Peatscapes Project: *Sphagna* as management indicators research

Final report to

North Pennines AONB

Partnership

Sphagnum magellanicum © ptyxis ecology

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Summary

Introduction
Ptyxis Ecology was contracted by the North Pennines Area of Outstanding Natural Beauty Partnership's Peatscapes project to research the autecology of *Sphagnum* species in blanket bog in the North Pennines.

The objectives included to identify whether or not any common *Sphagnum* species could be used as indicators of management impacts and if so, to develop a practical survey tool for:

- assessing the condition of blanket bog;
- providing feedback to land managers on the impact of their management; and
- evaluating peatland sites for restoration works.

The research involved a field survey element and a literature review element. The field survey involved collecting floristic and environmental data at 200 quadrats where *Sphagnum* species occur on peat in 20 randomly chosen 1km squares across the North Pennines. An additional 55 quadrats were recorded for the Moor for the Future project, which included peat samples (for analysis for heavy metals and various nutrients) and additional environmental variables, notably litter depth, and soil moisture content. Vegetation data collected comprised all higher plants, bryophytes (mosses and liverworts), and lichens.

Literature review
There is a vast amount of empirical evidence supporting the distribution of certain *Sphagnum* species along hydrotopographical and pH gradients. The relationship between nutrients and *Sphagnum* species is less clear and most species may only be placed into limited categories corresponding to broad nutrient levels. Despite bog management handbooks and conservation manuals referring to *Sphagnum* indicator species, there is an apparent lack of scientific evidence to support the use of many *Sphagnum* species as indicators of management impacts. Field observations are often untested empirically.

The impacts of land management practices and recreational use on blanket bog are still poorly understood. This is partly because it is difficult to control for other environmental factors during field experiments. There are few empirical studies assessing impacts on bryophytes, or *Sphagnum* species.

The impact of burning, when used as a management tool, is particularly uncertain and further studies are required. The impact of drainage grips on *Sphagnum* and other bog vegetation is better understood, although the review found only one published study on blanket bog, where drainage only impacted grip marginal areas. This single study is often cited to justify development impacts on blanket bog being evaluated as 'likely to cause minor damage'. It is, on balance, probable that cumulative impacts of burning and over-grazing and trampling from recreational pressures are more often the cause of Sphagna elimination than drainage alone.

Scientific studies support four *Sphagnum* indicator species, listed below; others are likely to exist but currently lack adequate supporting evidence:

- ***Sphagnum capillifolium*** (where it out competes other *Sphagnum* species) – increases suggest drying out
- ***S. compactum*** – increases suggest drying or recovery from burning
- ***S. cuspidatum*** – decreases suggest drying out
- ***S. fallax*** – increases suggest nutrient enrichment and/or recovery from bare ground / erosion / burning

Apparently no other authors in any region worldwide have produced any condition assessment survey tool that uses *Sphagnum* species extensively – generally cover of '*Sphagnum* sp.' is used; or publications refer to a limited range of species.

Field survey results

This study did not identify any key relationships or links between the environmental factors measured and the occurrence of *Sphagnum* species. The unexplained variation in the dataset may be due to unmeasured environmental factors, such as climate, or it may be due to random effects.

It was particularly surprising that there was no correlation between either *Sphagnum* diversity, or overall plant diversity levels, with nutrient levels (tested generally by conductivity and more specifically by ammonium ($NH4^+$) levels), as this relationship is well established in the literature. It may be that the gradient in the $NH4^+$ concentrations was too narrow to display any difference between vegetation samples. It is interesting that the Moors for the Future Project also found that "*Sphagnum* cover and diversity were also very notably not strongly correlated with peat extractable NH4+" in both South Pennines and Bowland samples (Carroll *et al*. 2008: 10).

The limited relationships shown in the data were:

- A significant correlation between vegetation height and overall plant diversity.
- A significant correlation between altitude and overall plant diversity.
- A significant correlation between peat depth and *Sphagnum* species diversity.
- A significant correlation between peat depth and seven *Sphagnum* species.

However, the data analyses did reveal some interesting patterns, even if the level of statistical confidence in the results is insufficient to draw any definite conclusions. These were:

- Patterns relating soil moisture content with litter depth, suggesting certain *Sphagnum* species are more tolerant of dry and low litter conditions, implicating management practices which cause drying and reduced litter levels, such as burning.
- An apparent association between certain *Sphagnum* species and lead concentrations.

Conclusion & key recommendations

The literature review combined with this study shows that there are a limited number of empirically tested *Sphagnum* indicator species suitable for use in the North Pennines.

The following *Sphagnum* species are useful and reliable indicators of management impacts in the North Pennines:

- *Sphagnum papillosum* as a positive indicator species; and
- *S. capillifolium* ssp. *rubellum* as a negative indicator species in certain circumstances. This needs to be carefully applied, as this species is also a feature of M19 blanket bog in good condition; it is only an indicator when increasing and ousting certain other Sphagna.

In addition, when conducting upland condition assessment in the North Pennines using the SNH methodology (SNH undated), the use of *Sphagnum fallax* as a negative indicator probably needs to be reconsidered.

More work is required on certain key species in relation to management impacts. Therefore constructing a novel management impact assessment tool is not possible based on information compiled so far. It seems likely that the standard condition assessment methodology, using walkover sampling, is insufficiently sensitive to detect responses in *Sphagnum* species to management impacts. A more targeted approach is required, similar to that used in empirical studies.

Recommendations are made for further work. Key recommendations are:

- A priority for research should be investigating the impacts of management burning and drainage grips on *Sphagnum* species.

- As *S. papillosum* is probably the best positive indicator species for bog condition in the North Pennines, burning and grip impacts on this species could be tested.

- The hypothesis that *Sphagnum rusowii* is an indicator of drying could be tested.

- The hypothesis that *S. fallax* it is not a reliable indicator of nutrient enrichment in the North Pennines could be tested in relation to nutrient changes after burning.

- Devise a management impact assessment tool using *Sphagnum* as indicators based around assessing direct impacts over time, rather than the walkover sampling approach (as used in condition assessment methodologies).

1 Introduction

1.1 Background

1.1.1 Ptyxis Ecology was contracted by the North Pennines Area of Outstanding Natural Beauty Partnership's Peatscapes project to research the autecology of *Sphagnum* species in blanket bog in the North Pennines.

1.1.2 The research involved a field survey element and a literature review element. The field survey involved collecting floristic and environmental variables at 200 quadrats where *Sphagnum* species occur on peat in 20 randomly chosen 1km squares (referred to as 'Sites') across the North Pennines.

1.1.3 This report is in three sections: the first section summarises the methodology used; the second section presents the results of the literature review and of the field survey; and the third section evaluates the findings and makes recommendations for further work. The appendices on the CD-rom comprise spreadsheets of the survey species data, statistical analyses reports, and photographs.

1.2 Aim & objectives

The objectives of the research are:

- To investigate in detail the specific ecological niches occupied by species of *Sphagnum* that occur in blanket bog and wet heath in the North Pennines.

- Using common *Sphagnum* species as indicators, to develop a practical survey tool for:

    - assessing the condition of blanket bog;
    - providing feedback to land managers on the impact of their management; and
    - evaluating peatland sites for restoration works.

- To generate hypotheses for future work.

2 Methodology

2.1 Literature review

2.1.1 A focussed literature review aimed to identify all key studies on the autecology of British *Sphagnum* species, particularly relating to land management practices.

2.1.2 The review was conducted using searches of on-line databases, including ISI Web of Science, to identify scientific papers, combined with references drawn from leading texts on bog ecology, including *The Biology of Bogs* (Rydin & Jeglum 2008), *Conserving Bogs: The Management Handbook* (Brooks & Stoneman 1997) and *Peatlands and Environmental Change* (Charman 2003). The review also included critical consideration of the findings of the Moors for the Future *Sphagnum* literature review (Carroll *et al*. 2008).

2.1.3 The literature review excluded extensive consideration of studies on atmospheric pollution (oxidised sulphur and nitrogen; and heavy metals) because this is not related to land management practices.

2.1.4 In this report, the nomenclature for higher plants follows Stace (1997) and for bryophytes (Hill *et al*. 2008). It should be noted that there have been many changes to *Sphagnum* species names; therefore this report consistently uses the most recent valid name. For higher plants, scientific and common plant names are used where a species is first mentioned and scientific names thereafter. The abbreviation 'ssp.' refers to subspecies and 'var.' to variety.

2.2 Field survey

2.2.1 Twenty 1km squares ('referred to as Sites') were located, using random grid coordinates, in areas of known peatland within the North Pennines Natural Area. Vegetation with Sphagna cover in each Site was sampled by stratified random sampling in November 2007, February and March 2008, and October and November 2008. Plots with Sphagna cover were located in the mire expanse along a transect and ten 0.25m^2 square quadrats placed using a random number grid. All higher plants, bryophytes (mosses and liverworts) and lichens were identified to species and a visual estimate made of their percent cover-abundance to the nearest 5%. Additional species within a 4m^2 quadrat were also recorded but without cover levels. A copy of the survey data collection form is at Appendix 1.

2.2.2 The following environmental data were measured in each quadrat:

- pH
- peat depth
- altitude
- aspect
- slope
- conductivity (as an assessment of ion exchange, indicating nutrient status)

- vegetation height
- saturated or not (qualitative measure)
- distance to nearest area burnt in last 2 years
- distance to nearest older burn/recovering vegetation
- distance to nearest grip
- distance to nearest significant change of slope
- distance to nearest area of eroding peat
- distance to nearest area of bare peat
- combined % cover of *Sphagnum capillifoilum sensu lato*, *S. magellanicum* and *S. papillosum* in 20m^2
- cover of hare's-tail cottongrass *Eriophorum vaginatum* in 20m^2
- National Vegetation Classification (NVC) community (Rodwell 1991; 1992)

2.2.3 pH and conductivity were measured from extruded water (from a random *Sphagnum* sample within each quadrat) using a portable combined meter (Hanna Instruments model HI98129), with built-in calibration for temperature. Conductivity is a widely-used measure of total ionic concentration in wetland research (Rydin & Jeglum 2008). A proxy measure of bog condition was used by calculating a novel 'Peat-Building Index' (PBI) based on vegetation type, as follows:

S+(EV/4)

where

S = cover of key peat-building *Sphagnum* species *Sphagnum capillifoilum sensu lato*, *S. magellanicum* and *S. papillosum* (according to Daniels & Eddy 1985); and
EV = cover of *Eriophorum vaginatum*

2.2.4 The sampling method deliberately did not target certain *Sphagnum* species or certain management features, such as drainage grips, and conduct transects across these. This approach is similar to that utilised by the Common Standards Monitoring (CSM) condition assessment methodology (Jerram & Drewitt 1998, JNCC 2004) and Scottish Natural Heritage's upland condition assessment methodology (SNH undated). These methodologies are used by conservation agencies to assess the condition of vegetation as part of national monitoring programmes. These methodologies are designed for rapid field assessment; therefore it was not appropriate to include environmental parameters in this study requiring laboratory analysis. Any survey tool developed using this study would also use this approach.

2.2.5 In this report, the data collected from the 200 quadrats is referred to as the 'Main Dataset'. An additional 55 quadrats recorded for the Moor of the Future project included peat samples and different environmental variables, notably litter depth, and laboratory analysis of soil moisture content, various nutrients and heavy metals. Of these 55 quadrats and peat samples, only those with *Sphagnum* are included in this report and are referred to as the 'Data Subset'.

2.3 Data analysis

2.3.1 The data sets of plant species diversity and abundance (expressed in terms of % cover) and environmental variables were analysed using a range of statistical techniques.

2.3.2 The Main Dataset was analysed in three stages. First, using direct and indirect ordination, in order to show the underlying structure in the data and explore the extent to which the environmental variables explained vegetation patterns. The analysis used two widely-used algorithms: detrended correspondence analysis (DCA) and canonical correspondence analysis (CCA). The DCA and CCA were performed using the vegan package in the R computing language (v1.8-3)(Oksanen *et al*. 2006). The CCA was performed with only independent variables. Twelve environmental variables produced the 'full model' and then redundant variables were removed, to produce the model explaining the most variance using the fewest possible environmental factors (known as the 'most parsimonious' model); three to five variables is the optimal number (Oksanen 2008). These analyses were initially performed with 150 quadrats and repeated with the full 200 quadrats.

2.3.3 Second, the more influential environmental parameters identified in the first stage were related to the cover levels of eight of the most common *Sphagnum* species using linear regression. *Sphagnum* species selected were *S. capillifolium ssp. rubellum*, *S. capillifolium ssp. capillifolium, S. fallax, S. magellanicum*, *S. palustre*, *S. papillosum*, *S. subnitens* and *S. tenellum*. Data were available for a further five species, but these were excluded from the analysis because of their rarity (all were restricted to four or fewer sites).

2.3.4 Third, the relationships between i) *Sphagnum* species richness ii) overall plant species richness and iii) the peat building index (PBI) to 11 environmental factors was investigated. For i) and ii), a generalised linear model (GLM) with a Poisson error distribution was used for the continuous environmental variables (altitude, slope, vegetation height, pH and conductivity) following the recommendations of Crawley (2005). A non-parametric measure of correlation (Kendall's tau) between richness and these environmental parameters was calculated. All analyses were performed using the R programming language. For iii), the relationship between PBI and the continuous environmental parameters was investigated via linear regression. The relationship between PBI and the ordinal environmental parameters was assessed by calculating a non-parametric index of correlation (Kendall's tau). All analyses were performed using the R programming language.

2.3.5 The Data Subset comprised vegetation data from 41 quadrats with corresponding peat chemical analyses. Five small peat samples (approximately 20g) were collected around each quadrat and stored as a single bulk sample under cool conditions before analysis by Manchester Metropolitan University. The soil analysis methods used are described in Carroll *et al*. (2008). Peat samples were analysed for: pH, % moisture, extractable ammonium, nitrate, sulphate, calcium, magnesium, copper, lead, zinc and aluminum. The statistical analysis for the Data Subset used DCA and CCA, as described in section 2.3.2. In addition, species richness and diversity (using the Shannon Diversity Index) was calculated for each quadrat and related to the environmental variables.

2.3.6 The reports on these analyses include further technical details of the data analysis methodology, including data transformation, and are included in Appendix 4.

2.4 Limitations

2.6.1 It should be noted that, while every effort has been made to produce a comprehensive literature review, several inter-library loans are outstanding. It is proposed to update the literature review during on-going research being conducted by Ptyxis Ecology on another bog research project.

2.6.2 The field survey was conducted during September – March, therefore higher plant species not or rarely visible at this time of year, such as sundews *Drosera* species, will be under-recorded. However, this limitation is unlikely to substantially affect the findings of this research project focusing on *Sphagnum* species.

3 Results: literature review

3.1 *Sphagnum* autecology introduction

3.1.1 *Sphagnum* (bog mosses) are specialised bryophytes adapted to water-logged, acidic, and extremely nutrient-poor conditions, and are partly responsible for creating the peatland habitat. Bog mosses in general act as 'ecological engineers', producing decay-resistant litter, increasing the peat accumulation rate, withdrawing nitrogen and phosphorous, and determining the carbon balance of the system (Nils *et al.* 2003).

3.1.2 The genus *Sphagnum* comprises approximately 300 species, with the greatest diversity in lowland tropics of South America, but the greatest biomass in Northern temperate and boreal regions (Shaw *et al.* 1996). Of the 35 species recorded from Britain (sensu Hill *et al.* 2008), 15 are widespread in blanket, raised and intermediate bog.

3.1.3 The overriding physical factor controlling the formation and development of peatlands is water table level (Rydin & Jeglum 2008). Two complex environmental gradients determine peatland types: moisture and aeration levels; and pH, which is linked to Ca content and base saturation (Rydin and Jeglum 2008). *Sphagnum* species have been extensively studied in relation to these gradients. Nutrient level is another interacting chemical factor which affects plant growth, and in peatlands phosphorus (P) may be more limiting than nitrogen (N), especially as the role of atmospheric N deposition in likely to be significant in upland ecosystems (Press *et al.* 1986).

3.2 Moisture level

3.2.1 *Sphagnum* species define water table depth and soil moisture levels on both macro- and microtopographical scales:

- from moist to inundated sites (Hill *et al.* 2007) and the mire margin-mire expanse gradient (Sjörs 1948) (perhaps only valid in Scandinavia (Bragazza *et al.* 2005)); and
- in the exceptionally well-documented hydrotopological hummock-lawn-hollow series (e.g. Malmer 1962; Vitt *et al.* 1975; Andrus *et al.* 1983; Gignac 1992; Vitt, Li & Belland 1995; Rydin *et al.* 1999).

3.2.2 The vertical distribution of *Sphagnum* species on the hummock-hollow gradient is a function of plant physiology (determining productivity and tolerance to drying conditions) and competition. A broad grouping of British *Sphagnum* species along the hummock-hollow gradient is set out in Table A below.

Table A: Selection of British *Sphagnum* species along the hummock-hollow gradient (Lindsay *et al*. 1988; Clymo & Hayward 1982)

'Hummock' species	Intermediate	'Lawn' species	'Hollow' species	Pool species
Sphagnum fuscum	*S. magellanicum*	*S. tenellum*	*S. fallax*	*S. cuspidatum*
S. capillifolium sensu lato	*S. papillosum*	*S. russowii*	*S. majus*	*S. inundatum*
	S. palustre			*S. denticulatum*

3.2.3 There is considerable evidence that hollow species grow faster and are more productive than hummock-formers. However, paradoxically, many hummock-formers with lower productivity generally are better adapted to survive drying conditions, and so may out-compete other *Sphagnum* species in drier conditions. There is little evidence of any general difference in desiccation tolerance between hummock and hollow species (Rydin 1993) except perhaps for *Sphagnum fallax*.

3.2.4 A literature review by Moore (1989) found lawn species had on average about a 100g m^{-2} y^{-1} higher productivity than hummock-formers. In field experiments, *Sphagnum fallax* and *S. cuspidatum* out produced *S. papillosum* and *S. magellanicum* (Pedersen 1975; Clymo & Reddaway 1971); and *S. majus* and *S. balticum* out grew *S. fuscum* by 200% in length and 50% in dry weight (Pakarinen 1978).

3.2.5 Clymo and Hayward's (1982) drying experiments found that *Sphagnum papillosum* is the most sensitive to desiccation followed by *S. capillifolium*, which survived poorly, and *S. inundatum*, which survived well. *S. fallax* tolerates a lower water tissue content and is tolerant of drying and heating compared to *S. fuscum* and *S. magellanicum* (Sagot & Rochefort 1996).

3.2.6 Rydin (1985) measured the decreases in capitula water content with water table lowered to 22cm below the surface and found that hummock species *S. fuscum* and *S. capillifolium* could tolerate drying, whereas a reduced water table seriously reduced photosynthesis in the lawn species *S. tenellum*, which is therefore a poor competitor in drier conditions (Rydin 1993). As a result, *S. fuscum* is also more productive in drier periods than hollow species like *S. angustifolium* (Moore 1989). Grosvernier *et al*. (1997) found that *S. fuscum* withstood a low (-40cm) water table due its higher capillarity and the higher water holding capacity of its capitula. Therefore hummock-formers have a competitive advantage in drier conditions, which was demonstrated by Clymo and Reddaway (1971, 1974) who used a transplant experiment to test the effect of depth to water table on competition between four *Sphagnum* species at Moor House NNR, North Pennines. All species (*S. fallax; S. capillifolium; S. magellanicum; S. cuspidatum*) grew best in the pools, compared to on lawns or hummocks. On the hummocks, *S. capillifolium* out-performed the other species. Titus *et al.* (1983) and Titus and Wagner (1984) confirmed that *S. capillifolium* out-competed S. *fallax* in water-stressed conditions on hummocks because it holds 30% more water at saturation. These findings are supported by field observations that *Sphagnum* hummocks are often moist during dry summers when hollow species are dried out (MacDonald pers.ob. cited in Tucker 2003).

3.2.7 The moisture level preferences of British *Sphagnum* species is summarised in Table B below.

Table B: Ellenberg values for moisture levels from Bryoatt (Hill *et al*. 2007) for extant British species. Species in bold were recorded from the North Pennines during this study.

Value	Descriptor	Species or subspecies
10	In pools and streams that may intermittently lack water	**Sphagnum cuspidatum** S. majus S. pulchrum
9	In waterlogged substrata, in streams or flushes	S. affine S. balticum S. contortum S. denticulatum **S. fallax** S. flexuosum S. inundatum S. lindbergii S. platyphyllum S. riparium S. squarrosum S. subsecundum S. teres
8	Intermediate between 9 and 7	**S. angustifolium** S. austinii S. compactum **S. fimbriatum** S. girgensohnii **S. magellanicum** S. molle **S. palustre** **S. papillosum** S. skyense S. strictum **S. subnitens** **S. tenellum** S. warnstorfii
7	On constantly moist/damp but not permanently waterlogged substrata	**S. capillifolium** ssp. **capillifolium** **S. capillifolium** ssp. **rubellum** S. fuscum **S. russowii**
6	On moist soils or rock or bark in humid places	**S. quinquefarium**

3.3 pH

3.3.1 In boreal peatlands, it is well-established that *Sphagnum* species define an ecological gradient from low to high pH (Gignac 1992; Rydin *et al.* 1999). *Sphagnum* species are therefore often used as indicators of the rich fen - poor fen - bog gradient, when this is principally defined by pH (Gignac *et al*. 1991; Gerdol 1995; Bragazza *et al*. 2005).

3.3.2 Table C below summarises the pH tolerance of British *Sphagnum* species. Hummock-forming species such as *Sphagnum capillifolium* are particularly sensitive to elevated pH and Ca^+ and are indicators of more acidic conditions (Clymo & Hayward 1982). 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 & Shaw 1995).

Table C: Summary of pH range tolerance of selected British *Sphagnum* species

Species	pH range (listed by increasing acidity)	Source
S. contortum	6-8	Rydin *et al*. (1999)
S. teres	6-8	Rydin *et al*. (1999)
S. warnstorfii	6-7	Gignac (1992)
S. fimbriatum	4.8-7; generates a more acidic micro-environment when hummock-forming	Rydin *et al*. (1999) Bellamy & Rieley (1967)
S. fallax	4.8-6	Rydin *et al*. (1999)
Sphagnum squarrosum	4.5 - 5 +	Clymo (1973)
S. subnitens		
S. inundatum		
S. cuspidatum	4-5	Rydin *et al*. (1999)
S. tenellum		Gignac (1992)
S. angustifolium		Gignac (1992)
S. russowii		Daniels & Eddy (1985)
S. palustre		Rydin *et al*. (1999)
S. magellanicum	3.5-5; generates a more acidic micro-environment when hummock-forming; associated with flushing to pH 5.2 in lowland bogs but garden experiments (Clymo 1973) contradict this	Bellamy & Rieley (1967) Chapman (1964) Money (1995)
S. capillifolium sensu lato	3.5-5	Gignac (1992)
S. papillosum	3.5-5.5	Rydin *et al*. (1999)
S. quinquefarium	3.5-4.5	Daniels & Eddy (1985)

3.4 Nutrients

3.4.1 Nutrients are the elements and chemical compounds needed for plant growth. Blanket bogs are nitrogen (N) and/or phosphorous (P) limited ecosystems (Beltman *et al.* 1996; Bragazza *et al.* 2004). N inputs result in increased microbial biomass (Gilbert *et al.* 1998) and may cause increased decomposition and reduced peat accumulation (Aerts *et al.* 1992). In acidic peatlands, N is mainly available for plants as ammonium (NH_4^+) rather than as nitrate (NO_3^-)(Rydin & Jeglum 2008).

3.4.2 Bryophytes lack a root system, being adapted to source atmospheric and surface nutrients directly through their tissues, and therefore are more easily influenced by nutrient inputs than higher plants. Prolonged increased nutrients reduce bryophyte growth and diversity (Carroll *et al.* 2000; Pitcairn *et al.*1998; Press *et al.* 1986; Carroll *et al.* 1999; Edmundson 2006). Sphagna are more susceptible to nutrient inputs than other bryophytes (Jappinen & Hotanen 1990).

3.4.3 The N/P ratio in plant tissue is used as a marker for ecosystem nitrogen saturation, which occurs at quite low levels in bryophytes, but without any difference between *Sphagnum* species (Gunnarsson & Rydin 2000). This efficiency of N uptake may make Sphagna especially vulnerable to elevated N levels (Press *et al*. 1986). Once N saturation in bryophytes is reached, vascular plant uptake will result in vascular plants out competing bryophytes. The critical load for bog *Sphagnum* species is around 10 kg N ha^{-1} y^{-1} (Gunnarsson 2005); above that N becomes available to vascular plants; and 80 kg N ha^{-1} y^{-1} will kill Sphagna (Limpens *et al*. 2003). Bryophytes on heather moorland (Edmundson 2006; Pilkington *et al*. 2007) and Sphagna on bogs (Bragazza *et al*. 2004, 2005) also show increased growth in response to P addition once N uptake is saturated.

3.4.4 A literature review of the field and laboratory tests of effects of ammonium (NH_4^+) and nitrate (NO_3^-) on *Sphagnum* species produced conflicting results, suggesting other environmental factors or aspects of plant physiology are involved (Carroll *et al*. 2008). However, field experiments at least, do strongly suggest *Sphagnum fallax* and the closely related *S. angustifolium* as more tolerant of, and respond positively to, both nitrates and ammonia (see section 3.11.9 below for species-specific details).

3.4.5 Table D below summarises the broad nutrient tolerance of British *Sphagnum* species. This literature review has been unable to locate any empirical evidence of nutrient tolerance by *Sphagnum fimbriatum*, *S. flexuosum* and *S. squarrosum* and enquiries made of Dr M. O. Hill are pending at the date of this draft report.

Summary

- There is a vast amount of empirical evidence supporting the distribution of certain *Sphagnum* species along hydrotopographical and pH gradients.
- The relationship between nutrients and *Sphagnum* species is less clear and most species may only be placed into limited categories corresponding to broad nutrient levels.
- Scientific studies repeatedly utilise the same limited range of *Sphagnum* species, particularly *S. fuscum* (very rare in the North Pennines), *S. magellanicum*, *S. capillifolium* and *S. fallax*.
- *S. fallax* and the closely related *S. angustifolium* are tolerant of elevated ammonium levels and can out-compete other *Sphagnum* species.

Table D: Ellenberg values for nitrogen (N) from Bryoatt (Hill *et al.* 2007) for extant British species. Species in bold were recorded from the North Pennines during this study.

Value	Descriptor	Species or subspecies
1	Indicator of extremely infertile sites	Sphagnum austinii S. balticum **S. capillifolium ssp. rubellum** S. compactum S. fuscum **S. magellanicum** S. molle **S. papillosum** S. pulchrum S. strictum **S. tenellum**
2	Indicator of infertile sites	S. affine **S. angustifolium** **S. capillifolium ssp. capillifolium** S. contortum **S. cuspidatum** S. denticulatum S. girgensohnii S. inundatum S. lindbergii S. majus **S. palustre** S. platyphyllum **S. quinquefarium** S. riparium **S. russowii** S. skyense **S. subnitens** S. subsecundum S. teres S. warnstorfii
3	Indicator of moderately infertile sites i.e. tolerant of elevated nutrient levels	**S. fallax** **S. fimbriatum** S. flexuosum S. squarrosum

3.6 Introduction to land use & management practices

3.6.1 Blanket bog in the North Pennines, in common with all of the English uplands, has been a managed and modified habitat for millennia (Ratcliffe & Thompson 1988; Simmons 2003). However, from the 1950s, land management massively intensified, with dramatic increases in grazing levels (Brown *et al*. 2001) and drainage. Burning to maintain heather stands of varied ages, palatable for grazing animals, has also been a long-standing practice but burning in the North Pennines occurs at greater rates and regularity than the national average. 30% of designated conservations sites (SSSI) bog is burnt (Yallop *et al*. 2006). Burning is now largely as management for red grouse *Lagopus lagopus scoticus* and other game birds (despite advice from the Game Conservancy Trust that burning blanket bog should be a low priority for grouse management (Hudson & Newborn 1995)). Afforestation and clear felling has had less of an impact in the North Pennines compared to other upland areas.

3.6.2 Grazing, burning, drainage and afforestation result in drying of the peat substrate, which increases peat oxidation and nutrient availability as the process of mineralisation is accelerated (Gorham 1956; Piisparen & Lahdesmaki 1983).

3.6.3 With all land management practise on bog, there is a fine line between sustainable management and damage (Charman 2002). The combination of high grazing intensity and burning is likely to be particularly detrimental to *Sphagnum*-dominated vegetation (Hobbs & Gimmingham 1987).

3.7 Grazing

3.7.1 Grazing levels determine vegetation offtake, which influences production, and therefore peat accumulation (Clymo 1984; 1992). Grazing also affects plant species composition and cover, nutrient load from dunging, and can cause physical damage (Hulme & Birnie 1997). All of these factors also vary according to grazing timing, intensity, frequency and the types and breeds of animals involved.

3.7.2 Most empirical studies relate to dry heather moorland rather than blanket bog (Shaw *et al*. 1996; Crowe 2007) and focus on impacts on heather rather than *Sphagnum*. Welch and Rawes (1966) found that stocking levels as low as 0.6 sheep per hectare was reducing heather *Calluna vulgaris* growth on a North Pennine blanket bog; <0.25 sheep per hectare are recommended for wet blanket bog (Brooks & Stoneman 1997), although there is still considerable uncertainty regarding appropriate stocking levels (Lindsay 1995).

3.7.3 At high grazing levels on blanket bog, Rawes (1983) found that bryophytes declined and cover of *Eriophorum vaginatum* and bare peat increased. *Sphagnum* is thought to be particularly susceptible to poaching and trampling especially by cattle (Pearsall 1950; Shaw *et al*. 1996).

3.7.4 However, there is some evidence suggesting that light grazing has either a negligible impact or is beneficial for blanket bog. In the long-term, light grazing may increase plant diversity on blanket bog (Welch & Rawes 1966) although high plant diversity may not necessarily correlate with a high diversity or cover of Sphagna, or with bog being in good condition. Chapman and Rose (1991) believed that cessation of grazing in the late 1950s at Coom Rigg Moss, Northumberland at least partly resulted in a decline of *Sphagnum* species cover and diversity by 1986, replaced by *Eriophorum angustifolium*, *Molinia caerulea* and heather, although their evidence is circumstantial. At Moor House NNR, North Pennines, studies by Rawes and Hobbs (1979) found that low levels of grazing (up to 0.37 sheep per hectare) did not result in major changes in vegetation or levels of biomass over twenty years. Rawes and Welch (1969) conducted a grazing exclosure experiment for 21 years, which resulted in cover of Sphagna (*Sphagnum capillifolium* ssp *rubellum* and *S. cuspidatum*) decreasing, except for *S. papillosum*, which increased, although other environmental factors may be involved, such as atmospheric pollution or climate change. Smith *et al*. (2003) studied floristic changes on Butterburn Flow, Cumbria in response to removal of grazing over 14 years, which showed decreases in *Sphagna* species around the mire margin, but results were inconclusive for the wetter central mire expanse. The authors concluded that external factors were probably more important than grazing levels.

3.8 Burning

3.8.1 Evidence of both natural and anthropogenic fire is a feature of the peat stratigraphy record throughout the Holocene (the time period since the last ice age ended c.12,000 years BP) (Tolonen 1983; MacDonald 1999). Blanket bog is not regarded as a naturally fire-dependent ecosystem (Segerstr*ö*m *et al*.1996) and presumably wild or anthropogenic fires did not occur on any where near the extent or regularity of management burns during recent centuries.

3.8.2 Burning impacts will vary according to burn frequency and intensity, and on a number of other factors, such as moisture levels at the time of the burn and the time of year. Burning is likely to raise substrate pH to above 5 for at least 3-5 years (Allen 1964; Stevenson *et al*. 1996) or possibly much longer according to palaeoecological evidence (e.g. Korhola *et al*. 1996); cause drying conditions; and affect nutrient dynamics. Nutrients may be lost, or at least temporally redistributed, as particulate matter, and through volatilisation in smoke and in blown /eroded ash. Short-term nutrient availability increases for up to about five years after a burn (Hansen 1969), depending on leaching and erosion levels, but the overall medium-term effect is thought to be a loss of P, with other nutrients replaced in rainfall. However, nutrient budgets are complex and understudied, and long-term effects of serial burning are unknown (Tucker 2003).

3.8.3 There is a general lack of understanding of the impacts on vegetation of fire when used for land management, and on bryophytes in particular. Anderson's (1997) discussion of fire damage on blanket mires does not mention bryophytes at all. Land management advice is generally to minimise or avoid burning, because of *potentially* damaging impacts, especially if a fire gets out of control (e.g. Brooks & Stoneman 1997). Similarly, low or no cover of *Sphagnum* is generally used by condition assessment methodologies as a *potential* indicator of frequent and/or intensive burning, in the absence of evidence to the contrary (e.g. Macdonald *et al*. 1998).

3.8.4 The presumption that burning always detrimental to *Sphagnum*-based vegetation has apparently never been empirically verified (Shaw *et al*. 1996), probably because it is difficult to isolate causes of bog degradation, with complex interactions between grazing, draining and burning (Rawes1983). In addition, post-fire vegetation succession is unpredictable because so many factors are involved, such as fire character (intensity, duration, temperature), moisture levels pre-burn, and interactions with grazing (Tucker 2003). Field observations (MacDonald 2000 in Tucker 2003) and at least one experimental study, have found that *Sphagnum* often survive low intensity burns and that the perception that fires are always extremely detrimental to *Sphagnum* is unsupported (Hamilton 2000). Burch (2008) studied bryophyte recolonisation after management burns on wet heath on the North York Moors and found that *Sphagnum* survived burning in all 18 plots ranging from 1 year to over 25 years post burn. *Sphagnum* was the most abundant bryophyte 3 years post burn and showed no significant difference in abundance between stands of different time since last burn.

3.8.5 Vegetation recovery post-burn particularly varies with fire intensity. Maltby *et al*. (1990) studied a severe fire in the North York moors in 1976, which burnt 5-10m into blanket bog, removing *Sphagnum* species completely, and found that after 9 years the surface was colonised by lichens and bryophytes, particularly *Polytrichum* species, but no *Sphagnum*. However, in this case, the depth and severity of the burn limited vegetation recovery, as a fire on Glasson bog NNR, Cumbria the same year recovered to produce "substantially the same" as the pre-fire vegetation (Maltby *et al*.1990). Localised light burns may be beneficial by removing plant litter to maintain an open, wetter mire surface (Chapman & Rose 1991) but again the evidence is limited and largely circumstantial. Rawes and Hobbs (1979) conducted famous burning and grazing studies at Moor House NNR, but unfortunately only record '*Sphagnum* sp' in most of the published data. The *Sphagnum* cover following 10 and 20 year rotational burning did recover, after an intermediate period of 0-7 years of *Eriophorum vaginatum* dominance. Although these studies extended over 20 years, the authors wirily comment that many questions remain only partly answered.

3.8.6 It is apparently untested whether excessive frequency of fires results in replacement of different *Sphagnum* species to those dominant pre-burn. It is speculated that hummock-formers may generally survive fire better as they have higher moisture cell retention (see section 3.2.6). One exception is *S. austinii* / *affine* (previously *S. imbricatum*) which was previously abundant throughout Britain, until about the 1400s. The consensus of palaeoecological studies is that natural and anthropogenic fires and disturbance were a major factor in its decline and disappearance (McClymont *et al*. 2008). However, overall "with current scientific information, it appears impossible to reliably identify bryophyte species that are actually significantly impacted by burning" (Tucker 2003: 82) who also records the need for further research into the effects of land management fires (as distinct from accidental fire) on *Sphagnum* species.

3.8.7 Fires may favour certain plant species. One study suggests *S. tenellum* is a good coloniser of bare burnt areas where these retain adequate soil moisture (Lindsay & Ross 1994). However, it should be noted that *S. tenellum* exhibits a different life strategy to other *Sphagnum* species, being adapted to high stress and ruderal conditions. Brooks and Stoneman (1997) state that frequent fires encourage tight cushions of *S. compactum*, *S. capillifolium* and *Racomitrium lanuginosum*, but unfortunately do not cite any reference for this statement. Økland (1990) and Slack (1990) showed that *S. compactum* is a coloniser of ruderal habitat.

3.8.8 Useful plant indicators of damage by, and recovery from fires, are *Polytrichum commune* (Maltby *et al*. 1990) and cloudberry *Rubus chamaemorus*, where these species increase at the expense of others. Cloudberry was seen to benefit from burning at Moor House, colonising rapidly by rhizomes (Hobbs 1984).

3.9 Drainage & afforestation

3.9.1 Since the 1930s, approximately 1.5 million hectares of upland blanket bog has been drained for agricultural and forestry use, often in combination with fertilisation (Brown *et al*. 2001). Afforestation, which includes small scale tree planting, also may have major ecohydrological impacts on nearby bog habitat. Drainage increases the depth of the aerated layer, increases peat oxidation, decay, microbial activity, mineralisation and nutrient losses and subsidence (Rydin & Jeglum 2008).

3.9.2 The overall effect of drainage on vegetation and *Sphagnum* species is likely to be detrimental and loss of *Sphagnum* cover or vigour is widely accepted as one of the first indications of drying impacts (Macdonald *et al*. 1998), but causation is uncertain. Indeed, field observations by Pearsall (1950:156) of drainage grips in the 1940s noted the “tenacity” with which *Sphagnum* persisted in spite of drainage, and that burning and grazing were more often the cause of Sphagna elimination. There is some evidence supporting this view, although apparently so far only one published study, Stewart and Lance (1981), on studies of blanket bog grips at Moor House NNR, North Pennines. This single study has been much cited as evidence that it is actually difficult to effectively drain a blanket bog (e.g. by Dargie (2007) during the Ecological Impact Assessment (EcIA) into the proposed Lewis wind farm development; and by Mackenzie Bradshaw (2005) in the Ray Wind Farm, Northumberland EcIA). However, the details of these experiments include finding drainage to be highly effective where grips were more closely spaced than 20m. A 2m margin either side of grips across shallow slopes showed a marked reduction in cover of *Sphagnum capillifolium*, a species normally regarded as relatively drought-tolerant (see section 3.11.9 above).

3.9.3 There has been considerable research on bog drainage for large-scale afforestation, from the perspective of the forester wishing to encourage tree growth, rather than looking at ecohydrological changes. However, ecological impacts on bogs within forestry at Kielder Forest, Northumberland and the

Flow Country in Caithness and Sutherland, Scotland, have been particularly well-studied. By contrast, there few studies on the impacts on bog of small scale localised tree planting, but there is no reason to believe that these would have negligible impacts by virtue of scale alone. Any tree planting situated adjacent to, or near, bog will increase transpiration levels, may lower the water table, and may potentially adversely impact bog habitat (Smith *et al*.1995). The magnitude of any adverse impact will be site specific and dependent on the number of trees planted, and there is considerable uncertainty involved. Similarly, habitat fragmentation due to forestry block plantation has been associated with decline in bog plant species diversity (Smith and Charman 1988).

3.9.4 Few studies on afforestation impacts include data on specific *Sphagnum* species but those that have done so invariably document the decline of diversity and abundance of *Sphagnum* species on sites directly or indirectly impacted by tree planting (e.g. Chapman & Rose 1991; Charman and Smith 1992).

3.10 Disturbance from recreational use

3.10.1 There have been only a few published studies on the impact of recreational access on bog vegetation. It is likely that more studies take place, especially as Environmental Impact Assessment monitoring under s106 planning agreements, but these are rarely published unless the planners include an obligation on the developer to do so. Yet peat compaction, caused by recreational pressure, is a major concern for bog conservation (Brooks & Stoneman 1997). Peat compaction is likely to increase substrate temperature and microbial activity, and therefore increase decay and reduce peat formation, as well as reduce plant diversity and cover.

3.10.2 Trampling is thought to adversely impact blanket bog by contributing to erosion in the South Pennies, although other factors are likely to be involved (Yalden and Yalden 1988).

3.10.3 There is increasing evidence that off-road vehicles are causing extensive and severe damage to vegetation (Bayfield *et al*. 1988) and this is a particular problem in the North Pennines (Robinson *et al*. 2006). Richard and Brown (1974) showed that off-road vehicles may have severe detrimental impacts on tundra vegetation, especially on sloping terrain, during wetter seasons and on wetter vegetation types like bog.

3.10.4 *Sphagnum* is thought to be particularly vulnerable to disturbance. Borcard and Matthey (1995) found that 10 minutes of experimental trampling three times a year for three years almost destroyed the cover of *Sphagnum fallax* and *S. fuscum* on a Swedish raised bog.

Summary

- The impacts of land management practices and recreational use on blanket bog are still poorly understood. This is partly because it is difficult to control for other environmental factors during field experiments.
- There are few empirical studies assessing impacts on bryophytes, or *Sphagnum* species.
- The impact of burning, when used as a management tool, is particularly uncertain and further studies are required.
- The impact of drainage grips on *Sphagnum* and other bog vegetation is better understood, although the review found only one published study on blanket bog, where drainage only impacted grip marginal areas. This single study is often cited to justify development impacts on blanket bog being evaluated as 'likely to cause minor damage'.
- It is, on balance, probable that cumulative impacts of burning and over-grazing and trampling from recreational pressures are more often the cause of Sphagna elimination than drainage alone.

3.11 *Sphagnum* as ecological indicators

3.11.1 Numerous studies, over many years, have shown that plants can be effective predictors of ecological conditions (e.g. Sjörs 1948; Jeglum 1971; Vitt 2000), especially bryophytes (Van Baaren *et al*. 1988; Nordbakken 1996; Albinsson 1997). As well as defining moisture, pH and nutrient gradients, *Sphagnum* species have also been widely used as indicators of environmental impacts, for example, atmospheric pollution - particularly heavy metals (Pakarinen 1981) and nitrogen and sulphur dioxide deposition (e.g. Lee & Studholme 1992; Malmer 1988; Ferguson *et al*. 1984) - and more recently for climate change (Whinam & Copson 2006). There is also a vast literature on *Sphagnum* species used in paleontology to infer historic climatic conditions, especially during the Holocene (the time period since the last ice age ended c.12,000 years BP). *Sphagnum* species are also regularly used in field guides or management handbooks as proxy indicators for bog in 'good' peat-forming condition (e.g. Foss & O'Connell 1998; Sims & Baldwin 1996; Paavilainen & Paivanen 1995; Wilkie *et al*. 1997; MacDonald *et al*. 1998).

3.11.2 There are several advantages to using plant indicator species to assess bogs, and *Sphagnum* in particular. Vegetation can be used to assess normal saturation levels independent of whether field visits are made in very wet or dry conditions (Rydin & Jeglum 2008), and to assess modal conditions over an extended period of time. This is especially important in ombrotrophic bogs because there can be much year to year variation in water table level (Glaser *et al*. 1996), which can drop over 30cm in one dry summer (Rydin 1986). Bryophytes can also be assessed at any time of year, unlike higher plants.

3.11.3 Although the literature on Sphagna autecology comprises studies from many countries other than Britain, arguably the results can be compared because of the strong influence Sphagna have on their environment (Rydin 1993). However, results should always be applied critically, as environmental conditions in ombrotrophic bogs do vary between regions and countries (Rydin & Jeglum 2008). It is also important to select *Sphagnum* as indicators which are appropriate to any given region, and of widespread distribution. For example, *Sphagnum majus* suggests some nutrient enrichment (Daniels & Eddy 1985) but it is of little use as an indicator species in Britain as it is so rare. *Sphagnum austinii* / *affine* (S. *imbricatum*) losses probably indicate excessive burning but this species is now restricted to Widdybank Fell, North Pennines, and scattered sites in Scotland. Similarly, many empirical studies include *S. fuscum*, but this species has a restricted distribution in Britain and is very rare in the North Pennines, so it is not suitable for detailed consideration in this report.

3.11.4 Overall, using *Sphagnum* species as indicators, if applied critically, is a valid, quick and simple proxy field technique to assess ecological conditions.

3.11.5 However, the scientific evidence supporting *Sphagnum* as indicators is sometimes rather inconsistent or lacking. Use of indicator species is perhaps often based solely on field observations and tends to be repeated in management guides without citation of supporting references. Daniels and Eddy (1985) has useful diagrams of *Sphagnum* ecological amplitudes, with dry/wet and oligotrophic/eutrophic axes, but does not cite any specific sources. An example of the resulting problems for a researcher relates to *Sphagnum magellanicum* and *S. papillosum*. Daniels and Eddy (1985) give *S. magellanicum* as a more oligotrophic indicator than *S. papillosum*, the latter being shown with a wider nutrient tolerance - presumably based on Clymo (1973) - but this view of *S. papillosum* is contradicted by field observations in Chapman (1964).

3.11.6 Existing blanket bog condition assessment methodologies either only utilise '*Sphagnum* sp.' cover (Jerram & Drewitt 1998) or only one species, *S. fallax*, as an indicator of poor condition (JNCC 2004). The SNH method has been further simplified by dropping the need to record cover of *S. fallax* in the 2008-9 Natural England research project 'English upland condition assessment of sites within and without agri-environment schemes' (O'Reilly pers. ob.) and the reasons for this are unknown.

3.11.7 Two publications identified during this literature review attempt to apply the use of Sphagna as management indicators: SNH's Phase 2 Impacts Survey for blanket bog (MacDonald *et al*. 1998); and the IPCC Peatland Management Handbook (Foss & O'Connell 1998). MacDonald *et al*. (1998) includes *Sphagnum* species as indicators of drying, burning and grazing impacts (see Table E below).

Table E: *Sphagnum* species used as indicators of land use impacts from MacDonald *et al.* (1998)

	Low impact	**Medium**	**High**
Drying	More than 3 *Sphagnum* species present	• one or more of *Sphagnum fallax*, *S. papillosum* and/or *S. cuspidatum* in hollows • on higher ground, only occasional *S. capillifolium* (or sometimes *S. fuscum* or *S. austinii*)	Absence of *Sphagnum* species
Burning - intensity	Degree and extent of bleaching of *Sphagnum* (and other moss) cushions used but not specific *Sphagnum* species		
Burning - frequency	More than 2 *Sphagnum* species	More than 2 *Sphagnum* species	Sparse thin mats of 1-2 *Sphagnum* species (*S. tenellum* and *S. compactum* likely to be most frequent species)
Grazing/trampling	Specific *Sphagnum* species not used		

3.11.8 The IPCC handbook includes a summary table of *Sphagnum* species used as indicators of management impacts. Unfortunately, it contains no references, and may be largely based on other contemporary secondary texts such as *Conserving Bogs: the Management Handbook* (Brooks & Stoneman 1997), rather than primary scientific papers. Table F below evaluates the scientific evidence for these indicator species, and further details, where required, are discussed in the species sections 3.11.9 to 3.11.20 below.

Table F: Evaluation of published scientific evidence for *Sphagnum* as indicators of bog management impacts as listed in Foss & O'Connell (1998)

Impact	Indicator species listed in Foss & O'Connell (1998)	Source	Evaluation
Increases suggest drying out	*Sphagnum compactum*	Daniels & Eddy (1995) Økland (1990) &/or Slack (1990)	(Papers on pending interlibrary loan).
	S. capillifolium (where out competes other *Sphagnum* species)	Clymo & Reddaway (1971, 1974) Titus *et al.* (1983) Titus and Wagner (1984)	Reliable - range of empirical experiments producing consistent results.
Decreases suggest drying out	*S. cuspidatum*	Much evidence of it being a hollow/pool species thriving during inundation (e.g. Clymo 1970) and therefore implicitly reliant on high water table levels	Generally reliable. Some conflicting evidence as tolerates desiccation more than other species e.g. Clymo & Hayward (1982).
	S. magellanicum	Pearsall (1956) Chapman & Rose (1991)	Unreliable. Field observations and speculations conflict with empirical studies e.g. Grosvernier *et al.* (1997); other factors such as competition not considered.
	S. papillosum	Clymo & Hayward (1982) Chapman & Rose (1991)	Unreliable for management impacts as sources conflict.
Decreases suggest excessive burning	*S. imbricatum* (now *S. austinii* and *S. affine*) *S. fuscum*	Pearsall (1956) from field observations	Unreliable as other factors likely to be involved.
Increases suggest recovery from drying out or burning	*S. tenellum*	Field observations in Pearsall (1956) cited in Økland (1990); Lindsay & Ross (1994) cited in Shaw *et al* (1996); tolerates desiccation according to Daniels & Eddy (1985) but not according to Rydin (1986)	Unreliable as empirical evidence limited; other factors likely to be involved due the complexity of burning effects and further work required.
	S. molle	Heikkila & Lindholm (1988)	(Papers on pending interlibrary loan).
	S. compactum	Økland (1990) &/or Slack (1990)	Some empirical evidence limited to ruderal characteristics.

Table F: Evaluation of published scientific evidence for *Sphagnum* as indicators of bog management impacts as listed in Foss & O'Connell (1998)

Impact	Indicator species listed in Foss & O'Connell (1998)	Source	Evaluation
Increases suggest nutrient enrichment	*S. fallax*	Twenhoven (1992) Limpens *et al*. (2003)	Reliable empirical evidence and well-established in the literature.
	S. subnitens	Daniels & Eddy (1985) mention it in more eutrophic habitats but its ecological amplitude is shown as close to that of *S. capillifolium* ssp. *capillifolium*, which prefers slightly mesotrophic habitats, so it is apparently not that strong an indicator	Unreliable as no field or empirical evidence identified.
Increases suggest recovery from bare ground / erosion	*S. fallax*	Grosvernier *et al*. (1997)	Reliable empirical evidence that it is a pioneer species.

3.11.9 ***S. capillifolium*** has been frequently studied in both laboratory and garden experiments. Empirical studies allowing for competition over medium term study periods, and field observations, consistently support its use as an indicator of drying substrates, where it increases at the expense of other *Sphagnum* species. Of the two subspecies, *capillifolium* is reported in Hill *et al*. (2007) as more tolerant of nutrients but this apparently has not been verified experimentally.

3.11.10 ***S. compactum*** is mentioned in Brooks and Stoneman (1997) as increasing with frequent burning, and therefore would also suggest drying impacts, as implied by Daniels and Eddy (1995), but no supporting evidence is cited. Økland (1990) and Slack (1990) verify that it is a good coloniser of ruderal ground, but these papers remain pending on interlibrary loan, and may not verify its tolerance of drying.

3.11.11 ***S. cuspidatum*** is a highly competitive species due to its very fast growth rate compared to all other British *Sphagnum* species except *S. fallax* (Clymo 1970) but is dependent on a surface water table, therefore declines in cover indicate that bog pools are drying out.

3.11.12 ***S. fallax*** growth rate is much faster than other species - in field experiments *S. fallax* and *S. cuspidatum* out produced *S. papillosum* and *S. magellanicum* (Clymo & Reddaway 1971). It can also tolerate higher levels of nutrients and therefore a combination of high productivity and nutrient tolerance means it tends to out-compete other *Sphagnum* species (Limpens *et al*. 2003), except perhaps for *S. cuspidatum* (Pedersen 1975). *S. fallax* out-competes *S. magellanicum* in hollows and lawns; on hummocks *S. magellanicum*'s better capillarity gives it the advantage (Twenhoven 1992). The evidence for *S. fallax* as an indicator for eutrophication is persuasive, even if some laboratory tests are inconclusive. In the Netherlands, field experiments comparing the frequency of bryophytes in fens from 1940-59, 1960-79 and 1980-99 showed a correlation between elevated ammonium after 1980 and invasion by *S. fallax* and *Polytrichum commune* (Paulissen 2004). *S. angustifolium* (closely related to *S. fallax*) responds positively to nutrient inputs (Aerts *et al*. 1992; Jauhiainen *et al*. 1992; Rochefort *et al*. 1990) although is less tolerant of combined N and P inputs during regeneration and establishment than in mature colonies (Yenhung & Vitt 1994). Vegetation dominated by *S. fallax* is a particularly good indicator of elevated P inputs (Limpens *et al*. 2003), from agricultural inputs, burning or other sources. It was the only *Sphagnum* species found on much of the south Pennines by the 1970s being tolerant of the high atmospheric sulphur dioxide and nitrous oxide pollution (Ferguson *et al*. 1978).

3.11.13 ***Sphagnum magellanicum*** is generally accepted as an indicator of undisturbed bog habitats, at least in Scotland (Chamberlain 2002) but its relationship with nutrients is rather equivocal. Some authors (Chapman 1964; Newbold 1960) state it suggests flushing with Ca^{+} in lowland bogs. Laboratory tests by Rudolf and Voigt (1986) showed that *S. magellanicum* tolerates elevated N levels (up to 322µM) compared to other *Sphagnum* species. However, this is not reflected by other sources e.g. Daniels and Eddy (1995), which states that *S. palustre* is much more of an indicator of more eutrophic conditions than either *S. magellanicum* or *S. papillosum*.

3.11.14 ***S. papillosum*** decomposes at half the rate of other common *Sphagnum* species (including *S. magellanicum*) (Clymo 1965) and so is probably the most important extant peat-forming species, at least in England. There is a consensus in the literature that it is a positive indicator of bog condition where it occurs at high cover levels. It is believed to be slightly more susceptible to drying than *Sphagnum magellanicum* (Daniels & Eddy 1995) which is supported by laboratory tests (e.g. Clymo & Hayward 1982). However, this conflicts with Pearsall (1956) who from field observations states it tolerates drying the most. The apparent paradox is due to its ability to survive temporary drying conditions (as opposed to complete desiccation) (see 3.2.5 above). At some point inadequate moisture levels will result in its decline and loss.

3.11.15 Both ***Sphagnum magellanicum*** and ***S. papillosum*** declined by 48% on Coom Rigg Moss, Northumberland over 30 years, possibly due to afforestation adversely impacting hydrology combined with drainage (Chapman & Rose 1991), but this is speculation and climatic factors may be involved. Similarly, these two species declined along with *S. cuspidatum*, on a border mire at Kielder after adjacent afforestation, but changes in grazing were thought to be involved rather than indirect drainage from the forestry (Smith & Charman 1988). However, these studies do suggest that declines in these two species indicate bog degradation, even if the precise cause cannot be ascertained.

3.11.16 ***S. palustre*** is sometimes cited as a clear indicator of more mesotrophic conditions (Daniels and Eddy 1995), but this review found no supporting evidence for this in the literature. It may get over-looked and/or mis-recorded as *S. papillosum* due to identification problems: species must be confirmed microscopically as field 'jizz' characters are not reliable, and even experienced surveyors may tend to base identification on habitat – assuming that a plant in a bog must be *S. papillosum*.

3.11.17 ***S. quinquefarium*** is not regarded as a bog species (Daniels & Eddy 1985) but does occur in the North Pennines blanket bogs. Of all European *Sphagnum* species, it is most tolerant of drier conditions according to Daniels & Eddy (1985) but no further evidence was found to support this assertion.

3.11.18 ***S. russowii*** increases may suggest further drying out of a bog area that has already seen a fall in the water table (Daniels & Eddy 1995). However, no corroboratory evidence, from field or empirical studies, for this assessment could be found in the literature.

3.11.19 ***S. subnitens*** is associated with elevated nutrient levels according to Brooks and Stoneman (1997) and this information was probably repeated by Foss and O'Connell (1998), yet this is apparently without any scientific basis. Hill *et al*. (2007) do not list this species within the group of most nutrient tolerant Sphagna.

3.11.20 ***S. tenellum*** is believed to be both an indicator of disturbance and excessive grazing, and acts as a primary colonist of bare peat. Pearsall (1950) stated from field observations that it is "particularly sensitive to modifying agencies [i.e. trampling by grazing]". This is supported by *S. tenellum* showing a decline on disturbed and grazed sites, on analysis of constancy tables from a survey of disturbed and undisturbed blanket bog vegetation on the Isle of Lewis and Harris (Hulme & Birnie 1997). Field observations in RSPB (1995) cited in Shaw *et al* (1996) report that *S. tenellum* is a colonist of bare peat, and likes trampled areas. It out-competed *S. balticum* during an exceptionally dry year, which is paradoxical as it desiccates more rapidly (Rydin 1986), although Rydin (1993) notes that its drought tolerance is untested. Lindsay and Ross (1994) showed that populations spread to colonise bare burnt areas but only if the surface is sufficiently wet and there is a nearby propagule source.

3.11.21 In conclusion, it is important to note that the need for further empirical evidence to support the use of *Sphagnum* indicator species has been recognised: The Macaulay Land Use Institute, Aberdeen, were working on using indicator species to help predict the likely effects of management on blanket bog (Shaw *et al.* 1996). However, the results of this work are apparently unpublished and could not be traced during this literature review. In 1996, discussions at a British Ecological Society conference recorded that there appears to be a gap in the models available to land managers for managing blanket bog, in particular for a model with the facility to predict impacts at various scales, including vegetation succession (Tallis & Meade 1997).

Summary

- There is an apparent lack of scientific evidence to support many *Sphagnum* indicator species.
- Field observations are often untested empirically.
- In particular, there is a lack of indicator species for assessing excessive burning impacts.
- Apparently no other authors in any region worldwide have produced any condition assessment survey tool that uses *Sphagnum* species extensively – generally cover of '*Sphagnum* sp.' is used; or publications refer to a limited range of species.
- Scientific studies support four *Sphagnum* indicator species, listed below; others are likely to exist but are currently lacking adequate supporting evidence:
    - ***Sphagnum capillifolium*** (where it out competes other *Sphagnum* species) – increases suggest drying out
    - ***S. compactum*** – increases suggest drying or recovery from burning
    - ***S. cuspidatum*** – decreases suggest drying out
    - ***S. fallax*** – increases suggest nutrient enrichment and/or recovery from bare ground / erosion / burning

Table G: Possible *Sphagnum* indicator species where further evidence required

Impact	Possible indicator species	Useful as an indicator species for North Pennines?
Increases suggest drying out	*S. quinquefarium* *S. russowii*	Yes
Decreases suggest drying out	*S. magellanicum* *S. papillosum*	Yes
Decreases suggest excessive grazing / trampling	*S. tenellum*	Yes
Increases suggest recovery from burning or excessive burning if these species increase at the expense of others	*S. tenellum* *S. fallax* *S. molle* *S. compactum*	Yes except *S. molle* (too rare in North Pennines)
Increases suggest nutrient enrichment	*S. subnitens* *S. squarrosum* *S. fimbriatum* *S. flexuosum* *S. palustre*	Yes except *S. flexuosum* (absent in North Pennines)

4 Results: field survey

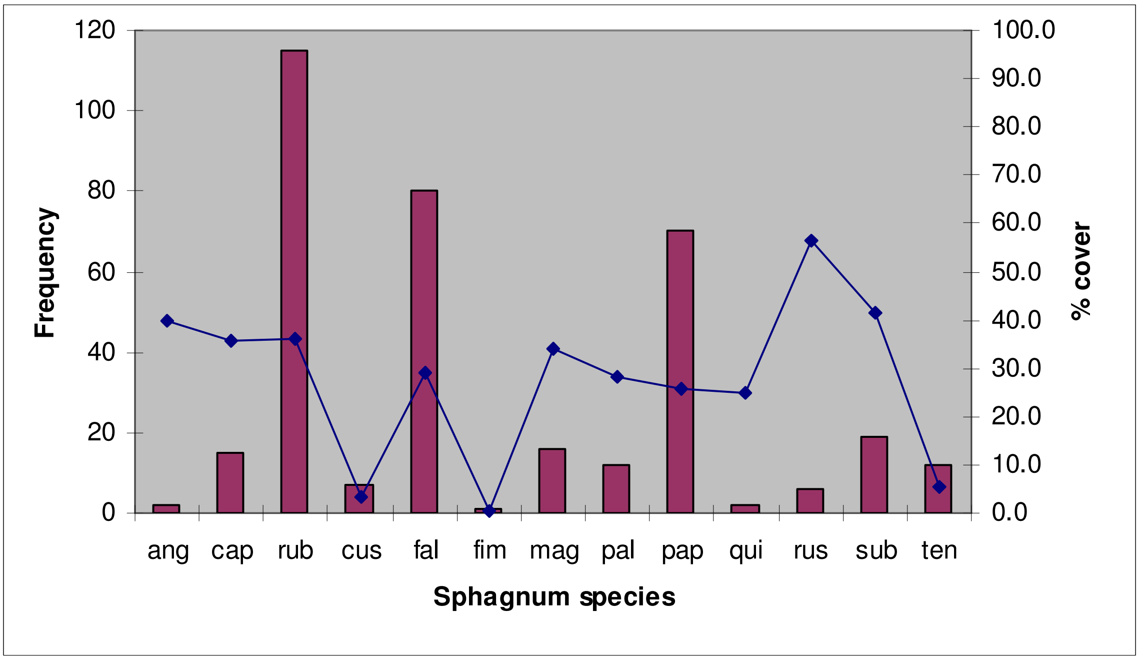
4.1 Vegetation survey data

4.1.1 Thirteen Sphagnum taxa (species or subspecies) were recorded, from a total of 119 plant species and subspecies. This included: 13 lichens; 23 liverworts; 40 mosses; 1 fern; and 42 flowering plants. The raw data matrices are presented in Appendix 2.

4.1.2 The records included 4 nationally scarce species (= recorded from 100 or fewer 10km squares in Britain) species and 3 new vice county records. Several of the scarce species have not been recorded in the North Pennines for fifty or sixty years. The full records are at Appendix 3.

4.1.3 The number of quadrats each *Sphagnum* species was found in out of the 200 quadrats (frequency) in relation to mean % cover (abundance) is shown in Figure 1 below. There is little difference between the three most common species (*Sphagnum capillifolium* ssp. *rubellum*; *S. fallax*; *S. papillosum*) in cover and abundance. The abundance levels of the 3 most uncommon species are not meaningful as the samples are so small. The high cover of *S. russowii* relative to a small sample is probably explained by its growth form, tending to form large patches in suitable conditions.

Figure 1: Frequency of occurrence (no. of quadrats) and abundance (% cover) of different *Sphagnum* species in 200 quadrats across North Pennines blanket bog and wet heath
Bars = frequency Line = % cover
Abbreviations: ang = *Sphagnum angustifolium*; cap = *S. capillifolium* ssp *capillifolium*; rub = *S. capillifolium* ssp *rubellum*; cus = *S. cuspidatum*; fal = *S. fallax*; fim = *S. fimbriatum*; mag = *S. magellanicum*; pal = *S. palustre*; pap = *S. papillosum*; qui = *S. quinquefarium*; rus = *S. russowii*; sub = *S. subnitens*; ten = *S. tenellum*



4.1.1 The most widespread main peat-forming species are *Sphagnum capillifolium* subsp. *rubellum* and *Sphagnum papillosum*. It was anticipated that species such as *Sphagnum subnitens*, *S. tenellum* and *S. compactum* may be associated with blanket bog in dry or damaged condition in the North Pennines and so would be useful as negative indicator species. However, none of these species occurred frequently enough to be useful as indicators; *S. compactum* was not found at all.

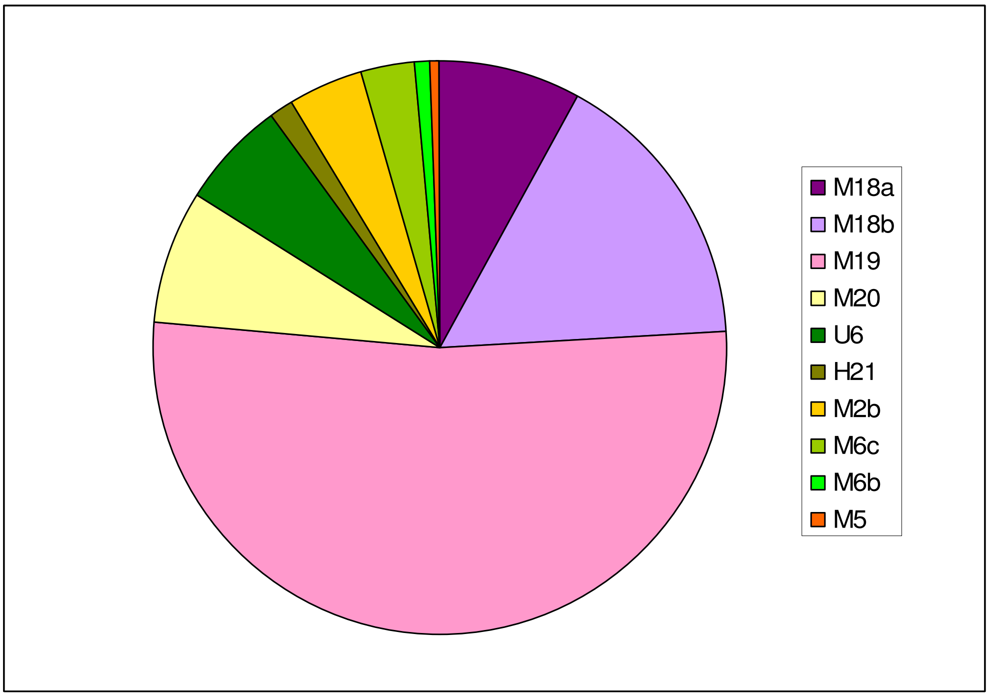
4.1.4 *Sphagnum fallax* was the second most frequently found species. This species is tolerant of a wide range of chemical, hydrological and ecological conditions. It is probably the species that is most tolerant of pollution and nutrient enrichment so it can remain frequent in damaged bogs when other species disappear. However, field observations during this study suggest that it is also common in bogs in good condition in the North Pennines.

4.1.5 *S. cuspidatum* was infrequently found largely because most of the North Pennines blanket bog is unsuitable for this pool species: pools tend to be restricted to level ground (not on gentle slopes typical of much of the North Pennines) and the climatic region is not conducive to bog pool formation (Lindsay 1995).

4.1.6 *S. russowii* would be a useful indicator species in the North Pennines because of its apparent abundance where present.

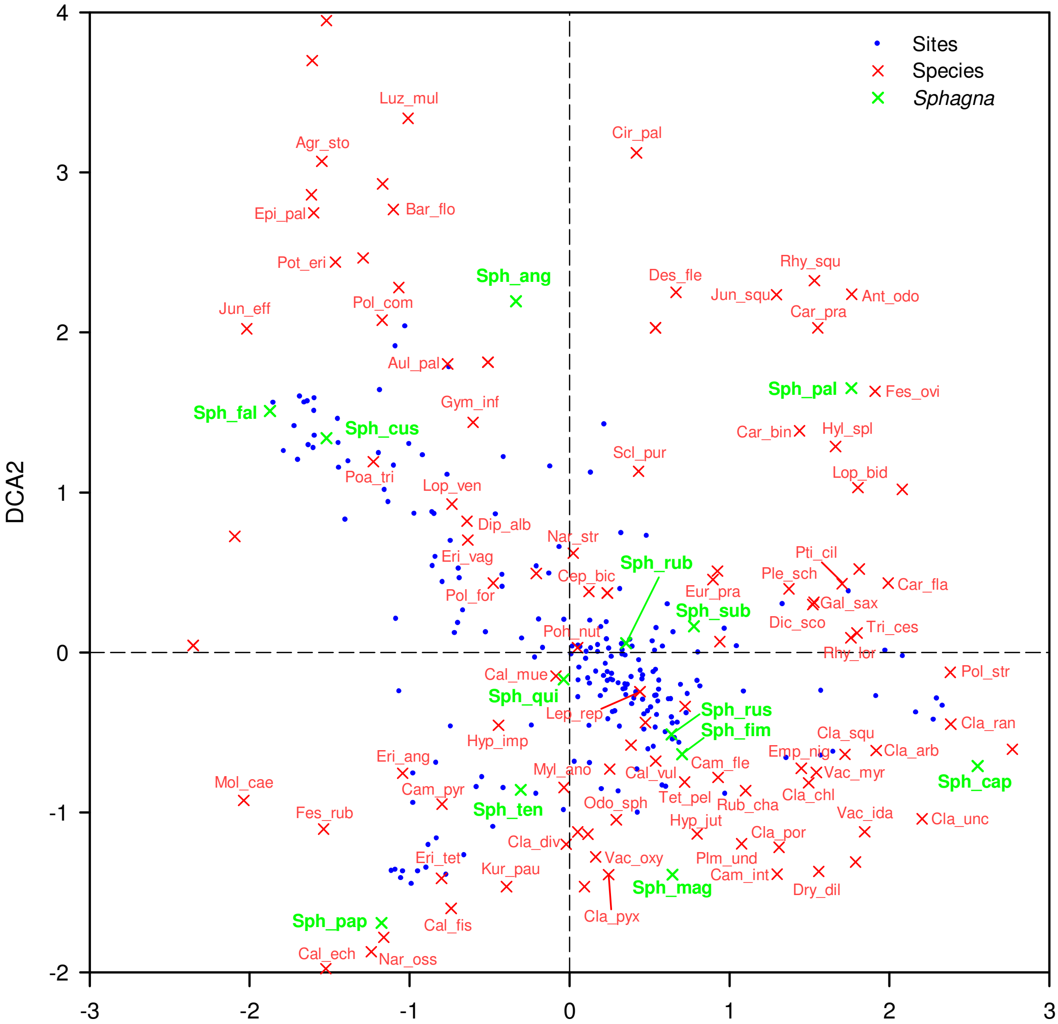
4.1.7 The most common NVC community was M19 *Calluna vulgaris – Eriophorum vaginatum* blanket mire. The proportion of NVC community types found during this study are shown in Figure 2 below.

Figure 2: Pie-chart showing proportion of different National Vegetation Classification (NVC) communities (Rodwell 1991; 1992) found in 200 quadrats across North Pennines blanket bog and wet heath The sub-communities are only shown where these represent distinctively different habitat (e.g. M18a is a high quality wet bog with high Sphagna cover; M18b is intermediate towards M19). M18 and M19 are types of blanket bog with moderate-high cover of Sphagna and M18 is usually of the highest conservation value; M20 is blanket bog dominated by hare's-tail cottongrass *Eriophorum vaginatum* with limited Sphagna; U6 is an upland acid grassland; H21 an upland wet heath with Sphagna; M2 is a bog pool dominated by certain Sphagna; M5 and M6 are flushes usually with some Sphagna present.



4.2 Vegetation & environmental variables

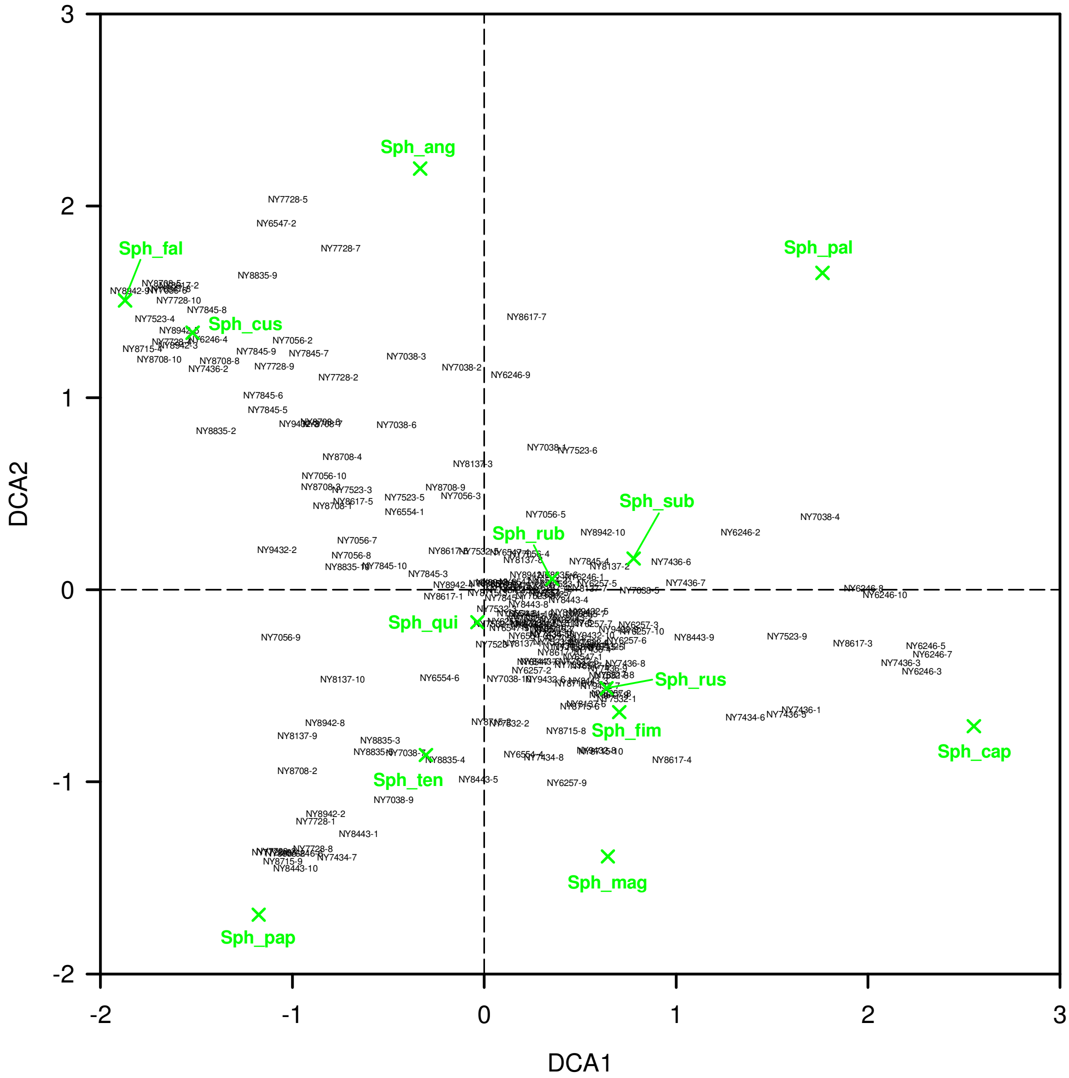
4.2.1 The *Sphagnum* species are distributed across the DCA plots (Graphs 1 and 2 below), suggesting varying environmental preferences. Four clusters may be distinguished corresponding to NVC community types M6 *Carex echinata – Sphagnum recurvum/auriculatum* mire, M18 *Erica tetralix – Sphagnum papillosum* mire, M19 *Calluna vulgaris – Eriophorum vaginatum* blanket mire, and a drier acid grassland group. The association of *Sphagnum* species with the NVC types and other plant species is generally in accordance with the published NVC communities, except for *Sphagnum palustre*, which is placed with acid grassland species. *S. fallax, S. cuspidatum* and *S. angustifolium* are closely associated, which reflects their similar ecological amplitudes for moisture (as hollow species) and tolerance of nutrients.



Graph 1: DCA of Peatscapes Dataset

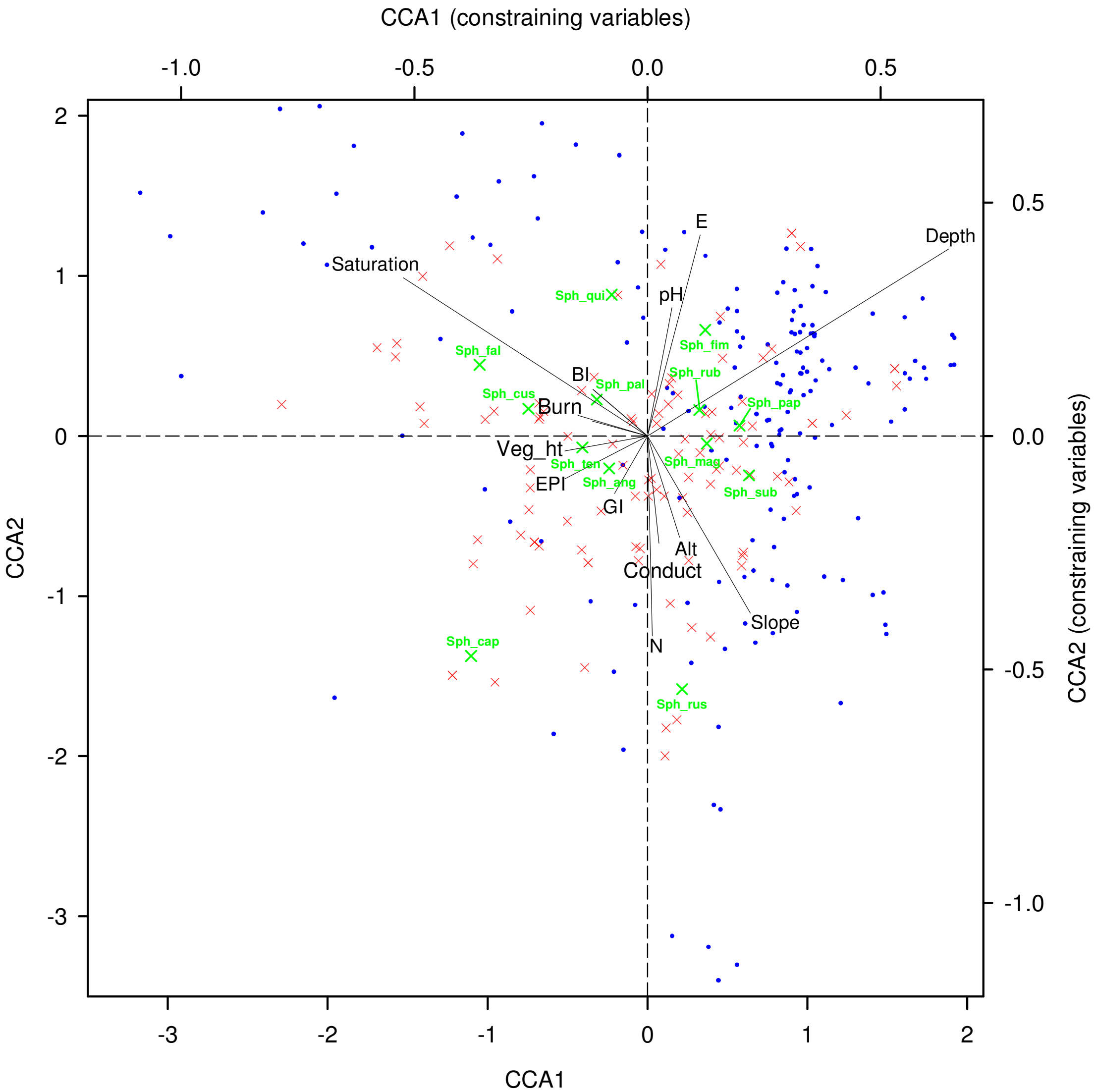
With the exception of *Sphagnum* spp., least common species (< 2 occurrences) not labelled

Plant species abbreviations used on the graph are given in Appendix 4



Graph 2: DCA of Peatscapes Dataset (sites and *Sphagna* only)
Plant species abbreviations used on the graph are given in Appendix 4

4.2.2 The full model CCA plot is presented as Graph 3 below. Twelve variables only accounted for 17% of the variance, which is weak, as strongly predictive results would usually exceed 25% with fewer variables (pers. comm. N. A. Cutler). This suggests that there are other variables which explain the vegetation composition and in particular the occurrence of *Sphagnum* species. Of the 12 variables included, only saturation and peat depth were important constraining variables, despite the data set having few saturated samples (n=37). The most parsimonious reduced model (Graph 4) used 6 variables to explain 9% of the variance. The environmental variables included in this study are clearly of limited value in accounting for vegetation composition.



Graph 3: CCA Analysis of Peatscapes Data (Full Model)

Notes:

Note difference in scaling between sites/ species and constraining variables

Constraining variables:

Alt = altitude
BI = distance to burn
Burn = time since last burn
Conduct = conductivity
Depth = peat depth
E = eastern aspect
EPI = distance to eroding peat index
GI = distance to grip index
N = northern aspect
S = southern aspect
Slope = slope angle
Veg_ht = vegetation height

Key:
- Sites
- Species
- *Sphagna*

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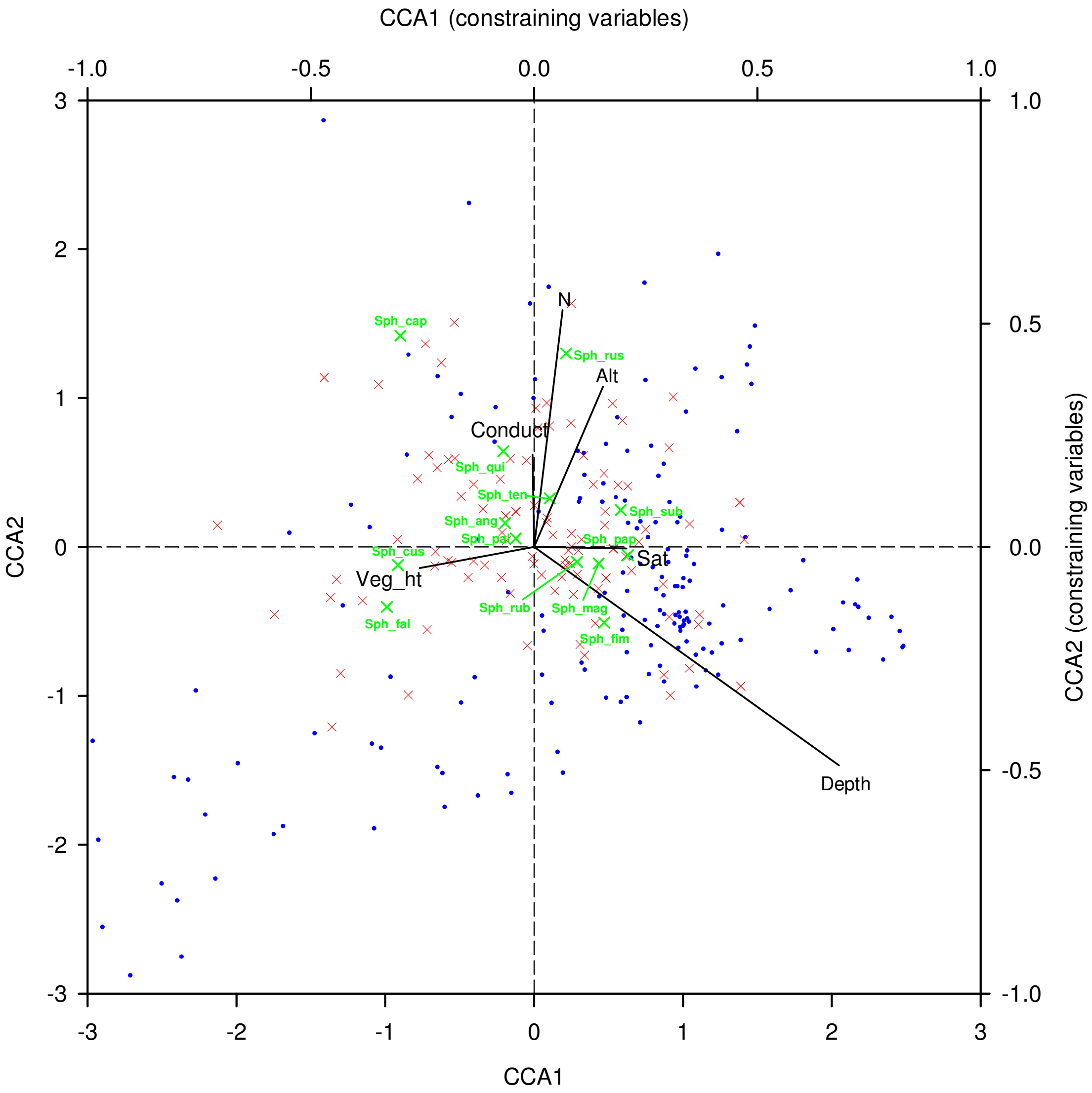


Graph 4: CCA Analysis of Peatscapes Data (Reduced Model)

Notes:

Note difference in scaling between sites/ species and constraining variables

Constraining variables:

Alt = altitude
Conduct = conductivity
Depth = peat depth
N = northern aspect
Sat = saturation
Veg_ht = vegetation height

Key:
Sites
Species
Sphagna

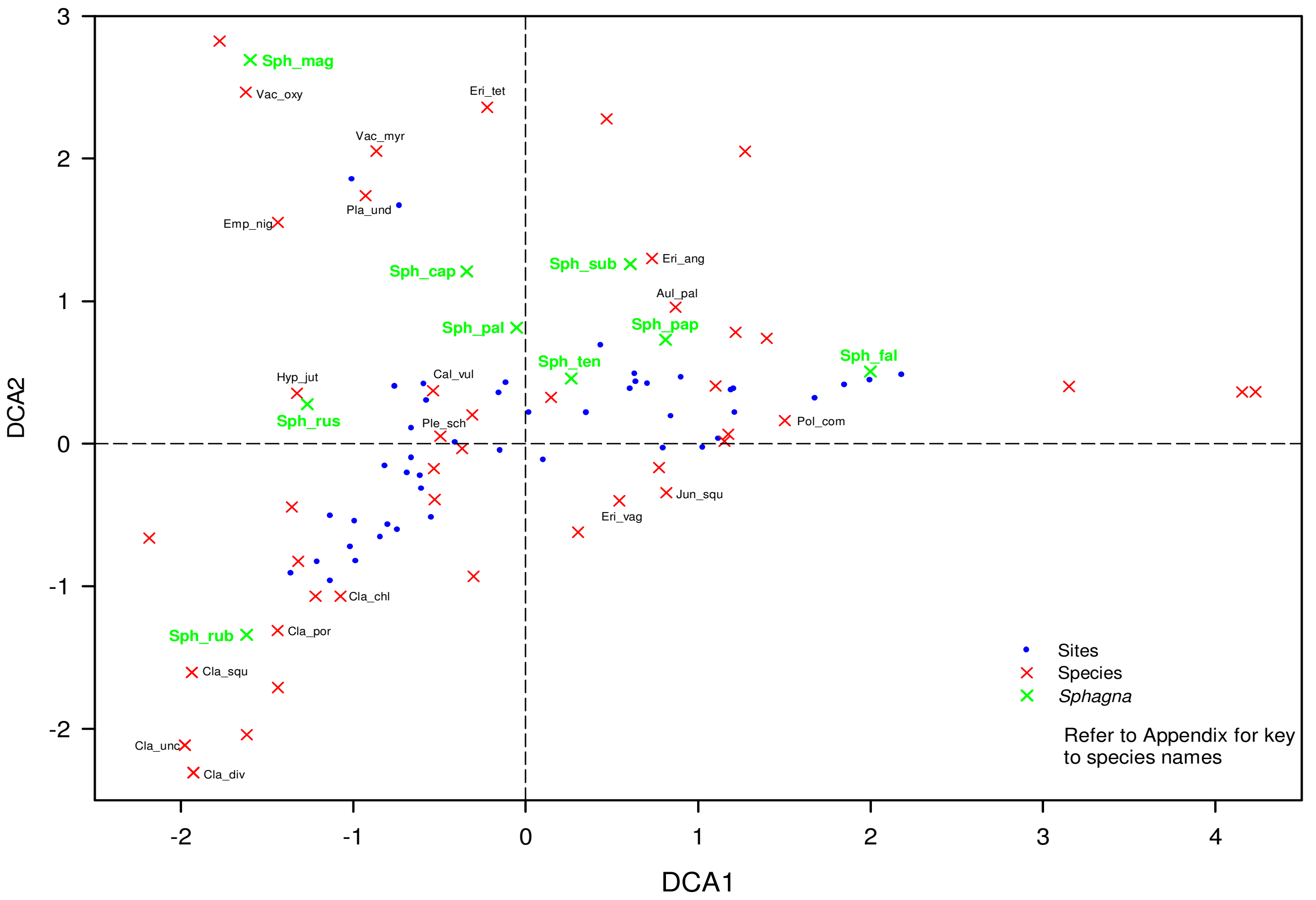
4.2.3 There was a significant relationship (P=0.02) between total plant species richness and vegetation height (species richness decreased as vegetation height increased) – and with altitude (P=0.03) (species richness increased with altitude). The vegetation height result was influenced by an outlier, and when this was removed, the significance of the result increased (P=0.007). There was also a significant relationship between peat depth and the Peat Building Index (PBI), but not between the PBI and any other variable.

4.2.4 *Sphagnum* species richness was significantly correlated with peat depth (tau = 0.2, z = 2.7, P = <0.001). This was the only significant relationship between *Sphagnum* species richness and the environmental factors measured.

4.2.5 Of the eight *Sphagnum* species analysed for relationships to the environmental variables, there were significant relationships with peat depth and saturation. Deeper peat was significantly (P=<0.001-0.05) correlated to all species except for *Sphagnum palustre*. The most significant relationships were for *S. papillosum* and *S. capillifolium* ssp. *capillifolium*. These two species may be contributing to more peat building than other *Sphagnum* in the North Pennines, as they are associated with sites on deeper peat, but the result cannot establish a causal link. *S. fallax* was highly correlated with saturated sites.

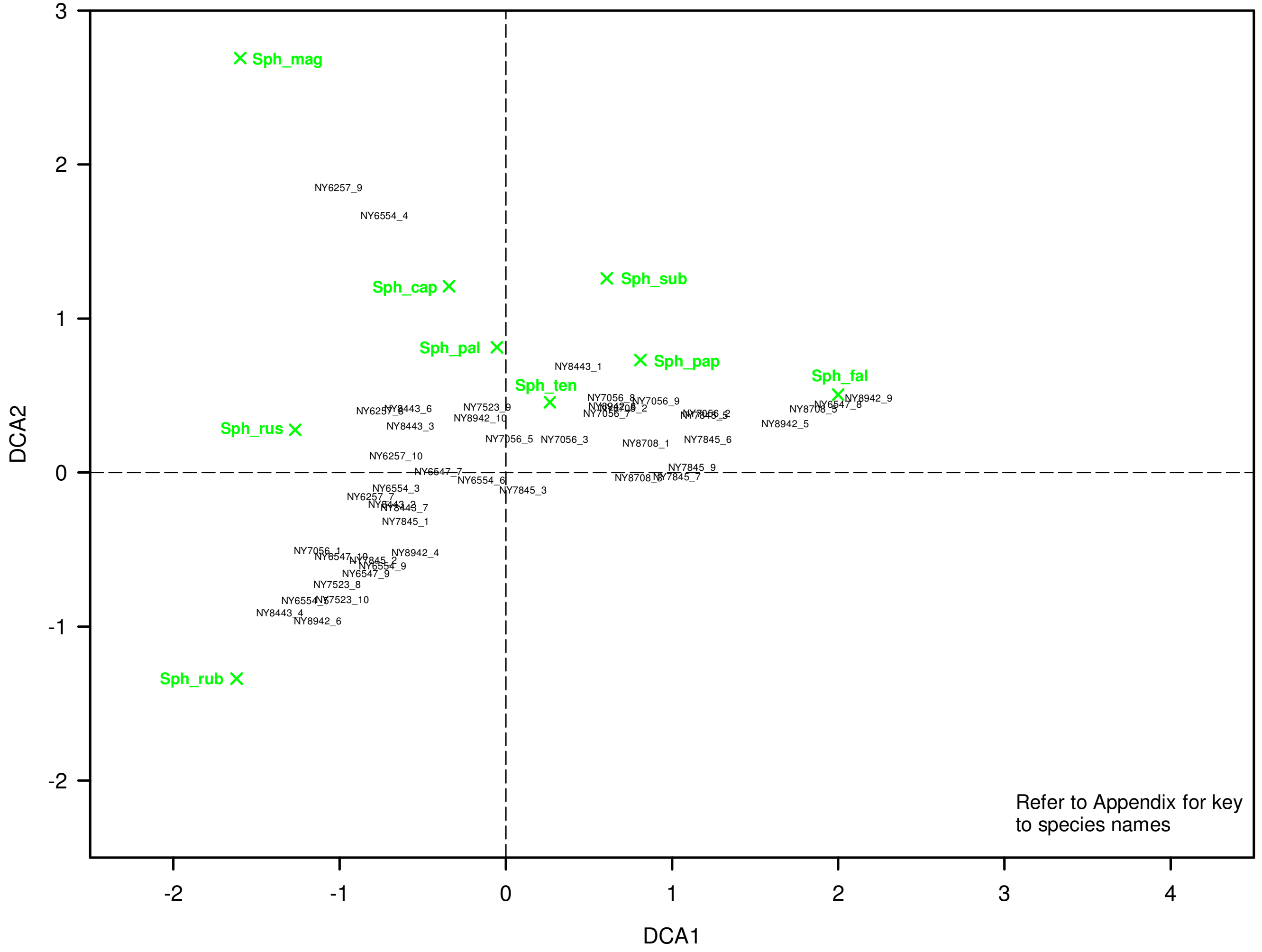
4.2.6 Graphs 1 and 2 below are the DCA graphs of the Data Subset with associated peat chemical data, which included 9 *Sphagnum* species. The first axis accounted for 17% of the variance.

4.2.7 Graph 3 is a full model CCA graph and Graph 4 a reduced 'intermediate' model, for the Data Subset. The full model with 13 environmental variables explained 36% of the variance, a marked improvement on the CCA of the Main Dataset. A graph of the CCA results suggests that the first axis is closely associated with moisture content and the second with pH/litter depth. The most parsimonious reduced model (not shown) reveals the explanatory power of peat moisture content, this single variable accounting for 6% of the variance. An 'intermediate' model (Graph 4) explained 16% of the variance. Inclusion of more environmental variables tended to complicate the model, without giving more explanatory power. Ammonium, a major nutrient form of nitrogen available to plants, did not account for much variation in the dataset.

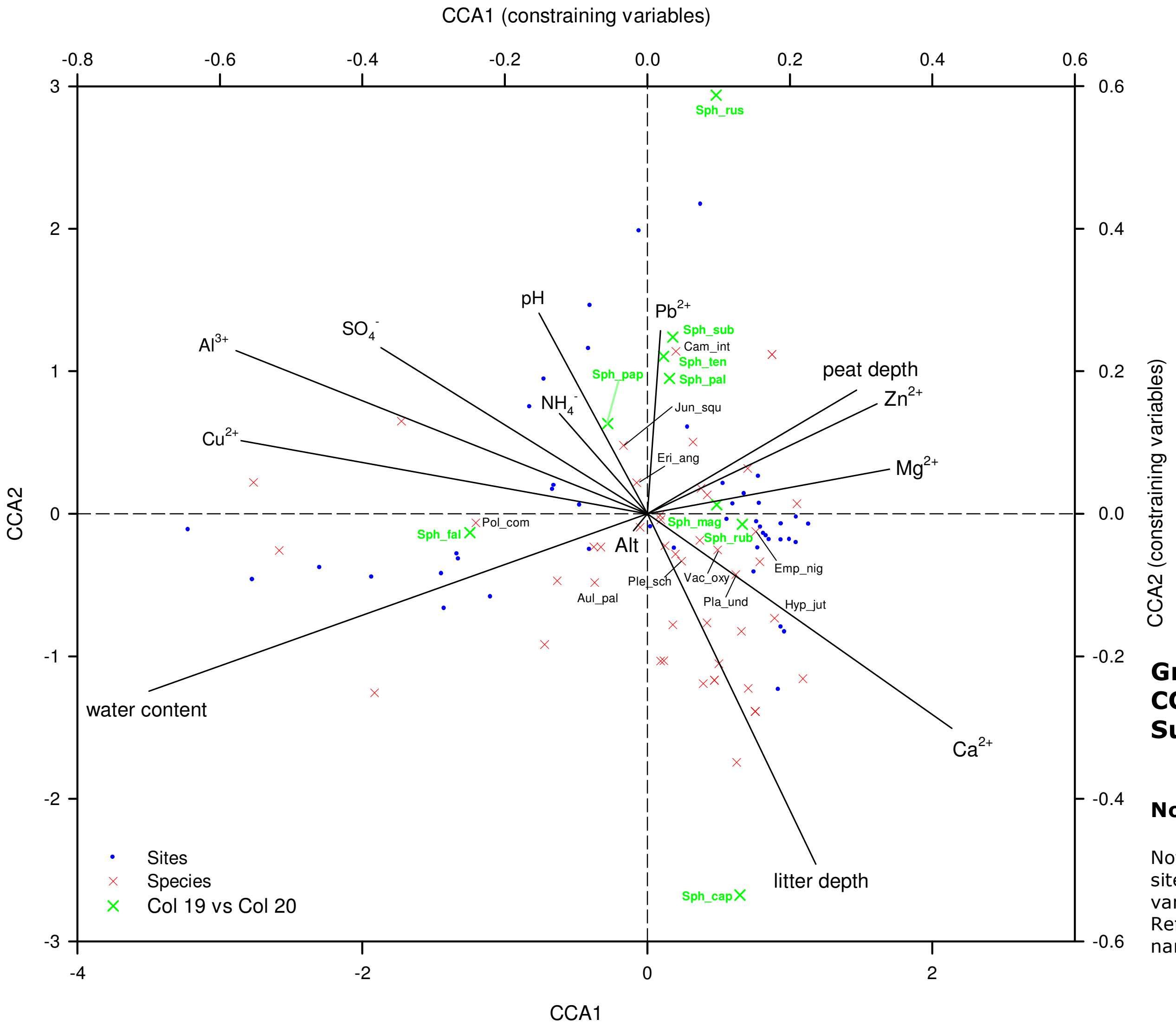


Graph 1: DCA of Peatscapes Subset

Sphagna, most common species (> 2 occurrences) and selected others referenced in text labelled



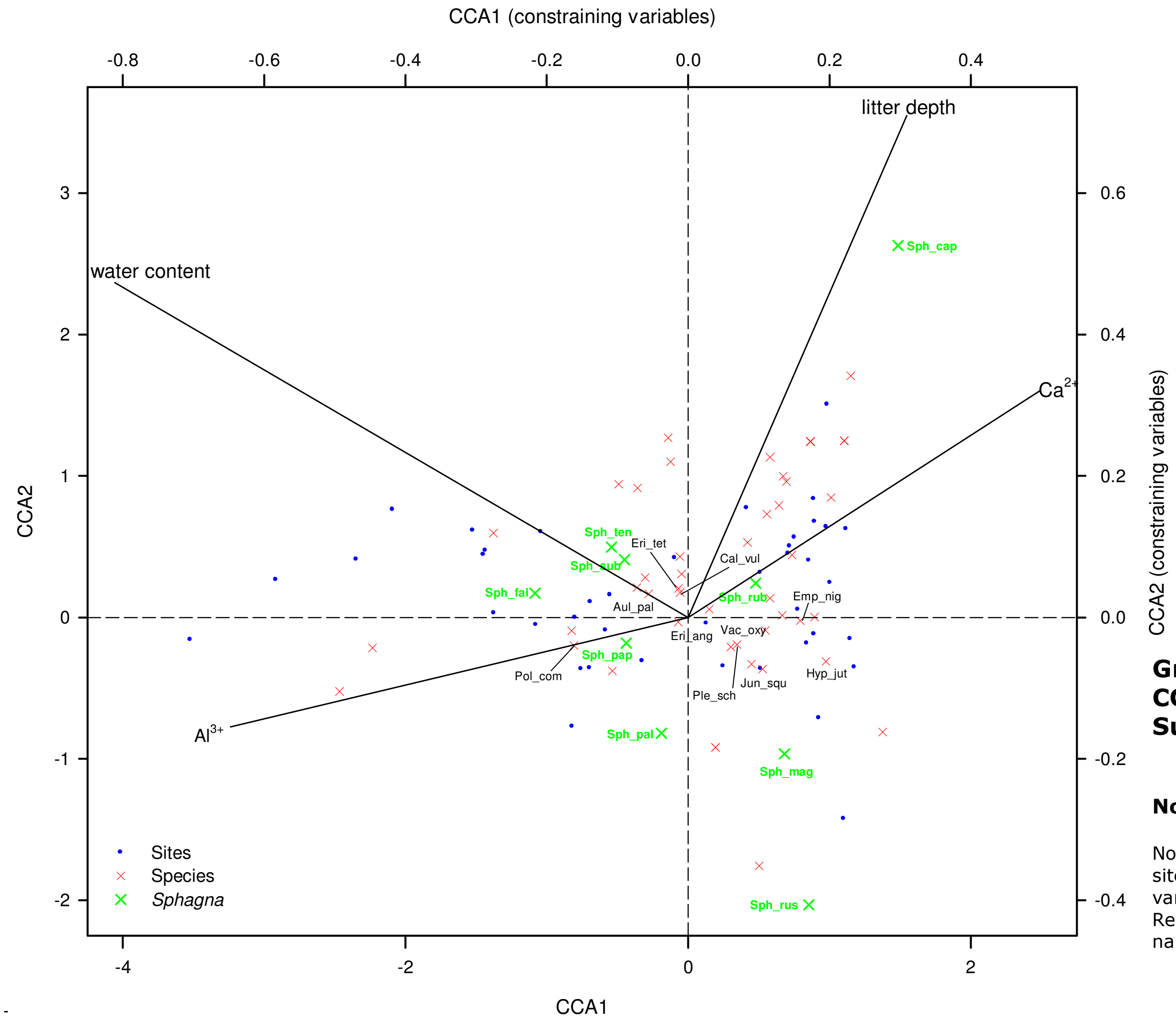
Graph 2: DCA of Peatscapes Subset (sites and *Sphagna* only)



Graph 3:
CCA Analysis of Peatscapes Subset (Full Model)

Notes:

Note difference in scaling between sites/species and constraining variables.
Refer to Appendix for key to species names.



Graph 4:
CCA Analysis of Peatscapes Subset (Reduced Model)

Notes:

Note difference in scaling between sites/species and constraining variables.
Refer to Appendix for key to species names.

4.2.8 *Sphagnum* species may be arranged along the gradients revealed by the CCA of the Data Subset (Graph 3) (see Table H below) although the results are of limited value because of the very small sample size for several species.

4.2.9 *Sphagnum russowii*, *S. subnitens*, *S. palustre* and *S. tenellum* were associated with elevated lead levels.

4.2.10 Plant species richness and diversity measures were analysed for each quadrat in the Data Subset against the environmental variables but produced no significant results.

Table H: arrangement of *Sphagnum* species along peat moisture levels and litter depth based on CCA of 41 quadrats from North Pennines blanket bog and wet heath

Peat moisture gradient	*Sphagnum* species	Litter depth gradient	*Sphagnum* species
Wettest	*S. fallax*	**Deepest**	*S. capillifolium ssp. capillifolium*
	S. capillifolium ssp. *capillifolium*		*S. capillifolium ssp. rubellum*
	S. papillosum		*S. magellanicum*
	S. magellanicum		*S. fallax*
	S. capillifolium ssp. *rubellum*		*S. palustre*
	S. palustre		*S. papillosum*
	S. tenellum		*S. tenellum*
	S. subnitens		*S. subnitens*
Driest	*S. russowii*	**Shallowest**	*S. russowii*

5 Discussion

5.1 Overview

5.1.1 This study did not identify any key relationships or links between the environmental factors measured and the occurrence of *Sphagnum* species. The unexplained variation in the dataset may be due to unmeasured environmental factors, such as climate, or it may be due to random effects. It was particularly surprising that there was no correlation between either certain *Sphagnum* species, or overall plant diversity levels, with nutrient levels.

5.1.2 The limited relationships shown in the data were:

- A significant correlation between vegetation height and overall plant diversity.
- A significant correlation between altitude and overall plant diversity.
- A significant correlation between peat depth and *Sphagnum* species diversity.
- A significant correlation between peat depth and seven *Sphagnum* species.

5.1.3 However, the data analyses did reveal some interesting patterns, even if the level of statistical confidence in the results is insufficient to draw any definite conclusions. These were:

- Patterns relating soil moisture content with litter depth, suggesting certain *Sphagnum* species are more tolerant of dry and low litter conditions, implicating management practices which cause drying and reduced litter levels, such as burning.
- An apparent association between certain *Sphagnum* species and lead concentrations.

5.1.4 The following *Sphagnum* species are useful and reliable indicators of management impacts in the North Pennines:

- *Sphagnum papillosum* as a positive indicator species; and
- *S. capillifolium* ssp. *rubellum* as a negative indicators species in certain circumstances.

5.1.5 The literature review combined with this study shows that there are a limited number of empirically tested *Sphagnum* indicator species suitable for use in the North Pennines. More work is required on certain key species and management impacts, which may reveal additional useful indicator species. Therefore constructing a novel management impact assessment tool is not possible based on information compiled so far. However, recommendations are made for further work. It seems likely that the standard condition assessment methodology, using walkover sampling, is insufficiently sensitive to detect responses in *Sphagnum* species to management impacts. A more targeted approach is required, similar to that used in empirical studies.

5.2 Plant diversity & environmental variables

5.2.1 As vegetation height increased, overall plant diversity decreased, which suggests that some form of light management such as light grazing is beneficial for plant diversity (a finding in accordance with several gazing studies in the literature - see section 3.7.4).

5.2.2 As altitude increased, from about 400m to over 700m, overall plant diversity increased, probably due to additional montane and submontane species adding to diversity on higher ground.

5.2.3 High levels of *Sphagnum* species diversity was associated with thicker peat deposits. This finding supports arguments for prioritising conservation of the deep peat deposits in the North Pennines.

5.2.4 Field observations during this study suggested that areas of disturbed peat may be associated with higher bryophyte (particularly leafy liverwort) diversity. However, the measures of disturbance used (distance to grip; % bare ground; and possibly vegetation height) were ineffective at capturing this apparent trend.

5.2.5 It was particularly surprising that there was no correlation between either *Sphagnum* diversity or overall plant diversity levels, with nutrient levels (tested generally by conductivity and more specifically by ammonium ($NH4^+$) levels), as this relationship is well established in the literature. It may be that the gradient in the $NH4^+$ concentrations was too narrow to display any difference between vegetation samples. It is interesting that the Moors for the Future Project also found that "*Sphagnum* cover and diversity were also very notably not strongly correlated with peat extractable NH4+" in both South Pennines and Bowland samples (Carroll *et al*. 2008:10).

5.3 *Sphagnum* species relationships to environmental variables

5.3.1 None of the environmental variables measured in the Main Dataset apparently strongly promote or limit *Sphagnum* occurrences. Saturation and peat depth were the most important factors. This finding accords with that of the Moor of the Future *Sphagnum* research project (Carroll *et al*. 2008) which also identified peat moisture levels as a likely key factor promoting more abundant *Sphagnum* growth in the North Pennines compared to the South Pennines.

5.3.2 However, the Data Subset showed some associations which may merit further investigation, particularly between:

- peat moisture content, and litter depth and the implications for management by burning; and
- certain *Sphagnum* species and lead concentrations.

5.3.3 The arrangement of *Sphagnum* species along peat moisture and litter depth gradients agree with moisture values in *Bryoatt* (Hill *et al*. 2007) and the literature review results, especially for the three species tolerating a combination of the driest conditions and the least depth of litter, *S. tenellum*, *S. subnitens* and *S. russowii*. Low litter levels may be explained by high grazing intensity and/or burning, and low litter cover in combination with drying suggests burning impacts.

5.3.4 The multivariate analyses suggest a potential relationship between four *Sphagnum* species and lead concentrations, especially *S. russowii*. The relationship may not be causal, and the samples for each of these species is small; therefore the interpretation of this result is limited. In the Moors for the Future project, the Northern Pennines sites had much higher lead levels than sites in Bowland or the South Pennines, with the highest values overall for all the survey sites found at Well Hopehead, Whimsey Cleugh and Northedge (126–153 mg kg-1). 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. It may be speculated that these elevated lead levels are linked with the North Pennines lead mining areas, which left a legacy of major environmental impacts (Simmons 2003). Lead levels may be a constraining factor on *Sphagnum* species occurrence (and therefore bog condition) in the North Pennines, which may merit further investigation, but is not considered a priority for further research.

5.4 *Sphagnum* as ecological indicators in the North Pennines

5.4.1 The literature review combined with this field study shows that *S. papillosum* is suitably widespread and therefore would be a useful **positive indicator** of bog condition in the North Pennines. This species was recorded much more frequently than was anticipated at the outset of this study.

5.4.2 Regarding potential **negative indicators**, *S. capillifolium* ssp. *rubellum* is both widespread in the North Pennines and a reliable indicator of drying where it increases at the expense of certain other *Sphagnum* species. This needs to be carefully applied on a site by site basis, as this species is also the most abundant peat-forming species of M19 blanket bog in good condition in the North Pennines; it is only an indicator when increasing and ousting *S. magellanicum* and *S. papillosum*, indicating a M18 bog drying out. However, if it increases at the expense of *S. fallax* and *S. cuspidatum*, it probably indicates that peat-forming bog is encroaching on a pool or flush, and so in this circumstance is not a negative indicator.

5.4.3 *S. fallax* was widespread but field observations in this study and the statistical analysis suggest it is not an indicator for elevated nutrient levels in the North Pennines. However, this potential relationship could be investigated further (see further work section 5.5 below). Vegetation dominated by *S. fallax* is a particularly good indicator of elevated phosphorus (P) inputs (see section 3.11.12), which suggests that agricultural inputs and/or burning in the North Pennines may be linked to the high frequency of this species throughout the sites sampled. None of the other potential negative indicator species revealed by the literature review (such as *S. tenellum* or *S. compactum*) are frequent enough to be useful in a survey tool assessing the condition of blanket bog in the North Pennines.

5.5 Further work

5.5.1 A priority for further research should be investigating the impacts of management burning and drainage grips on *Sphagnum* species. This research could incorporate the other key issues that this study highlights, namely:

- The hypothesis that *Sphagnum russowii* is an indicator of drying;
- The hypothesis that *S. fallax* is not an indicator of nutrient enrichment in the North Pennines; and
- Impacts of burning on all *Sphagnum* species, especially *S. papillosum*, because this species is probably the best positive indicator species for bog condition in the North Pennines, yet we do not know how management burns impact on its autecology.

5.5.2 This research would be best conducted using stratified transect sampling across grips and burnt and unburnt stands and use adequate replicates and controls. Environmental variables tested should preferably include peat moisture content and litter depth pre and post burns. The experimental design would need to be careful devised, to eliminate as far as possible climatic factors and other management impacts including grazing. The studies at Moor House NNR from the 1960s and 1970s into grazing and burning would inform the experiment design. Indeed, a preliminary step should be to contact Moor House to verify whether any *Sphagnum* species data exists from these experiments – as noted in the literature review, the published papers only refer to '*Sphagnum* sp.' in respect of burning impacts, but this does not necessarily mean that the species data was not collected.

5.5.3 Additional work, beyond the scope of this study, has already included a preliminary analysis of relationships between plant diversity, and bryophyte and lichen diversity, with a dataset of nitrogen (N) deposition levels across the North Pennines. Initial analyses show a significant correlation between increased N deposition and a decline in plant species diversity. Relationships with *Sphagnum* species will also be investigated. The North Pennines AONB Partnership's permission would be sought to publish any findings if further work supports these initial results. In the event of successful publication, the Peatscapes Project would be appropriately credited.

6 Recommendations

- The literature review highlighted how little we still know about bog conservation management, and *Sphagnum* autecology in particular. A priority for research should be investigating the impacts of management burning and drainage grips on *Sphagnum* species.

- As *S. papillosum* is probably the best positive indicator species for bog condition in the North Pennines, burning and grip impacts on this species could be tested.

- The hypothesis that *Sphagnum russowii* is an indicator of drying could be tested.

- The hypothesis that *S. fallax* is not a reliable indicator of nutrient enrichment in the North Pennines could be tested in relation to nutrient changes after burning.

- When conducting upland condition assessment in the North Pennines using the SNH methodology (SNH undated), the use of *Sphagnum fallax* as a negative indicator probably needs to be reconsidered.

- Devise a management impact assessment tool using *Sphagnum* as indicators based around assessing direct impacts over time, rather than the walkover sampling approach (as used in condition assessment methodologies).

7 Outcomes

This study produced the following additional outcomes:

- An accurate assessment of the *Sphagnum* resource of the North Pennines, the fundamental plant resource driving the bog ecosystem.

- Generating 2343 plant records, including 1361 bryophyte records, with 3 new bryophyte vice county records and 4 nationally scarce bryophyte species. It would not have been feasible for these records to have been collected by volunteers as there are only 1 or 2 active amateur bryologists in North-east England.

- Collaboration and support to key peatlands projects elsewhere, especially the Moors for the Future Project in the South Pennines.

- Important evidence to support granting funding of future nitrogen (N) deposition research at the Open University.

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Appendices (on CD-rom)

Appendix 1: Survey form

Appendix 2: Raw quadrat and environmental data spreadsheets

Appendix 3: Full records of notable bryophytes, including three new vice county records

Appendix 4: Reports on Statistical Analyses

Appendix 5: Photographs