potassium from peat-binding sites, leading to increased leaching and nutrient loss. Acidification is reduced under waterlogged conditions by the conversion of sulphate to sulphide. Wetting and drying cycles then release flushes of damaging sulphate and acidity. The breakdown of organic matter on ombrotrophic bogs also leads to the release of ammonium ions (mineralisation), and drying of the peat increases mineralisation rates, leading to the accumulation of high concentrations of ammonium especially on bare surfaces, where there is no plant uptake. Bare and eroded peats are therefore typically very acidic, (pH< 4) and high in ammonium and sulphate.

Sphagnum Ecology

Tables of ecological amplitude related to pH (Andrus 1986) show few *Sphagnum* records below approx. pH 3.5. The most tolerant species are S. *cuspidatum*, S. *fallax,* S. *fuscum, S. magellanicum, S. papillosum,* and *S. rubellum*. A pH of <4 is probably sub-optimal for many *Sphagnum* species. Growth impairment of some *Sphagnum* species has been shown at pH < 3. (Wheeler *et al*. 1995).

Calcium ions have been shown to have negative effects on *Sphagnum* growth and survival at concentrations above approximately 20 mg l^{-1} (Money 1995).

Hummock-forming species eg. *S. capillifolium*, *S. papillosum* and *S. magellanicum*, have greater water holding capacity, are more resistant to low water and pH levels, less tolerant of high ionic strength and increased nutrient inputs and tend to create their own micro - environment. Lawn/aquatic species e.g. *S. fallax* and *S. cuspidatum* by contrast have been shown to tolerate higher pH and higher nutrient inputs. *S. fallax* very notably however retains its competitive advantage under a wide range of conditions, mainly due to its high productivity under suitable conditions.

Effects of Nitrogen and Sulphur

Bryophytes, including *Sphagnum*, show rapid increases in tissue nitrogen concentration in response to increased deposition. Nitrogen concentrations in *Sphagnum* samples taken from the Peak District in 1970s were very high (15-25 mg g^{-1}) and were considered supra-optimal for growth and survival. *Sphagnum* tissue nitrogen concentrations from the Peak District are now much lower, reflecting reductions in atmospheric deposition.

Relationships between growth and survival and bog water NH_4^+ and NO_3^- concentrations are not very clear. Effects were seen at low concentrations by Press *et al.* (1986) in laboratory experiments on *S. cuspidatum.* Otherwise the data suggest negative effects on *S. fallax* and *S. magellanicum* at ammonium concentrations in the range 2.24-10.8 mg l^{-1}. Current bog water concentrations in pools from Holme Moss are <1 mg l^{-1}, but values from areas of bare peat could be higher. There was no clear pattern of negative effects for nitrate at concentrations up to 20mg l^{-1}.

Both field and laboratory experiments show no negative effects of sulphate on *Sphagnum* below 96 mg l^{-1}, and few below 480mg l-^{1}. Current bog water concentrations are well below this level, and SO_4^{2-} concentrations as such are not likely to limit *Sphagnum* recovery or regeneration, although the associated acidity could still be a problem.

Heavy Metals

Experimental studies on other mosses suggest that it is the intracellular heavy metal concentrations that are important for toxic effects. *Sphagnum* mosses are capable of binding very high concentrations of heavy metal ions in their cell walls, and this may protect them from toxic metal effects.

Heavy metals form stable complexes with soil organic matter. Concentrations in soil water are dependent on pH and the other ions present in solution. Peak District heavy metal soil solution concentrations are significantly below thresholds identified for effects on micro-organisms and vascular plants, with the possible exception of lead and zinc.

Lead concentrations in *Sphagnum* tissue have however fallen dramatically when compared with data from 1978, and are now lower in the Peak District than they were in unpolluted areas in 1978, which does not suggest any obvious toxic effect on *Sphagnum* at current levels of exposure.

Approaches to Restoration

A number of approaches have been taken to the restoration of *Sphagnum* rich bog surface, almost entirely in the context of raised bog restoration, usually following peat extraction. There is very little specific information available on blanket bogs. The methods applied generally assume a high and stable water table as an essential precondition, and secure this by initial landscaping work of various types.

In the Canadian/USA approach, the provision of suitable hydrological conditions is followed by the introduction of diaspores (a thin mulch of *Sphagnum*-rich bog “surface”) collected from an undamaged area and spread as a thin layer on the bare peat surfaces to be restored. This surface is then protected from dessication by straw mulch, followed in some cases by fertilization with phosphorus.

The UK methodology developed by Wheeler, Money and Shaw (see section 2.7.4) is again based mainly on work on raised mires. Suitable hydrology is considered crucial and some natural regeneration is usually present. Nurse crops are sometimes used. *Sphagnum* regeneration in trial pits has been shown to be dependent on consistently high water levels.

Regeneration of hummock species in these studies was facilitated by an initial template of aquatic species such as S. *cuspidatum*, which is notably resistant to periodic drying. This is considered to be linked to higher growth rates of aquatic/lawn species under favourable conditions.

Grosvernier *et al.* (1995 and 1997) however, working in the Swiss mountains, have reported successful recolonisation of bare peat areas in areas of much lower water tables than those generally considered essential in most restoration approaches. These areas were characterised by high surface humidity and rainfall, due to altitude, and also by the presence of suitable companion species. S. *fallax* was identified as a key early *Sphagnum* recoloniser in difficult conditions.

The main aim of the Peak District Blanket Bog restoration work has been to restore vegetation cover to eroded areas by liming and fertilizing, followed by the establishment of nurse crops stabilised by the application of heather brash and heather seed. *Sphagnum* regeneration has been seen in re-vegetated gullies (Crowe 2007) usually following the re-establishment of mixed *Eriophorum* cover and improved hydrology.

Sphagnum regeneration techniques have also been developed by Geoff Eyre on areas of burnt *Eriophorum* and *Molinia*-dominated moorland where the conditions were wet enough.

Collation of Existing Records

In order to provide additional information on *Sphagnum* distribution on the Peak District moorlands and to inform the final choice of survey sites, existing *Sphagnum* records for the area were collated from a number of sources.

The most common species present on the Peak District Moorlands, based on the collation of existing records, were *S. fallax, S. fimbriatum, S. palustre, S. denticulatum, and S. sub-nitens.*

The mapped data showed a wide distribution of records over the blanket bog areas of the moorland, with some indication of lower record numbers and abundance over the Bleaklow plateau, but as these were records of presence rather than absence, this must be interpreted with caution; there did not appear to be any marked clustering of particular species on the basis of these records.

Survey and Environmental Sampling

The aim of the survey work was to identify the abundance and species composition of the *Sphagnum* present on the surface of the blanket bogs rather than in the gullies or pools, and to examine their relationships with various environmental variables.

In order to meet these aims data were collected both from the Peak District moorlands, Bowland Forest and the North Pennines AONB.

In order to allow detailed comparison with environmental variables, a quadrat-based approach was adopted, with detailed species and environmental data collected from 2 x 2m quadrats, and more general information on vegetation structure, species abundance and land use noted for a wider 20 x 20m area around each quadrat.

Each quadrat was associated with a superficial peat sample, analysed for pH, % moisture, extractable ammonium, nitrate, sulphate, calcium, magnesium, copper, lead, zinc and aluminium.

Species Distribution

Sphagnum abundance and species distribution at the more northerly survey sites showed higher levels of active bog-forming species such as S. *papillosum* and S. *capillifolium*, and is indicative of “healthier” bog surface when compared with the Peak District.

Higher frequencies were obtained in the Peak District for *S. fimbriatum*, *S. subnitens* and *S. squarrosus*, whereas S. *palustre* and S. *fallax* were more frequent in Bowland and the North Pennines. No Peak District ocurrences were found for *S. magellanicum*, *S. tenellum* and *S. russowii*.

Relatively low cover levels were obtained for *S. fallax* in the Peak District, despite high numbers of records from other survey data and anecdotal reports. This may be due to the emphasis in this study on the sampling of open moorland rather than gullies or pools and suggests that surface moisture levels may be significantly lower in the Peak District when compared with the more northerly areas.

pH and Surface Moisture

pH and surface moisture was higher at the more northerly sites, and showed some correlation with *Sphagnum* cover at the quadrat level. These could be important factors in *Sphagnum* distribution.

Nutrients

Extractable ammonium and sulphate levels were significantly higher at the more northerly survey locations, and variable between survey locations within areas. There was, however, no indication of any strong correlation of ammonium with *Sphagnum* cover at the quadrat level.

Current pollution data shows similar current deposition levels for Peak District and Bowland, although levels in the Northern Pennines are significantly lower.

Factors that may be important in explaining the higher extractable ammonium and sulphate include the dominance of wet deposition in the more northerly areas and the likely lower microbial activity and plant uptake and nitrification levels in these areas, particularly during winter. Relationships with bog-water concentrations could also be very complex, with very pronounced seasonal patterns. The wide variation in ammonium levels does however suggest that local factors may also be very important.

There was no indication of a negative impact of extractable sulphate and ammonium levels on *Sphagnum* cover or species distribution.

Metals

There were some significant differences in extractable metal levels between the survey areas. Aluminium levels were significantly higher in the Southern Pennine samples, and showed a clear negative correlation with pH at all sites.

Magnesium levels in the Peak District were markedly lower and also showed some positive correlation with total *Sphagnum* cover at the quadrat level.

Calcium levels were highly variable, and showed no strong geographic pattern. Levels did however show a clear correlation with water levels, pH and magnesium content.

Extractable heavy metals did not show strong patterns across the survey sites. Copper levels were significantly higher in the Peak District, whereas zinc levels were lower.

No strong regional pattern was seen in lead levels. Comparison of lead levels with critical load data showed that the data were indicative of critical load exceedences over the whole survey area, with no strong geographical pattern.

Overall the data identify a number of differences between the Peak District and the more northerly sites that could be significant in *Sphagnum* abundance and distribution. The clearest of these are pH and moisture, although the concentrations of other nutrients and metals could be relevant.

The data obtained in this study do not show higher peat accumulations of either ammonium or sulphate in the peat samples from the Peak District when compared with the more northerly sites, despite the higher current and historical nitrogen and sulphur deposition levels to the area.

Overall nitrogen and sulphur deposition to the Pennines overall has been high over the past 100 years. One important difference between the Peak District and Bowland and the North Pennines, however is likely to be the dominance of wet deposition at the more northerly sites, with much lower atmospheric concentrations of nitrogen oxides and sulphur dioxide, and this may have protected the bog vegetation.

In conclusion, the data obtained in this study do not identify any key limiting factors likely to constrain the regeneration of *Sphagnum* in the Peak District seriously, but do suggest that moisture levels and pH could be important.

Overall Conclusions and Main Recommendations

The data presented in the literature review show a pattern of peat and water chemistry for the Peak District that clearly reflects a legacy of industrial and notably atmospheric pollution.

The analysis presented, however, suggests that in most cases current levels of nitrogen, sulphur and heavy metals are not likely to prevent *Sphagnum* growth, although pH values are still low.

There was general agreement in the literature that a high and stable water table was an essential requirement for successful *Sphagnum* regeneration, but most of the work carried out has been on raised bogs at lower altitude. There is some indication that at high altitude, under conditions of high humidity and rainfall, this condition may not always need to be met.

The literature review findings are borne out by the results of the survey and associated environmental sampling, which shows higher *Sphagnum* cover and diversity at the more northerly locations, associated with higher pH and peat moisture content.

Sphagnum cover and diversity were also not strongly correlated with peat extractable ammonium or sulphate content, which were higher at a number of the more northerly locations than in the Peak District.

Overall the results suggest that the higher *Sphagnum* cover and diversity of the more northerly locations, although influenced by a number of factors, are most likely to be due to the fact that the integrity of the bog surface never suffered the major damage that occurred in the Peak District.

Based on these points therefore, the key requirement for the restoration of an actively growing *Sphagnum* surface on restored areas of the Peak District will be the provision of a suitable microclimate with stability, shelter, moisture and pH as the key issues.

The various restoration approaches emphasize the need for moisture retention at the surface, using mulches and nurse crops to achieve this aim, and in some cases the use of phosphorus fertilizer.

S. *fallax* is identified in a number of studies as the colonising species of choice for nutrient-rich conditions, although the results of the survey suggest that it is not very frequent across the open surface of the Peak District moorlands.

The analyses carried out in this survey have not included a high representation of the highly degraded areas which form a major part of the restoration programme, where pH and ammonium levels could present more of a problem. Similarly the continued applications of lime and fertilizer to the restored areas could also have long-term effects. Monitoring of peat chemistry throughout the restoration process is therefore very important, and will yield essential additional information.

1. INTRODUCTION

1.1 Context and Aims of the Project

Large areas of the blanket bogs of the Peak District are currently in an unfavourable condition, with very significant areas of bare peat (8%), and high levels of gullying and erosion. A number of factors are likely to have led to this situation including over-grazing, wildfires and climatic factors. A major factor, however, is considered to be the high levels of atmospheric pollution.

The very high levels of sulphur dioxide and acidic deposition in particular, which were a feature of the area over many decades from the 1850s onwards, are thought to have led to the almost complete disappearance of *Sphagnum* mosses from areas where they were once a dominant component of the vegetation. Atmospheric sulphur dioxide levels have fallen dramatically over the last 40 years, and studies have shown that *Sphagnum* mosses and other bryophytes are now returning to the moorlands. However, recovery is slow and many areas remain in a highly degraded condition; a number of factors could be responsible for this. High levels of acidity, sulphate and heavy metals have been retained on the peats of the Southern Pennines; atmospheric nitrogen deposition to the Southern Pennines has also been high over the last thirty years, leading to significant accumulation of ammonium ions. Grazing levels are now much lower over large areas of the Southern Pennines, but in many areas the loss of vegetation cover has altered the hydrology, leading to repeated cycles of drying and erosion. Recovery in more suitable areas may also be slowed by the absence of suitable propagules.

Restoration work on the degraded blanket mires of the Peak District has concentrated on establishing vegetation cover on bare surfaces to prevent further erosion, and to form a baseline for further restoration (Anderson *et al.* 1997). Only recently has attention turned to attempting to restore the hydrological integrity of damaged blanket mires. Achieving this would provide the conditions in which *Sphagna* could thrive.

Full restoration of the blanket mires to favourable, and ideally to “peat forming” status would require the restoration of a significant proportion of *Sphagnum* cover to the area. *Sphagna* are just beginning to re-colonise naturally, but the opportunity to facilitate this recovery and introduce *Sphagna* to the moorlands is the subject of this study.

The overall aim of this research project was therefore to provide the information required to inform a pilot *Sphagnum* restoration project on the blanket bogs of the Peak District. The project comprised:

1.2 Literature Review

- Providing a comprehensive review of the information available on the growth requirements of a range of *Sphagnum* species relevant to the study area, and on possible limiting factors relating to atmospheric pollution, peat chemical and physical properties, land use etc.
- Collation of available information on peatland restoration techniques as these relate to the re-establishment of *Sphagnum* species, with the aim of establishing a set of guidelines for *Sphagnum* re-establishment as part of a wider moorland restoration programme.

1.3 Collation of Existing *Sphagnum* Records for the Peak District

- The collection and GIS mapping of existing data on *Sphagnum* species and abundance on the Peak District Moorlands, using data from a number of sources, including PAA field notes, Natural England Condition Assessment results, and records collected by other local recorders

1.4 A Survey of *Sphagna* Distribution in the Peak District and Control Areas in the North Pennines and the Forest of Bowland

- Use of a quadrat technique to survey the abundance and species composition of *Sphagnum* species at survey sites across the Peak District and in more northerly locations in the Forest of Bowland and North Pennines AONB.
- Collection of data on other species present in the quadrats and surrounding area and on range of other environmental variables eg. land-use, altitude, drainage etc.

1.5 *Sphagnum* Survey carried out by PDNPA Ranger Service

- Collection and identification of *Sphagnum* samples and simple environmental data by PDNPA rangers in the course of their work.

1.6 Environmental Sampling

- Laboratory analysis of peat samples collected from around each quadrat for moisture content, pH, extractable ammonium, nitrate and sulphate, and a range of metals.

1.7 Data Analysis

- Analysis of the data collected from the survey and environmental sampling, with the aim of identifying any factors that might affect the distribution and abundance of *Sphagnum* species across the three survey areas,

2. SPHAGNUM LITERATURE REVIEW

2.1 Context and Aims of the Project and the Literature Review

Restoration work on the degraded blanket mires of the Peak District has concentrated on establishing vegetation cover on bare surfaces to prevent further erosion, and to form a baseline for further restoration (Anderson *et al*. 1997). Only recently has attention turned to attempting to restore the hydrological integrity of damaged blanket mires. Achieving this would provide the conditions in which *Sphagna* could thrive.

A significant feature of change in the Peak District blanket peats has been the loss of *Sphagnum* mosses on these areas since the industrial revolution. Full restoration of the blanket mires to favourable, and ideally to "peat forming" status would require the restoration of a significant proportion of *Sphagnum* cover to the area. *Sphagna* are just beginning to re-colonise naturally, but the opportunity to facilitate this recovery and introduce *Sphagna* to the moorlands is the subject of this study.

The overall aim of this research project is therefore to provide the information required to inform a pilot *Sphagnum* restoration project on the blanket bogs of the Dark Peak. The project comprises:

- Collation of existing *Sphagnum* records for the Peak District;
- A literature review;
- A survey of *Sphagna* distribution in the Peak District and other sample moorlands;
- The collection of environmental data; and
- Data analysis and preparation of a final report.

The aims of the literature review presented here are to review:

- The ecology of *Sphagnum* species;
- The chemical and physical conditions required for successful establishment of *Sphagnum* cover;
- Current conditions on the Peak District blanket bogs, and the legacy of industrial pollution; and
- The restoration projects that have sought to re-establish *Sphagnum* cover on degraded moorlands.

2.2 Introduction and Historical Background

A number of important moorland Sites of Special Scientific Interest (SSSI) within England, including those in the Dark Peak area of the Peak District, are currently in an unfavourable condition when assessed according to the JNCC common standards framework monitoring; these include sites established over areas of deep peat. One of the key reasons for this unfavourable condition is the absence or low abundance of *Sphagnum* species within the vegetated areas. From palaeoecological and botanical records it is evident that the current rarity of *Sphagnum* is not a recent phenomenon with Moss (1913) mentioning the degradation and paucity of *Sphagnum* circa 100 years ago.

The blanket bogs of the Southern Pennines are unquestionably the most modified and degraded in the British Isles. Some 8% of the total peat surface in the Southern Pennines is now bare, and peat is currently being eroded away at rates of up to 3cm year -1 (Tallis 1997) Gullying affects 74% of the peat blanket, and recent work suggests that some of this could have originated as long ago as 500 – 700 years during periods of drier and warmer climate in medieval times (Lamb 1985).

The blanket bogs of the Southern Pennines have been the subject of a great deal of research, much of which is summarized in Phillips, Yalden and Tallis, (1981) and updated in Anderson *et al*. (1997) and Holden *et al*. (2007). These mires have been subjected to a unique combination of environmental conditions. The area is surrounded by an urban population in excess of five million and receives lower annual rainfall and suffers higher summer temperatures than most other British mires. It has also very notably been exposed to unprecedented levels of atmospheric sulphur dioxide (SO_2), acid and sulphur deposition. These mires now have the largest accumulation of acid deposition of any region in the British Isles or indeed in Europe (Skeffington *et al*. 1997).

Blanket bog degradation in the Southern Pennines has led to reduced floristic diversity, loss of *Sphagnum* species, increasingly discontinuous plant cover and reduced productivity and peat accumulation.

A few species have reached increased dominance (notably *Eriophorum vaginatum* and *Empetrum nigrum*) with increasing scarcity of others. Local floras of the 1850s for instance record a much greater presence of *Andromeda polifolia*, *Vaccinium oxycoccos* and *Drosera rotundifolia* (Grindon 1859).

Peat stratigraphy shows quite clearly that *Sphagnum* species were abundant on many of the South Pennines mires as recently as 250 years ago, whereas there are now only a few very small areas of blanket bog where ombrotrophic *Sphagnum* species survive (Conway 1954, Montgomery and Shimwell 1985, Conlan 1991). This disappearance coincides with the first appearance of soot particles in the peat profile, strongly implicating air pollution in this loss, a point which receives strong support from studies showing clear sensitivity of *Sphagnum* species to gaseous and solution products of SO_2 pollution (Tallis 1964, 1995, 1997, Ferguson and Lee 1978).

It is very likely that both the decline in mire condition and the loss of *Sphagnum* can be attributed to a variety of main factors acting in combination, namely climate change, inappropriate burning and grazing, trampling and atmospheric pollution.

Wildfires have been a significant feature of Peak District history with high incidences recorded during periods of prolonged summer drought, and increased frequency of managed burns has also been a feature over the last 50 years (Anderson *et al.* 1997, McMorrow *et al.* 2008).

The high levels of sheep grazing since the 1950s, with an up to four-fold increase in sheep numbers, is also likely to be a significant factor and exclosure studies and grazing level reductions have led to substantial improvement in vegetation cover over a period of ten years although no specific data is available for *Sphagnum* mosses Anderson and Yalden 1981, Anderson *et al.* 1997).

However, it is thought that the effects of air pollution are likely to be the most influential in many upland areas sited close to industrial centres (Tallis 1997, Phillips *et al*. 1981, Anderson *et al.* 1997, Caporn and Emmett 2008).

Total deposition of oxidised sulphur over Europe has been calculated for the period 1880 – 1991 using the EMEP model (Mylona 1993). These figures show that over this period the Southern Pennines received the highest anthropogenic deposition in Europe totalling 6400 kg S ha^{-1}, equivalent to 1litre of concentrated sulphuric acid on every m^2. Comparative figures for the Southern Pennines and other blanket bog areas are shown in Table 2.1 below.

Table 2.1 Comparative Figures for the Total Deposition of Oxidised Sulphur to Blanket Bogs over the Period 1880 – 1991

Location	**Deposition of Oxidised Sulphur (kg S ha^{-1})**
Southern Pennines	6400
North Pennines	1580
Central Scottish Highlands	1000
North-Western Scotland and Ireland	400

Sulphur dioxide concentrations over the Peak District and acid deposition have fallen sharply and dramatically since the early 1960s (see Figures 2.1 and 2.2) and are now below the critical levels established in 1990s (UK CLAG 1996) for the protection of vegetation, including mosses and lichens. The continued impact of acidified soils must however be taken into consideration.

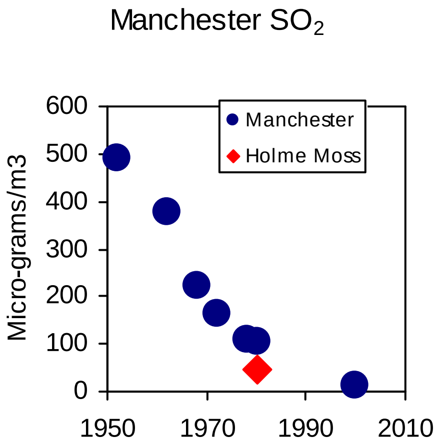

Figure 2.1 Decline in Atmospheric SO_2 Mean Annual Concentration in Manchester. Data also for Holme Moss (diamond symbol) in 1980 (Ferguson & Lee, 1983), (except for the Most Recent Date from the UK Air Quality Archive)

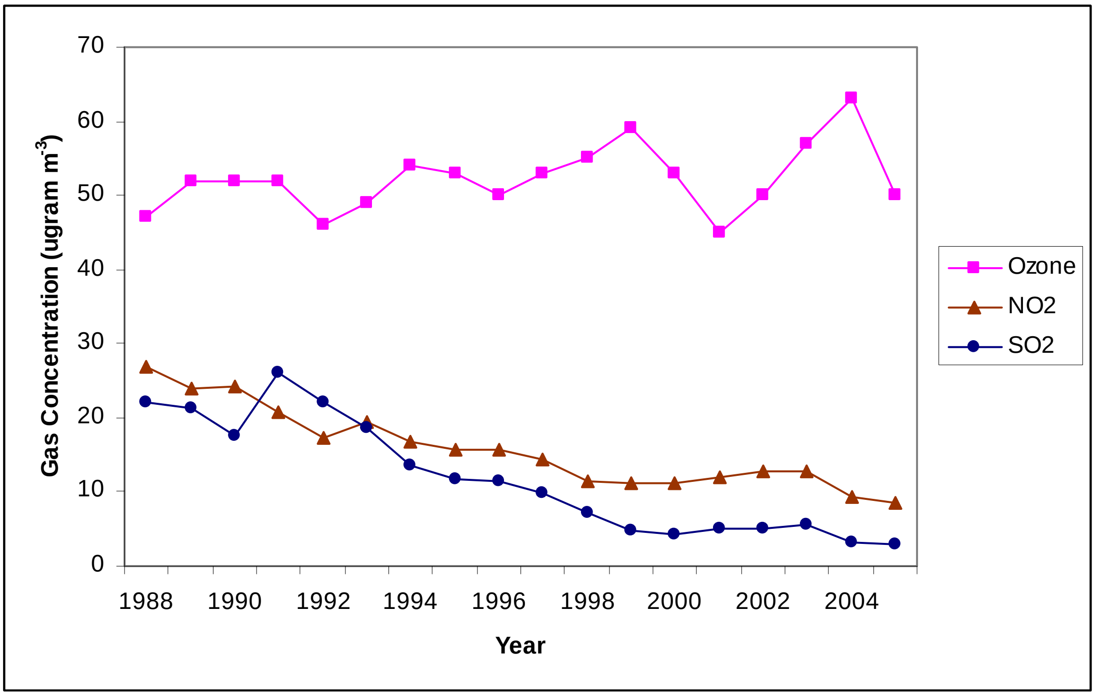

Figure 2.2 Changes in Gaseous Concentrations of Major Air Pollutants at Ladybower and in Ionic Concentrations of Major Solutes in Wet Deposition at Wardlow (SK179740). Data courtesy of the UK Air Quality Archive

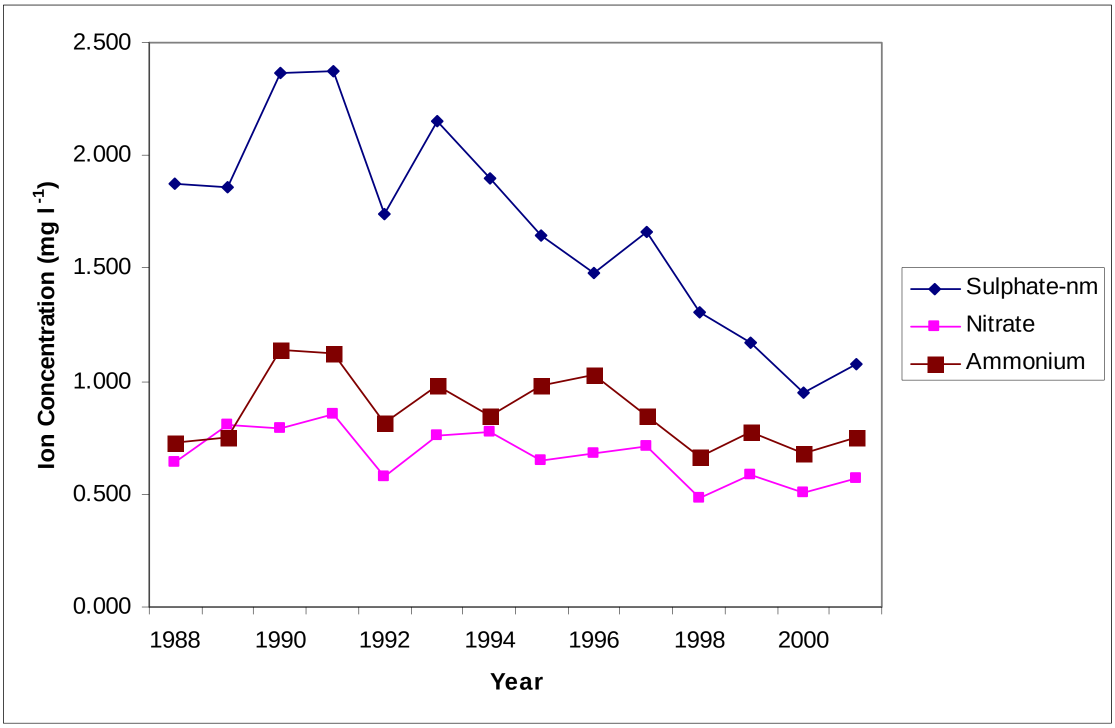

Figure 2.3 Rainfall concentrations of major solutes for Wardlow weather station (SK179740). Data courtesy of the UK Air Quality Archive

Since the 1980s the fall in sulphur dioxide pollution has continued (Figure 2.1) but other major air pollutants such as nitrogen compounds and ozone have not changed in the same way (NEGTAP 2001, Fowler *et al*. 2005).

Atmospheric nitrogen oxide (NOx) concentrations reached a maximum in most urban areas in the early 1990s (NEGTAP 2001) and are now falling, but the decline in emissions of ammonia, derived mainly from agricultural sources is much slower. Atmospheric nitrogen deposition, mostly in the form of ammonium (NH_4^+) and nitrate (NO_3^-) ions in rainfall, has however not declined markedly over the same period (see Figure 2.2).

From the mid 1970s onwards, prompted by the observed decline in sulphur air pollution (Ferguson and Lee 1983a), two re-introduction experiments were established at Holme Moss on an intact peat surface with a high water table (Ferguson and Lee 1983b). The first experiment involving the re-introduction of five ombrotrophic *Sphagnum* species, *S. papillosum*, *S. magellanicum*, *S. capillifolium*, *S. tenellum* *S. imbricatum*, plus the minerotrophic species *S. recurvum* failed, but a second resulted in a number of species surviving for several years, at least from the early 1980s. The minerotrophic species *S. recurvum* (now known as *Sphagnum fallax*), which was locally fairly widespread on mire surfaces in the Southern Pennines survived both experiments. Large increases were seen in the total nitrogen content of the transplanted mosses (Press *et al*. 1986, Ferguson *et al*. 1984), and laboratory studies showed inhibition of growth and key enzyme activities at NH_4^+, NO_3^- and sulphate (SO_4^{2-}) concentrations well within the range found in rainwater and bog water samples from Holme Moss. These results were interpreted as evidence of continuing effects of air pollution on the viability of bryophyte populations.

During the 1980s a series of studies was undertaken of Southern Pennine bog pools and their vegetation. In particular, Dr Colin Studholme surveyed apparently permanent bog pools for the presence of the ombrotrophic species *S. cuspidatum* (Studholme 1989). He also recorded the presence of all bryophytes within a 100m radius of the pools. Studholme surveyed 17 sites from the Kinder massif northwards, as well as Ringinglow Bog. He found *S. cuspidatum* at only three localities: Holme Moss, Alport Moor and Ringinglow Bog. The survey was carried out between 1983-1986, following a period of sharply declining sulphur dioxide concentrations in the surrounding industrial cities, dating back to the 1940s (Figure 2.1).

Since the 1980s sulphur pollution levels have continued to fall markedly, but nitrogen deposition and ozone concentrations have not followed the same pattern, and continue to remain high over the Peak District Moorlands. Against this background Simon Caporn, with the help of John Lee and Colin Studholme, repeated some of this original work during 2005 (Caporn *et al*. 2006).

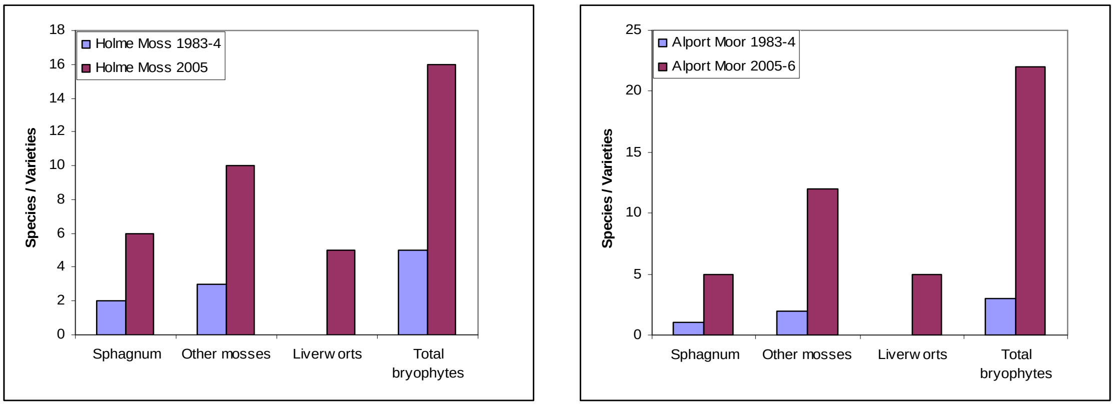

Figure 2.4 The Increase between 1983-5 and 2005-6 in the Number of Species (or Varieties) of *Sphagnum*, other Mosses and Liverworts at Holme Moss and Alport Moor

Table 2.2 *Sphagnum* Moss Species Found in Ombrotrophic, Un-marked Plots at Two Sites in the Dark Peak SSSI in the Period 1983-4 Reported by Studholme (1989) and in 2005-6 (Caporn *et al.* 2006)

	1983-1984		2005-2006	
	Holme Moss	**Alport Moor**	**Holme Moss**	**Alport Moor**
S. cuspidatum	●	●	●	●
S. fallax ssp. *fallax*			●	
S. fallax ssp. *isoviitae*			●	
S. fimbriatum	●		●	●
S. palustre				●
S. papillosum			●	●
S. subnitens			●	●

The results (see Figure 2.4) showed a marked recovery in total bryophytes and *Sphagnum* species in 2005 both at Holme Moss and Alport Moor, when compared with 1983-1985. Table 2.2 shows the *Sphagnum* species identified on both dates. The results show clear evidence of the spread of *Sphagnum* species between these two sampling dates. Overall however, the cover and frequency of *Sphagnum* species in the area still appears low when compared with areas further north (see later sections). This could be due to a number of factors, including the absence of suitable propagules (fragments or spores), hydrology, water or peat chemistry and atmospheric conditions. The relative importance of these factors will be explored further in later sections of the report.

In Summary:

Loss of *Sphagnum* from the Peak District blanket bogs is likely to be due to a number of factors, including:

- Burning: managed burns and wildfires;
- High grazing levels;
- Drainage;
- Atmospheric Pollution;

The high levels of sulphur dioxide and associated sulphur and acid deposition over the last 100 years are considered to be the major factor.

These levels have now fallen dramatically, but nitrogen deposition remains high.

Sphagnum species and bryophytes generally are now returning to the Peak District but recovery is slow and conditions may still not be suitable for many species. Reasons for this could include:

- Changes in hydrology;
- Lack of suitable propagules;
- Continued unsuitability of water or peat conditions;
- Climate change.

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2.3 BOG COMMUNITY STRUCTURE AND SPHAGNUM ECOLOGY

2.3.1 Structure and Chemistry of Intact Ombrotrophic Mires

2.3.1.1 Structure and Plant Communities

As predominantly rain-fed systems, blanket mires are closely controlled by climate, requiring high precipitation and low evaporative losses for their maintenance. Lindsay *et al.* 1988 identified the following criteria as necessary for the maintenance of blanket bog:

- Mean rainfall >1000mm per year;
- Warmest month mean temperature <15^{o}C;
- Limited seasonal temperature variability.

Northern Scotland contains the greatest single expanse of blanket mire from upland sites at 500m to coastal fringes at 50m, whereas in contrast in the Southern Pennines blanket bog is only found above 500m, due to the higher summer temperatures below this level. The warmer and drier summers associated with climate change could therefore have a significant impact on these types of mire (Crowe 2007).

The key distinguishing feature of blanket mire was defined by Wheeler and Shaw (1995) as the occurrence of ombrotrophic peat on hill slopes with a slope of greater than 10 degrees, with rainfall > 1200mm a^{-1} and 160 wet days per year. These authors thought that it was “Far from clear that blanket mires were fundamentally different in origin and general form from the raised mires of drier climates.” This point is relevant, in that a significant amount of the work reviewed here is based on studies on raised bogs, particularly in the restoration section.

Mires can be considered as consisting of two layers:

- **Acrotelm**: The active functional horizon, containing living and dead plant remains. This is usually <50cms in depth, with water moving freely through it. Water movement and fluctuations keep it largely aerobic and this is the area of strongest microbial activity. An intact acrotelm is critical to the normal development and functioning of an intact mire surface and plays a major role in holding water levels close to the surface. The water table should lie within this layer for successful functioning of the mire surface. The boundary of the acrotelm can be defined as the minimum level of the water table in summer in intact mire (Proctor 1995).
- **Catotelm**: Defined as the zone of permanent saturation. This comprises the bulk of the peat in the system. This layer is well consolidated and strongly humified. The catotelm generally lies below the permanent water table and is therefore anoxic most of the time, leading to very slow rates of further decomposition.

Active blanket mire, defined as supporting a significant area of vegetation that is normally peat forming, is considered to be a priority habitat under the EU Habitats and Species Directive (92/43/EEC) and supports important plant and animal species (Thompson *et al*. 1995).

Key ombrotrophic blanket communities are shown below (Rodwell 1991). Many of these communities are typical of more oceanic or more unpolluted conditions than those of the Southern Pennines.

- M1. *S. auriculatum* bog pool;

- M2 *S. cuspidatum/S. recurvum* bog pool community; *S. recurvum* sub-community;
- M15 *Scirpus cespitosus – Erica tetralix* wet heath
- M17 *Scirpus cespitosus - Eriophorum vaginatum* blanket mire;
- M18 *Erica tetralix – S. papillosum* raised and blanket mire
- M19 *Calluna vulgaris-Eriophorum vaginatum* blanket mire;
- M20 *Eriophorum vaginatum* blanket and raised mire; species-poor sub-community;
- M25 *Molinia caerulea-Potentilla erecta* mire.

In Summary:

- Key feature of blanket bog is the occurrence of ombrogenous peat on hill slopes (>10 ^{o}) with rainfall > 1200mm a^{-1} and 160 wet days per year.
- Acrotelm: active functional horizon. Contains living and dead plant remains. Usually <50cms in depth, with water moving freely through it. Largely aerobic with strong microbial activity.
- High and stable water table within intact acrotelm usually given as condition for successfully functioning bog surface.
- Boundary of acrotelm can be defined as minimum level of water table in summer.

2.3.1.2 Bog Water and Peat Chemistry

Intact ombrotrophic bogs are by definition rainwater fed (Proctor 1995). The soil solution chemistry of unpolluted mire therefore generally shows some approximation to rainfall under pristine conditions with some concentration due to evaporation, and a strong oceanic gradient.

The pH is typically less than 4, with hydrogen ions (H^+) as the dominant cation and SO_4^{2-} as the dominant anion.

SO_4^{2-} concentrations in an unpolluted system are generally lower than would be expected from rainfall input.

NO_3^- and NH_4^+ are present in substantial concentrations in rain water, but at much lower or undetectable levels in ombrotrophic bog surface waters (Proctor 1995), due to rapid uptake by plant and microbial communities. Mire surfaces act as efficient sinks for both NO_3^- and NH_4^+ ions. Mean NO_3^- concentrations in rainfall over ombrotrophic bogs range from 0.248mg l^{-1} in unpolluted areas of the Western Highlands to 2.4mg l^{-1} in the North York Moors and Southern Pennines. It is rare however, to measure concentrations in bog surface waters above 62 µg l^{-1}, except during near freezing conditions, when biological processes are inhibited, (Proctor 1995).

Gorham in 1956 recorded concentrations of 4mg l^{-1} Ca, < 0.186mg l^{-1} NO_{3-} – N, and < 0.095 mg l^{-1} phosphate P, in bog water surrounding *S. cuspidatum* and *S. auriculatum* at Moor House National Nature Reserve.

There is considerable temporal variation in bog surface water composition, with concentrations tending to be higher in summer due to increased evaporation (Proctor 1995).

In Summary

- Ombrotrophic mires – rainwater fed. The soil solution chemistry should approximate to the rainfall with some concentration due to evaporation.
- Typically pH </=4, with H^+ as the dominant cation and SO_4^{2-} as the dominant anion.
- Sulphate concentrations are generally lower, but sometimes higher than would be expected from rainfall input.
- NH_4^+ ions are present in substantial concentrations in rainwater, but at much lower or undetectable levels in ombrotrophic bog surface waters, (Proctor 1995).
- Proctor *et al*. (1995) suggests that bog water NO_3^- concentrations should rarely be above 62 µg l^{-1} in unpolluted systems.

2.3.1.3 Conditions in Polluted Mires

Conditions in polluted mire systems may however be very different. Figure 2.5 and Table 2.4 show the concentrations of the major pollutant ions in bog water samples collected from Holme Moss and from the Migneint in Wales (Caporn *et al*. 2006). The approximate rainfall concentrations for Wardlow are shown in Table 2.3.

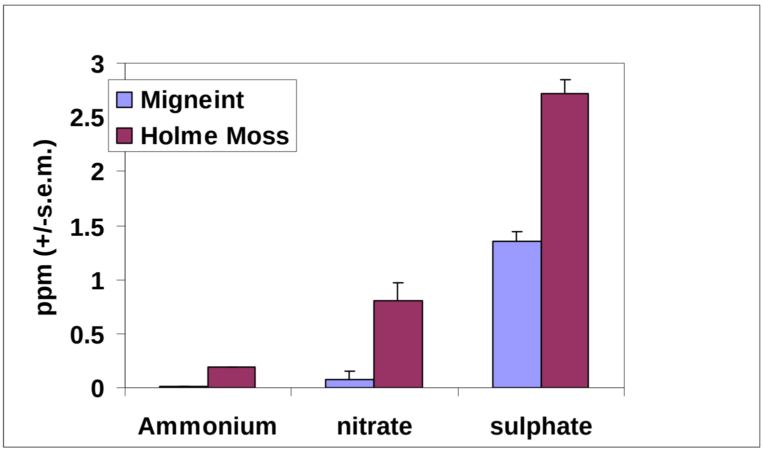


Figure 2.5 Major Pollutant ions in Bog Pool Water at the 'Clean' Site at the Migneint, North Wales and Holme Moss Sampled in January 2006

Table 2.3 Approximate Rainfall Averages for 2000 (Wardlow) (Caporn *et al.* 2006)

	Rainfall Concentration (mg l^{-1})
Sulphate (SO_4^{2-})	1.2
Nitrate (NO_3^-)	0.6
Ammonium ($NH4^+$)	0.8

The data in Figure 2.5 therefore show values not far removed from local rainfall for NO_3^-, and lower for NH_4^+, although the values for NO_3^- are tenfold higher than those suggested in Proctor *et al.* (1995) for unpolluted mires.

SO_4^{2-} concentrations of 10.4mg l^{-1} and 23.7mg l^{-1} were obtained for Holme Moss and Moss Moor respectively by Proctor and Maltby 1998, suggesting that levels are now considerably lower, and well below the value of 96mg l^{-1} SO_4^{2-} quoted by Ferguson and Lee (1978) for negative effects on the growth of *Sphagnum*.

Table 2.4 Concentrations of Major Soluble Inorganic Ions in Bog Pool Water Sampled from the Migneint, North Wales and Holme Moss in January 2006. Units are mg $l^{-1}$of the compound or single element as appropriate; values are average of eight pools in each locality. Two-tailed t-test, significant differences between site: * = p<0.05, **p<0.01, ***p<0.001 (Caporn *et al.* 2006).

		Migneint	Holme Moss	Ratio HM/M	T-Test
mg l^{-1}	Ammonium (NH_4^+)	.0137	.187	13.6	*
	Nitrate (NO_3^-)	.082	.812	9.8	***
	Phosphate	.062	.126	2.0	NS
	Sulphate (SO_4^{2-})	1.38	2.72	2.0	***
	Iron (Fe)	.268	.432	1.6	***
	Calcium (Ca)	.157	.319	1.6	**
	Magnesium (Mg)	.185	.257	1.3	*
	Chloride (Cl^-)	3.67	4.58	1.2	**
	Sodium (Na)	2.68	2.82	1.1	NS
	Potassium (K)	.304	.216	0.6	*
	Zinc (Zn)	.0009	.012	12.9	**
	Aluminium (Al)	.011	.0569	5.0	**
	Lead (Pb)	.0022	.0055	2.6	NS
	Manganese (Mn)	.019	.0084	0.4	NS

In Summary

- NH_4^+, NO_3^-, and SO_4^{2-} ionic concentrations in bog water at Holme Moss in 2005 were still much higher than those from cleaner areas in Wales.
- Higher concentrations were also obtained for a range of other ions.
- Current SO_4^{2-} concentrations are well below toxic levels as defined by Ferguson and Lee (1978) for toxic effects on *Sphagnum* growth.

2.3.1.4 Effects of Drying and Erosion of Peat Surfaces

The deposition of large quantities of sulphuric acid to peat surfaces is thought to lead to acidification by displacement of calcium (Ca), magnesium (Mg) and potassium (K) ions from binding sites on the peat. These ions are then leached from the system by the mobile SO_4^{2-} ion, leading to net acidification, loss of buffering capacity and a reduction in the availability of these important nutrients for plant and microbial uptake. Mineral soils have some ability to resist this process due to the replacement of these ions by weathering from rock and soil minerals, a process which is not available in deep ombrotrophic peats (Skeffington *et al.* 1997).

However, studies by Skeffington *et al*. in 1997, in which concentrations of exchangeable Ca and Mg were measured in peat from a range of ombrotrophic mires, found no relationship with total sulphur deposition, suggesting that the situation may be more complex. Ca and Mg are not generally considered to be limiting for mire species, with phosphorus and potassium more likely to limit growth under polluted conditions where nitrogen levels are high (Goodman and Perkins 1968a, 1968b, Hayati and Proctor 1991).

The process of acidification can be reduced under conditions of low oxygen availability, such as waterlogging, by the conversion of SO_4^{2-} to sulphide. However as peat dries the sulphide is converted back to SO_4^{2-}, leading to a flush of acidification, with potential release of acid to stream waters.

The breakdown of organic matter on ombrotrophic mires, leads to the release of NH_4^+ and NO_3^- ions, a process known as mineralisation. Under acidic or waterlogged conditions there is very little conversion to NO_3^- (nitrification) and NH_4^+ remains the main source of nitrogen normally available for plant uptake under pristine conditions (Lee and Stewart 1978).

This process is accelerated by drying and oxidation of the peat, (Wheeler and Shaw 1995) and where plant and microbial uptake is low, due to unvegetated surfaces, high levels of NH_4^+ can build up in the superficial peat surfaces.

Drying of peat has been observed to increase total soluble nitrogen (Piisparen and Lahdesmaki 1983, Gorham 1956). Money (1995), in studies based on Thorne Moors, found the water table on abandoned peat workings to be unstable, remaining close to the surface in winter, but falling to 80cm below the surface in the summer months. Water samples from milled peat fields at Thorne showed higher concentrations for all ions, when compared with values by other workers for undisturbed sites, with pH values in the range 3.0 – 3.6, SO_4^{2-} at 30 – 40mg l^{-1} and NH_4^+ at 5 – 30 mg 1^{-1}, compared with values of around or < 5 mg l^{-1} on undisturbed sites. These effects were suggested as due to aeration and biological oxidation due to drainage and water table instability (Money 1995).

Table 2.5: below shows pH data for bog water samples taken from the Southern Pennines by Proctor and Maltby (1998), and Caporn *et al.* (2006). The higher 2006 values could be due to seasonal differences, or to the reduction in acid inputs.

Table 2.5 Bog Water pH Values (Proctor and Maltby 1998, Caporn *et al*. 2006)

Proctor *et al*. 1998 - Sampled December 1992	
Location	**pH**
Holme Moss	3.86
Snake Pass	3.66
Moss Moor Oldham	3.34
Caporn *et al.* 2006 - Sampled May 2005	
Migneint	4.52
Holme Moss	4.18

In Summary:

- The deposition of large quantities of sulphuric acid leads to acidification and displaces Ca, Mg and K from peat binding-sites, leading to increased leaching and nutrient loss.
- Acidification is reduced under waterlogged conditions by the conversion of sulphate to sulphide. Wetting and drying cycles then release flushes of damaging SO_4^{2-} and acidity.
- Breakdown of organic matter on ombrotrophic bogs leads to the release of NH_4^+ ions (mineralisation).
- Drying of the peat increases mineralisation rates, leading to the accumulation of high concentrations of NH_4^+ especially on bare surfaces, where there is no plant uptake.
- Bare and eroded peats are therefore likely to be very acidic, (pH< 4) and high in NH_4^+ and SO_4^{2-}.

2.3.1.5 Heavy Metals

Ombrotrophic peat accumulates metals from atmospheric deposition. The metals most closely associated with toxic effects on terrestrial plants, invertebrates and microorganisms are chromium, (Cr), Nickel (Ni), zinc (Zn), mercury (Hg) and lead (Pb).

Heavy metals deposited from the atmosphere can become incorporated into the peat either directly wherever bare peat is exposed at the surface, or indirectly via the vegetation cover which later decays. Measurements of peat profile heavy metal concentrations were made by Livett *et al.* (1979) at 15 moorland sites across the UK. Considerable variation was found in both maximum and surface heavy metal concentrations, with Pb concentrations ranging from 21 µg g^{-1} to 800 µg g^{-1} and Zn and copper (Cu) in ranges 85 – 524 and 6 – 160 µg g^{-1} respectively; the sites could be divided into low and high background sites. At the low background sites Pb concentrations were between 30 – 150 µg g^{-1}, Zn a little higher, and Cu considerably lower. At the high background sites however the Pb concentrations were on average at least five times higher, and those of Zn and C also increased.

The total range for Pb concentrations in surface peat layers across all the sites was between 50 – 500µg g^{-1} and showed a clear correlation with distance to the large urban centres. A similar pattern was also seen for Cu, but Zn was more complex and less well defined.

A general pattern of Pb accumulation in decaying matter was seen, with very little movement through the peat profile even over long periods. Zn by contrast was much more mobile both in plant and soil possibly reflecting its status as an essential plant micronutrient and much more readily leached from the profile overall.

Analysis of plant material from Ringinglow Bog showed Pb concentrations in the range 18.1 µg g^{-1} for *Eriophorum vaginatum* compared with 136 µg g^{-1} for the underlying peat and 12.1 µg g^{-1} for *S. papillosum*.

Pb may be accumulated in older plant organs as a heavy metal resistance mechanism or could simply be a reflection of exposure time. This effect was not however seen in the *Sphagnum* samples.

Critical loads and limits have been set in the UK for Pb and cadmium (Cd), in line with EEC legislation (www.critloads.ceh.ac.uk). The critical load or limit is defined as "a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements do not occur according to present knowledge"

The critical limit for Pb is expressed as a soil solution concentration and is currently set at 8µg l^{-1}, derived from long-term studies on organic soils in Scandinavia. The reactive soil concentrations in equilibrium with this concentration are shown in Figure 2.6 for different upland soil types together with the distribution of the different soils, and illustrate the almost tenfold variation in sensitivity based on soil properties, with the highest values in areas where metal is most tightly bound to the soil matrix. Figure 2.7 shows the upland areas which currently exceed this critical limit and the overall critical load.

It can be seen that the Dark Peak areas of the Southern Pennines currently significantly exceed both the critical limit and the critical load for Pb, suggesting a clear potential for toxic effects on vegetation and soil microbial activity.

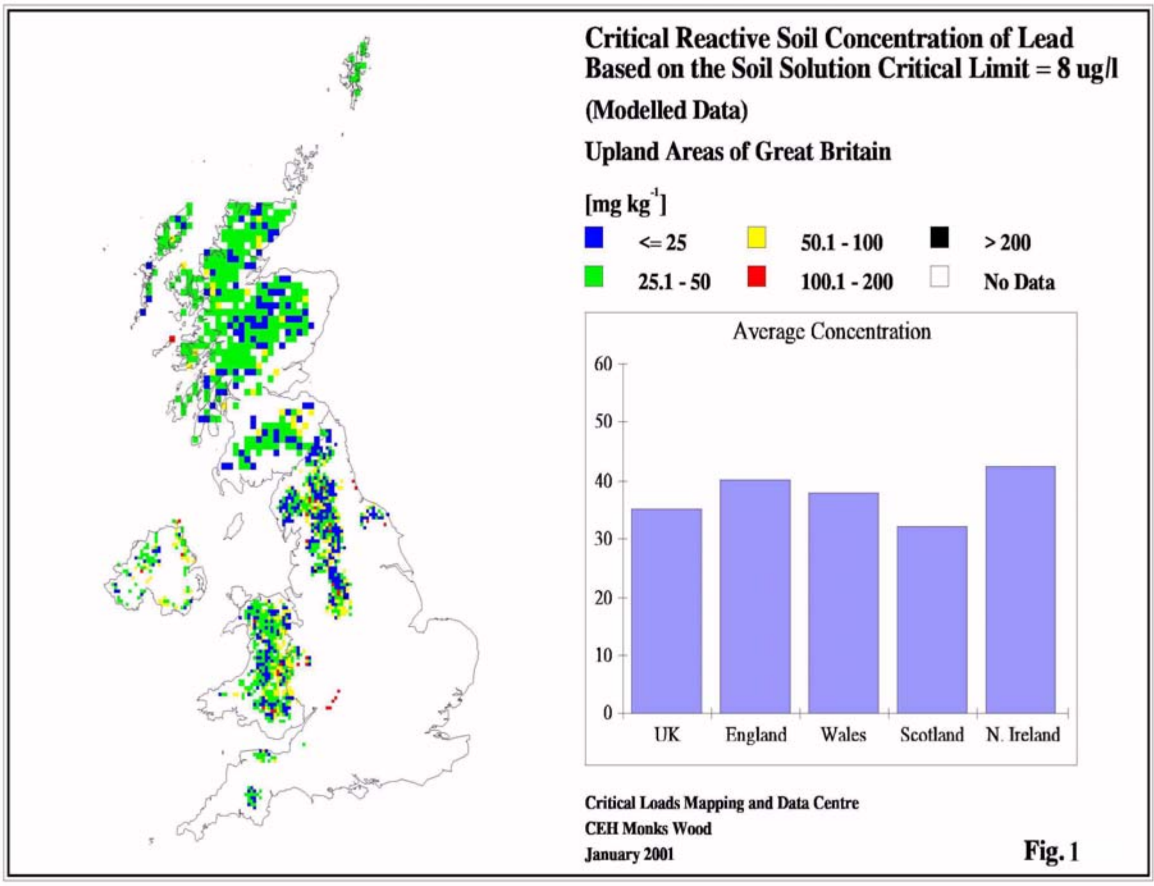


Figure 2.6 Critical Reactive Soil Concentrations of lead for Upland Areas of Great Britain, Based on a Soil Critical Limit of 8µg l^{-1} (www.critloads.ceh.ac.uk)

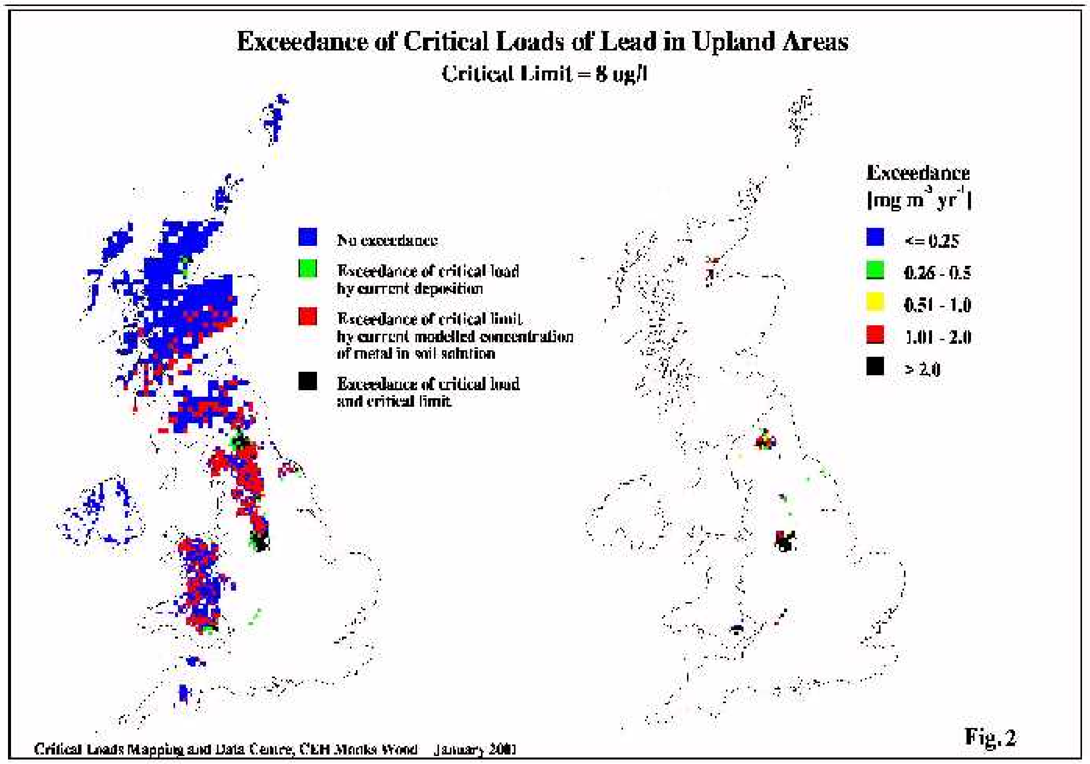


Figure 2.7 Exceedance of Critical Loads for Lead in Upland Areas (www.critloads.ceh.ac.uk)

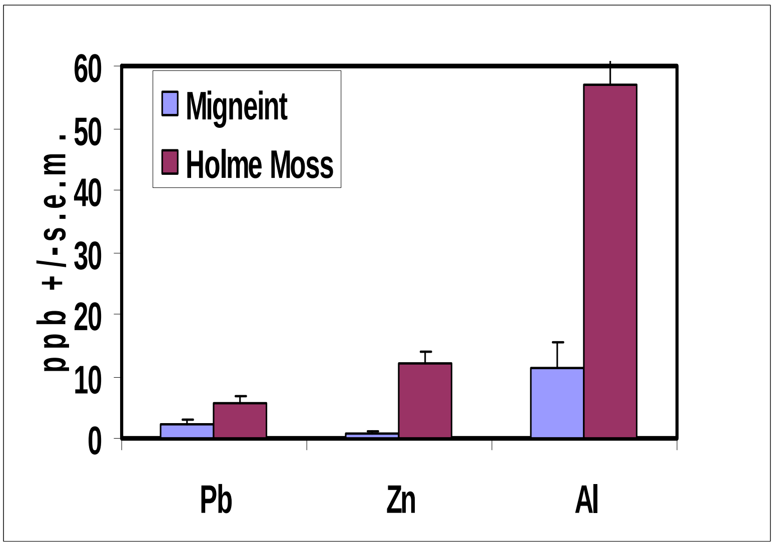


Figure 2.8 Lead (Pb), Zinc (Zn) and Aluminium (Al) Concentrations in Bog Water Samples (µg l^{-1}) Collected from Holme Moss and the Migneint (Mid-Wales) in 2005

Data for bog water samples collected in Wales in 2005 (Caporn *et al.* 2006) give values of 5.5 µg l^{-1} for Holme Moss, compared with 2.15 µg l^{-1} in Wales.

Rothwell and Evans (2005) obtained mean stream water levels for Pb for the Peak District of 5.75 µg l^{-1}, and total Pb levels in intact peat in the range 500 – 1600 mg kg^{-1}. Average Pb concentrations at Upper North Grain were 524 +/-90.4 mg kg^{-1} for intact peat, and 119+/-122 mg kg^{-1} for bare peat (Rothwell *et al.* 2007).

It is very difficult to assess the actual reactive metal concentration relevant to ecological processes. Lawlor and Tipping (2003) obtained dissolved Pb concentrations in the range 0.10 – 4.5 µ l^{-1} from three streams and two pools near to the Upper Duddon Valley and Great Dunn Fell, an area where there has been lead mining in the past, associated with pH values of between 4.89 – 7.07.

In a study on the effects of sudden pH changes on dissolved metals in polluted ombrotrophic peats (Tipping *et al.* 2003) total dissolved Pb in surface waters from sites close to urban centres in the Pennines (Stainmore and Blackstone Edge) was also measured. Values were in the range 1.49 – 10.56 µg l^{-1} at pH values of 3.7 to 4.1. Modelled data, derived from this baseline chemistry, suggested that a drop in pH of 4.3 – 3.3/3.6 (which would be possible, based on the sulphur loading of polluted sites, during rewetting periods following drought), could increase the solubility of dissolved metals such as Mg, Al, Ca, Cu, Zn, Cd, Pb by an order of magnitude or more.

In Summary:

- Heavy metal concentrations in peat and the associated bog waters from the Southern Pennines are high and exceed both the critical load and critical level for Lead (Pb).
- Concentrations of Pb, Zn and Aluminium (Al) in bog water samples were significantly higher at Holme Moss (5.5 µg l^{-1}) when compared with cleaner areas in Wales.
- Solubility of heavy metals in soil solution can increase steeply at low pH (less than 4).
- Actual reactive concentrations of heavy metal in solution that are relevant to ecological effects are very difficult to assess.

2.4 Factors Affecting the Distribution of *Sphagnum* Species on Ombrotrophic Bogs

2.4.1 Basic Sphagnum Ecology

Of all bryophyte species none has reached the ecological dominance or economic importance of the *Sphagnum* species. There are 300 species of *Sphagnum* worldwide, with the greatest bulk and diversity in the North temperate and boreal zones.

The genus is separated into sections with the more common UK species in each section summarized in Table 2.6 below (based on Smith 2004).

Table 2.6 Sphagnum Taxonomy (Smith 2004)

***Section* Sphagnum**	*S. magellanicum* *S. palustre* *S. affine* *S. austinii* *S. papillosum*
***Section* Rigida**	*S. compactum* *S. strictum*
***Section* Squarrosa**	*S. squarrosum* *S. teres*
***Section* Subsecunda**	*S. auriculatum* *S .contortum* *S. denticulatum* *S. inundatum* *S. contortum*
***Section* Cuspidata**	*S. tenellum* *S. pulchrum* *S. cuspidatum* *S. fallax*
***Section* Acutifolia**	*S. capillifolium* *S. fimbriatum* *S. subnitens* *S. fuscum* *S. russowii*

Sections *Cuspidata* and *Subsecunda* are aquatic, with the capitulum typically at the level of the free water surface. These species are generally lax in structure and lack the water holding capacity of the hummock-forming species. Section *Sphagnum* are more robust in structure and form carpets or low hummocks, whereas several species of the section *Acutifolia* including *S. capillifolium* and *S. fuscum* usually form hummocks some way above the water table (Clymo and Hayward 1982).

Sphagnum is restricted to wet and mostly acidic conditions but also plays a considerable role in creating these conditions. Various *Sphagnum* species have the ability to direct succession through acidification or paludification (Clymo and Hayward 1982).

Sphagnum leaf structure holds high levels of water and *Sphagnum* species have the ability to alter acidity by releasing hydrogen ions in exchange for dissolved cations.

As a group, *Sphagnum* species are classified as xerophytic hydrophytes, i.e. water loving plants with numerous adaptations for dealing with periodic drought conditions.

Although *Sphagnum* species vary in their ability to withstand desiccation (as will be shown in the following sections) successful establishment of *Sphagnum* species is generally agreed to require a high and stable water table at or just below the peat surface. The achievement of these conditions is generally assumed to be required in most discussions of restoration approaches, although at high altitude, and under conditions of high humidity, this may not always be necessary.

2.4.2 Calcium and Acidity

The distribution and growth rate of *Sphagnum* plants and the performance of one species relative to another are determined primarily by water supply and solute concentration, particularly Ca and acidity.

Sphagnum plants function as cation exchangers (Andrus 1986) with the exchange matrix consisting of negatively charged polyatomic acid in the plant cell walls. Many *Sphagnum* species have exceptionally high cation exchange capacities, with polyuronic acid content ranging from 10 – 30% dry weight. Positively charged ions (cations) such as hydrogen ions (H^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+) bind to these sites in proportion to their affinities and concentrations in the soil solution. The sites have the highest affinity for the divalent captions, such as Ca^{2+} and certain heavy metals. The proportion of the various ions bound to the exchange sites is therefore a function of the balance of concentrations in the soil water. High levels of Ca^{2+} binding are thought to reduce the growth of many *Sphagnum* species, but the level of binding is proportionally reduced by high concentrations of hydrogen ions (low pH) or of other solutes. The relationship between the effects of pH (hydrogen ions) and the concentration of Ca^{2+} and other positively charged solutes is therefore complex, species and site specific (Clymo 1987) and is not always easy to predict.

Most *Sphagnum* species cannot survive in water which has flowed through calcareous rocks or soils, although exceptions to this would include *S. squarrosum*, *S. teres*, and *S. fimbriatum*, which are adapted to base-rich conditions with Ca^{2+} concentrations > 40mg 1^{-1}. Clymo (1973) in a study of the relative growth of *Sphagnum* species in relation to pH and Ca^{2+} concentration found clear growth reductions for *S. papillosum*, *S. capillifolium*, *S. magellanicum*, *S. cuspidatum* and *S. recurvum* above pH 5 and 40mg 1^{-1} Ca $^{2+}$, whereas *S.subnitens S. squarrosum* and *S.inundatum* were less sensitive.

Water with a high Ca^{2+} concentration usually also has a high pH. Where these two factors have been separated (Clime and Hayward 1982), it can be seen that high concentrations of Ca^{2+} or high pH alone are not sufficient to reduce the growth rate of most species significantly. pH is generally considered more critical than ionic strength and if the pH is suitable a wider range of ion concentrations will be tolerated.

Hummock-forming species such as *S. capillifolium* seem to be particularly sensitive to combined high Ca^{2+} and pH, while immersed species are less sensitive (Clymo and Hayward 1982).

Greenhouse growth experiments conducted by Money (1994) in which *Sphagnum* species were grown for 60 days at pH 4 and >20 mg l^{-1} Ca^{2+} ion concentration showed significant growth reduction only for *S. magellanicum*. Similar experiments looking at a range of pH values found reduced growth below pH 4 for *S. cuspidatum* and *S. recurvum* and a non-significant trend below pH 3.5 for S. *magellanicum*.

Andrus *et al*. (1983), and Andrus (1986), examined the ecological amplitude of a wide range of species growing in New York State in relation to the pH of the surrounding water. The different species show a range of sensitivity with *S. magellanicum*, *S. rubellum*, *S. fallax* and *S. angustifolium* the most acid tolerant, showing growth down to approximately pH 3.5. In general however, the maximum ecological amplitude for all species was between pH 4 and 5, with no significant presence below pH 3.5.

Andrus pointed out that conditions could be deceptive for some hummock-forming species, which may in fact generate more acidic micro-environments than were measured. Bellamy and Rieley (1967) noted this for *S. fuscum*, *S. magellanicum* and *S. fimbriatum* . On the other hand the narrow pH ranges recorded for *S. capillifolium* may indicate more precise requirements.

2.4.3 Water Supply

The effects of water supply on *Sphagnum* are complex. Many hummock-forming species resist desiccation well, because of the ability of the leaf structure to hold very large amounts of water, compared with some of the finer-leaved aquatic species.

Many of the aquatic species such as *S. cuspidatum*, and *S. recurvum* in particular, although more dependent on water levels, recover well from desiccation and their higher intrinsic productivity under wet conditions improves their survival (see restoration sections). In experiments by Clymo and Hayward (1982) *S. auriculatum* survived desiccation well, whilst the hummock formers such as *S. capillifolium* survived very poorly, and the most sensitive species was *S. papillosum*.

The effects of water table depth in natural conditions are shown by Clymo and Reddaway (1971, 1974) in studies at Moor House National Nature Reserve. Batches of similar plants of four species were transplanted to pools, lawns and hummocks. The highest growth rates were seen in the pools for all species compared with lawns or hummocks, with the highest overall productivity for *S. cuspidatum* and *S. recurvum*. *S. capillifolium* (a hummock-forming species) however out-performed all other species on the hummocks, showing the complexity of the competitive relationships.

There was also a strong correlation between polyuronic acid content and optimum height above the water table for various species (Clymo 1963) with hummock species having higher amounts than carpet formers. (Clymo 1963) working with *S. papillosum* demonstrated that cation exchange capacity increased intraspecifically both with increasing pH values, and increasing cation concentrations, thus allowing adaptation to chemically different conditions.

The vertical distribution of *Sphagnum* species along a hummock-hollow gradient is a function of water relations and competitive relationships, with wide ranges around the means for most species and with the widest ranges for the hummock-forming species such as *S. nemoreum* and *S. fuscum*. This reflects their ability to grow lower down, but their outcompetition by faster growing hollow species such as *S. fallax* and *S. angustifolium*, which in turn are limited physiologically and morphologically at the higher elevations.

Sphagnum shows distinct interspecific differences in ability to prevent desiccation and its physiological effects. Work by Titus *et al*. (1983) and Titus and Wagner (1984) on *S.*

capillifolium and *S. fallax*, typical hummock and hollow species respectively, shows that when these two species are slowly dried, different response curves emerge. The lower growing *S. fallax* continued to photosynthesize at substantially lower water content than S. *capillifolium* but the water holding capacity of *S. capillifolium* was far greater, with S. *capillifolium* holding 30% more water at saturation. When hummock species are fully dried they show lower survival and recovery (Clymo and Hayward 1982) and carbon balance models clearly show that *S. fallax* fixes more carbon at low water sites and *S. capillifolium* at high water sites.

These results are in good agreement with greenhouse experiments carried out by Grosvernier *et al*. (1997). These authors studied the growth in length and weight of three species of *Sphagnum* (*S. fuscum*, *S. magellanicum* and *S. fallax*) in a glasshouse experiment, looking at a number of different peat types and low and high water levels (-1 cm and -40 cm). The species in this study were chosen as representative of the different microhabitats along a hydrological gradient: hollows *S. fallax*, lawns *S. magellanicum*, hummocks *S. fuscum*.

The results showed clear differences between species, in relation to the water table. *S. fuscum* was almost insensitive to water level compared with *S. magellanicum* and *S. fallax*. *S. fallax* in particular was strongly dependent on the water level, but at high water levels showed much higher growth rate than other species.

The authors considered that the ability to respond to stress markedly influenced the growth of different *Sphagnum* species, with each species filling a particular niche in the hydrological gradient. Hummock species were generally considered to be better adapted to the physiological stress of lasting water deficit, with the competitive advantage of S. *fuscum* and of hummock-forming species generally under dry conditions thought to be due to the greater water-holding capacity of capitula of section acutifolia. The bleaching of hummock species is also thought to reflect sunlight and reduce further drying. The growth of *S. magellanicum* was similarly not greatly influenced by water level.

Hollow species such as *S. fallax* dry out much faster than hummock species. However *S. fallax* has higher growth rates in wet conditions than either of the other species, giving it a competitive advantage under many conditions.

In Summary:

- Growth of some *Sphagnum* species is impaired at pH < 3 (Wheeler and Shaw 1995).
- pH of <4 probably sub-optimal for many *Sphagnum* species.
- Table of ecological amplitude related to pH (Andrus 1986) shows few records below approx. pH 3.5. Most tolerant species are *S. cuspidatum*, *S. fallax*, *S. fuscum*, *S. magellanicum*, *S. papillosum*, *S. rubellum*.
- Ca^{2+} >approx. 20 mg l^{-1} likely to produce negative effects (Money 1995).
- Hummocks are more acidic and lower in nutrients (Karlin and Bliss 1984).
- Hummock-forming species e.g. *S. capillifolium*, *S. papillosum* and *S. magellanicum*:
  - Have greater water holding capacity;
  - More resistant to low water and pH levels;
  - Less tolerant of high ionic strength and increased nutrient inputs;
  - Create their own micro - environment ;
- Lawn/aquatic species *S. fallax* and *S. cuspidatum* tolerate:
  - Higher pH;
  - Higher nutrient inputs.
- *S. fallax* retains its competitive advantage under a wide range of conditions.

2.4.4 Nitrogen

Mire plants typical of ombrotrophic mires are adapted to low levels of nutrient availability and do not respond vigorously to added nutrients. Mosses lack a root system and are very efficient scavengers of atmospheric and surface nutrients, a factor which probably accounts for their high sensitivity to pollutant inputs.

Bryophytes exposed to increased nitrogen inputs show rapid increase in tissue concentration and reduced growth cover and diversity (Pilkington *et al*. 2007, Carroll *et al*. 1999, 2000, Edmondson 2006).

Long-term nitrogen manipulation experiments on upland *Calluna* moorland in North Wales have shown a consistent pattern of reduced bryophyte and lichen cover in response to nitrogen addition at total nitrogen deposition rates of 26.4 kg N ha^{-1} y^{-1} and above. Regional surveys of bryophytes on *Calluna* moorlands in Scotland, Wales and the Peak District, covering a range of nitrogen deposition (12 – 33 kg N ha^{-1} y^{-1}) similarly showed reduced diversity at high deposition rates (Edmondson 2006).

Nitrogen additions to acidic and calcareous grasslands (Carroll *et al*. 2000) have also resulted in rapid loss of bryophyte cover following only one year of treatment at 30 kg N ha^{-1} y^{-1} above ambient, with more rapid losses when nitrogen was applied as ammonium sulphate. This pattern of differing responses to nitrogen form has also been seen in other studies.

Very high moss tissue nitrogen concentrations were reported by Pitcairn *et al*. (1998) along ammonia (NH_3) transects into woodland, running away from poultry farming units, with values of 25mg g^{-1} dry wt for mosses at 20 – 25 kg N ha^{-1} y^{-1} (equivalent to 5 – 10 µg m^{-3} NH_3).

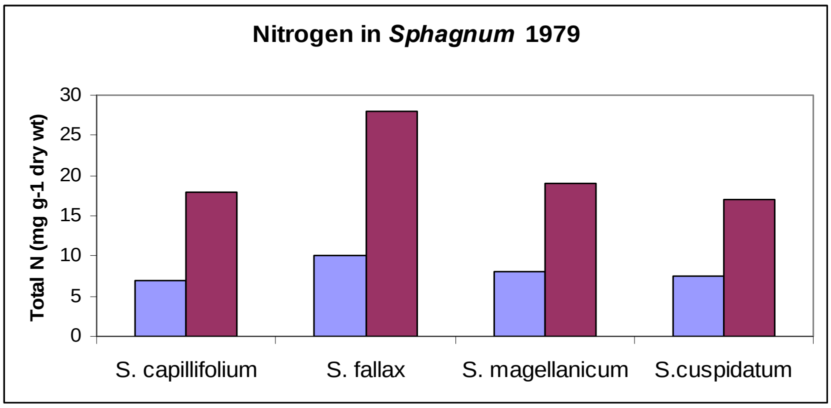
Results from nitrogen manipulation experiments at Whim Moss (Sheppard *et al*. 2005) also showed higher tissue nitrogen concentrations for *Hypnum jutlandicum* when nitrogen was applied as NH_3 or NH_4^+ compared with NO_3^-, with maximum values of 18 mg g^{-1} dry wt. at input levels of 30 kg N ha^{-1} y^{-1} as NH_3 over two years. Similar results were obtained for *Sphagnum capillifolium* in response to wet deposited NH_4^+, with reduced shoot extension and significantly elevated nitrogen status. Effects in this case developed over five years and were significant even at the lowest N dose of 8 kg N $ha^{-1}y^{-1}$.

Lamers *et al*. (2000) plotted the tissue nitrogen levels of ombrotrophic *Sphagnum* species against nitrogen deposition for different locations. At low levels of input (5kg N ha^{-1} y^{-1}) nitrogen was rapidly taken up by the *Sphagnum* (Aerts *et al*. 1992) in line with strong nitrogen limitation under these conditions, and with nitrogen concentrations determined largely by other factors controlling productivity.

Press *et al*. (1986) found tissue nitrogen concentrations of 32.5 mg g^{-1} dry wt in indigenous S. *cuspidatum* populations collected from Holme Moss in the early 1980s, compared with levels of 12.1 mg g^{-1} nitrogen for similar material from the Berwyn Mountains in Wales. S. *cuspidatum* samples transplanted to Holme Moss increased in tissue nitrogen concentrations from 12.1 – 24.7 mg g^{-1} over a period of six months and showed reduced growth compared with equivalent Welsh controls.

The tissue nitrogen content of a range of *Sphagnum* species collected from Holme Moss and Butterburn Flow in Cumbria are shown in Figure 2.9 for 1979 and 2005, and show a similar pattern, with large differences in the nitrogen content of all species collected in 1979. This was associated with the long-term failure of most of the species transplanted to Holme Moss over this period (Ferguson *et al*. 1984).

The 2005 data show large decreases in the nitrogen content of the Peak District *Sphagnum* samples, with only small differences between sites for most species. The one exception to this is S. *cuspidatum*, where the nitrogen content of the samples remains high, possibly due to close contact with bog water containing high concentrations of NH_4^+ and NO_3^- .



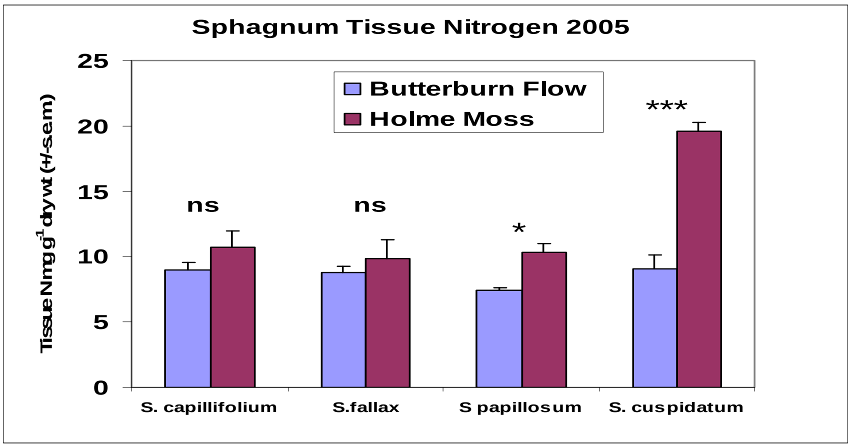


Figure 2.9 Total Nitrogen Concentration in *Sphagnum* of Different Species from the 'Clean' site at Butterburn, Cumbria (NY666761) and from Holme Moss (SE096036) in 2005 (Caporn *et al.* 2006) and 1979 (Ferguson *et al.* 1984, Studholme 1989). For 2005 data Two-tailed t-test, Significant Differences between Site: * = $p<0.05$, **$p<0.01$, ***$p<0.001$

Nitrogen is likely in most cases to limit growth on unpolluted mires. However, as nitrogen inputs increase many systems show a shift from nitrogen to phosphorus limitation, and the ratio of nitrogen to phosphorus in plant tissue (N/P ratio) has been used as a marker of nitrogen saturation in many ecosystems (Koerselmann and Meuleman 1996). Bryophytes in particular show a rapid shift in limitation at quite low levels of input (Aerts *et al*. 1992) and results from nitrogen manipulation experiments (Edmondson 2006, Pilkington *et al*. 2006) on heather moorland in North Wales show a positive growth response of bryophytes to phosphorus addition in the absence of added nitrogen.

Clymo and Hayward (1982) suggested that the growth rate of adult *Sphagnum* could be limited by phosphate supply. Rock phosphate applied to a mire surface appeared to increase the growth rate of *S. auriculatum*, *S. cuspidatum*, and *S. tenellum*.

Lamers *et al*. (2000) found that at increasing nitrogen input (12 – 18 kg N ha^{-1} y^{-1}) nitrogen gradually accumulated in the tissues (Bobbink 1998), with *S. recurvum* and shallow-rooted vascular species gaining a competitive advantage (Twenhoven 1992).

At higher levels of nitrogen input however, a number of studies have shown nitrogen uptake to saturate (Bragazza *et al*. 2004, 2005) and phosphate to become limiting. Aerts *et al*. (1992)

showed that the productivity of *Sphagnum* at a low nitrogen site in northern Sweden (0.6 – 2 kg N ha^{-1} y^{-1}) was increased four fold by nitrogen addition, whereas phosphorus had no effect. At the high nitrogen site (7 – 9 kg N ha^{-1} y^{-1}) however, phosphorus addition caused a threefold increase in growth but nitrogen had no further effect, suggesting a fairly sensitive relationship.

Work carried out by Gunnarson (2000) also showed a shift from nitrogen to phosphorus limitation after one year of 10 kg N ha^{-1} y^{-1} addition to a background of 4.2 kg N ha^{-1} y^{-1}, with no difference between the responses of different *Sphagnum* species.

Lamers *et al*. (2000) considered that above 18 kg N ha^{-1} y^{-1} airborne inputs were no longer bound within the acrotelm and were lost to deeper layers, becoming available to vascular plants and thus allowing invasion by competitive species such as *Molinia caerulea* (Roelofs 1986). Using data from a number of sources, and plotting nitrogen concentrations in ombrotrophic *Sphagnum* against nitrogen deposition, Lamers *et al*. (2000) showed that this saturation point was equivalent to a maximum *Sphagnum* nitrogen concentration of approximately 12 mg g^{-1} dry wt at 18 – 20 kg N ha^{-1} y^{-1}, with significant increases in *Sphagnum* tissue concentration above 10 kg N ha^{-1} y^{-1} in line with the critical load of 10 kg N ha^{-1} y^{-1} for ombrotrophic mires (Bobbink and Roelofs 1995).

Berendse *et al*. (2001) in a comparison of four mire sites with nitrogen depositions in the range 4 – 39 kg N ha^{-1} y^{-1} looked at the effects of increased CO_2 and nitrogen addition (30 – 50kg N ha^{-1} y^{-1} above ambient). CO_2 had no effect on *Sphagnum* production, but high nitrogen deposition plus further additions reduced *Sphagnum* growth and increased vascular plant cover at the two most polluted sites. *Sphagnum* nitrogen concentrations increased from 10 to approximately 15 mg N g^{-1} across the four sites with increasing nitrogen deposition, with further increases to 18 – 20 mg N g^{-1} with further nitrogen addition. Berendse *et al*. (2001) also interpreted these results in line with the “Lamers” model, suggesting that at higher inputs nitrogen became available to the roots of higher plants.

Limpens *et al*. (2003), in a further development of this approach, looked at the effect of various nitrogen additions (0 – 80 kg ha^{-1} y^{-1}) on bog surface transplants (mesocosms), with introduced seedlings of *Molinia caerulea* and *Betula pubescens*. In general the results were in line with Lamers *et al* (2003), with clear correlations between bog water nitrogen concentrations and vascular plant growth. These authors however found that at 80 kg N ha^{-1} y^{-1} there was a direct toxic effect of nitrogen on *Sphagnum*.

The mechanism of growth reduction obtained in all these studies is however not clear. A number of studies suggest that *Sphagnum* response to nitrogen is dependent on deposition history (Baxter *et al*. 1992, Twenhoven 1992), with reduced rates of nitrogen uptake in material from polluted sites and reduced NO_3^- reductase activity (Press *et al*. 1986, Juhainen *et al.* 1998, Woodin and Lee 1987, Press and Lee 1982, Woodin *et al*. 1985), suggesting that given enough time *Sphagnum* can adapt to a broad range of deposition loads, providing there is no light competition.

Nitrogen mineralization on ombrotrophic mires results in NH_4^+ release. There is very little conversion of NH_4^+ to NO_3^- (nitrification) and under unpolluted conditions NO_3^- levels will remain very low. The vegetation of bog systems is assumed to be adapted to these conditions (Lee and Stewart 1978).

Most typical mire plants are considered to be adapted to NH_4^+ uptake, with very low levels of the key nitrogen assimilation enzyme nitrate reductase. This enzyme is however “inducible”, and rapidly increases in activity in response to increasing NO_3^- levels.

Sphagnum species however regularly show considerable nitrate reductase activity following induction of the enzyme by rainfall supply in the rain, and may obtain significant nitrogen supply as NO_3^- (Press *et al*. 1986, Woodin and Lee 1987). Rudolf and Voight (1986) found that *S. magellanicum* did better with predominantly NO_3^- .The efficiency of nitrogen uptake may therefore make *Sphagnum* vulnerable to nitrogen supply.

These results therefore suggest that although levels of sulphur dioxide pollution had decreased by the late 1970s the nitrogen supply was at that time and may still be supraoptimal for the growth of several ombrotrophic *Sphagnum* species, although exact concentrations and conditions for different species are confusing.

Table 2.7 below summarizes the effects of a range of different NH_4^+ and NO_3^- concentrations on the growth of *Sphagnum* species under various conditions. The results are rather confusing, and show a very wide range of effects, suggesting that other factors may be involved, such as phenotypic plasticity or phosphorus limitation.

Table 2.7 Summary of the Effects of a Range of Different NH_4^+ and NO_3^- Concentrations on the Growth of *Sphagnum* Species under Various Conditions

		Effects on *Sphagnum*			
		Negative	**Neutral**	**Positive**	
NO_3^- (mgl^{-1})	0.62	*S.cuspidatum*			Press *et al*. (1986)
	13.2		*S.fallax*		Austin and Weider (1987)
	18.6	*S.magellanicum*		*S.fallax*	Twenhoven (1992)
	20			*S.magellanicum*	Rudolf and Voight (1986)
	20			*S.cuspidatum*	Baker and Boatman (1990)
NH_4^+($mg\ l^{-1}$)	0.18	*S.cuspidatum*			Press *et al*. (1986)
	1.22			*S. fallax*	Austin and Weider (1987)
	2.24	*S. fallax*			Austin and Weider (1987)
	>4			*S. magellanicum*	Rudolf and Voight 1986)
	6.7		*S. magellanicum*	*S. fallax*	Twenhoven (1992)

Of the laboratory based studies the most sensitive effects for both NO_3^- and NH_4^+ were shown by Press *et al*. (1986) with negative effects for S *cuspidatum* at 0.62 mg l^{-1} NO_3^- and 0.18 mg l^{-1} NH_4^+.

Other laboratory based experiments (Austin and Weider 1987) showed a wider range of effects with slight negative effects on growth of S. *fallax* at 2.24 mg l^{-1} NH_4^+ and no effect of NO_3^- up to 13.2 mg l^{-1}.

Rudolf and Voight (1986) found that NO_3^- concentrations up to 20mg l^{-1} were favourable to *S. magellanicum* cultivations under defined laboratory conditions, but that NH_4^+ resulted in growth inhibition and decreased chlorophyll content at concentrations greater than or equal to 4.05mg l^{-1} with, for instance, a 20% reduction in photosynthesis and nitrate reductase activity at 10.8 mg l^{-1}.

Twenhoven (1992) in field experiments on small areas of mire vegetation found that the growth of *S. fallax* was significantly promoted by both NO_3^- and NH_4^+ over two growing seasons both in hollows and partly on lawns, but was inhibited by NO_3^- on hummocks. No positive effects of treatment were seen for *S. magellanicum* in either year, and NH_4^+ was inhibitory at 10.8mg l^{-1}.

In Summary:

- Bryophytes, including *Sphagnum,* show rapid increases in tissue nitrogen concentration in response to increased deposition.
- Nitrogen concentrations in *Sphagnum* samples taken from the Peak District in the1970s were very high (15-25 mg g^{-1}) and were considered (supra-optimal) for growth and survival.
- A number of studies showed a clear shift to phosphorus limitation for *Sphagnum* and other bryophytes as nitrogen deposition increased.
- *Sphagnum* tissue nitrogen concentrations from the Peak District are now much lower, reflecting clear reduction in the rate of supply.
- Relationships between growth and survival and bog water NH_4^+ and NO_3^- concentrations are not very clear.
- Very sensitive effects were seen by Press *et al.* (1986) in laboratory experiments on *S. cuspidatum.*
- Otherwise data suggest negative effects on *S. fallax* and *S. magellanicum* at NH_4^+ in the range 2.24-10.8 mg l^{-1}. Current bog water concentrations in pools from Holme Moss are <1 mg l^{-1}, but values from areas of bare peat could be higher.
- There was no clear pattern of negative effects for NO_3^- at concentrations up to 20mg l^{-1}.

2.4.5 Sulphur

The fact that some lower plants, notably bryophytes and lichens, were sensitive to sulphur pollution both in solution and in gaseous form has been accepted for many years (Inglis and Hill 1974). Gilbert (1968) noted that where mean atmospheric SO_2 concentrations in the Tyne valley exceeded 50 µg m^{-3} the more sensitive bryophytes disappeared and Bell (1973) found that fumigations with 191 µg m^{-3} SO_2 significantly reduced the cover of two moss species.

Bottrell and Novak (1997) and Thompson and Bottrell (1998) measured the sulphur content of *Sphagnum* from pristine and polluted mires and compared this with SO_4^{2-} concentrations in rainfall and bog water samples. Under pristine conditions (Isle of Mull and Connemara) sulphur was shown to be present in *Sphagnum* at around 1mg g^{-1} and uptake into growing *Sphagnum* accounted for 5 – 10% of total sulphur input to the mire, with bog water concentrations in the range 1.1 – 4.3 mg l^{-1}. Similar measurements at Thorne Moor however showed higher *Sphagnum* sulphur content at 2 mg g^{-1}, despite lower present day atmospheric sulphur inputs overall, suggesting a legacy of pollutant sulphur accumulation.

Laboratory and field studies by Ferguson and Lee in the late 1970s and early 1980s suggested that the growth of a number of *Sphagnum* species was sensitive to sulphur pollution, including sulphur dioxide and the solution products bisulphite and SO_4^{2-} within the range of concentrations found in Britain at the time.

In the first study (Ferguson and Lee 1978) *Sphagnum* was collected from unpolluted sites in Cumbria and Wales and the sensitivity to sulphur dioxide, bisulphite and SO_4^{2-} tested in gaseous fumigations, laboratory experiments and field trials.

The phytotoxicity of sulphur dioxide solutions is markedly pH dependent, with greater damage to photosynthetic rates (Hill 1971, Pucket *et al*. 1973) at low pH, when sulphur dioxide dissolves in bog waters mainly as bisulphite.

Analyses of Manchester rainwater samples in the 1970s showed bisulphite concentrations up to 12.15 mg l^{-1} and SO_4^{2-} up to 173 mg l^{-1}. Davies (1976) obtained maximum bisulphite concentrations in the Sheffield area of 176 mg l^{-1}.

Sphagnum plants were set up under growth cabinet conditions and exposed to artificial rain at pH 4.2 for five months, containing 0 – 81 mg l^{-1} bisulphite or 96 – 480 mg l^{-1} SO_4^{2-} and measurements made of growth and chlorophyll content. *S. cuspidatum* was exposed to similar conditions in an immersion experiment and similarly prepared material from all species was also fumigated with 131 µg m^{-3} sulphur dioxide.

A consistent pattern of growth stimulation was seen at low bisulphite and SO_4^{2-} concentrations, attributed to a degree of sulphur limitation on the growth of the unpolluted material, with increasing inhibition at higher concentrations of bisulphite (0.81 – 81 mg l^{-1}) and SO_4^{2-} (96 – 480 mg l^{-1}). There were clear differences between species, with sensitivity in the order *S. tenellum*>*S imbricatum* = *S. papillosum* >*S. capillifolium* >> *S. magellanicum*> *S. recurvum.*

For *S. recurvum* bisulphite concentrations of 0.81 mg l^{-1} reduced both ^{14}C fixation and O_2 evolution rates by 30 – 40% at pH 4.5 (Ferguson and Lee 1978).

Growth of *S. cuspidatum* was also very sensitive, with growth reduced to zero at 40.5mg l^{-1} bisulphite, but only slightly affected by 96mg l^{-1} SO_4^{2-}, which was also not lethal at 480mg l^{-1}. Significant reductions in shoot length were also seen in the fumigation experiments for all species except *S. magellanicum*.

In general the authors concluded that SO_4^{2-} was inhibitory on the growth of all *Sphagnum* species at 480mg l^{-1} with some negative effects at 96mg l^{-1} and above. Bisulphite was at least ten fold more toxic (4.05 – 8.1mg l^{-1}).

The ability of *S. recurvum* to resist the effects of SO_4^{2-} and bisulphite exposure were suggested as a significant factor for its continued survival in the Southern Pennines over the period of the most serious atmospheric sulphur pollution.

In field experiments carried out on blanket bog in Snowdonia, Ferguson and Lee (1980) confirmed the pattern of results from the first set of studies. Experimental plots were treated for around 12 months with 0.81 – 733 mg l^{-1} bisulphite and 480 mg l^{-1} SO_4^{2-}.

Dose-related reductions in the chlorophyll content of *S. recurvum* and *S. magellanicum* were seen with effects at the lowest level of application, and marked bleaching of the moss surface after only five applications of 733 mg l^{-1} bisulphite. There was also some reduction in the 480 mg l^{-1} SO_4^{2-} treatment.

Similar effects were also seen on the growth of all species (*S. magellanicum, S. papillosum, S. imbricatum, S. recurvum*) with marked effects at higher doses of bisulphite. Negative responses were also seen with 480 mg l^{-1} SO_4^{2-}, except for *S. recurvum* which showed a maximum growth reduction of only 17%.

Current SO_4^{2-} concentrations in rainwater and bog water in the Southern Pennines fall well below the 96 -480 mg l^{-1} range even on degraded peats with high sulphur accumulation and it is unlikely therefore that SO_4^{2-} as such now limits the growth of *Sphagnum* species. The associated acidity may however still be a problem.

No data were found on current bisulphite concentrations in either rain or bog water, but with the marked reduction in gaseous sulphur dioxide concentrations and sulphur deposition these can probably be assumed to be below the level associated with phytotoxic effects. .

In Summary:

- Both field and laboratory experiments show no negative effects of SO_4^{2-} on *Sphagnum* below 96 mg l^{-1}, and few below 480 mg l^{-1}.
- Current bog water concentrations are well below this level, and SO_4^{2-} concentrations as such are not likely to limit *Sphagnum* recovery or regeneration although the associated acidity could still be a problem.
- Bisulphite ion, a direct solution product of sulphur dioxide, is much more toxic, but concentrations are now likely to be well below levels associated with negative effects

2.4.6 Heavy Metals

Heavy metals are generally present in soils in the form of stable complexes with organic matter. Several factors, including most notably pH and the concentrations of other ions, can influence the heavy metal concentrations in solution, and therefore the availability for plant uptake at pH <5 (Tyler *et al*. 1989).

Toxic actions of heavy metal ions are essentially exerted on enzymes, due mainly to the masking of active site and disruption of sulphydryl bonds. Prolonged exposure of soils to heavy metals can result in marked decreases in soil enzymatic activity, and impeded litter decomposition and soil respiration are common features of heavy metal pollution, (Tyler *et al*. 1989).

Baath *et al*. (1989), in a review of the data on the possible toxic effects of metals on microbial communities, set the following “Lowest observable effect concentrations” (LOEC) ranges for heavy metals ions in solution.

Table 2.8 LOEC (Lowest Observable Effect Concentrations) Ranges (µg g-1) for Microbial Processes, Based on Review by Baath *et al*. (1989)

	Microbial LOEC µg g^{-1}
Ni (Nickel)	100 - 1000
Cu (Copper)	25 - 100
Zn (Zinc)	70 -280
Cd (Cadmium)	1-2
Pb (Lead)	80-260

Smith *et al.* (2005) collected samples of ombrotrophic peat from ten upland locations in a transect from the Southern Pennines to the Highland Boundary Fault, and analysed the peat for total, extractable and soil solution metal concentrations, together with a number of other environmental variables.

Acid extractable soil metal contents of Ni, Cu, and Cd were appreciably below the LOEC for toxicity towards micro-organisms in organic soils, but Zn at two locations, and Pb at sites in the Southern Pennines (Featherbed Moss and Blackstone Edge) exceeded LOEC, suggesting some possible toxic effects on microbial communities. A study by Linton *et al.* (2007) on Southern Pennine peats also showed differences in microbial species diversity on the most heavily metal-polluted sites.

Pahlsson *et al*. (1989), looking at effects on vascular plants, found that the lowest concentrations at which toxic effects were exerted were generally in the range 1µM for Cu, Zn, Cd, and Pb. Soil solution concentrations of free heavy metals ions (Cu, Zn, Cd, Pb) in the Smith *et al*. (2005) study were substantially (at least x10) below this limit, whereas Al concentrations were close to toxic levels at two locations.

Bryophyte leaves lack a protective cuticle, and their high atmospheric exposure makes them susceptible to the accumulation of heavy metals. Mosses have been widely used as biomonitors of metal pollution (Clymo and Hayward 1982).

Bryophyte tissues have a high cation exchange capacity in their cell walls. A review of metal uptake in bryophytes (Brown 1982, 1984) shows that this exchange complex in the cell wall is often an excellent though incomplete barrier against the penetration of the sensitive intracellular space and it is possible that the differences between species in terms of sensitivity to metal exposure may be largely due to the capacity of the cell wall cation exchange complex.

The bryophytes include examples of both high susceptibility and apparently unlimited tolerance to heavy metals. Studies on the effects of heavy metals on mosses have looked at short-term exposure to specific soluble metal concentrations and at the loss of moss species along transects towards metal smelting plants (Tyler 1989). In none of these studies however were the intracellular concentrations of the actual metal measured.

Membrane damage is cited as one of the most significant effects of toxic metals on lower plants. Brown and Wells (1990) in experiments on *Rhytidiadelphus squarrosus* showed reduced photosynthetic rates and increased potassium leakage in response to exposure to 10µM to 0.1M Ca, Cu, Ni, Pb and Zn. An approximately linear relationship was demonstrated between photsynthetic decline and intracellular metal concentration irrespective of duration of exposure or morphological differences.

A limited search of the literature has not found any specific studies on the effects of heavy metals on *Sphagnum* growth. *Sphagnum* tissue consists of a network of living cells and dead water holding hyaline cells. The cell walls have a very high cation exchange capacity and their ability to retain heavy metals is considerable (Clymo and Hayward 1982). On the same basis however, establishing intracellular metal concentrations is very difficult, and showing a relevant dose relationship to environmental exposures even more problematic (Brown 1982).

In general ,divalent cations have a higher affinity than monovalent cations for cation exchange sites and ions with higher atomic weight displace lighter elements (Ruhling and Taylor 1970). The order obtained for *Hylocomium splendens* was Cu, Pb> Ni> Co>Zn, Mn. Excluding particulate systems, any soluble ion presented to a bryophyte cell will first establish an equilibrium with the binding sites on the cell wall, and only when this equilibrium has been established will the remaining atoms become available for uptake into the cell.

Techniques developed to show the proportion of ions bound intracellularly and extracellularly (references in Brown 1982) have generally shown Na and K ions to be present inside the cell, whereas Ca was mainly bound to the cell wall. Metals such as Pb with no role as plant micronutrients were found to be almost entirely extracellularly bound, although there were problems with some of the displacement techniques, due to the very high binding affinity of Pb.

Table 2.9 shows the total Pb concentrations in *Sphagnum* tissues collected from Holme Moss and Butterburn in Cumbria in 1979 and 2005. The results show a dramatic fall in moss Pb content at both sites over the last 25 years, in line with the reductions in atmospheric Pb concentrations and the introduction of unleaded petrol. Levels in samples collected from Holme Moss are still significantly higher than those from Butterburn, and this is likely to be related to both current inputs and to much higher peat and bog water concentrations.

It must be noted however, that these concentrations do not reflect the intracellular exposure, with the results from the other studies quoted here strongly suggesting that the majority of the Pb is extracellularly bound. The current levels in Holme Moss samples are also considerably lower than those from Butterburn in 1979/85, an area which has retained an extensive and species-rich *Sphagnum* flora.

Taking both these points into account, there is no real evidence to suggest that current heavy metal exposure is limiting the growth of *Sphagnum* in the Southern Pennines.

Table 2.9 Pb (µg g-1 dry wt) in *Sphagnum* Tissue from Holme Moss and Clean Sites near Butterburn, Cumbria in 1979/85 (Studholme 1989 and Ferguson *et al*. 1984) and (Caporn *et al* 2005). Two-tailed t-test, Significant Differences between Site: * = p<0.05, **p<0.01, ***p<0.001

	1979/85		**2005**	
	Butterburn	**Holme Moss**	**Butterburn**	**Holme Moss**
S. cuspidatum	180	350	2.04 +/-0.3	80.3+/- 1.4**
S. fallax	50	600	0.1+/- 0.001	3.12 +/- 0.3*

In Summary:

- Heavy metals form stable complexes with soil organic matter. Concentrations in soil water are dependent on pH and the other ions present in solution.
- Experimental studies on other mosses suggest that it is the intracellular heavy metal concentrations that are important for toxic effects.
- *Sphagnum* mosses are capable of binding very high concentrations of heavy metal ions in their cell walls, and this may protect them from toxic metal effects.
- Southern Pennine heavy metal soil solution concentrations are significantly below thresholds identified for effects on micro-organisms and vascular plants, with the possible exception of Pb and Zn.
- Pb concentrations in *Sphagnum* tissue have however fallen dramatically when compared with data from 1978 and are now lower in the Peak District than they were in unpolluted areas in 1978, which does not suggest any obvious toxic effect on *Sphagnum* at current levels of exposure.

2.5 Land use

2.5.1 Burning

In general burning is not recommended as a form of management for blanket bog vegetation, and most of the available studies relate to the management of grouse moors and lowland heath. A lot of deep blanket-bog peat however, has *Calluna*-dominated vegetation, and is burned.

Studies on the effects of sheep removal in combination with 10 or 20-year burning rotations at Moor House Nature reserve (Rawes and Hobbs 1979) show an intermediate period of high *Eriophorum vaginatum* dominance following burning, followed by patchy *Calluna* re-growth to form an uneven-aged stand in combination with *Eriophorum angustifolium* and *Sphagnum* spp.

Vegetation on the Moor House reserve was classed as blanket bog, with the three dominant species given as *Calluna vulgaris*, *Eriophorum vaginatum* and *Sphagnum rubellum.* Removal of sheep grazing for a period of seven to thirteen years led to some increase in total bryophyte cover, and notably in lichen cover, but changes in *Sphagnum* cover were not significant. Specific measurements in the wettest areas showed a pattern of increased drying with a loss in cover for the most common *Sphagnum* species, particularly *S. rubellum*, but some increase in the cover of *S. papillosum*.

Replicated experiments combining burning and grazing treatments over a period of 18 – 19 years showed maximum *Sphagnum* levels in the short burn rotation/sheep excluded plots when compared with no burn and no sheep or no burn controls. Lowest *Sphagnum* levels in this experiment were on the long burn rotation plots with sheep grazing.

A further unreplicated sheep grazing trial was also carried out over a period of eight years, and comparing heavy and light grazing with and without burning. Light grazing (0.37 sheep per hectare) had no significant effect on botanical structure. Heavy grazing with or without burning decreased *Sphagnum* cover in all cases, with the most marked effects in the unburnt and heavily grazed (3.4 sheep per hectare) plots.

Accidental fire however, is thought to have been a major factor in the development of bare peat in the Southern Pennines, and is strongly associated with increased risk of erosion (Anderson 1986, Tallis 1987).

The effects of fire are dependent on vegetation composition, fire intensity, frequency and timing, and notably on the wetness of the mire surface.

Water level at the time of the burn is likely to have a major effect on the impacts of the fire. Wet peat acts as an excellent insulator (Watson and Miller 1976) and protects both buried seed and spores and the roots and basal buds of vascular plants. Maltby *et al.* (1990), in a report on a severe fire in the North York Moors, showed that the effects of fire were strongly influenced by peat depth, water content and previous desiccation cracks. Where peat depth was >80 mm and moisture content >5 times the dry weight of the peat, the fire affected only the surface vegetation.

Speed of recovery from accidental fire will depend on altitude, rainfall, pollution levels and grazing.

2.5.2 Grazing

Grazing by domestic livestock is an important upland management practice and is thought to have been a factor in the original development of blanket mires (Shaw *et al.* 1996). However, over the last 50 years many upland areas have been overstocked, resulting in decreased dwarf shrub cover and damage to the structure of some blanket mires (Dixon 1984, Thompson *et al*. 1995).

As grazing pressure increases, dwarf shrub cover is reduced and the mire surface is increasingly dominated by graminoids such as *Molinia caerulea*, *Nardus stricta*, *Eriophorum vaginatum* and *Scirpus caespitosa* (Ratcliffe 1959).

Anderson and Yalden (1981) considered that loss of heather moorland in the Peak District National Park was clearly related to an increase in sheep numbers from 0.7 ha^{-1} in the 1930s to 2.07 ha^{-1} in 1970, and similar conclusions were drawn in Cumbria (Thompson and Kirby 1990).

The intensity and extent of grazing damage is dependent on stocking rate, species composition, site wetness, time of year etc. These factors can however be difficult to separate and most of the available studies relate to “dry” heather moorlands rather than blanket bog (Crowe 2007). Doyle (1982) however considered grazing mainly by cattle to have a fundamental influence on the floristic composition of blanket bog in the West of Ireland.

Wet areas and *Sphagnum* cover are particularly susceptible to trampling, with severe damage to the margins of pools, leading to loss of *Sphagnum* and the development of areas of bare peat.

This may cause changes in microtopography and species distribution, such as reductions in hummock-forming species such as *S. papillosum*. *S. tenellum* may however benefit as a colonist of wet bare peat and this species is often associated with trampled areas and animal tracks.

Cattle in particular have been associated with a high risk of trampling. Shaw *et al.* (1996) noted greater damage by cattle compared with sheep and increased soft rush (*Juncus effusus*) invasion, while in Ireland *Juncus effusus* and bog myrtle (*Myrica gale)* grew abundantly on flat blanket bog where trampled by cattle.

Rodwell (1991) considered that where the wetter of the blanket bog communities (M1 and M2) are burnt or grazed, the wetness of the ground afforded some protection to the vegetation. Rawes and Hobbs (1979) and Rawes (1983), investigated changes in bog pool area at Moor House 21 years after exclosure. They found that whereas the area of driest habitat occupied by *Calluna* and *Eriophorum vaginatum* increased by 14%, the wettest areas, dominated by *S. cuspidatum* and *Eriophorum vaginatum* in open water decreased by 12%. Overall the cover of all *Sphagnum* species except for *S. papillosum* decreased, in some cases quite significantly. The authors thought that climate change could however also have been a factor. The main consequence of 20 years of sheep removal over the whole area was found by these authors to be an increase in *Calluna* cover and a decrease in that of *Eriophorum vaginatum*, with increased lichen growth. Overall these authors concluded that the best long-term management strategy would be light sheep grazing, without burning, in the interests of nature conservation.

In a more recent study the role of sheep grazing on vegetation change in upland mires removed from livestock farming was investigated by Smith *et al.* (2003), at Butterburn Flow on the edge of Kielder Forest, over a period of 14 years. Some species were significantly affected by change in grazing intensity, particularly at the drier edges of the mire where conditions allowed increased cover of *Calluna* and *Eriophorum vaginatum*, with an overall decrease in cover of species typical of ombrotrophic mires. External factors such as climate change and atmospheric pollution were however considered to be more important in determining site condition on the wettest mires. Butterburn Flow had previously been noted for its large area of *Sphagnum* lawn. Exclusion of grazing has led to increased cover of dwarf shrubs and hypnoid mosses, particularly at the drier edges of the bog favoured by the sheep Specific effects on *Sphagnum* species were mixed, with decreased cover for *S. Magellanicum* at the edges of the mire in the absence of grazing.

2.5.3 Drainage

In the 1930s the invention of the Cuthbertson plough allowed the creation of steep-sided open ditches (or grips) and led to the draining of 1.5 million ha of blanket peatland in upland Britain.

Stewart and Lance (1991) looked at the effects of moor-draining at Moor House NNR in the North Pennines and found reductions in water tables of up to 2m on shallow slopes following drainage, with marked reductions in the species characteristic of water-logged communities (such as *Eriophorum vaginatum, Eriophorum angustifolium, and S. capillifolium*). The opposite pattern was seen in a moorland restoration (Kommulainen *et al.* 1998) project in Finland, with *Eriophorum vaginatum* increasing in range and becoming dominant in the second year following a 20cm rise in water table. A similar process was also seen in Quebec (Van Seters and Price 2002), where change in vegetation was attributed to decreased evapotranspiration associated with increased plant cover.

Drainage has obviously had a major negative effect on the integrity of blanket mire communities, and is clearly an important factor in the falling water tables.

2.6 Remote Sensing *Sphagnum* Studies

2.6.1 Introduction

Northern peatlands (those above 45^{o}N) contain up to one third of the world’s terrestrial carbon and have a fundamental role in the terrestrial carbon cycle. The importance of terrestrial carbon stores and their resilience to climate change are becoming better understood and more intensively studied, as part of a wider effort to understand global climate change and carbon dynamics.

Part of this research includes the application of remote sensing techniques, frequently in conjunction with GIS technologies, as tools to map, analyse, interpret and understand northern terrestrial carbon stores, their formation, development, stability and degradation.

The application of remote sensing and GIS techniques in *Sphagnum* studies is thus a key part of the wider understanding of peat bodies in the global context.

2.6.2 Remote Sensing Techniques

In the broadest sense, remote sensing is the measurement or acquisition of information of an object or phenomenon, by a recording device that is not in physical or intimate contact with the object. In practice, remote sensing is the utilisation at a distance (as from aircraft, spacecraft, satellite, or ship) of any device for gathering information about the environment. In environmental studies, the term generally refers to techniques involving the use of instruments aboard aircraft and spacecraft.

Most remote sensing techniques make use of reflected (or emitted) electromagnetic radiation from the object of interest in a certain frequency domain, eg. near/far infra-red, visible light or microwaves. This is possible because the examined vegetation or waterbody reflects or emits radiation at different wavelengths and intensities according to the habitat's surface roughness and condition. These passive remote sensing techniques are predominant in the research and literature relating to S*phagnum* and other moorland vegetation and habitat studies.

A major advantage of remote sensing is that if the object is at a distance away the sensor can cover a large area more easily. The large spatial coverage is partially important with *sphagnum* upland areas which maybe be remote and access to them maybe time consuming and costly. If a sensor is permanently or regularly in the correct position above the object being monitored, the information can be collected easily and often at a high temporal resolution.

Early research in the field led to the discovery that the nature of the ground at any particular point on earth (i.e. its soil, vegetation and land use properties, together with surface roughness) determines the spectral reflectance (and absorbance) of electromagnetic radiation across the entire electromagnetic spectrum. Thus, using portable and laboratory spectroradiometers, it was possible to determine characteristic spectral reflectance 'signatures' for commonly occurring soil, vegetation and land cover types (Mather 2006, Huete and Escadafal 1991, Lillesand and Kiefer 1999) over a range of parts of the electromagnetic spectrum. These early studies concentrated on specific spectral wavelength ranges, in particular visible, near infra-red, far infra-red and ultraviolet spectral ranges. Later studies have applied the same principles to different wavelengths (e.g. microwave) and many combinations of different wavelength ranges; so-called hyperspectral remote sensing data.

2.6.3 Summary of Existing Literature

A non-exhaustive review of current academic literature reveals a small but increasing body of published work describing the application and suitability of remote sensing and GIS techniques in *sphagnum* studies. Four key research themes are identified, these include:

- The spectral behaviour of S*phagnum* canopies under varying conditions of water stress (hydrology), in support of the research themes listed below;
- The remote detection/discrimination (and subsequent mapping) of *Sphagnum*-dominant moorland vegetation;
- The remote derivation or inference of near-surface hydrological conditions via the measurement of moisture stress in *Sphagnum* species, principally in the infra-red spectral wavebands;
- The potential application of hyperspectral remote sensing techniques into S*phagnum* research and moorland studies in general.

These are now reviewed in further detail.

2.6.4 Spectral Reflectance Studies

Early research in the field of remote sensing using portable and laboratory spectroradiometers identified characteristic 'spectral reflectance signatures' for commonly occurring soil, vegetation and land cover types (Mather 2006, Huete and Escadafal 1991, Lillesand and Kiefer 1999) *Sphagnum* moss vegetation is low ground cover with high water levels and generally produces a very distinctive spectral reflectance signature in satellite data, however, ground truthing needs to be undertaken in order to correlate this more precisely. The spectral frequencies used are located between approximately 990 and 1200nm (unlike other vascular species at 970-900nm) but this does vary depending on what *Sphagnum* species is being studied (Harris *et al.* 2005).

A variety of literature exists on measuring spectral reflectance recorded from remote sensing satellites and ground truthing to understand the complex relationship between the amount of biomass and water and the type of vegetation (Riedel *et al.* 2005). Biomass measurements can be calculated by collecting all vegetation from a defined area of habitat and weighing and burning it to calculate biomass and water content to help calibrate the results with spectral reflectance (Ustin *et al*. 1998). Many research papers deal with mosaics of habitats including forests with high tree coverage (Li and Chen 2005).

Methods are available that are less destructive to moorland habitats such as hand-held spectrometers to correlate spectral reflectance of remote sensing images. The reflectance varies depending on whether the *Sphagnum* is saturated or not and its signature increases over certain parts of the wavelength when it is under water stress. Water levels in the ground and vegetation are higher in winter and, due to the smooth surface, have higher amounts of spectral reflectance which show up as brighter sections on satellite images. Different authors have had varying success rates depending on variables such as season. Vegetation indices include the water band index (WBI) which uses two bands in the infra-red wavelengths, where water is typically absorbed compared to wavelengths where water is not absorbed. The moisture stress index (MSI) assesses levels of vegetation moisture stress but is a more broad-band ratio which uses short wave infra-red (SWIR) and can be used in conjunction with Landsat TM satellite imagery (Harris *et al.* 2005 2006).

Gilvear and Watson 1995 studied the depth of wetland water tables and surface water at Insh Marsh, Scotland using Airborne Thematic Mapper (ATM) imagery bands 10 and 11, flown by NERC in 1992. The paper concluded that while it is possible to use remotely sensed data for mapping the water tables in thermal or middle infra-red the most suitable bands are not available from LANDSAT or SPOT.

2.6.5 Mapping Sphagnum-dominant Vegetation Communities from Aerial Photography and Satellite Imagery

As discussed, the wavelengths that are reflected and emitted from objects can be detected using sensor arrays mounted to airborne or satellite based platforms. In general, remote sensor technology can be divided into two categories; either the sensor platform detects the reflectance from natural light that is reflected back from the target, which is called passive remote sensing, or alternatively the platform emits radiation and a component is returned to the sensor as backscatter. With both methods the collected data is converted to a 'raster image' made up of pixels as a raw or processed or enhanced image.

Early research into the use and application of remote sensing in peatland studies tended to concentrate on using remotely sensed imagery to map the location, extent and condition of peat bodies, together with other habitat and land cover information. For example, Cox (1992) combined the use of Landsat TM satellite imagery together with aerial photography to map existing wetlands and peat bodies in Cumbria. Other examples include Reid *et al*. (1994) who attempted to map blanket bogs across Great Britain, again using Landsat TM imagery. Much of this early work was, however, only partially successful, primarily due to two important reasons:

- the spatial resolution of the Landsat TM sensor, which at 30m is too coarse for many peatland (and other environmental) studies; and
- the relatively narrow spectral resolution of the sensor, which only obtained spectral data across a relatively limited number of visible and infra-red wavebands.

In recent years, there has been acceleration in technological advances associated with remote sensing, image processing and computing power. The combined effect of these has led to the development and deployment of a range of commercial satellite and airborne sensors and image products which offer high temporal availability (low image, revisit times) and high spatial resolution, often of 3m or less (Ikonos, Quickbird, HyMap, ifSAR, LIDAR etc.). Importantly, the costs associated with acquiring such data are becoming increasingly competitive.

At the same time, advances in remote sensing, image processing and GIS software and technologies have led to the development of sophisticated image processing, image classification (both supervised and unsupervised) and expert systems which can be very effective in mapping a range of vegetation community types on the ground from high resolution satellite imagery and aerial photography. Cost-effective software system for this type of work include ERDAS Imagine (Leica Geosystems), ERMapper, Idrisi Andes, GRASS GIS and ESRI Image Analysis software to name a few. Other systems such as Feature Analyst (Visual Learning Systems) can be quickly and effectively 'trained' to classify and automatically extract target habitats and vegetation communities from image data, though no direct evidence exists in the literature as to the potential of such techniques to the mapping of *Sphagnum* species and S*phagnum*-dominant communities.

2.6.6 Derivation of Soil Moisture and Water Table (Hydrological) Conditions

This theme is by far the most popular field of current research, with papers by Yoshikawa (2004), Harris *et al.* (2005) and Harris *et al.* (2006) describing the use of near infra-red and shortwave infra-red absorption bands, combined with biophysical indices such as the chlorophyll index, in determining estimates of near surface moisture, based on moisture stress in *Sphagnum* species. Strong positive correlations were observed between near surface moisture and absorption / reflection of radiation at these key infra-red spectral bands.

2.6.7 The Potential of Hyperspectral Remote Sensing

The term hyperspectral is a remote sensing term denoting a sensor system observing a target in hundreds of spectral bands. The high sampling of the spectrum provides a great increase in information. The wavelengths and resolution would depend on the choice of sensor and the application. Hyperspectral Imaging (HSI) is a passive remote sensing technique using the hyperspectral definition above. HSI has a spatial component and each image pixel contains spectral information over the hundreds of bands to generate a "data cube." These cubes can be mined for spectral information to use with the spatial context. HSI data are used to detect, classify and identify as well as quantify materials present in the image.

The narrow bands in which radiance is measured, combined with the high number of bands, allows detection of minute variations in the spectral signatures. This can, for instance, be used for the identification of minerals, the measurement of plant chemical composition or the approximation of water content in vegetation canopies, such as S*phagnum* communities.

Hyperspectral remote sensing is mostly performed using airborne or handheld sensors. A few hyperspectral satellite systems are operational, of which Hyperion is the most well-known. Common handheld spectrometers are the field spectrometers by Integrated Spectronics, GER and ASD. Airborne platforms are operated by a number of companies including HyVista (The HyMap system), SpecTIR (The ProSpecTIR and HyperSpecTIR systems) and the Galileo Group (The Aisa system) (wikipedia.org 2006).

The use of commercially-available hyperspectral remote sensing imagery in peatland studies is becoming an increasingly popular field of study. Several researchers at the University of Manchester, in particular, are involved in recent and ongoing studies which, although focusing on the upland blanket peat of the South Pennines, nevertheless have a relevance to S*phagnum*-related studies.

The research undertaken at the University of Manchester is described in a series of related papers by Cutler and McMorrow (2002), McMorrow, Evans and Cutler (2002), McMorrow *et al.* 2004, McMorrow *et al*. (2006a) and McMorrow *et al.* (2006b). In this series of papers, HyMap high resolution, hyperspectral imagery from the British National Space Centre is employed, together with high-resolution digital SAR-derived terrain data, ground truthing measurements of bare and eroding peat spectral reflectance and peat sampling, to investigate and assess the suitability and applicability of the HyMap imagery in studies to determine peat erosion, composition, degree of humification and soil moisture content.

The research uses common remote sensing and image classification techniques to attempt to determine peat condition and soil moisture content using a variety of techniques including:

- Unsupervised classification (via cluster analysis);
- Supervised maximum likelihood classification, where the image classification is trained to discriminate different areas from the image, based on measurements of spectral information taken on the ground, such as areas of well humified peat, areas of poorly humified peat and re-deposited peat;
- Fuzzy classification via ‘trained’ neural network classification.

In these studies, it was found that different types of bare and exposed peat showed different, characteristic spectra (spectral ‘signature curves’), and these may be used to distinguish between four categories of blanket peat; washed, burned, well humified and poorly humified).

A relationship was also observed between spectral reflectance and peat soil moisture content, but this was complex, non-linear and not statistically significant in these studies. However, it is argued that with further studies, the nature of this relationship would be better understood and that the hyperspectral image data could be used for estimating blanket peat soil moisture, in addition to the range of other variables. Work undertaken to date is described in a paper by McMorrow *et al*. (2004).

The hyperspectral remote sensing research being undertaken at the University of Manchester and elsewhere is in its early stages, but shows considerable promise in estimating and mapping peat soil condition, including soil moisture content, although it is apparent that there is a considerable amount of research still required.

Although no specific published research was identified with respect to hyperspectral remote sensing and S*phagnum*, by inference it is entirely feasible that plant water content / stress can be determined in some way from hyperspectral imagery, together with the identification and mapping of S*phagnum*-dominant vegetation communities using the types of image classification and processing described above. Further, as hyperspectral remote sensing data is collected at high spatial resolution, the potential for rapid, accurate vegetation community mapping is obvious.

The combination and continued convergence of remote sensing, image processing, geographic information systems and digital technologies offer extremely powerful tools for the environmental researcher. These allow large volumes of data to be analysed very quickly and easily, allowing large-scale, ambitious environmental-based studies to be undertaken effectively using fairly modest manpower and IT resources. These technologies offer the key to success in studies of this type and this will become even more apparent with future technological developments and improvements.

2.7 Approaches to Restoration

2.7.1 Introduction and Background

The exploitation, degradation or destruction of areas of raised or blanket mire can occur for a range of reasons. Blanket mire degradation can mainly be attributed to inappropriate land-use (burning, over-grazing and drainage), together with the effects of air pollution, notably in the Southern Pennines. On lowland raised mires however, degradation or destruction is usually attributable to agriculture, forestry or peat extraction.

The majority of the restoration techniques that have been developed over the last 10 - 20 years have been on lowland raised mires damaged or destroyed by peat extraction and the overall aim of this section of the report is to summarize and critically assess the techniques available in the context of their possible usefulness under the differing conditions of blanket mire restoration.

Restoration of a *Sphagnum*-dominated bog surface can be separated into a number of stages:

- Re-wetting: Establishment and maintenance of consistently wet surface conditions;
- Re-naturation: redevelopment of appropriate vegetation;
- Regeneration: renewed accumulation of peat.

The desired end-point of the restoration process needs to be carefully considered. Re-naturation can in some cases occur naturally or may additionally require inoculation with suitable diaspores (vegetative *Sphagnum* fragments), or the establishment of nurse crops that would not be considered as appropriate vegetation in the long-term. The achievement of the third stage may not be realistic in all or many cases.

A number of different approaches have been taken in Britain, Europe, Canada and the USA depending on the different land-uses of peatlands, peat mining methods and restoration goals.

2.7.2 Canadian and USA Restoration Approach

This is a well-characterised approach summarised in Rochefort *et al.* 2003 and laid out in useful practical detail in the Peatland Restoration Guide (Quinty and Rochefort 2003). It has been applied mainly to areas of peat extraction by vacuum harvesting methods or mechanical block cutting.

The short-term goal of the approach has been to establish a plant cover composed of peat bog species and to restore a water regime characteristic of a peatland ecosystem.

The long-term objective is to return the restored areas to functional peat accumulating ecosystems.

The approach can be summarised as follows:

- **Field preparation**: provision of suitable hydrological conditions for *Sphagnum* diaspores through the creation of microtopography and water retention basins, ditch blocking and reshaping.
- **Diaspore collection**: collection of the top 10cm of the living vegetation in natural bog as a source of diaspores (ratio of surface collected to surface restored of between 1:10 and 1 :15 in order to minimise impact on natural bogs, and to ensure plant establishment in less than four years.)

- **Diaspore introduction**: Diaspores spread as thin layer on bare peat surfaces to be restored.
- **Diaspore protection**: Diaspores covered by straw mulch at a rate of 3000kg h^{-1} which improves water availability and temperature conditions.
- **Fertilization**: Phosphorus fertilization favours more rapid colonization by vascular plants which act to stabilize the peat surface and act as nurse crops to the *Sphagnum* mosses.

2.7.2.1 Field Preparation

The main goal of surface preparation (Quinty and Rochefort 2003, Gorham and Rochefort 2003) is to improve site conditions, most importantly water availability. The methods detailed in the Canadian/USA literature are aimed at the restoration of lowland mires used for peat extraction, and are therefore only generally applicable to blanket mire systems.

The key is to retain as much water at the surface as possible with the aim of compensating for low water tables and for loss of the peat storage capacity inherent in the acrotelm. Landscaping measures include ditch blocking/filling, general blocking of drainage systems, and berm (bank) construction.

The construction of banking is dependent on the topography of the site. Terracing approaches might be the most useful on sloping surfaces typical of blanket bog, although care should be taken not to increase exposure of bare peat. Flooding over long periods or large areas should be avoided (Rochefort *et al.* 2002).

Loose peat surfaces can be scraped to provide a flat surface, again to allow good contact between diaspores and a wet, compact, water conducting peat surface. This could also in some cases allow the removal of highly oxidised and mineralised peat surfaces which in the context of the South Pennines are likely to be very acidic and high in NH_4^+, although in some cases surface layers may already have eroded and metal levels may be higher further down.

The overall aim is to achieve smooth flat peat surfaces with a high water table. “Microtopography” is not generally considered helpful, because of dryness on the higher relief.

The removal or use of existing vegetation is dependent on type and likely to include:

- More or less dense cover of ericaceous shrubs;
- Dense cover of cottongrasses and other graminoids;
- Presence of non – bog species and /or trees.

The presence of peat bog species is obviously a good sign. Scattered cover of dwarf shrubs or grasses should be preserved as it represents a source of diaspores and protective cover for the establishment of new plants.

Dense cover will prevent *Sphagnum* diaspores reaching the ground and should be scraped or trimmed or “opened up” in some way.

2.7.2.2 Diaspore Collection and Introduction

Rochefort *et al*. (1995) have reported a number of field and glasshouse experiments investigating various techniques for diaspore collection, application and viability. Aspects of these studies are also reported in Campeau and Rochefort (1996), Price *et al*. (1998), Grosvernier *et al*. (1997) and Ferland and Rochefort (1997).

Campeau and Rochefort 1996 found that diaspore fragments from the top 10cms of an intact peat profile contained sufficient material for successful re-colonization in both field and laboratory experiments, with similar rates of re-colonisation with 0.5cm, 1cm or 2cm diaspore size ranges. The use of material from lower layers in the peat profile was not advantageous. Similar results were obtained by Quinty and Rochefort (2003), with the use of intact mire surface providing both *Sphagnum* diaspores and seeds/fragments of other pioneer mire primary colonisers

Rochefort *et al.* (1995) found that four common Quebec *Sphagnum* species (*S. magellanicum*, *S. nemoreum* , *S. angustifolium* and *S. papillosum)* showed good ability to regenerate from fragments as small as only 1-2mm in extreme cases.

The choice of source material was considered to be important. Not all species were equally suitable for regeneration. Hummock-forming species such *S. fuscum* or *S. rubellum* were the most desiccation resistant and usually performed the best.

The best technique for spreading was found to be a thin cover over the entire target site at a ratio of 1:15 to 1:10 of the collection versus the spreading area, spread under damp conditions (Quinty and Rochefort 2003, Rochefort *et al*. 2003, Campeau and Rochefort 1996).

Improving the humidity conditions in laboratory experiments improved re-colonisation rates for all except *S. fuscum* (*S. angustifolium* also desiccation resistant), with low rates of growth for all species at water levels of 25cm or more below peat surface (Campeau and Rochefort 1996). Improved humidity in laboratory experiments was also shown to increase percent cover at given spreading ratios (Campeau and Rochefort 1996). This group found that generally the laboratory trials gave a similar pattern of results to the field experiments. Inoculum was in some cases stored for up to a year in cold (Canadian) conditions, with some loss of activity (Quinty and Rochefort 2003).

2.7.2.3 Straw Mulch Addition

This was considered by the Canadian workers to be essential for success (Quinty and Rochefort 2003, Rochefort *et al*. 2003) and more useful than other approaches such as companion planting and protective covers.

Spreading should take place immediately following spread of inoculum at a rate of 3000kg/hectare with fresh long-stemmed straw.

2.7.2.4 Fertilization

Phosphorus fertilization increased the spread and development of mosses such as *Polytrichum* and vascular plants (Quinty and Rochefort 2003), leading to more sheltered conditions for *Sphagnum* establishment. Granulated phosphate rock at 150kg /hectare, equivalent to 19.5 kg phosphate hectare^{-1}, was usually applied after the mulch in spring/late summer to allow maximum plant uptake.

Fertilization could in some cases favour the growth of non peat bog species but generally impacts could be reduced by low doses, slow release, low mobility of phosphorus within the peat and general lack of drainage.

Rochefort, Gauthier and Lequere (1995) found that high water table close to the peat surface, and mineral amendments (12-12-12- NPK fertiliser or bone meal) enhanced the establishment of four commom *Sphagnum* species (*S. magellanicum, S. nemoreum, S. angustifolium, S. papillosum)*, in both laboratory and field experiments. The addition of a shade cover carried no further advantage. Algal growth was noted in the fertilized treatments but did not seem to reduce re-colonization in the long-term.

In general terms therefore, the Canadian approach

- assumes the water table can be raised by suitable landscaping;
- does not generally use nurse crops, adopting a straw mulch technique which they consider of some importance;
- does not report the problems of surface chemistry unsuitability in terms of very low pH, and high SO_4^{2-} and NH_4^+ that are a particular feature of the Southern Pennines;
- has problems of "fen-like" nutrient levels (higher pH, base cations and NO_3^-) that can lead to scrub and forest succession under dry conditions.

2.7.3 Grosvernier "Swiss" Approach

Grosvernier and colleagues, working on bog systems in the Jura Mountains in Switzerland, have however taken a slightly different approach, in particular to issues of low water table.

This group has studied the regeneration of cut-over mires on what is described as ombrogenous and transitional mires under conditions "where raising the water table to effective levels is often out of the question" (Grosvernier *et al.* 1995). Mires in this series are developing at altitudes of 900 - 1100m, with mean annual rainfalls of 1446mm and high humidity and fog levels. *Sphagnum* mosses, mostly *S. fallax* have reappeared on these mire surfaces following peat extraction, mainly where cover is provided by other pioneer species notably dwarf shrubs, *Polytrichum alpestre* and *Eriophorum vaginatum*, subsequently leading to continuous *Sphagnum* cover.

In a series of two glasshouse experiments this group has looked at the main factors likely to be affecting successful re-colonisation.

Grosvernier *et al.* (1997) studied the growth in length and weight of three species of *Sphagnum* (*S. fuscum, S. magellanicum and S. fallax*) in a glasshouse experiment, looking at a number of different peat types and low and high (-1 cm and -40 cm) water levels.

Buttler *et al.* (1998) studied the growth of *S. fallax* under glasshouse conditions, growing capitulum diaspores of *S. fallax* on different types of peat cores with three microclimates in combination with two water levels.

The results showed clear differences between species, in relation to water table. *S. fuscum* was almost insensitive to water level compared with S. *magellanicum* and *S. fallax*. Growth of *S. fallax* in particular was strongly dependent on the water level, but at high water levels showed much higher growth rate than the other species.

Peat type had no clear effect on growth at high water tables but was more critical at low water levels. Peat properties were found to be critical when diaspores were growing in direct contact with decomposed peat with surface porosity becoming an important factor.

Protection measures, such as shading mesh and perforated plastic film, allowed improved diaspore development when compared to bare peat and compensated for the effects of low water table.

Despite its greater sensitivity to water deficit, the authors therefore recommended *S. fallax* as a very effective species in mire restoration based on its rapid growth rate, ability to recover from desiccation and its ability to colonise unfavourable situations. This reflects the observation that in mined mires, despite the various disturbance features, it is mainly *S. fallax* which re-vegetates abandoned surfaces.

2.7.4 The UK Approach to the Restoration of Raised Mires

The UK approach to the restoration of raised mires (again with very little specific information on blanket bog studies) is summarised by Wheeler and Shaw (1995) in 'The restoration of damaged peatlands', Money and Wheeler (1999), Money (1994, 1995) and Wheeler (2003).

Rewetting techniques quoted by Wheeler and Shaw (1995), include ditch blocking, water containment within bunds, and lowering of peat levels to form shallow lagoons.

The main factors affecting re-vegetation are given as availability of recolonist species, physical and hydrochemical conditions and the condition of the peat surface.

Concentrations of most ions were generally higher in peat and water from peat workings, with conditions more like those of poor fen than ombrotrophic mires. Drainage and water table fluctuations could result in increased acidity (pH <3), and mineralisation, leading to increased nutrient levels.

Little direct evidence was found for the effects of this on *Sphagnum*. Weakly humified peat generally provided better conditions for re-vegetation, due to better water retention, closer to an intact acrotelm, but could be very low in nutrients. At least 50cms of strongly humified peat was needed to hold water at the surface.

The aim was usually to restore *Sphagnum* cover. The spread of *Sphagnum* was facilitated by the presence of nurse species such as *Molinia caerulea* or *Juncus effusus*, introduced either by inoculation or transplant. The presence of a natural seedbank was found to be helpful, and ditches could act as useful sources of propagules. Local donor sites were preferable, to avoid undesirable translocation of non-local species or gene pools.

In UK restoration projects on raised mires, re-vegetation was in many cases found to have occurred naturally and, on nutrient rich sites, problems were more likely to be due to succession to undesirable vegetation such as scrub or *Molinia caerulea*.

On sites where *Sphagnum* had survived, for instance in ditches or gullies, re-wetted areas could be inoculated by hand. Many site managers have successfully spread *S. cuspidatum* in this way, and it has been suggested that *S. fuscum* and *S. capillifolium, S. magellanicum* and *S. recurvum* can all be transplanted in sods (Wheeler and Shaw 1995).

Trials by Money (1994) however, suggested that hummock and lawn species would regenerate more easily if a template of aquatic *Sphagnum* was first created from direct broadcasting into open water pools. For larger scale operations removal of large quantities of *Sphagnum* from donor sites might require *Sphagnum* "farming" operations.

Techniques have been investigated (Money 1994, 1995) for the increase of *Sphagnum* plant availability using nursery pools of aquatic *Sphagnum* such as *S. cuspidatum.* These were generally found to be more suitable than hummock-forming species such as *S. papillosum* which might require a template of aquatic *Sphagnum* on which to regenerate.

S. cuspidatum was found to regenerate well from fragments, and the growth of lateral buds could be stimulated by damage to the plant apex. Small scale trials showed good regeneration of *S. cuspidatum* fragments broadcast into pools, but regeneration was inhibited by either periodic desiccation or deep water (>50 cm).

The regeneration capacities of other *Sphagnum* species are less clear (Money 1994). Hummock and lawn-forming *Sphagnum* have been grown successfully from fragments in laboratory conditions (Wheeler and Shaw 1995). However growth is usually less prolific than *S. cuspidatum* and may require permanently moist rather than saturated conditions.

Further work is needed to formulate adequate guidelines for optimal conditions for sustainable farming and it is recommended that nursery pools are established at an early stage in restoration programmes.

The establishment and spread of *Sphagnum* may be facilitated in some situations by the presence of nurse species such as *Molinia caerulea*, *Eriophorum vaginatum* and *Juncus Effusus* (Grosvernier *et al.* 1995, Joosten 1992). These can provide protection against wind; provide a climbing frame and a more suitable microclimate. Joosten (1992) refers to this as "tussock buffering". However, a critical balance may exist between conditions that lead to high levels of dominance or cover of these species and those which permit effective use of nurse species for *Sphagnum* development. Soft rush produces large quantities of viable seed and can spread quickly to dominate a site.

Transplantation of suitable local vascular bog species is probably only practical over small areas and will be restricted by availability of labour and cost. This could include tillers, turves or whole plants, transplanted from donor sites, or cultivated in a greenhouse.

Money (1994, 1995) looked at the effects of a number of alterations in pH and calcium status on the regeneration of *Sphagnum* species both in the laboratory and in trial pits in the field. Field reintroduction experiments showed that water table fluctuations severely limited long-term regeneration, which was largely unsuccessful. *S. cuspidatum* was notably able to tolerate periodic desiccation and the overall success of pool species was also thought to be due to their higher productivity during moist periods.

Money and Wheeler (1999) referred to the work of Grosvernier *et al*. 1995 and suggested that the success reported in dried-out mires in the Jura mountains with low water tables was difficult to reconcile with the need for rewetting identified by other workers (Wheeler and Shaw 1995, Quinty and Rochefort 2003), but that key factors could be the presence of "nursery species" and the cool climate of the mountains, with near 100% humidity every night, leading to fog, as well as high mean annual rainfall.

The use of phosphorus was shown experimentally to assist in the establishment of certain *Sphagnum* species. *Sphagnum* growth in field pits was enhanced by mineral enrichment with P (30g $Na\ H_2PO_4$ in 4l water).

Laboratory experiments (Money 1995) suggested that the low pH (<pH3) recorded on cut-over peat fields could be inhibiting *Sphagnum* growth. Raising the pH in trial pits did not however improve growth, and the growth of *S. recurvum* and *S. cuspidatum* was inhibited at Ca concentrations of 18-28mg l^{-1} and above, although no effects were seen at 10mg l^{-1}.

2.7.5 Peak District Blanket Bog Restoration Studies

Restoration techniques and study areas developed in the Peak District National Park for the re-vegetation of bare peat are detailed in Philips *et al*. 1981, Tallis and Yalden 1983, Anderson *et al*. 1997.

Techniques being used or attempted have included:

- addition of lime and fertiliser;
- peat stabilization using nurse crops together with geotextiles such as geojute;

- introduction of heather using seed or brash;
- planting of other blanket bog species e.g. *Eriophorum angustifolium* and *Erica tetralix*;
- grazing removal;
- grip and gully blocking; and
- re-introduction of *Sphagnum* and other mosses.

The target pH for restoration has been taken as pH 3.5 – 4.0. Phosphorus and potassium may be added at low levels. Nitrogen, although it has been added, is not required because of high atmospheric inputs. Typical levels of inputs suggested in Chapter 5 of Anderson *et al.* 1997 where necessary to support nurse crops in particular, would be 1000 to 2000 kg lime ha^{-1}, and 125 kg h^{-1} NPK plus 200 kg h^{-1} of slow release, high phosphorus fertilizer.

There is concern that fertilization could accelerate mineralization and oxidation of surface dry peat layers, leading to mineralisation and increased rates of nitrogen supply. Fertilized swards have also been shown to remain attractive to stock for many years. This treatment should therefore not be used without grazing exclosure.

Stabilization techniques have included the use of nurse crops (*Deschampsia flexuosa*, *Agrostis castellana* and *Lolium perenne*) for instance at the Holme Moss radio mast, areas of Kinder. *Eriophorum vaginatum* and *Eriophorum angustifolium* have also been used in these areas, transplanted into the peat as individual shoots or as small turves as well as other species.

Geojute, a fibrous mesh that disintegrates with time, with 3cm pore diameter, has been used to stabilize peat surfaces in trials at Holme Moss, in combination with fertilizer, grass seed nurse crop and *Calluna* seed. These treatments were effective, but expensive. Extra phosphorus additions were found to be beneficial and 50% geojute was as successful in promoting colonization as 100% cover (Anderson *et al.* 1997). A similar approach without the geojute was taken for the 4.5ha of bared ground associated with the Holme Moss BBC aerial in 1984. Other species such as *Empetrum nigrum* and *Erica tetralix*, were then added as plants grown from cuttings, with the long-term aim of restoring a typical moorland vegetation of cotton-grasses and ericaceous shrubs, (Anderson *et al.* 1997). In the latter project, moorland pleurocarpous mosses (mostly *Hypnum* not *Sphagnum*) were collected from a nearby blanket bog site, liquidised, dried and spread over part of the site. Subsequent monitoring did not show any significant difference between moss cover between the treated and untreated areas. This could be due to the natural rate of colonisation of the mosses being adequate without assistance, or to issues associated with the polluted nature of the peat. The re-establishment of *Sphagnum* cover requires the restoration of permanently wet, high water table conditions, and presents other problems.

Crowe (2007) in a detailed study examining the processes underlying the natural re-vegetation of eroding gullies in the Southern Pennines, was able to show a predictable pattern of natural gully re-vegetation over a period of approximately 30 years, with evidence of periodic phases of erosion, indicating that re-vegetation is a cyclic rather than a linear process.

Both *Eriophorum vaginatum* and *Eriophorum angustifolium* were identified as “keystone” pioneer species in this process, and were the two most dominant species recorded. The importance of these species has also been highlighted in other studies (Tuitila *et al*. 2000, Lavoie *et al*. 2005) in the regeneration of eroded peatlands and the establishment of favourable conditions for the colonisation of other key species such as *Sphagnum* (Rochefort 2000).

These two species have different environmental preferences; *Eriophorum angustifolium* preferring waterlogged peat and humidity levels above 70-80%, whereas *Eriophorum vaginatum* has a wider tolerance for drier and more acidic substrates. *Eriophorum vaginatum* in particular, is an early colonizer of bare ground, and nutrient recycling in the microenvironment of the tussocks (Rochefort *et al*. 2002) has been shown to provide nutrients and shelter for the establishment of spores (Chapin *et al.* 1979). Other patchy colonisers of re-vegetated gullies included *Juncus effusus* frequently found associated with *Polytrichum commune* and *Sphagnum* (usually *cuspidatum*).

Data from peat stratigraphy (Crowe 2007) suggested that there was a ten-year period of rapid pioneer colonization with pioneer species playing a key role in stabilizing the peat surface and providing a suitable microenvironment for less resilient colonizers. This was followed by a more gradual period of successive community development by slower establishing species (Evans *et al.* 2005) in a secondary community which ultimately allowed the gully to progress to a functional peatland with *Sphagnum* playing a key role in the process.

Three main trajectories were identified leading to final communities dominated by *Sphagnum* over a period of approximately 15 years.

- ***Eriophorum angustifolium*** - A pioneer colonisation followed by *Eriophorum angustifolium* dieback and gradual *Sphagnum* dominance;
- ***Eriophorum angustifolium*** - pioneer colonisation with *Juncus effusus* and *Polytrichum commune* also present, leading to gradual S*phagnum* dominance without total loss of *Eriophorum angustifolium* ;
- ***Eriophorum vaginatum*** - pioneer re-colonisation leading to *Sphagnum cuspidatum* in gullies where *Eriophorum angustifolium* has been unable to colonise and *Eriophorum vaginatum* is still co-dominant in the final community, clearly attributed in this case to the microenvironment created by *Eriophorum vaginatum* tussock structure (Rochefort 2000).

The technique of gully blocking was developed in the Peak District in the 1990s with the aim of preventing further erosion of the intact peat domes. This technique has shown considerable success in creating areas of waterlogged re-deposited peats in the gullies, thus allowing re-vegetation (Evans *et al.* 2005). In the course of the Peak District restoration work, gully blocking has shown that the natural processes described above can be initiated artificially thus speeding up the recovery process.

Results showed that it was not the depth of peat created which was important, but the moisture content, with crucial 70 – 80% moisture content crucial to rapid re-colonization, in good agreement with the 70% moisture level suggested by Lavoie *et al.* (2005) for spontaneous re-vegetation of mined peatlands in Quebec.

Molinia caerulea can however form dominant species-poor vegetation, which can block the colonization of other species. The approach taken by Geoff Eyre in the Peak District National Park can be summarized as follows:

- Defined areas (patches) are sprayed with glyphosate in early summer (no wetting agents) and the area left to “dry off” and brown.
- The dry areas are burnt in August/September by special licence, using the live green material around the patches as a natural fire-break.
- Burnt areas are seeded with *Calluna* in the autumn (November).

- Where areas appear wet enough, chopped *Sphagnum* is added to the seed spreader.
- Treated areas are fenced to exclude stock.

The addition of glyphosate was considered to be fairly crucial to the destruction of the *Molinia caerulea*, and the opening up of the vegetation, primarily for the re-establishment of *Calluna*, but some of the same issues would apply to *Sphagnum* regeneration as well.

The technique worked best on dead grass with a high water table. Areas that dried out for periods in the summer were less successful.

The introduction of *Sphagnum* and other bryophytes as macerated vegetative material onto moorland areas has also been detailed by Bayfield (1976).

Russ Money (Natural England), when consulted as to the possibilities for restoration suggested the following course of action:

- Raising the water table by gully and grip blocking and low contour bunding (although creation of bare peat should be avoided).
- Establishing vegetation cover to act as nurse crop and create wet conditions in advance (not instead of) raised water table.
- Initially propagating *S. recurvum, S. palustre and S. magellanicum*, with the aim of creating a patchwork of extending *Sphagnum* foci in depressions.
- Weakly mineratrophic conditions were considered an advantage, but liming was not advised. Very low pH was not helpful, but difficult to amend. Phosphorus and potassium addition were potentially useful and would certainly help to establish the nurse crops.
- Availability of propagules for rarer species would require field nurseries.

The spreading of *Sphagnum* on bare or re-vegetating peats may be compromised by the liming and fertiliser additions and Caporn and colleagues (Manchester Metropolitan University (MMU)) are currently investigating the effects of these soil treatments on *Sphagnum* growth under greenhouse conditions. Preliminary studies indicate that fertiliser treatments, in particular, have markedly negative effects on *Sphagnum* establishment while liming was less problematic.

The liming and fertilizer treatments on the bare peat are intended to allow nurse vegetation to establish, and this is probably a necessary preliminary to any *Sphagnum* regeneration. It may however be necessary to give careful consideration to the timing of the various restoration treatments; application of lime and fertilizer to areas where *Sphagnum* regeneration is in progress may not be advisable.

In Summary:

Canadian/USA Approach:

- Field preparation: provision of suitable hydrological conditions.
- Diaspore collection: collection of top 10cm of the living vegetation in natural bog.
- Diaspore introduction: diaspores spread as thin layer on bare peat surfaces to be restored (ratio of surface collected to surface restored of between 1:10 and 1:15).
- Diaspore protection: diaspores covered by straw mulch at rate of 3000kg h^{-1} which improves water availability and temperature conditions.
- Fertilization: phosphorus fertilization (19.5kg h^{-1} y^{-1}).

Grosvernier Approach:

- Reports of *Sphagnum* re-colonization on much lower water tables with favourable microclimate, eg. Grosvernier *et al.* 1995. Companion species present. Rainfall 1446mm and very high humidity 900 – 1100m.
- *S. fallax* identified as key early *Sphagnum* recolonizer in difficult conditions.

UK Wheeler, Money and Shaw Approach:

- Based on work on raised mires. Suitable hydrology considered crucial and some natural regeneration usually present. Nurse crops sometimes used. *Sphagnum* regeneration in trial pits dependent on consistently high water levels.
- Regeneration of hummock species facilitated by an initial template of aquatic species such as *S. cuspidatum*.
- *S. cuspidatum* notably resistant to periodic drying. Considered to be linked to higher growth rates of aquatic/lawn species under favourable conditions.

Peak-District Blanket Bog Restoration:

- Main aim has been to restore vegetation cover to eroded areas.
- Natural *Sphagnum* regeneration in re-vegetated gullies (Crowe 2007) usually followed the re-establishment of mixed *Eriophorum* cover and improved hydrology.
- *Sphagnum* regeneration techniques have been developed (Geoff Eyre) on areas of burnt *Eriophorum* and *Molinia* dominated moorland where the conditions were wet enough.

3. CONSULTATION

A number of people with relevant expertise were contacted in order to extend the range of opinion and expertise available to the review and to allow full and ongoing discussion of the relevant issues.

The consultees were contacted by letter, telephone and/or email, and in each case asked

- whether they had or were aware of any suitable *Sphagnum* records for the Peak District which could be used in the data collation exercise;
- what they considered were likely to be the most important factors limiting the restoration of *Sphagnum* species to the Peak District moorlands, and if appropriate, what methodological approaches they would suggest;

A summary of the contacts made and responses received is shown in Table 3.1 below. A number of the more extensive and relevant responses have been incorporated into the literature review and where this is the case the position of the material has been indicated.

Table 3.1 Summary of Contacts made and Reponses Received for Literature Review

Name	Position	Summary of reply
Dr S. Shaw	University of Sheffield	Provided a few Sphagnum records and a list of useful references.
Dr R. Money	Natural England	Very useful telephone conversation. Advice included in the Literature Review section 2.7.4.
Prof J.Lee	University of Sheffield, Department of animal and plant sciences. (Emeritus)	Suggestions of possible contacts with relevant records.
Dr J.Tallis	University of Manchester Department of Environmental Biology (Emeritus).	Offer of support, suggestions for further contacts.
Dr Martin Evans	University of Manchester	Main observations in the context of gully revegetation, where Sphagnum forms second succession stage following gully floor stabilisation by common cottongrass. Substrate stability, mulching and water table critical to Sphagnum re-establishment, and naturally provided by the revegetated gullies.
Dr Joe Holden	University of Leeds	Worked at Moorhouse NNR. Major factors would be changes in grazing pressure and climate: drier summers and milder winters.
Dr J.Rothwell	Manchester Metropolitan University	Metals in peat. Useful references.
Tom Blokeel	Local Recorder (Derbyshire and SW Yorkshire) for the British Bryological Society.	Provided large number of records for inclusion in “existing records”, data collation. Most of records not on ombrotrophic open moorland. Concentrated on moorland and gully edges, and slightly flushed areas. Associated lack of other sensitive species such as small leafy liverworts.
Geoff Eyre	Local Moorland Manager	Explanation of restoration and Sphagnum regeneration techniques with photographs. Included in literature review text (section 2.7.5)
David Shimwell	Durham University	Contacted
Roger Meade	Independent Consultant – Previously Natural England	Considered that some of the Canadian bunding techniques could be transferable to flat areas of blanket mire Suggested the adoption of a ”more stratigraphically

Name	Position	Summary of reply
		hydrological approach" with detailed consideration of water supply mechanisms as in WETMECS approach for lowland wetlands
Joan Daniels	Natural England	Contacted.
Ron Porley	Natural England	Contacted.
Sarah Crowe	Environmental Research Institute, UHI Millennium Institute, Thurso.	Natural revegetation of erosion gullies in the Peak District. Copy of thesis and summary document. Included in the literature review (section 2.7.5).
Angela Harris	University of Plymouth	Not contacted
Andrew Baird	Department of Geography, Queen Mary, University of London. (Now University of Leeds).	Telephone conversation. Work on Silver Flowe in Dumfries and Galloway. Long-term recovery of blanket bog surface and Sphagnum from serious wildfire. Lawn species viable at 4–5cm below burn surface. Hummock species more seriously damaged.
John Adamson	(CEH/ECN) Management of Moorhouse (MH) NNR experimental site	Sphagnum never lost from North Pennines. 21 species listed for Moorhouse in 1961. Sphagnum species colonise gullies following stabilisation by common cottongrass. List of references covering grazing removal at MH included in the review.
Martha Newton	Independent Consultant Bryologist	Question of gullies versus open surfaces - will be range of species in the wetter and slightly flushed environments, these not necessarily relevant to situation on the open moorland.
Nick Moyes	Derbyshire Wildlife Trust	Records provided for the existing Sphagnum records data collation (Chapter 4).
Alistair Crowle	Natural England	Provided list of further relevant Natural England contacts.
Ros Tratt	Natural England	List of further useful contacts.
Ian Rotherham	Sheffield Hallam University	Has a number of Sphagnum data sets for the Peak District, which he is hoping will form basis of published paper. Happy to consider collaboration.

4. MAPPING OF EXISTING *SPHAGNUM* RECORDS

In order to provide additional information on *Sphagnum* distribution on the Peak District moorlands and to inform the final choice of survey sites, existing *Sphagnum* records for the area were collated from a number of sources, and the results mapped on Figures 1 – 3 Appendix 1.

Sphagnum records from the last ten years (1989 – 2007) were obtained from the following sources:

- PAA field notes (17 records);
- PAA field notes and NE SSSI sheets (78 records);
- Natural England data provided by Phil Eades:
    - GPS points (109 records) ;
    - Paper maps (Goyt) (46 records);.
- Moors for the Future Edale – 9 records;
- Nick Moyes (Derbyshire Wildlife Trust) 29 records;
- Tim Blockeel (Local Recorder (Derbyshire and SW Yorkshire) for the British Bryological Society ;
- 100m square (7 records); and
- 1 km square (441 records).

The majority of the Natural England records were compiled from condition assessments carried out by Phil Eades and Ros Tratt over the last two years in the Dark Peak and the South Eastern moorland area. *Sphagnum* cover is not a required condition assessment field, but note was taken, especially of interesting species.

South Western records were collected by Sara Barratt, Natural England Conservation Advisor for the Goyt Valley and Leek Moor, arising from various types of survey and local knowledge. No GPS locations are included.

4.1 GIS Methodology

The *Sphagnum* baseline GIS files have been compiled from Penny Anderson Associates Ltd and Natural England Data using ESRI ArcGIS 9.2. The data is in both ESRI shapefile format and Mapinfo tab files.

4.1.1 Sphagnum Point Locations

There are 121 records in the form of point locations from GPS surveys where *Sphagnum* is present, provided in MS excel format by Phil Eades.

Table 4.1 GPS Survey Point Locations for the Peak District

GIS File Headings	Example of Data
Site	Dark Peak
Unit	38.000000
x_coordinates	402130.000000
y_coordinates	409400.000000
Broad_location	eg Alport Head
Species	S. *palustre*, S. *subnitens*, S. *fimbriatum*
Unit_Burns	unknown
Data_source	'condition assessment' OR 'Phil Eades Paper Maps'
Date_	2007.000000
Notes	frequent but scattered in area of wet grips
Cover_PAA	ie Abundant or Rare

4.1.2 Sphagnum Areas/polygons

These areas indicate where *Sphagnum* has been recorded during PAA field surveys often at on SSSI Unit level or has been mentioned on English Nature SSSI Assessment sheets. The SSSI Assessment sheets are either held in PAA project files or the data were summarised and provided in MS excel format by Phil Eades.

There are 141 broad areas (0.3 ha to 388 ha) where *Sphagnum* has been recorded. *Sphagnum* is likely to be present somewhere within these areas but does not indicate complete coverage. These areas should only to be used as a broad indicator of *Sphagnum* distribution.

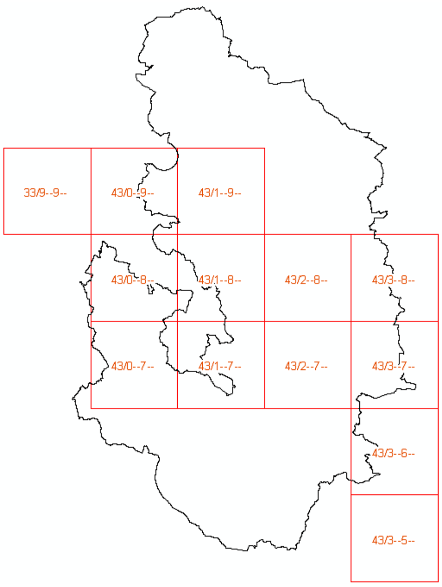
Table 4.2 below shows an example of the area/polygon data provided

Table 4.2 GPS Broad Area Locations for the Peak District

GIS File Heading	**Example of Data**
Id	101144 (From SSSI Data)
SSSI_NAME	Goyt Valley (or The Dark Peak, Leek Moors etc)
ENSIS_ID	1002841 (where SSSI id is known)
NUMBER	23 (From SSSI Data)
UUFarm	Goyt Area (United Utilities Farm Estate)
Surveyor	PAA -Sue Mackenzie
Sphagnum	*Sphagnum fallax*
DateSurvey	08/03/2003
AreaNos	eg 3 (PAA field survey reference)
Notes	*Sphagnum* lawn 2x3m
Cover_PAA	Abundant (Local frequent, Rare or No *Sphagnum*)
Hectares	58.7
AreaSize	SSSI Unit Boundary
TEMP	PAA (or NE)

4.1.3 Additional Sphagnum Species

Additional data were provided by Tom Blockeel. Six records are at 100m square areas and 214 records are at 10km square areas or greater. As the 10km square area records are at a broader scale many records exist for each square and are more complicated to show on a map at 1:250,000.



43/0--9-- = Grid references to 10kmsq (centre point eg. 40000,39000)

Figure 4.1 Peak District Grid References

4.2 Results

The mapped data are presented on Figures 1-3 Appendix I.

Unless specifically mentioned, absence of species records does not necessarily imply that species are not present, but simply that no records have been found, which in this limited exercise could be due to a number of reasons; possibly the altitude and inaccessibility of the area.

Figure 1 Appendix I shows the distribution of the records from the different sources/recorders, given as either GPS points or discrete areas.

Figure 2 Appendix I shows the abundance of *Sphagnum* species based on the records collected, where sufficient information was available. *Sphagnum* is mapped as rare or abundant based on notes provided with the records.

Figure 3 Appendix I shows the distribution of the different species as provided in the records.

Table 4.3 below shows the number of records for each species, based on the data provided by Tom Blockeel and Phil Eades.

Table 4.3 Number of Records for Each *Sphagnum* species . Peak District Data Collation

	Species	**Total Number of Records**
1	Species not recorded	163
2	*S.fallax*	174
3	*S.fimbriatum*	149
4	*S.palustre*	120
5	*S.denticulatum*	102
6	*S.subnitens*	112
7	*S.papillosum*	65
8	*S.squarrosum*	40
9	*S.russowi*	26
10	*S.cuspidatum*	25
11	*S.capillifolium*	12
12	*S.flexuosum*	12
13	*S.girgensohni*	7
14	*S.palustre/pap*	6
15	*S.quinquefarium*	5
16	*S.inundatum*	4
17	*S.teres*	4
18	*S.magellanicum*	1
19	*S.subsecundum*	1
20	*S.warnstorfi*	1

The data brought together by this collation exercise, gives some idea of the most common species present on the Peak District Moorlands, with maximum record numbers for *S. fallax, S. fimbriatum, S. palustre, S. denticulatum and S. sub-nitens.*

The mapped data (Figures 1–3 Appendix I) shows a wide distribution of records over the blanket bog areas of the moorland. There is some indication of lower record numbers and abundance over the Bleaklow plateau, but as these are records of presence rather than absence, this must be interpreted with caution. There does not appear to be any marked clustering of particular species on the basis of these records.

5. PDNPA *SPHAGNUM* RANGER SURVEY

5.1 Methodology

In addition to the formal survey, we conducted a sphagnum survey with the PDNPA ranger service to increase the records of *Sphagnum* locations in the Peak District.

Rangers were asked to put 2-3 stems of *Sphagnum* plants into an envelope and answer the questions printed on the envelope. Phil Eades identified the species.

We are very grateful to the PDNPA Rangers for enhancing this study!

5.2 Results

The full data table table is shown as Table 1 in Appendix IV, and the recording “envelope” as Table 2.

The records are mapped for total species in relation to wetness in Figure 1 Appendix IV.

The data collected is summarized in Tables 5.1 and 5.2 below.

In total 90 envelopes were returned, which added 56 records for 7 *Sphagnum* species and additional records for other moss species. Most species were found in wet or water-logged condition. Surrounding vegetation/habitat was not always recorded, but records were mainly for cottongrass, flush or heather habitats.

Table 5.1 Summary of Species/wetness Data Collected by PDNPA Rangers

Species/Wetness	dry	medium	wet, standing water	water-logged	pool	flowing water	**Total**
Sphagnum cuspidatum		2	2	5	1	2	**12**
Sphagnum denticulatum				1			**1**
Sphagnum fallax			2	6		3	**11**
Sphagnum fimbriatum	1	2	4	7	4	2	**20**
Sphagnum inundatum			1				**1**
Sphagnum palustre			2	5		1	**8**
Sphagnum subnitens	1		1	1			**3**
Total	**2**	**4**	**12**	**25**	**5**	**8**	**56**

Table 5.2 Summary Habitat Data Collected by PDNPA Rangers

Species / Habitat	Cottongrass	Flush	heather	heather/cottongrass	heatherFlush/Molinia	Molinia	MoliniaHeather/cottongrass/	MoliniaHeather/cottongrass/flush	**Total**
Sphagnum inundatum		1							**1**
Sphagnum cuspidatum	2	4	1	1	1	1			**10**
Sphagnum denticulatum		1							**1**
Sphagnum fallax		1	5	3		1		1	**11**
Sphagnum fimbriatum	4	2	7	1		2	1		**17**
Sphagnum palustre	3	2	2			1			**8**
Sphagnum subnitens	1								**1**
Total	**10**	**11**	**15**	**5**	**1**	**5**	**1**	**1**	**49**

6. SPHAGNUM SURVEY AND ENVIRONMENTAL SAMPLING

6.1 Methods

The aim of the survey work was to identify the abundance and species composition of the

Sphagnum present on the surface of the blanket bogs rather than in the gullies or pools, and to examine their relationships with various environmental variables.

In order to meet these aims data was collected from:

- The Peak District National Park Moorlands;
- Bowland Forest (in collaboration with United Utilities); and
- North Pennines AONB (in collaboration with the PEATSCAPES project).

In order to allow detailed comparison with environmental variables, a quadrat-based approach was adopted, with detailed species and environmental data collected from 2 x2 m quadrats, and more general information on vegetation structure, species abundance and land use noted for a wider 20 x 20m around each quadrat.

In order to provide information on a wide range of environmental conditions, suitable and potentially non-suitable for *Sphagnum* growth, a proportion of the quadrats at each survey location were deliberately placed to contain no *Sphagnum*. At the Forest of Bowland and in the North Pennines AONB this was not always possible. In total, 256 sets of quadrats and related data were collected. The record sheet used for the survey is shown as Table 6 in Appendix II. Peat samples were also collected at each quadrat location for environmental analysis as described below.

Table 6.1: Number and Type of Quadrats in the Three Survey Areas

Location	**Sample Number**		
	***Sphagnum* Presence**	***Sphagnum* Absence**	**Total**
The Peak District Moorlands	84	66	150
Bowland Forest	49	1	50
North Pennines AONB	37	19	56

6.1.1 Survey Methods

A stratified approach was adopted in the choice of survey locations, in line with criteria outlined below, with the aim of covering a range of altitudes, land uses and levels of erosion and degradation:

Geographic location – Sites were chosen which covered the full geographic cover of the Peak District, from east to west and north to south.

Altitude - Taking in sites at moderate altitudes (*c*.400-500m) and high altitudes (500m+).

Vegetation types - Sampling a range of vegetation types including bare peat.

***Sphagnum* -** Sampling areas known to support *Sphagnum* species, and areas where *Sphagnum* was believed to be absent.

Management - Sheep grazed / sheep excluded
Burned / not burned.
Grips or gullies present / artificially blocked
Natural revegetation / areas limed and reseeded.

As agreed with the Technical Advice Group (TAG) (representatives from Natural England, United Utilities, PDNPA , MfF and the project team), quadrat locations were chosen as representative of open moorland locations, and did not include gullies or pools.

Due to time restraints, it was decided to ensure that in the Peak District, as far as possible the surveyor was visiting known *Sphagnum* locations, in order to reduce time spent searching for *Sphagnum* mosses.

Position, estimated land-use, altitude etc for all the quadrat locations are summarised on the Site Data Sheet in Table 7 Appendix II, for all the quadrat locations.

Data recorded for each quadrat included:

- Altitude/aspect/slope;
- GPS location;
- Depth of peat;
- Vegetation structure (height without flowering culms, depth of litter);
- Hydrology (proximity of closest grip or gully, width and depth);

- Erosion features (bare peat, gaps from past wildfires, rills and incipient gullies);
- Land-use and management history;
- *Sphagnum* cover and species diversity;
- % cover of other species; and
- NVC classification.

6.1.1.1 Peak District

A total of 150 quadrats were collected in the Peak District, between November 2007 and January 2008, by Dr Phil Eades, with between 3–10 samples in a total of 22 areas. The survey locations are shown on Figure 4 Appendix I and the Site Data Sheet Table 7 Appendix II.

6.1.1.2 Bowland

Quadrats were recorded in the same way over the same time period and by the same surveyor. Sample areas were chosen as known areas based on detailed survey work carried out as part of the SCaMP United Utilities project, on moorland to the North of Slaidburn and Dunsop Bridge, and are shown on Figure 5 Appendix I and Table 7 Appendix II. Within these areas a range of land-use and altitude categories were chosen by Phil Eades, using the criteria described above.

6.1.1.3 North Pennines AONB

The data from the North Pennines AONB (56 samples) were collected by Clare O'Reilly in collaboration with the PEATSCAPES project. Samples were collected on blanket bog areas south of the A69 between Haltwhistle and Hexham and to the north and south of the A66 between Appleby in Westmorland and Barnard Castle. The exact positions of the sample sites are shown on Figure 6 Appendix I. Further site details are provided in the Site Data Sheet Table 7 in Appendix II.

The survey areas were chosen in line with the criteria established for the Peak District survey, and the data collected by Clare O'Reilly.

2km squares ('referred to as Sites') were located, using random grid coordinates, in areas of known blanket bog within the North Pennines Natural Area. Vegetation with *Sphagna* cover in each Site was sampled by stratified random sampling in November 2007 and February and March 2008. Plots with *Sphagna* cover were located in the mire expanse and 2 x 2m square quadrats placed using a random number grid. All vascular plants, bryophytes and lichens were identified to species level and a visual estimate made of their percent cover-abundance to the nearest 5%. Species cover data was also collected for the 20 x 20m area, together with environmental and land-use data, in line with the criteria established for the Peak District.

6.1.1.4 Environmental Analysis

Five small peat samples (approximately 20g) were collected immediately around each quadrat using a small bulb planter. These were stored as a single sample under cool conditions, and transferred to the freezer as soon as possible, usually within one to three days. Samples were analysed at Manchester Metropolitan University for pH, % moisture, extractable ammonium, nitrate, sulphate, calcium, magnesium, copper, lead, zinc and aluminium.

Peat samples were thawed at room temperature and carefully mixed prior to analysis. pH measurements were made in a peat/water slurry (5g peat + 10mls distilled water) using a standard calibrated bench-top pH meter. % moisture of the peat was measured by air-drying weighed aliquots of the mixed peat samples until a stable final weight was obtained. Ion and metal elements were measured in 6% potassium chloride extracts of the peat samples, prepared by shaking and centrifugation. Metal concentrations in the extracts were measured by inductively coupled plasma emission spectrometry (ICP - AES) Varian Scientific Instruments Inc. Vista AX. Sulphate, nitrate and ammonium levels were measured by Ion exchange chromatography (DIONEX ICS 2000).

Results are presented as either mg kg $^{-1}$ dry wt or mg g^{-1} dry wt, as shown on the graphs and tables

6.1.1.5 Statistical Analysis

Several approaches were taken to the statistical analysis of the data from the vegetation survey and environmental sampling.

Data from different survey areas was compared using ONEWAY ANOVA analysis SPSS version 12.0.1. Correlations between variables were examined using correlations analysis SPSS version 12.0.1. Detrended Correspondence analysis (DCA) and canonical correspondence analysis (CCA) (CANOCO for Windows 4.5) was used to examine the relationships between the vegetation data and the environmental variables.

Statistical presence/absence analysis in R version 2.7.2 was also carried out for all *Sphagnum* species, and separate models were also presented for *S. papillosum, S. capillifolium* ssp. *cap, S. fallax, S. fimbriatu,* and *S. subnitens*

6.2 Results

6.2.1 Vegetation Data

Data from the survey record sheets were transferred to EXCEL spreadsheets and a number of approaches taken to further analysis and presentation.

Marked species differences were seen in the data collected from the three survey areas. Total *Sphagnum* cover in the 2 x 2m quadrats containing *Sphagnum* was higher in the Bowland and North Pennine samples and the distribution of species also showed differences (Figure 6.1 and Figure 6.2). This analysis excludes the quadrats deliberately chosen as not containing *Sphagnum* species, and therefore obviously does not represent the overall mean *Sphagnum* cover in the survey area.

The frequency of the hummock-forming species *S. papillosum* and *S. capillifolium* was clearly higher in the Bowland and North Pennine samples. The same pattern was seen for *S .palustre* although the overall frequencies were much lower.

The overall frequency of *S. fallax* was low in the Peak District samples, both overall and in comparison to the other study areas. This species is generally considered one of the most widespread in the Peak District (see Table 4.3), and is thought to show a relatively high tolerance to less favourable environmental conditions. The sampling strategy adopted in this study may not however have recorded much data from the wetter areas where this species may be more abundant.

Higher frequencies, although low overall, were recorded in the Peak District samples for *S. fimbriatum*, *S. subnitens*, and *S. squarrosus* was recorded only from this area. There are no Peak District records from this survey for *S .magellanicum*, *S. tenellum* and *S. russowii*. The distribution of *S.cuspidatum* appears similar across the survey areas, at very low frequency. This species is mainly aquatic and would not have been strongly sampled in this survey design.

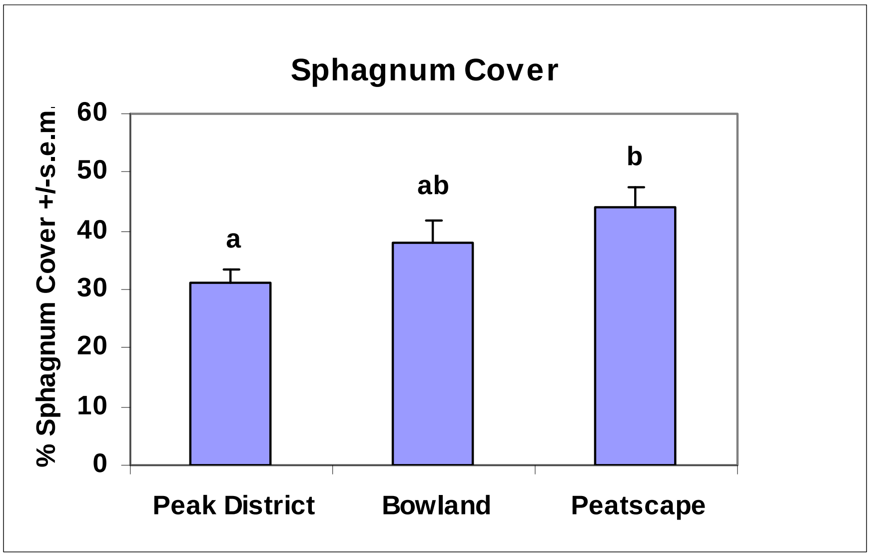


Figure 6.1 Mean % *Sphagnum* cover (all species) in the "+*Sphagnum*" 2 x 2m quadrats for the three survey areas. ANOVA Oneway analysis Significant differences between the sites at $p<0.05$ in all cases. Columns sharing a letter not sig. different at $p<0.05$

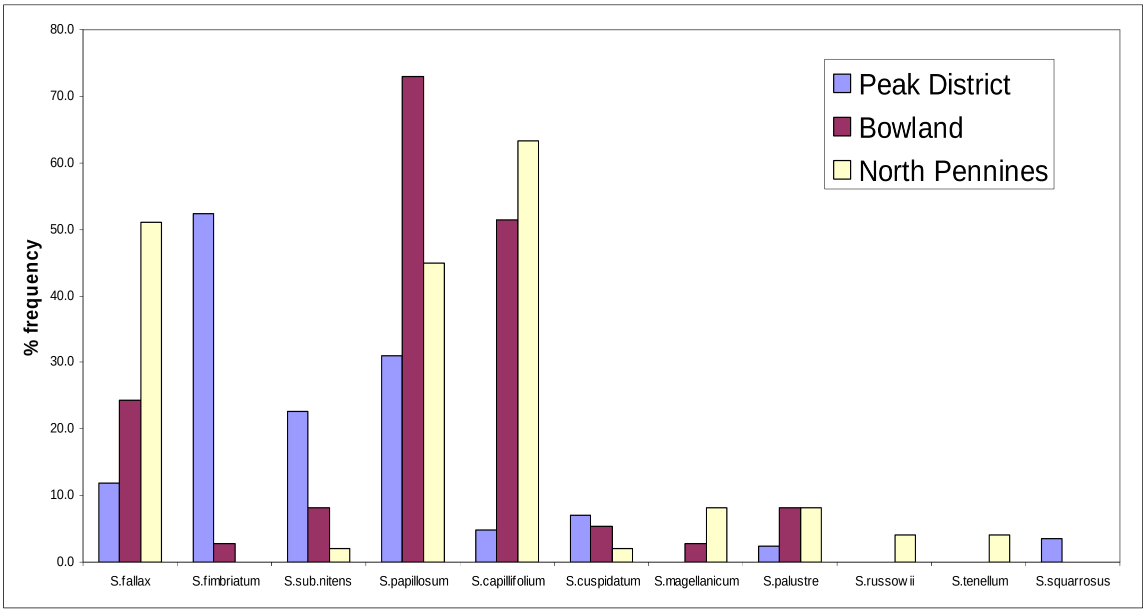


Figure 6.2 % frequency (% of quadrats in given area containing *Sphagnum*) in the "+*Sphagnum*" 2 x 2m quadrats for all *Sphagnum* species for the three survey areas

Figure 6.3 and Table 2 Appendix II compare the quadrat frequencies of the most common moorland species across the three study areas. The frequency of *Calluna vulgaris* was slightly higher in the Bowland and North Pennine quadrat samples, when compared with the Peak District, but no difference was seen in the frequency of *Eriophorum vaginatum*, present in 90% of all quadrats in this study. The frequency of *Eriophorum angustifolium*, and *Deschampsia flexuosa* was however higher in the Peak District samples, when compared with the other areas.

Frequency of *Vaccinium myrtillus* was very much higher in the Bowland samples, when compared with the other areas, and *Erica tetralix* was also markedly more common in the more northerly survey areas.

The spread of acrocarpous moss species across the survey sites (Table 2 Appendix II) was fairly even, except for *Polytrichum commune*, which was more frequent in the North Pennines. The frequency of *Hypnum* sp. increased from 46.7% in the Peak District to 78.6 – 92% in Bowland and the North Pennines, representing a clear increase in overall bryophyte cover.

A number of other species were also recorded at very low frequency in this study, with the results showing no clear pattern, *Vaccinium oxycoccus*, *Andromeda polifolia*, and *Trichophorum cespitosa* were however all recorded at significant frequencies in the Bowland samples, but were absent or rare elsewhere.

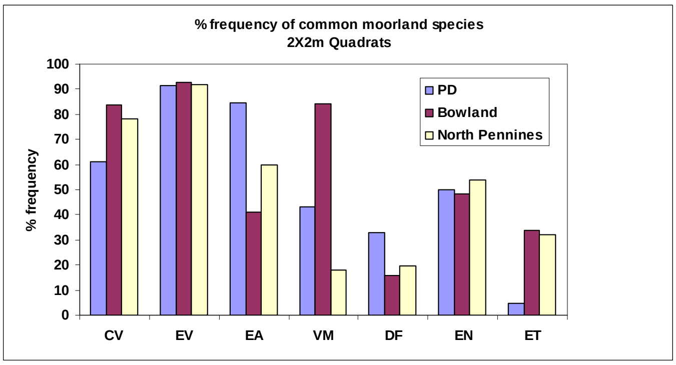


Figure 6.3 Frequency of common moorland species in the 2 x 2m quadrats, across the three survey areas

Similar overall patterns were seen in the vegetation data (Figures 6.4 and 6.5) from the 20 x 20m wider survey areas, (Table 3 Appendix II) although the methods used were not directly comparable. In this case all the quadrats are included in the cover analysis, and these data may provide a more representative measure of the overall survey areas.

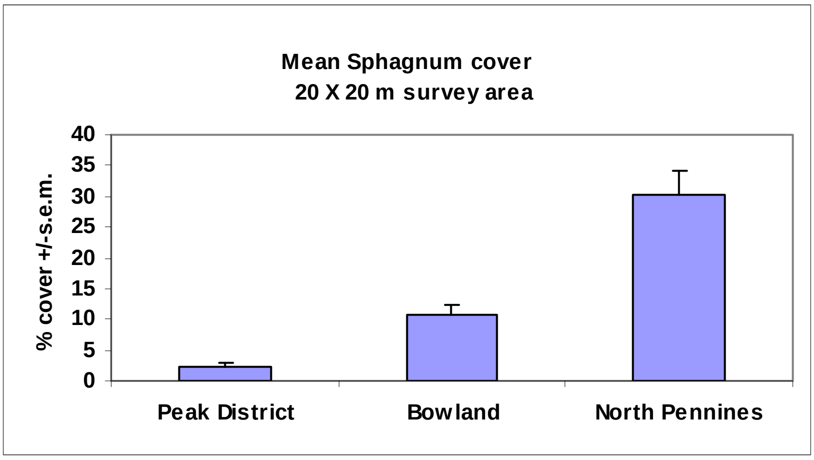


Figure 6.4 Mean % *Sphagnum* cover for the 20 x20m survey areas, for the three survey areas

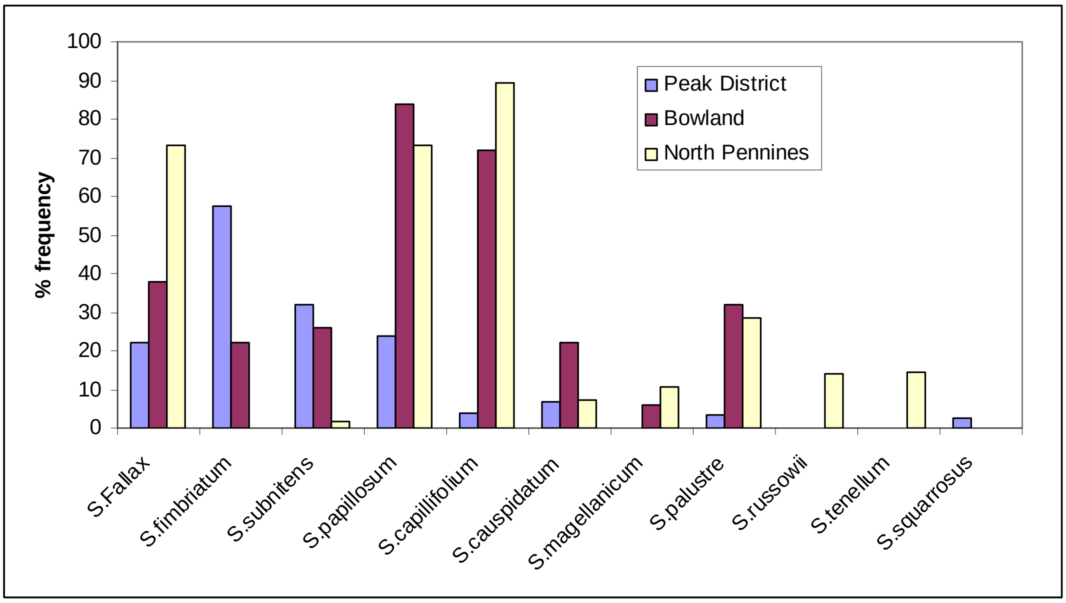


Figure 6.5 % frequencies for the 20 x 20m survey areas (% of samples in given area containing *Sphagnum*) for all *Sphagnum* species for the three survey areas

Sphagnum cover was lower overall in the 20 x 20m survey areas, but showed the same general pattern seen in the 2 x 2m quadrats, with higher cover at the more northerly sites.

Similar patterns of distribution were seen for *S. papillosum*, *S. capillifolium* and *S. fimbriatum*, whereas the frequency of *S. palustre* was significantly higher using this method and higher levels of *S. cuspidatum* were also recorded in Bowland.

The distribution seen for *S. fallax* however, was slightly different using the data from the wider survey areas, with 20% frequency in the Peak District compared with 10% in the 1 x1 m quadrats, higher values for Bowland, and lower for the North Pennines.

The detailed spatial distribution of the *Sphagnum* species across the survey areas is shown in the mapping figures in Appendix I:

Appendix I Figures 7-9 show the presence/absence records for all *Sphagnum* species for the 20 x 20 m survey areas.

Appendix I Figures 10–12 show the total % *Sphagnum* abundance data for all *Sphagnum* species for the 20 x 20m survey areas

Appendix I Figures 13–20 show the distribution of the separate *Sphagnum* species, based on the 2 x 2m quadrat data.

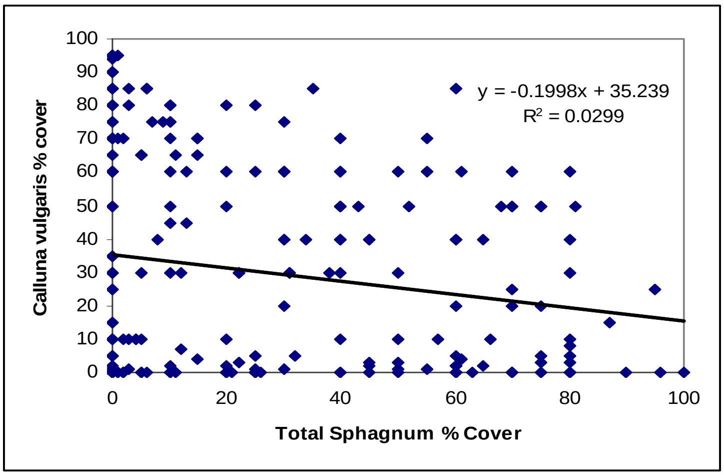
The presence/absence and abundance mapping figures are shown for all areas based on the 20 x 20m survey areas in order to give a representative picture of *Sphagnum* cover in the survey areas.

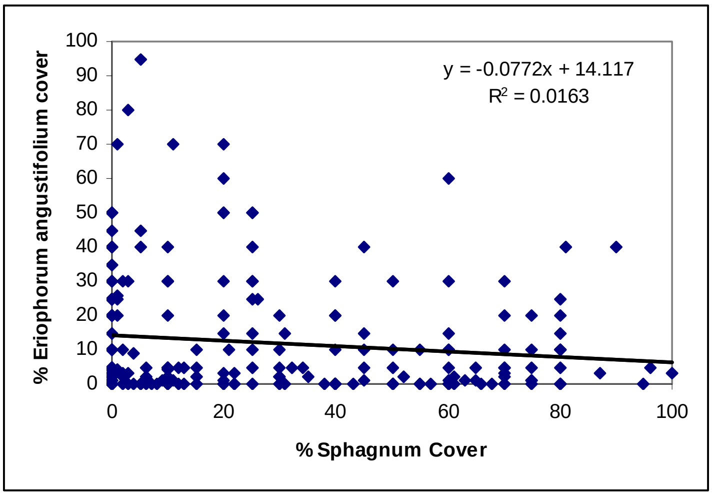
The presence/absence data (Appendix I Figure 7) for the Peak District show higher numbers of absence records for Featherbed Moss, Bleaklow and, notably, Marsden Moor (see Table 7 Appendix II for site details). Very few *Sphagnum* absence results were recorded for the more northerly sites.

The *Sphagnum* abundance mapping figures (Appendix I Figures 10–12)) reflect the data shown in this section for the three survey areas, with clearly higher overall abundance at the more northerly sites. No clear pattern is shown in the Peak District data.

Appendix I Figures 13-20 show the distribution of the most common *Sphagnum* species across the survey areas. The maps demonstrate the increasing cover of *S. papillosum* and *S. capillifolium* on the more northerly sites.

Scatterplots of total *Sphagnum* cover against the total cover of the three dominant moorland species: *Calluna vulgaris*, *Eriophorum vaginatum* and *Eriophorum angustifolium*, shown in Figure 6.6 below, do not show any strong relationship with no clear suggestion of either positive or negative effects of high cover of these three species on *Sphagnum* cover overall.





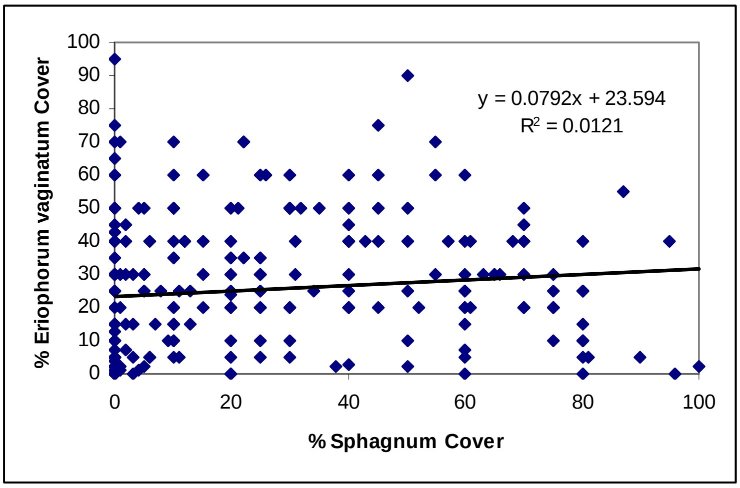


Figure 6.6 Scatterplots of total *Sphagnum* cover against the % cover of the three dominant moorland species, based on data from the 2 x 2m quadrats

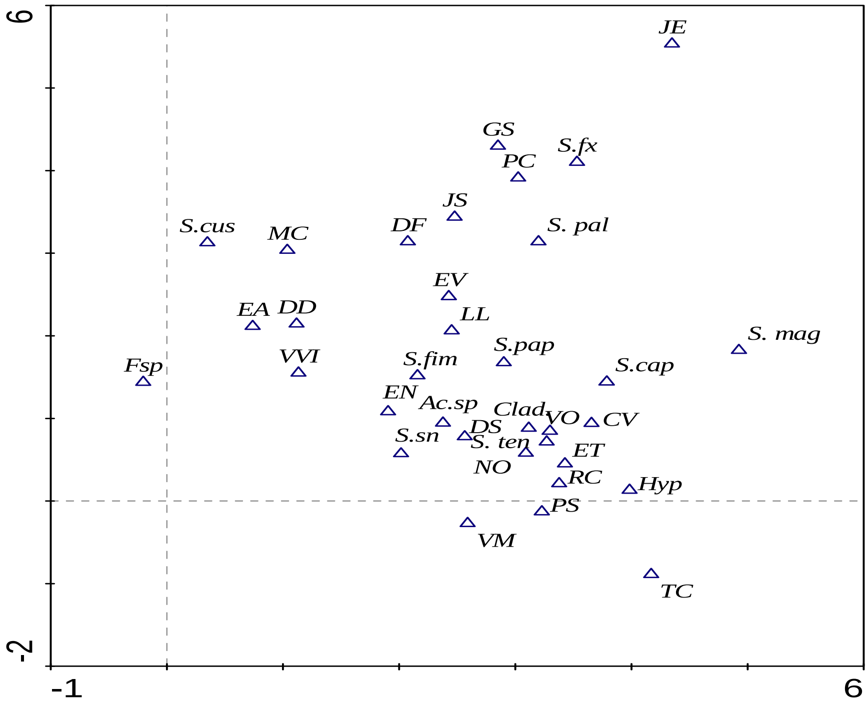


Figure 6.7 Preliminary detrended correspondence analysis (DCA) for the main species recorded in the 2 X 2m quadrats. Data for a number of non-characteristic species present at very low frequency have been excluded from the analysis

KEY

CV-*Calluna vulgaris,* EV-*Eriophorum vaginatum,* EA-*Eriophorum angustifolium,* VM-*Vaccinium myrtillus,* MC-*Molinia caerulea,* ET-*Erica tetralix,* EN-*Empetrum nigrum,* VVI-*Vaccinium vitis-ideae,* GS-*Galium saxatile,* DS-*Dicranum scoparium,* RC-*Rubus chamaemorus,* PS – *Polytrichum strictum,* PC-*Polytrichum commune,* JS- *Juncus squarrosus,* VO -*Vaccinium oxycoccus,* DD – *Dryopteris dilatata,* DF-*Deschampsia flexuosa,* TC-*Trichophorum cespitosa,* NO – *Narthecium ossifragum,* LL- *Leafy liverwort,* Fsp – *Festuca* sp., Hyp - *Hypnum* sp., Clad – *Cladonia* sp., Ac.sp – *Acrocarpous mosses*, *S*.fx*, S.pal, S.pap, S.fim, S.cap, S.mag, S.fim, S.cus, S.ten, S.sn.*

The Detrended Correspondence Analysis (DCA) ordination diagram for all species recorded in the 2 x 2m quadrats is shown in Figure 6.7 and Table 4 Appendix III. The data showed relatively little clear clustering of species with no indication of specific communities, based on this data set. Outlier species included *Festuca* sp., *Juncus effusus*, *S. magellanicum* and *Trichophorum cespitosa.*

Similarly, ordination of the *Sphagnum* species alone, shown in Figure 6.8 and Appendix III Table 5, showed no distinct clustering of species, although *S. fimbriatum* and *S. subnitens*, the two species most characteristic of the Peak District, did form a separate grouping to *S. magellanicum*, S. *capillifolium*, *S. fallax* and *S. cuspidatum*.

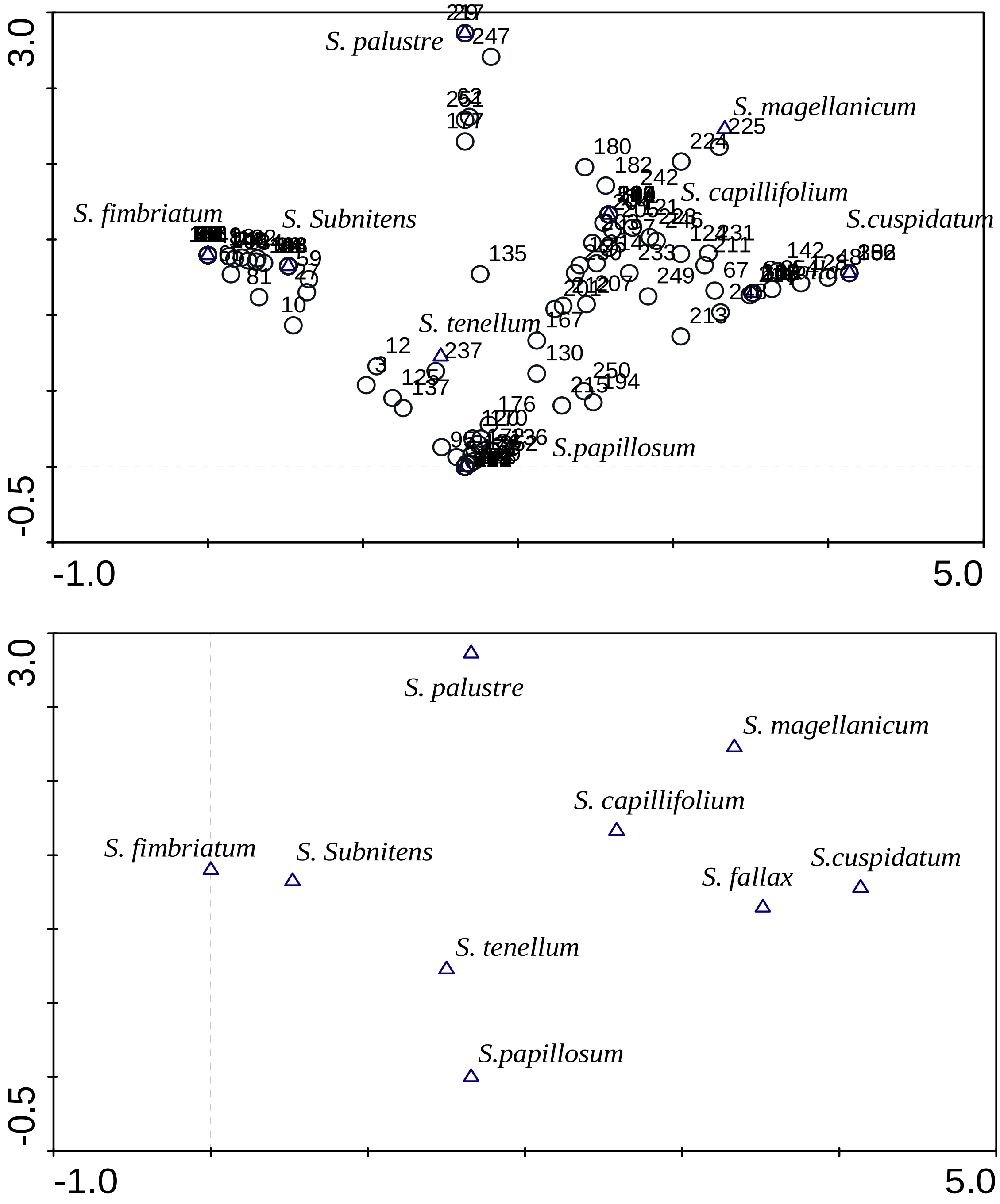


Figure 6.8 Detrended correspondence analysis (DCA) for the *Sphagnum* species recorded in the 2 x 2m quadrats. Data for a number of non- characteristic species present at very low frequency have been excluded from the analysis

Overall, the *Sphagnum* data obtained in the survey results presented here is indicative of higher abundance and species diversity at the more northerly sites, with higher representation of the hummock-forming species more characteristic of intact and peat-forming blanket bog vegetation. The other species present show no major shifts in vegetation composition. The *Sphagnum* species found at higher frequency in the Peak District could be considered as representative of slightly more nutrient rich conditions (Smith 2004) than *S. papillosum* and *S. capillifolium* in particular, which are more typical of ombrotrophic blanket bog.

The data analysis shows no major differences in overall vegetation structure across the survey sites, based on this survey technique, although a number of further analytical techniques could be applied to the vegetation data, which might identify more detailed spatial differences.

6.2.2 Environmental Data

6.2.2.1 pH, Water Content, Ammonium and Sulphate Levels

Mean pH, % water content, and extractable ammonium and sulphate values are shown in Figure 6.9 below for samples collected from the three survey sites. ANOVA Oneway analysis showed significant differences between the sites at $p<0.05$ in all cases. Nitrate concentrations were in most cases too low to measure, and were not included in the analysis.

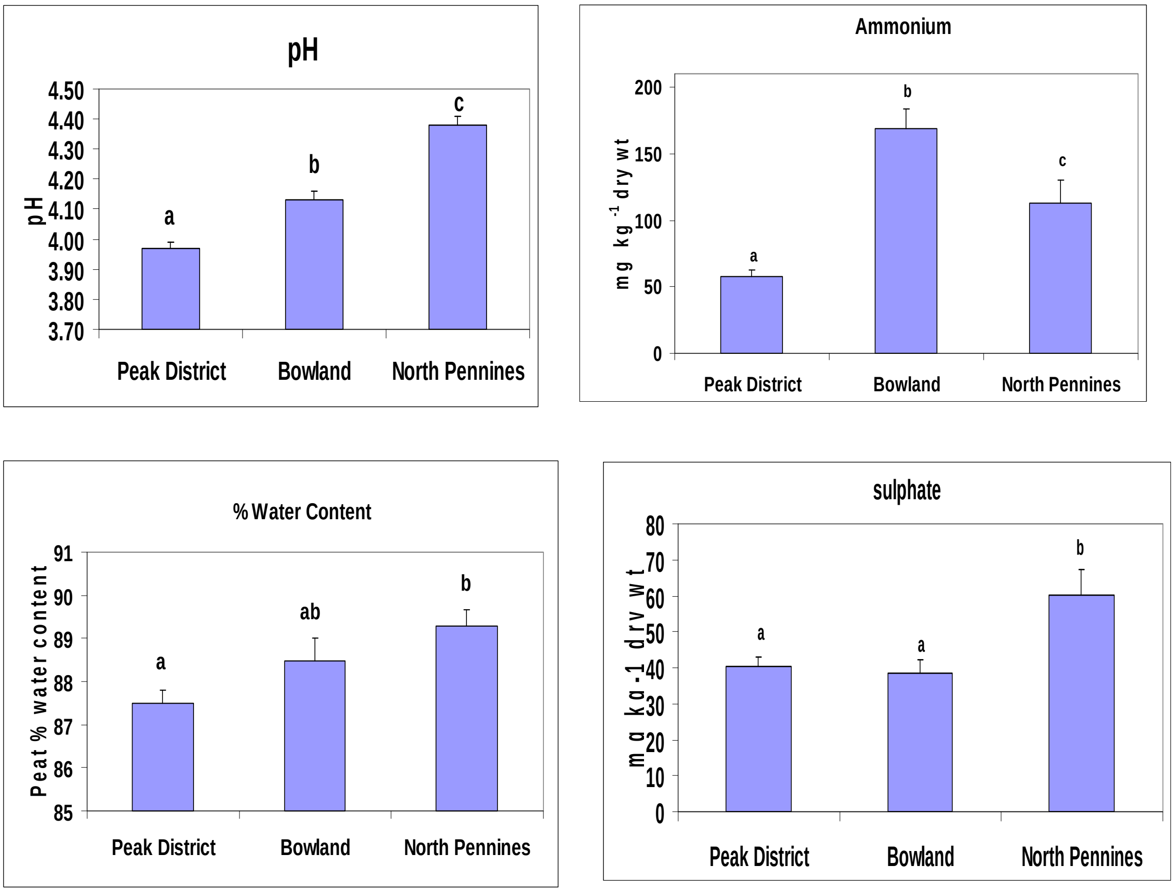


Figure 6.9 Mean % water content, pH, and extra table ammonium and sulphate levels for the three survey areas. ANOVA Oneway analysis Significant differences between the sites at $p<0.05$ in all cases. Columns sharing a letter not sig. different at $p<0.05$

A clear and significant trend was seen towards higher mean pH values in Bowland and the North Pennines. The values for the separate survey areas are shown in Table 4 Appendix II. The range of pH values obtained overall was small and the data set showed low variability. The lowest value obtained for the Peak District was pH 3.7. All measurements were therefore above the pH 3.5 level suggested as the threshold for negative effects on *Sphagnum* growth and survival (Andrus 1986).

Percentage peat water content also increased significantly in the North Pennine samples when compared with the Peak District. The range of values here is also narrow (87.5 – 89.2%)

across the survey areas and suggests very consistent peat water content across the survey period.

The extractable ammonium and sulphate levels were much more variable both within and between sites and individual survey areas. Ammonium levels were significantly higher in both Bowland and the North Pennines when compared with the Peak District survey areas.

The mean values for separate survey areas are shown in Table 4 Appendix II. The ammonium values ranged from 20.6 – 112.9 mg kg^{-1} for the Peak District sites, with the majority of values in the 50 – 60 mg kg^{-1} range.

The values for the more northerly sites however, were much more variable between survey locations. The Bowland values ranged from 170 to 190 g kg $^{-1}$ except for Lamb Hill which were much lower at 54.2 mg kg^{-1}. The North Pennine values were extremely variable, covering a range from 24.2 – 273.3 mg kg^{-1}, with marked differences between survey areas that showed no obvious relation to any other variables recorded. Mean sulphate levels were also significantly higher in the Northern Pennines when compared with the other areas; these data are also very variable, both within and between survey locations.

Potassium chloride extracts from superficial peat samples collected close to the experimental plots at Holme Moss in June 2007 (Jacky Carroll, personal data) showed values in the range 70–80 mg kg^{-1} dry wt, allowing an approximate wet to dry weight correction and using the same analytical techniques and equipment. This showed good general agreement with values obtained for the Peak District in this study. Sulphate values from this data set were also in the range 25–50, mg kg^{-1} dry wt again in good agreement with the survey data. Nitrate levels from these previous data were 71 mg kg^{-1} dry wt. This is much higher than the current study values, which are not measurable. This could possibly be due to seasonal effects.

Comparisons with other measurements of potassium chloride extracted peat ammonium levels available in the literature show a very wide range of values. Sanger *et al* 1996. obtained a range of values, from 4.53 mg kg^{-1} at Strathvaich (6.0kg N ha^{-1} y^{-1}) to a maximum of 273.6 mg kg^{-1} at Chartley Moss, with values of 183.6 mg kg^{-1} for Hatfield Moor (both high N deposition sites) and a clear correlation with nitrogen deposition.

Yesmin *et al.* 1996a also obtained low values of 9.18 mg kg^{-1} at Strathvaich, and 47.52 mg kg^{-1} at Glen Dye (14.1 kg N ha^{-1} y^{-1}), compared with 96.7 mg kg^{-1} for Glen Dye under *Calluna* vegetation in a different publication (Yesmin *et al* 1996b).

These values cover a wide range and do show a clear correlation with nitrogen deposition. The results suggest that the values obtained from the Peak District in this and other studies are quite low whereas the values for some of the northerly sites are very much higher.

Table 6.2 APIS Atmospheric Deposition Figures for the Three Survey Areas

Site	N Deposition kg N h^{-1} y^{-1}	NOx µg m^{-3}	NH_3 µg m^{-3}	SO_2 µg m^{-3}	Acid Deposition keq ha^{-1} yr^{-1}
Peak District (Bleaklow)	29.1	10.6	0.6	2.1	2.69
Bowland	28.8	7.6	0.7	1.2	2.64
North Pennines	17.1	6.9	0.7	0.7	1.50

Table 6.2 shows the approximate nitrogen deposition figures for the three survey sites based on APIS (apis.ac.uk) data. Current overall nitrogen deposition to the Peak District and Bowland sites is similar, but inputs to the North Pennines moorlands are significantly lower. SO_2 levels at all three survey areas are now low.

The mean extractable ammonium levels for the three survey areas do not appear to correlate well with the current nitrogen deposition data for the survey areas and there is no other obvious pattern in terms of location, altitude, land-use or collection date.

These figures do not however give any information on the long-term history of pollutant inputs to these sites, which is likely to have been very different, or of the balance of wet to dry deposition.

A number of factors may be important in explaining the apparently high extractable NH_4^+ and SO_4^{2-} levels at the more northerly survey locations. The colder and wetter conditions at the more northerly sites could lead to high levels of wet or fog related deposition particularly at high altitude. Microbial transformations in the peat could also be strongly limited, with low levels of plant uptake and nitrification, a conclusion that would receive support from the very low nitrate levels obtained in this study.

The relationship between the salt extractable ion contents and actual bog-water concentrations is also not clear from this study. It is possible that in the Peak District, due to the higher NO_x levels and associated dry deposition and the lower rainfall, as well as overall soil moisture levels, “bog-water” NH_4^+ concentrations could be higher than the extractable NH_4^+ levels would suggest, and that this trend could be reversed at the more northerly locations.

This conclusion would be supported by NH_4^+ and SO_4^{2-} levels obtained from bogwater samples collected from Holme Moss and the Migneint in Wales (Section 2.3.1.3).

Studies carried out with samples of *Racomitrium* mosses collected from clean upland sites in Scotland, (Pearce and Van der Waal 2007) have shown that reduced growth was most strongly correlated with exposure to high nitrogen concentrations in solution, rather than the total dose. These and other studies have led to a growing awareness that unacceptable habitat change can derive not only from high levels of nitrogen deposition, but also from high nitrogen solution concentrations. Maps of mean rainfall concentrations of NO_3^- and NH_4^+ (NEGTAP 2001) also show higher levels of these ions in the Peak District when compared with the more northerly sites.

Local effects are also likely to be relevant to the Northern Pennine samples, where the values show a very wide range across the survey locations.

Although the reasons for the high extractable ammonium and sulphate concentrations at some of the northerly sites are therefore likely to be complex, the data do not suggest that these high levels are associated with any negative effect on *Sphagnum* cover. Local and seasonal effects are likely to be very important in the exact balance of ions present in the different soil compartments and data collected at a different time of year could show a very different picture.

Scatter Plots of quadrat *Sphagnum* cover against range of measured environmental variables are shown below for all three survey areas.

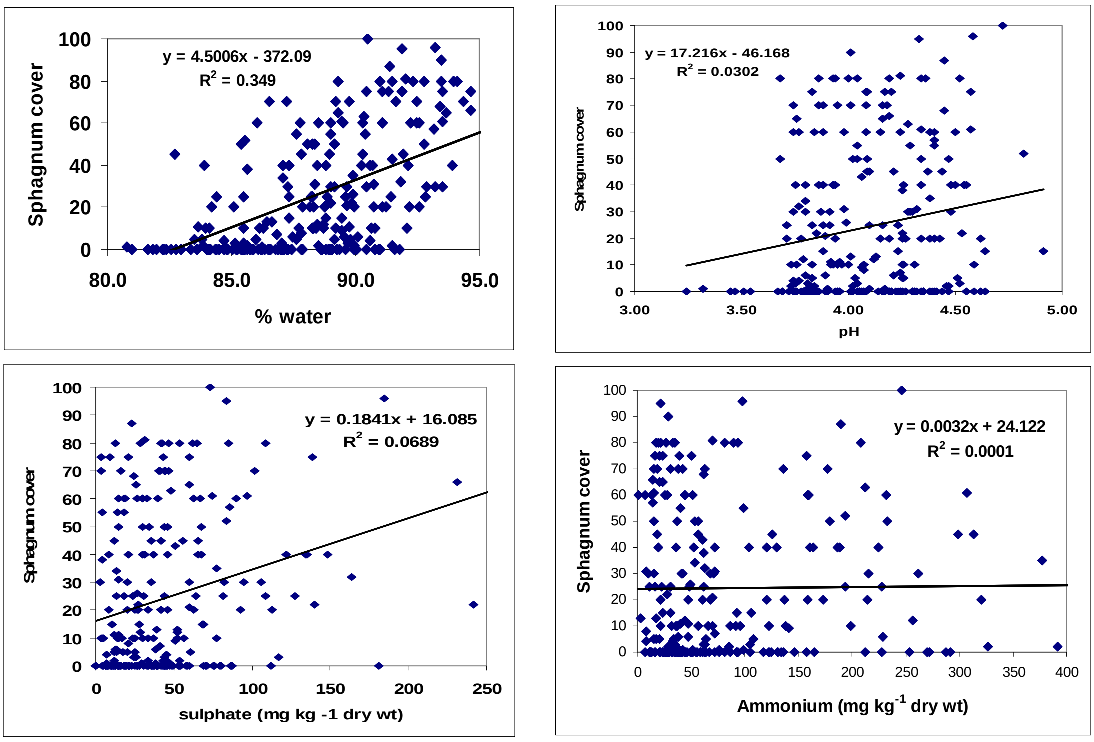


Figure 6.10 Scatter Plots of quadrat *Sphagnum* cover against range of measured environmental variables shown above for all three survey areas

The strongest correlations at the quadrat level are between *Sphagnum* cover and % water content and pH. Although ammonium levels show some clear differences between sites and survey areas, there does not appear to be any strong relationship at the quadrat level between % total *Sphagnum* cover and extractable NH_4^{+}. Significant correlations (Pearson Correlation (2 tailed) $p<0.05$ Tables 2 and 3 Appendix III) were obtained between % *Sphagnum* cover and pH, water content and sulphate.

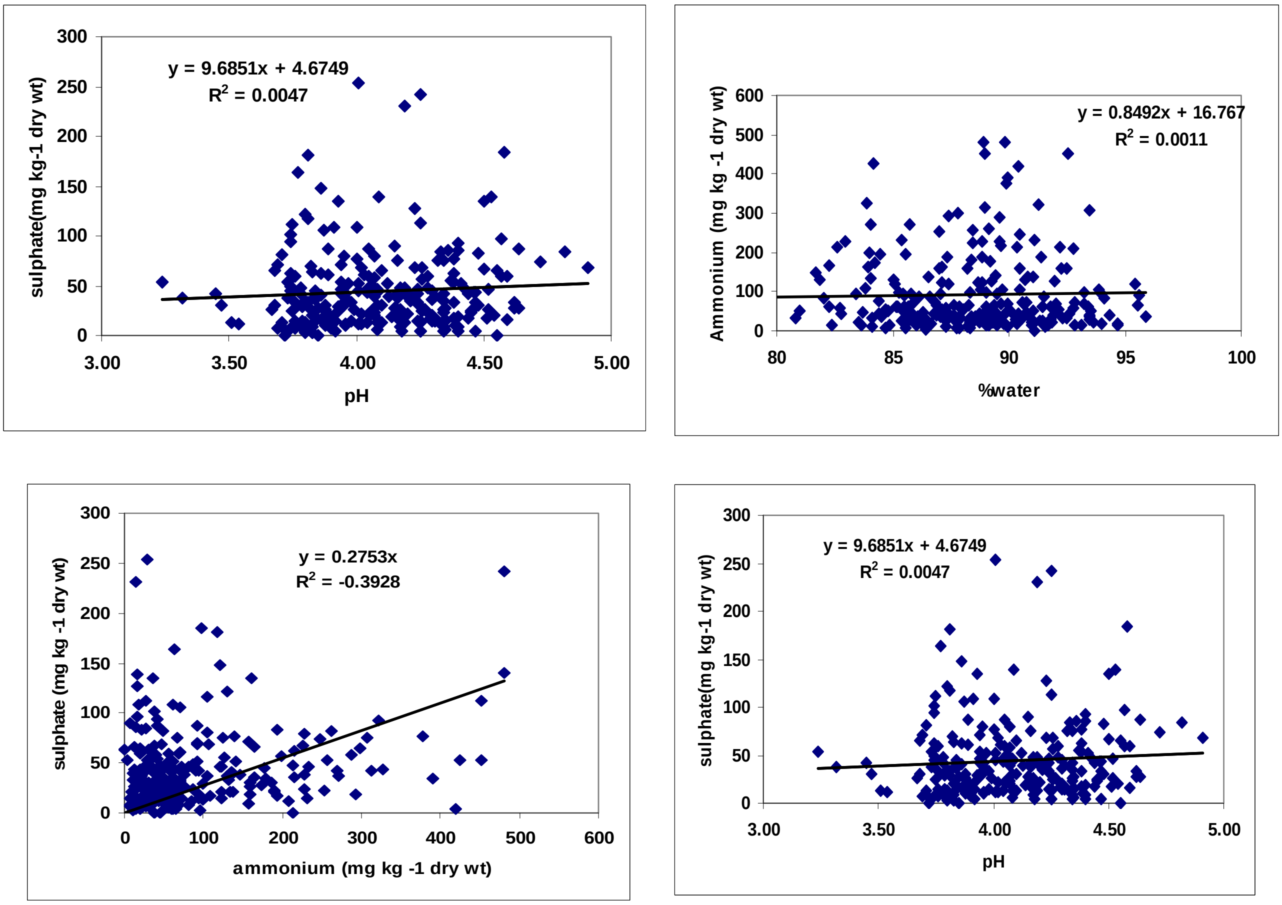


Figure 6.11 Scatterplots for other combinations of environmental variables

Significant positive correlations were also (see Tables 2 and 3 Appendix III) obtained between pH and peat extractable ammonium concentration, and between ammonium and sulphate levels, based on the individual quadrat data. Separate correlation analysis of the Peak District data showed a very similar pattern of relationships, although in this case the correlations between pH and ammonium and sulphate were not significant.

An ordination diagram based on CCA analysis of the vegetation data together with the environmental variables % moisture, pH and extractable ammonium is shown in Figure 6.12 and Appendix III Table 6. Sulphate data were not included in the analysis because of the high variability in the data.

The axes of variation show some correlation between increasing pH and ammonium content and a clear association with some of the more northerly species such as *S. tenellum* and *Narthecium ossifragum*, and also *Vaccinium myrtillus* and the *Hypnum* species.

Increasing water content was associated with *Molinia caerulea*, *S. papillosum* in the higher pH and ammonium quadrant, and *S. cuspidatum*, *S. fimbriatum* and *S. subnitens* in the lower pH and ammonium quadrants.

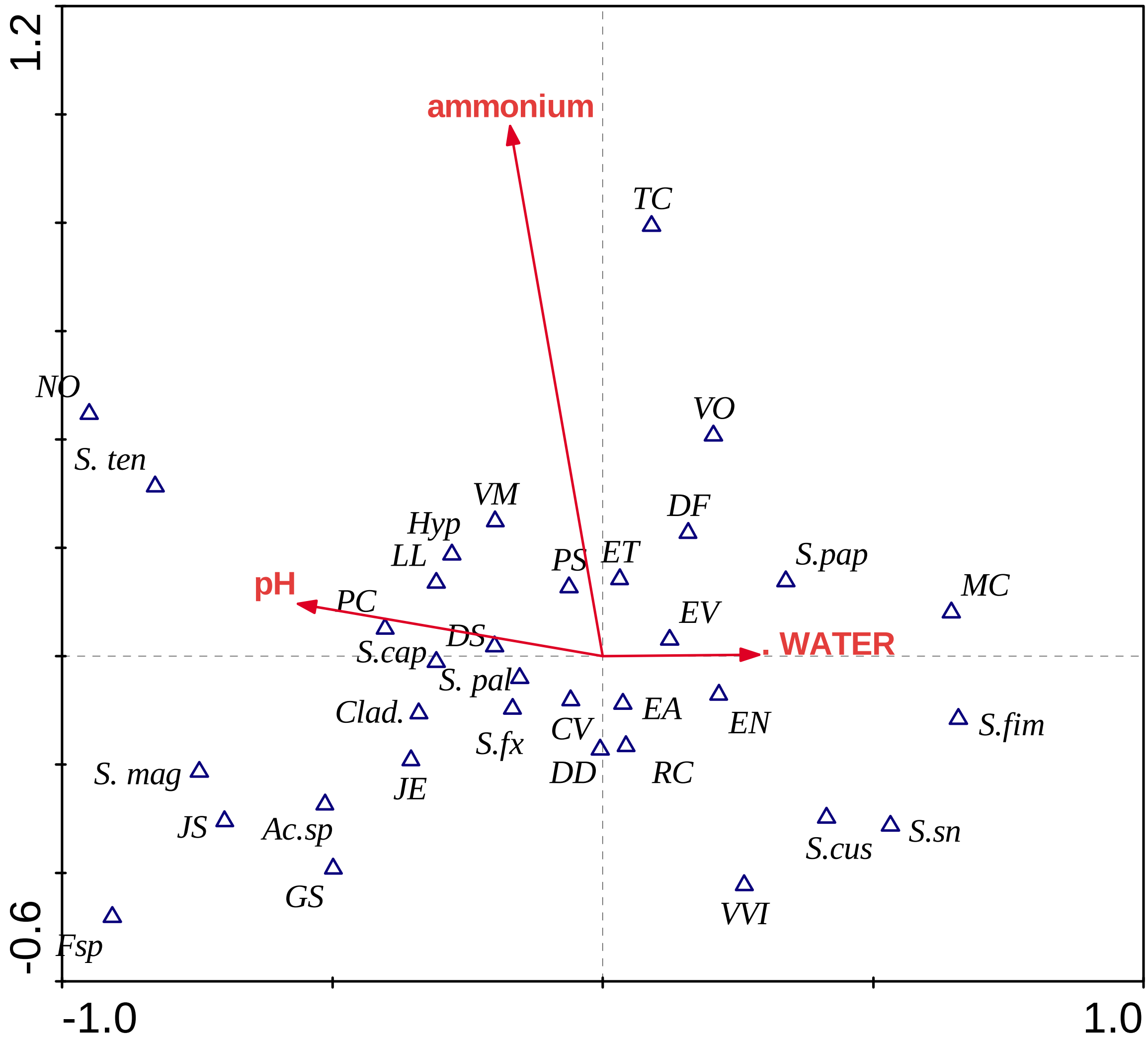


Figure 6.12 CCA (canonical correspondence analysis) analysis for all species cover data recorded in the 2 x 2m survey quadrat, and the associated peat sample variables pH, moisture content and extractable ammonium content . Statistical analysis shown in Table 6 Appendix III

KEY

CV-*Calluna vulgaris*, EV-*Eriophorum vaginatum*, EA-*Eriophorum angustifolium*, VM-*Vaccinium myrtillus*, MC-*Molinia caerulea*, ET-*Erica tetralix*, EN-*Empetrum nigrum*, VVI-*Vaccinium vitis-ideae*, GS-*Galium saxatile*, DS-*Dicranum scoparium*, RC-*Rubus chamaemorus*, PS – *Polytrichum strictum*, PC-*Polytrichum commune*, JS- *Juncus squarrosus*, VO-*Vaccinium oxycoccus*, DD-*Dryopteris dilatata*, DF-*Deschampsia flexuosa*, TC-*Trichophorum cespitosa*, NO – *Narthecium ossifragum*, LL- Leafy liverwort, Fsp – *Festuca* sp., *Hyp- Hypnum* sp., *Clad – Cladonia sp*, *Ac*.sp. – *Acrocarpous mosses*, *S.fx*, *S.pal*, *S.pap*, *S.fim*, *S.cap*, *S.mag*, *S.fim*, *S.cus*, *S.ten*, *S.sn*

6.2.2.2 Metals

The extractable metal concentrations for the three survey areas are shown in Figures 5.13 and 6.14 and Appendix II Table 5. There were a number of differences across the survey areas, some of which were statistically significant. Scatterplots of metal levels against *Sphagnum* cover are shown in fig 6.15. and 6.16.

Magnesium and zinc levels were significantly higher in Bowland and the Northern Pennines when compared with the Peak District. Aluminium and copper levels by contrast were significantly higher in the Peak District samples. Calcium levels showed high variability and no strong geographical trend. Magnesium levels also showed a significant correlation with *Sphagnum* cover for the three survey areas analysed together, (Table 3 Appendix III) and Figure 6.15, and the low levels found in the Peak District could indicate low levels of this plant nutrient in this area.

Aluminium levels showed a significant negative correlation with pH at the quadrat level, (see Tables 2 and 3 Appendix III) and the differences in the levels of this ion across the survey areas could therefore be related to the lower pH.

Calcium and magnesium levels were within the range obtained by Sanger *et al.* (1996) for ammonium acetate extracts of peat samples collected from a range of polluted and unpolluted mires and suggest that the metal levels recovered by the methods used in this study were representative.

Lead levels showed no strong pattern across the sites, and zinc levels were higher at the more northerly sites. Zinc and lead levels were fairly consistent across the Peak District and Bowland sites, although copper measurements showed a greater variation. A wider range of lead levels was however obtained from the Northern Pennine sites, with the highest values overall for all the survey sites found at Well Hopehead, Whimsey Cleugh and Northedge (126–153 mg kg^{-1}) (see Table 5 Appendix II). These levels were not correlated in any way with high levels for any other variable measured, such as other metals, ammonium or sulphate and the sites were not grouped geographically.

Differences in methodology make it difficult to compare these values with the literature. However, data from the Southern Pennine sites (Matt Buckler, personal communication) suggests that values for lead, and zinc are in similar ranges, although copper levels from this study are lower.

Critical levels for lead (www.critloads.ceh.ac.uk) are expressed as the reactive soil concentration (mg kg^{-1}) associated with a soil solution concentration in excess of 8 µg l^{-1} . Figure 2.6 shows these values ranging from <25 – 100-200 mg kg^{-1} for different soil types in the Southern and Northern Pennines. Figure 2.7 indicates some critical load exceedance for lead for the whole of the Southern and Northern Pennines. The results obtained in this study (65–90 mg kg^{-1}) are therefore in good agreement with the critical load modelling data, and confirm the presence of consistently high peat extractable lead levels across the whole of the Pennines, with no marked differences in this case between the three survey areas.

It is difficult to assess potential phytotoxicity based on extractable metal levels. However the data do not suggest any strong negative relationship between *Sphagnum* abundance or species distribution, and peat extractable heavy metal levels based on the data obtained here.

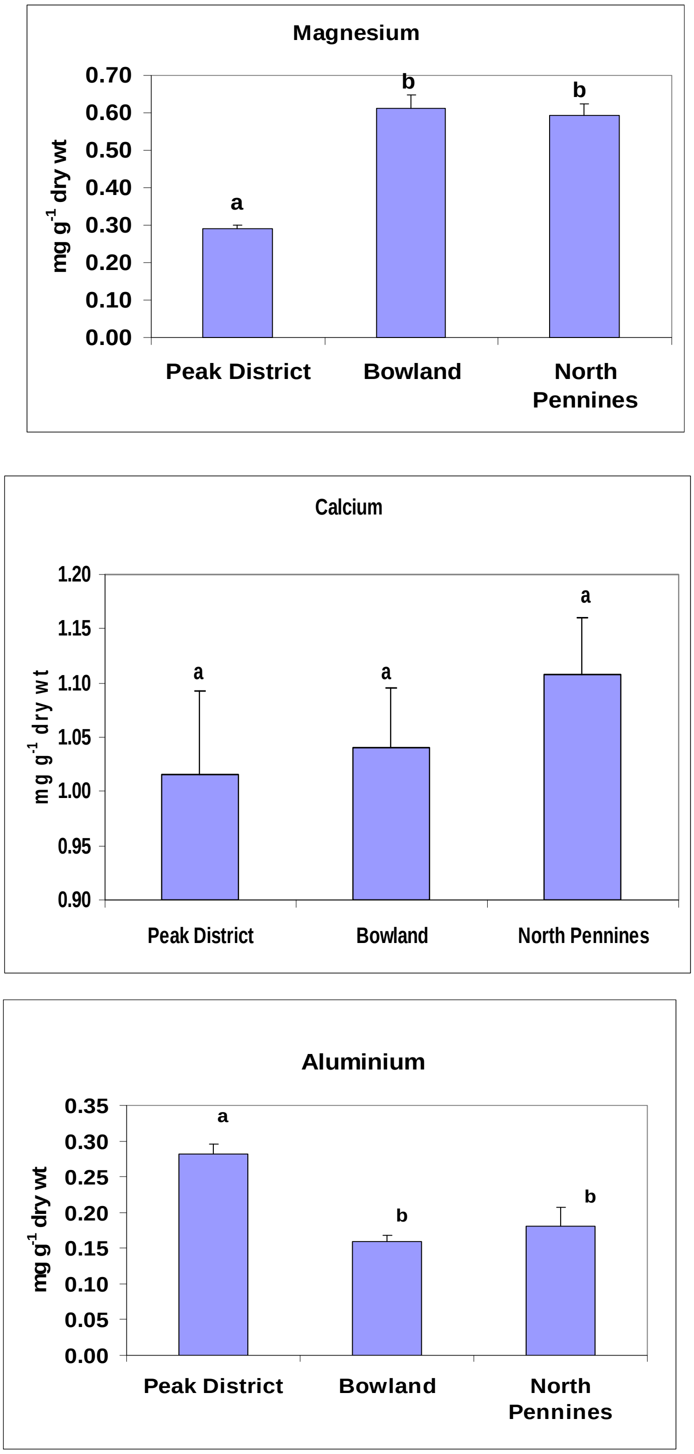


Figure 6.13 Extractable magnesium, calcium and aluminium contents for the peat samples collected from the quadrats for the three survey areas: Columns within given graph not sharing a letter are significantly different at $p<0.05$. ANOVA analysis

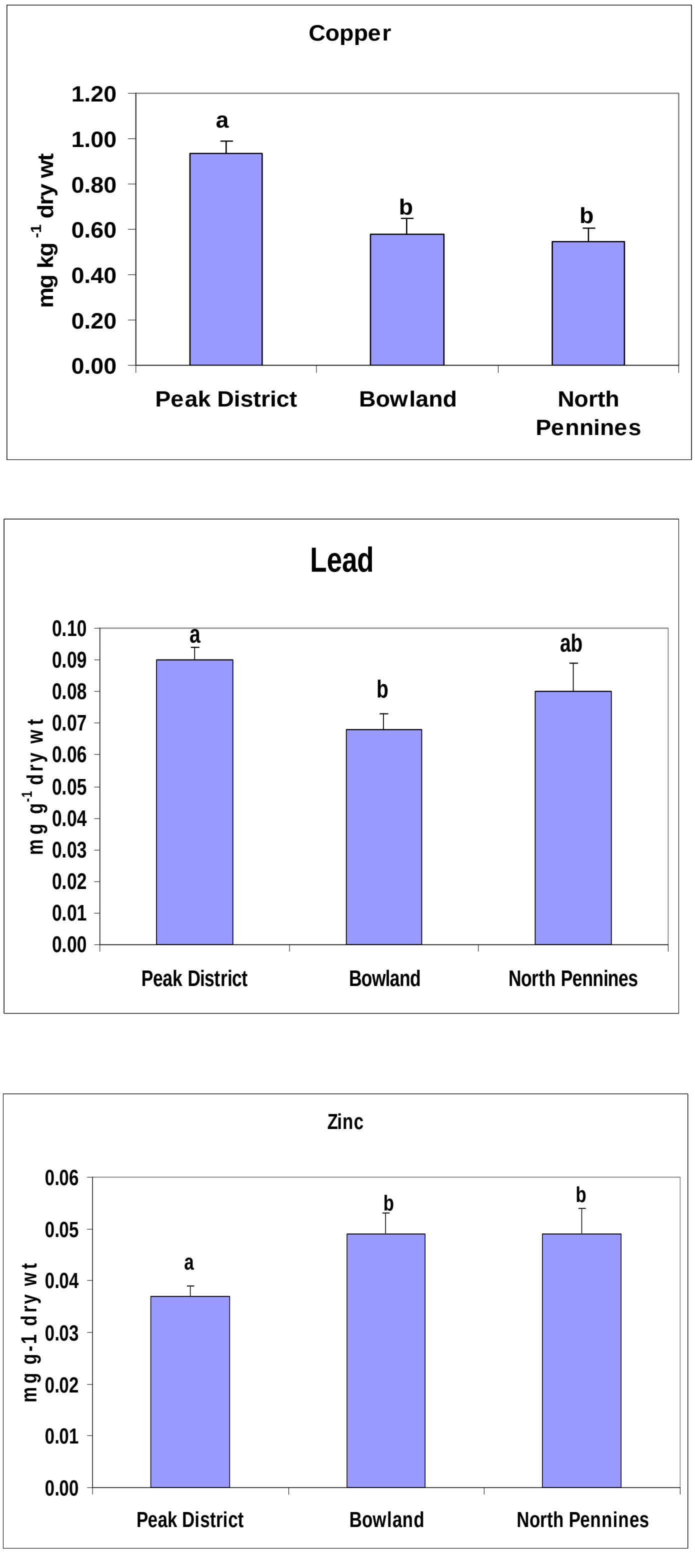


Figure 6.14: Extractable copper, lead and zinc contents for the peat samples collected from the quadrats for the three survey areas: Columns within given graph not sharing a letter are significantly different at $p<0.05$. ANOVA analysis

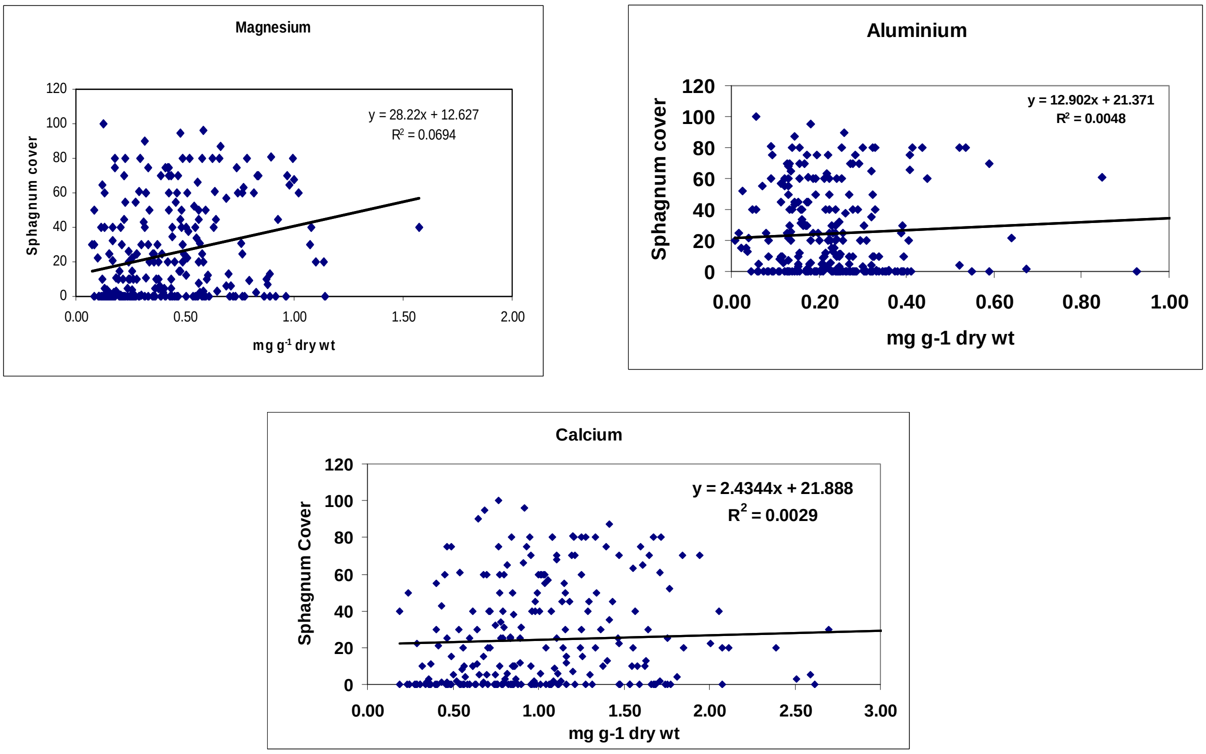


Figure 6.15 Scatterplots for total S*phagnum* cover in the 2 x 2m quadrats plotted against extractable calcium, magnesium and aluminium concentrations for all the survey data

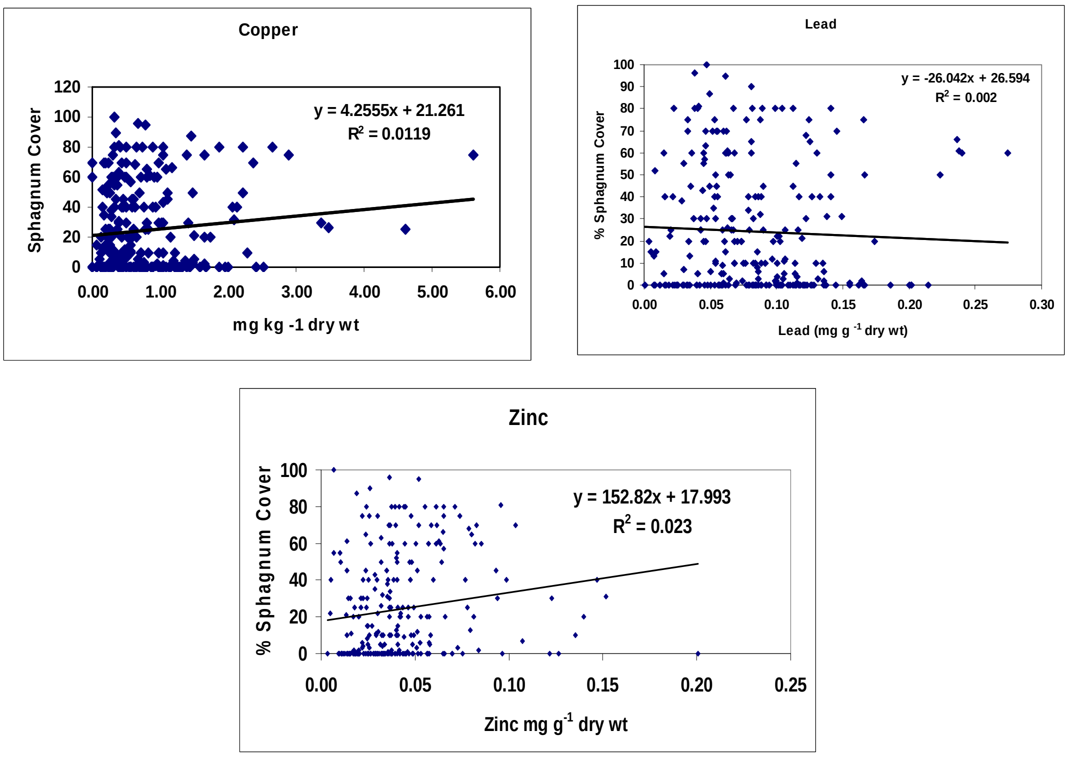


Figure 6.16 Scatterplots for total S*phagnum* cover in the 2 x 2m quadrats plotted against extractable copper, lead and zinc concentrations for all the survey data

Statistical analysis based on the presence or absence of all or particular *Sphagnum* species analysis (R STATS version 2.7.2) is presented in Table 7 of Appendix III

Several analyses were carried out to test for the effects of different parameters on presence and absence of all *Sphagnum* species and separate individual species. Overall soil moisture (‘Water’) was the main factor associated with *Sphagnum* distribution, also when the dataset is tested separately for the three areas ‘Bowland’, ‘North Pennines’ and ‘Peak District’. It is, of course, difficult to determine whether this factor is causal or derived from the species presence, as *Sphagnum* species act as ecosystem engineers creating their own microhabitat.

There are some other significant relationships, but overall the models do not show very different results to the results using the more specific % cover data. Therefore, as the % cover data are more comprehensive, we did not conduct further detailed analyses with the presence/absence data.

As discussed in the report, the nutrient and heavy metal levels varied significantly across the study areas. For instance magnesium levels were higher in the Forest of Bowland and the North Pennines (Figure 6.13). Therefore a positive association with Magnesium may not be causal but linked to other factors varying geographically and within-site variation is mainly determined by soil moisture (see last 3 models). Single species models are not really feasible if the presence/absence ratio is distorted significantly (i.e. too few presence or too few absence records).

The following species had the highest presence records in the 256 quadrats, and therefore models could be estimated for these separately:

S. papillosum	= 75 (i.e. present in 75 quadrats out of 256)
S. cap. Ssp. *Cap*	= 54
S. fallax	= 45
S. fimbriatum	= 45
S. subnitens	= 24

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APPENDICES

APPENDIX I
Mapping Figures

Appendix I – Mapping Figures

APPENDIX II
Data Tables

Appendix II - Data Tables

1	% Frequencies (Presence of each Species as % of Total Number of Quadrats in the Area Set) for all the *Sphagnum* Species Recorded in the 2 x 2m Quadrats for the Three Survey Areas
2	% frequencies (presence of each species as % of total number of quadrats in the area set) for all non Sphagnum species recorded in the 2 x 2 m quadrats for the three survey areas
3	% frequencies (presence of each species as % of total number of quadrats in the area set) for all non *Sphagnum* species recorded in the 20 x20m survey areas for the three survey areas
4	Mean pH, % moisture, and extractable ammonium and sulphate concentrations for the Peak District, Bowland and North Pennine survey locations
5	Mean extractable aluminium, calcium, magnesium, copper, lead and zinc concentrations for the Peak District, Bowland and North Pennine survey locations
6	Survey Record Sheet
7	Site Data Sheet

Table 1 % Frequencies (Presence of each Species as % of Total Number of Quadrats in the Area Set) for all the *Sphagnum* Species Recorded in the 2 x 2m Quadrats for the Three Survey Areas:

	Peak District	**Bowland**	**North Pennines**
S*. fallax*	11.9	24.3	51.0
S*. fimbriatum*	52.4	2.7	0.0
S*. sub.nitens*	22.6	8.1	2.0
S*. papillosum*	31.0	73.0	44.9
S*. capillifolium*	4.8	51.4	63.3
S*. cuspidatum*	7.1	5.4	2.0
S*. magellanicum*	0.0	2.7	8.2
S*. palustre*	2.4	8.1	8.2
S*. russowii*	0.0	0.0	4.1
S*. tenellum*	0.0	0.0	4.1
S*. squarrosus*	3.6	0.0	0.0

Table 2 % frequencies (presence of each species as % of total number of quadrats in the area set) for all non Sphagnum species recorded in the 2 x 2 m quadrats for the three survey areas:

	% Frequency		
	Peak District	**North Pennines**	**Bowland**
Bare Peat	8.7	7.1	0.0
Open water	6.0	0.0	0.0
Calluna vulgaris	61.3	83.9	78.0
Eriophorum vaginatum	91.3	92.9	92.0
Eriophorum angustifolium	84.7	41.1	60.0
Deschampsia flexuosa	32.7	19.6	16.0
Vaccinium myrtillus	43.3	17.9	84.0
Vaccinium.oxycoccus	6.7	5.4	56.0
Vaccinium vitis ideae	0.7	1.8	0.0
Empetrum nigrum	50.0	48.2	54.0
Erica tetralix	4.7	33.9	32.0
Narthecium ossifragum	0.0	1.8	0.0
Polytrichum commune	8.7	39.3	0.0
Polytrichum strictum	4.7	0.0	16.0
Hypnum sp.	46.7	78.6	92.0
Dicranum scoparium	12.7	14.3	10.0
Acrocarpous sp.	36.7	60.7	10.0
Juncus effusus	2.0	3.6	0.0
Juncus squarosus	0.0	10.7	2.0
Molinia caerulea	6.0	0.0	2.0
Leafy liverwort	11.3	32.1	0.0
Cladonia sp.	4.7	14.3	10.0
Rubus cham	4.7	8.9	0.0
Dryopteris dilatata	2.7	1.8	0.0
Festuca sp.	6.0	1.8	0.0
Galium saxitile	0.0	5.4	0.0
Carex binerva	0.0	1.8	0.0
Carex flacca	0.0	1.8	0.0
Carex pilulifera	0.0	1.8	0.0
Tric cesp	0.0	0.0	16.0
Andromeda polifolia	0.0	0.0	22.0

Table 3 % frequencies (presence of each species as % of total number of quadrats in the area set) for all non *Sphagnum* species recorded in the 20 x20m survey areas for the three survey areas:

	% Frequency		
Species Name	**Peak District**	**Bowland**	**North Pennines**
Bare Peat	28.6	0	1.8
Open Water	0.6	0	0
Calluna vulgaris	74.6	92	82.2
Eriophorum vaginatum	94	96	91.1
Eriophorum angustifolium	90	68	8.9
Deschampsia flexuosa	0	2	12.5
Vaccinium.myrtillus	70	88	0
Vaccinium vitis-idaea	2	2	0
Empetrum nigrum	62.6	68	16.1
Erica tetralix	12.6	46	1.8
Molinia caerulea	10	18	0
Juncus effusus	0.6	0	3.5
Juncus squarrosus	0	2	3.5
Rubus chamaemorus	13.3	4	0
Vaccinium oxycoccus	8.6	56	1.8
Andromeda polifolia	0	32	0
Narthecium ossifragum	0	6	0
Hypnum sp.	59.3	98	16.0
Polytrichum commune	2.66	2	21.4
Acrocarpous sp.	5.26	8	8.8
Cladonia sp.	2.66	4	0
Pleurozium schreberi	0	0	12.5
Plagiothecium undulatum	0	0	3.6

Table 4 – Mean pH, % moisture, and extractable ammonium and sulphate concentrations for the Peak District, Bowland and North Pennine survey locations

Peak District					
Site	**Number of Samples**	**pH**	**% Water**	**Ammonium (mg kg $^{-1}$ dry wt)**	**Sulphate (mg kg $^{-1}$ dry wt)**
Ringinglow Bog	3	3.81+/- 0.05	87.8+/-1.26	20.6+/-3.36	85.7+/-21
Midhope-Howden	8	3.82+/-0.02	87.4+/-1.13	24.02+/-2.74	13.1+/-5.6
Kinder	9	4.2+/- 0.04	89.3+/-.98	30.8+/-4.5	27.3+/-10.3
Hordron	3	4.06+/- 0.02	85.4+/-1.36	35.45+/-3.3	59.3+/-16.2
Stanage	2	4.25+/-0.02	87.7+/-1.79	82.5+/-10.5	47.7+/-21
Middle Hills	5	4.24+/- 0.04	90.8+/-.72	44.36+/-10.1	28.9+/-9.5
Turn Edge	4	3.98+/- 0.25	86.2+/-1.05	54.3+/-11.2	47.4+/-2.9
Alport	10	4.07+/-0.06	89.2+/-0.84	66.2+/-28.4	40.8+/-7.2
Crowden	10	3.94+/-0.02	89.6+/-0.83	66.2+/-13.1	88.1+/-23.9
Chew	9	3.88+/-1.58	83.9+/-1.58	40.1+/-6.4	20.2+/-5
Good Bent	5	3.92+/-0.05	88.2+/-1.48	62.7+/-30.7	43.4+/-15.4
Flake Moss	5	3.99+/-0.05	85.9+/-3.61	42.1+/-3.7	24.4+/-5.9
Cutthorn	5	3.8+/-0.05	87.6+/-2.36	51.4+/-10.2	70.3+/-19.5
Derbyshire Bridge	4	3.88+/- 0.05	89.2+/-1.95	65.01+/-8.5	66.9+/-41
Leash Fen	6	3.83+/-0.05	90.1+/-2.44	112.9+/-14	98.4+/-29.8
Marsden	10	3.88+/-0.05	84.5+/-0.4	91.25+/-42	17.8+/-5.2
Holme Moss	7	3.7+/-0.1	87+/-1.9	83.9+/-64.5	31.3+/-4.6
White Path Moss	3	3.79+/-0.04	92.7+/-1.3	33.7+/-3.11	64.5+/-21
Featherbed-Ashop	10	3.75+/-0.02	86.18+/-0.47	47.5+/-2.51	17.6+/-6.23
Combs	10	3.80+/-0.06	88.91+/-.24	37.78+/-19.9	52..2+/-19.7
Howden-Strines	11	4.23+/-0.07	86.44+/-3.36	60.94+/-23.2	32.5+/-8.8
Bleaklow	11	4.4+/-0.06	85.59+/-1.36	84.5+/-14.5	18.9+/-7.6

Bowland					
Site	**No samples**	**pH**	**% Water**	**Ammonium**	**Sulphate**
Lamb Hill	12	3.83+/-0.03	90.04+/-0.99	54.2+/-6.1	32.3+/-10.3
Sykes	13	4.21+/-0.05	86.9+/-0.95	250+/-35	45.6+/-7.9
Whitendale	14	4.25+/-0.03	90.4+/-0.5	190.5+/-15.1	36.9+/-6.4
Brennand	11	4.2+/-0.03	86.2+/-1.5	170.9+/-22.4	39.5+/-3.2

North Pennines					
Site	**No samples**	**pH**	**% Water**	**Ammonium**	**Sulphate**
Wolf Clough	4	4.3+/-0.09	90.15+/-1.42	29.24+/-17.6	29.31+/-7.2
Well Hopehead	7	4.23+/-0.05	93.25+/-0.49	24.2+/-6.8	90.6+/-33.1
Whimsey Cleugh	6	4.41+/-0.07	90.6+/-1.06	31.3+/-14.98	93.3+/-23.7
Northedge	5	4.31+/-0.03	88.6+/-0.27	140+/-79.5	26.8+/-9.3
Ravencrag	7	4.18+/-0.03	85.95+/-0.79	38.05+/-9.8	30.1+/-5.55
Long Moss	7	4.54+/-0.11	87.01+/-0.66	137.8+/-50.4	81.3+/-9.9
Stang End	7	4.46+/-0.06	88.56+/-1.08	132.3+/-31.5	39.5+/-7.22
Asholme Common	7	4.42+/-0.05	90.05+/-0.58	218.16+/-68.1	63.11+/-31
Molds Hill	6	4.57+/-0.04	89.97+/-0.51	273.3+/-64.7	74.8+/-16

Table 5 Mean extractable aluminium, calcium, magnesium, copper, lead and zinc concentrations for the Peak District, Bowland and North Pennine survey locations

Peak District							
Site	**Number of samples**	**Aluminium mg g^{-1} dry wt**	**Calcium mg g^{-1} dry wt**	**Magnesium mg g^{-1} dry wt**	**Copper mg kg^{-1} dry wt**	**Lead mg g^{-1} dry wt**	**Zinc mg g^{-1} dry wt**
Ringinglow Bog	3	.295+/-.065	0.723+/.09	0.114+/-0.02	1.967+/-0.7	0.107+/-0.05	0.021+/-0.003
Midhope-Howden	8	.260+/-0.02	0.543+/-0.065	0.171+/-0.02	1.171+/-0.1	0.087+/-0.008	0.026+/-0.004
Kinder	9	.250+/-0.03	1.009+/-0.073	0.298+/-0.022	1.345+/-0.14	0.092+/-0.008	0.046+/-0.006
Hordron	3	.269+/-0.041	1.129+/-0.095	0.172+/-0.033	1.947+/-1.32	0.072+/-0.009	0.038+/-0.001
Stanage	2	.259+/-0.023	1.021+0.14	0.23+/-0.025	0.596+/-0.032	0.099+/-0.013	0.037+/-0.004
Middle Hills	5	.208+/-0.021	1.259+/-0.16	0.317+/-0.05	1.856+/-1.02	0.074+/-0.012	0.042+/-0.006
Turn Edge	4	.252+/-0.026	1.02+/-0.17	0.303+/-0.05	0.395+/-0.081	0.091+/-0.013	0.041+/-0.005
Alport	10	.271+/-0.037	0.99+/-0.15	0.37+/-0.051	0.671+/-0.18	0.097+/-0.014	0.052+/-0.007
Crowden	10	.210+/-0.016	0.721+/-0.11	0.25+/-0.026	1.055+/-0.32	0.075+/-0.009	0.027+/-0.004
Chew	9	.318+/-0.018	0.566+/-0.09	0.23+/-0.037	0.702+/-0.12	0.108+/-0.016	0.029+/-0.005
Good Bent	5	.232+/-0.025	.464+/-0.128	0.248+/-0.078	0.959+/-0.267	0.07+/-0.015	0.030+/-0.009
Flake Moss	5	.286+/-.0.5	0.388+/-0.095	0.168+/-0.03	0.834+/-0.156	0.095+/-0.022	0.021+/-0.007
Cutthorn	5	.211+/-0.039	0.525+/-0.054	.165+/-0.019	0.861+/-0.138	0.122+/-0.025	0.021+/-0.003
Derbyshire Bridge	4	.246+/-0.012	1.006+/-0.196	.213+/-0.033	1.103+/-0.411	0.081+/-0.004	0.034+/-0.001
Leash Fen	6	.275+/-0.032	.846+/-0.077	0.166+/-0.023	0.853+/-0.171	0.102+/-0.011	.026+/-.002
Marsden	10	.291+/-0.062	.621+/-0.178	.286+/-0.093	0.832+/-0.308	0.095+/-0.018	0.033+/-0.009
Holme Moss	7	.331+/-0.045	0.582+/-0.074	.280+/-0.032	0.908+/-0.163	0.094+/-0.035	0.031+/-0.005
White Path Moss	3	.349+/-0.128	1.282+/-0.363	0.175+/-0.025	1.22+/-0.576	.062+/-.003	.039+/-.007
Featherbed -Ashop	10	.222+/-.045	0.681+/-0.03	.275+/-0.029	.951+/-.274	0.103+/-0.03	0.033+/-0.002
Combs	10	.424+/-0.077	1.64+/-0.131	.312+/-0.021	.798+/-.248	0.096+/-.011	0.038+/-0.007
Howden-Strines	11	.406+/-0.109	.406+/-.109	.501+/-.206	.911+/-.458	.092+/-.023	.056+/-0.024
Bleaklow	11	.235+/-0.054	2.597+/-.516	.521+/-0.066	.296+/-0.04	.057+/-0.02	.058+/-0.017

Bowland							
Site	**Number of Samples**	**Aluminium mg g^{-1} dry wt**	**Calcium mg g^{-1} dry wt**	**Magnesium mg g^{-1} dry wt**	**Copper mg kg^{-1} dry wt**	**Lead mg g^{-1} dry wt**	**Zinc mg g^{-1} dry wt**
Lamb Hill	12	0.189+/-0.017	.928+/-0.118	.700+/-0.094	.579+/-.072	.103+/-0.01	0.075+/-0.014
Sykes	13	0.153+/-0.022	1.265+/-0.138	.551+/-0.081	.473+/-0.122	.0.49+/-0.009	.029+/-0.005
Whitendale	14	.137+/-0.015	.942+/-0.09	.525+/-0.056	.533+/-0.069	0.053+/-0.006	0.04+/-0.005
Brennand	11	.163+/-0.021	1.024+/-0.087	.692+/-0.07	.493+/-.23	.07+/-.011	.056+/-.006

North Pennines							
Site	**Number of Samples**	**Aluminium mg g^{-1} dry wt**	**Calcium mg g^{-1} dry wt**	**Magnesium mg g^{-1} dry wt**	**Copper mg kg^{-1} dry wt**	**Lead mg g^{-1} dry wt**	**Zinc mg g^{-1} dry wt**
Wolf Cleugh	4	.235+/-0.09	.979+/-0.16	.725+/-0.078	.405+/-0.07	0.097+/-0.023	0.034+/-0.006
Well Hopehead	7	.215+0.042	1.078+/-0.139	.757+/-.092	.874+/-0.179	0.134+/-0.024	0.072+/-0.008
Whimsey Cleugh	6	.455+/-0.201	.843+/-0.123	.487+/-0.069	.638+/-0.114	.153+/-0.049	.04+/-0.007
Northedge	5	.127+/-0.011	1.436+/-0.137	.471+/-0.041	0.355+/-0.03	.126+/-0.024	.037+/-.004
Ravencrag	7	.164+/-0.027	1.187+/-0.147	.698+/-0.74	.291+/-0.037	0.027+/-0.002	0.084+/-0.022
Long Moss	7	0.102+/-0.04	1.478+/-0.076	.739+/-.101	.278+/-0.057	.023+/-0.008	.053+/-0.011
Stang End	7	.141+/-0.037	1.276+/-0.061	.699+/-0.079	.395+/-0.084	.089+/-0.023	.069+/-0.016
Asholme Common	7	0.095+//0.018	.921+/-.189	.442+/-.07	.701+/-.188	.043+/-0.012	0.019+/-.003
Molds Hill	6	.114+/-0.026	.680+/-.105	.231+/-0.054	.978+/-0.44	.051+/-0.011	0.014+/-0.003

APPENDIX III
Statistical Tables

Appendix III – Statistical Tables

1 Summary of ONEWAY Analysis of Variance
2 Correlation Matrix for the Environmental Data for all Survey Sites
3 Correlation Matrix for the Environmental Data for the \Peak District Correlation
4 DCA Output for all Species
5 DCA Output for *Sphagnum* Species
6 Output file for all Species Plus Environmental Data (pH, % moisture, ammonia)
7 R Statistical package *Sphagnum* presence/absence analysis data table

APPENDIX IV
PDNPA Ranger Survey

Appendix IV - PDNPA Ranger Survey

FIGURE

TABLES