RELATIONSHIPS BETWEEN HYDROLOGY, HYDROCHEMISTRY AND VEGETATION PATTERNING ON SCOTTISH FENS.

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ABSTRACT

Fens are increasingly recognised as important habitats in terms of biodiversity, and this has been formalised in recent legislation (EC Habitats Directive, 92/43/EEC). The influence of groundwater and surface water inputs on the fen habitat increases its vulnerability to water pollution, particularly from nutrients. Despite the conservation importance and potential vulnerability of the habitat, fens have not been widely studied in Scotland, in terms of extent, location, sensitivity to increased nutrient inputs, or in comparison to similar European sites.

This study found that fens were widespread throughout mainland Scotland, and that basin fens were the most commonly occurring fen type; representing 43 % of the 355 sites assessed. A survey of 18 basin fens found that 72 % were potentially vulnerable to elevated nutrient inputs, being surrounded by improved/modified land. Despite this, only four sites showed greater nutrient concentrations in sub-surface water samples or water inputs. There was, however, a significant amount of variation in hydrochemistry between the sites.

Detailed studies further assessed spatial and temporal variations in hydrochemistry, and associated hydrologic regimes, on two similar basin fens; one in an agricultural catchment, the other surrounded by unimproved grassland. Spatial patterning of vegetation was associated with both base-richness and nutrient concentrations of subsurface water, and the frequency of water inundation. General relationships between the six fen vegetation types and the observed hydrological and hydrochemical variation were presented.

DECLARATION

The contents of this thesis are original and all the work was carried out by the author - the results presented herein are not taken from any other thesis by the author.

Sarah Y. Ross

CHAPTER 1

General Introduction

1.1 Mires, fens and bogs

Mire and peatland are terms that are often used interchangeably, and include both fens and bogs. The term *mire* has been used in a number of ways to indicate a predominantly peat-forming wetland (Ratcliffe 1964, Moore 1987, Gore 1983, Wheeler 1980a), while *peatlands* are by definition areas that have a peat soil, but are not necessarily actively forming peat (Immirzi *et al.* 1992). Peatlands can, therefore, include areas such as drained agricultural peat soils that are no longer peat-forming wetlands.

Fens and bogs are traditionally separated on the basis of their hydrological inputs (Sjors 1950, Wheeler 1995). Bogs receive their water and nutrient input wholly from precipitation, to include rain, snow, mist and dry deposition. Fens receive water and nutrients from groundwater and surface water inputs in addition to precipitation. Fens can, therefore, be defined as all those waterlogged potentially peat-forming habitats that are "largely dependent on water provided by the mineral catchment" (Fojt 1991), which is supplemented by precipitation.

The characteristic waterlogged, peat-forming substrate makes fens, and mires in general, important and unique habitats. Peat is formed where dead plant material is only partly decomposed. This leads to a substrate with a high amount of organic material. *Sphagnum* peat can contain less than 1 % inorganic material, although most peat can contain up to 20 % inorganic matter (Clymo 1983). The low rates of decomposition have been attributed to low soil temperatures, low soil pH, microbial and/or plant toxins, and the characteristics of the litter (Dickinson 1983). Generally, however, waterlogging is considered to be a main factor in limiting decomposition. On waterlogging the peat pore spaces fill with water, limiting oxygen diffusion. Aerobic microbial activity responsible for organic matter decomposition is reduced, while the number of anaerobic micro-organisms increases, and chemical processes within the fen alter.

The resulting waterlogged conditions affect the nutrient transformations that occur within the peat substrate, particularly for nitrogen and phosphorus. Nitrogen can be lost from waterlogged peat by *denitrification*, an anaerobic microbial process which transforms nitrate to nitrous oxide or dinitrogen gases (Ponnamperuma 1972). In the more aerobic surface layers of peat ammonium may be converted to nitrate through the oxic microbial process of *nitrification*. Nitrate may then be either rapidly taken up by plants, or diffuse down to the anaerobic layers where it can undergo denitrification (Gambrel & Patrick 1978).

In addition to biological transformations, waterlogging can affect physiochemical processes in peat. For example, waterlogging promotes the release of orthophosphate through the reduction of iron and aluminium phosphates (Patrick & Khalid 1974, Ponnamperuma 1972). In addition, ammonium can be leached due to displacement by iron (Fe^{2+}) and manganese (Mn^{2+}) ions on the peat colloid.

The predominant anaerobic conditions that lead to peat formation generally also reduce nutrient cycling within the fen system. The major plant nutrients, nitrogen and phosphorus, are therefore naturally limiting in fens (Verhoeven *et al.* 1990), and the vegetation that develops there is characteristic of these nutrient-poor conditions. As such the plants develop mechanisms peculiar to these nutrient-poor conditions, such as retranslocating nutrients into storage organs over the winter (Aerts 1993), supplementing nutrient uptake by trapping and digesting insects (Crowder *et al.* 1990), oxygenating the rhizosphere (Armstrong *et al.* 1994), or producing enzymes to break down organic phosphorus (Press & Lee 1983, Kroehler & Linkins 1988, Helal 1990).

Along with the problems of nutrient acquisition, plants also must tolerate the hypoxic and anoxic conditions in the peat. The lack of oxygen in the peat requires plants to either provide an alternative source of oxygen to the roots for metabolism, or to modify their metabolism to suit the low oxygen conditions. Well developed aerenchyma in many mire plants allow a supply of oxygen to the roots (Justin & Armstrong 1987), while metabolic adaptations to anoxia are reported (Braendle & Crawford 1987). The anoxic conditions can also lead to accumulation of toxins in the peat, such as iron and manganese compounds and hydrogen sulphide, the by-products of anaerobic microbial activity (Gambrel & Patrick 1978, Ponnamperuma 1984). A supply of oxygen to plant roots via aerenchyma enables oxygen diffusion across the root surface to the immediate surroundings, leading to a thin aerobic layer around the root system which prevents the production of these toxins (Armstrong *et al.* 1994).

The problems faced by plants in anoxic or fluctuating oxic/anoxic conditions has led to the development of some specific assemblages of species and vegetation types on fens and bogs. Mechanisms for such plant adaptations to such environmental stress have been discussed in terms of the 'ecological strategies'' of plant species, with species classified as having 'competitor', 'stress-tolerator'' or 'ruderal' life-cycle strategies (Grime 1979a,b). Many plant species typical of low productivity fens are classified as stress-tolerators and survive under slightly sub-optimal conditions that restrict the invasion of more vigorous competitive species.

1.2 Fen description and classification

The need to describe fen systems and group them together on the basis of their similarities is necessary, for example, to produce a common language to enable communication of results, to divide an essentially continuous, complex habitat type into simpler compartments, and to aid in developing and implementing protective legislation. To achieve satisfactory classifications and definitions the fundamental characteristics of the fen habitat type need to be identified. One of the main characteristic features of fens is the hydrologic regime, which covers many aspects such as water source, water nutrient content, frequency and depth of flooding and water flow. Other features such as topography and vegetation are also important and widely used in characterizing fen systems.

The topographical position of a fen is fundamental to the hydrology and peat formation processes in the fen, which, in turn, relate to nutrient processes and vegetation development. Classification in terms of topographical type are, therefore, widespread. The main topographical fen types identified are *valley-bottom/floodplain* fen, *valleyhead* fen, *basin* fen, *open water transition* fen, and *hillslope* fen. These terms provide a broad framework over which differences in vegetation and hydrology can be placed. Brief definitions (after Fojt 1989 and Wheeler 1995) are as follows:

- *valley bottom floodplain fen* - occurring on low altitude flat land in valley bottoms or on river floodplains. Not associated with depressions or lake basins that can also occur in these situations.

- *valleyhead fen* - small, often soligenous fens associated with the upper areas of valleys.

- *basin fens* - associated with discrete depressions or deep basins that are infilling with peat, and have less than 50 % cover of open water (if any).

- *open water transition fens* - associated specifically with lake basins where the open water covers 50 % or more of the basin area.

- *hillslope fen* - areas of spring or flush fens on sloping ground or hill sides, often within predominantly ombrotrophic blanket mire.

Fens are also classified on the basis of their major water source. One widely used classification distinguishes between *ombrotrophic* inputs (precipitation) and *rheotrophic* inputs (both surface and groundwater) (Moore 1986, 1987). *Minerotrophic*, meaning predominantly mineral groundwater fed, is often used in a similar way to rheotrophic (Sjors 1950, Tansley 1939). Gilvear & McInnes (1994) use all three terms to classify Scottish fens and bogs. Here rheotrophic distinguishes surface water flow (and not in the wider context of Moore 1987), while minerotrophic indicates a dominance of groundwater input. In addition, Gilvear and McInnes (1994) use *omnitrophic* to describe those mires that have no single dominant water input. All fens have water inputs from these various sources, but the primary water source will characterize the fen type.

Although fen systems are typically nutrient-poor habitats they have been divided on the basis of the relative nutrient status of their water. Nutrient-poor waters are termed *oligotrophic* and relate mainly to precipitation inputs. Those rich in solutes are termed *eutrophic*, which can be the result of natural mineral inputs or, increasingly, from artificial inputs such as agricultural fertilizer run off. Those waters neither exceptionally poor or rich in solutes are termed *mesotrophic* (Ross 1995). Similar definitions are used by Van Wirdum (1981) in the lithotrophic - atmotrophic - thalassotrophic (LAT) model of water types. These types are linked to groundwater (*lithotrophic*), precipitation (*atmotrophic*) and seawater and/or polluted water (*thalassotrophic*) inputs respectively, so are similar to mesotrophic, oligotrophic and eutrophic water types. These definitions are also related to the rich fen - poor fen - bog gradients common throughout the literature (*e.g.* Sjors 1950).

Water flow through a fen system is also important in fen characterization, and can be described in two main ways; *topogenous* or *soligenous*. Topogenous is generally associated with fens that retain a high water table due to the topography. Gore (1983) clarifies the term to indicate fens with a slow percolation of water, as opposed to soligenous fens with faster flowing water. Wheeler (1993) suggests soligenous should relate only to hillslope fens with faster lateral water movement more akin to springs. These tend to be different in their topography, hydrology and vegetation in comparison to topogenous basin, floodplain and open water transition fens.

Classifications are widely based on the vegetation, and there are several approaches to fen vegetation classification. One approach is the European phytosociological school (Sjors 1950, Diersson 1982, Diersson & Diersson 1985, Steiner 1997). This describes vegetation floristics and physiognomy, and distinguishes vegetation types on the basis of floristic composition. Rybnicek (1985) reviews this system in Europe from the early 1900s. The phytosociological classification system has not been widely used in British ecological studies of mires, although a similar approach was taken to describe the base-rich fen flora of England and Wales (Wheeler 1980a,b,c), and on the classification of fen vegetation in Scotland (McVean & Ratcliffe 1962, Ratcliffe 1964, Spence 1964, Charman 1993, Tratt 1997). A British phytosociological classification of fen types is embodied in the National Vegetation Classification, which gives a total of 66 mire vegetation groups, not including sub-communities and variants (Rodwell 1991, 1995). This is widely used across Britain, and cross-references to associated vegetation types such as the European phytosociological classes, although some problems with the classification have been highlighted, particularly with regard to fens (Tratt 1997).

Single plant species have also been the focus for fen classifications. Sjors (1950) discusses the use of terms such as *exclusive fen plants, facultative bog plants* (those found in both bogs and poor fens), and *exclusive bog plants*. This division is based on field observation related to environmental gradients between rich fen, poor fen and bog habitats. Other more pragmatic classification systems have also been developed around plant species in response to the need for assessing fens in terms of 'habitat condition' and 'nature conservation interest'. For example, Wheeler (1988, 1993) and Wheeler & Shaw (1991) use *'species density'*, *'principle fen species'* and *'rare fen species'* to classify fen vegetation types in relation to their nature conservation value. Species density is used as a measure of the *diversity* of a fen site, on the assumption that more diverse species compositions indicate a fen of greater conservation value with regard to biodiversity. In addition, principle and rare fen species highlight potential nature conservation interest according to species composition (Tratt 1997). The use of indicator species does have limitations. For example, in his review of work published on the peatland species autecology, Gignac (1994) found that species could tolerate a wide range of environmental conditions, and so need to be used with caution as predictors of environment.

Fens, as with any other natural or semi-natural system, are found in a wide variety of situations. They therefore develop a continuum of types along environmental gradients. Classification systems have been developed to describe this variation, but any classification system will have problems incorporating transitional fen types that develop between the major distinguishable groups. This problem is compounded if the data on which the classification is based does not cover the spectrum of diversity found. In addition, human impacts (*e.g.* drainage, peat cutting, mowing) will influence fen development. This natural variation is confounded by a profusion of descriptive terms used in the literature. Many of these terms appear similar but actually describe very different aspects of the fen ecosystem, *e.g.* rich- and poor-fen can relate to species number or to water nutrient concentrations. Definitions also tend to fail to link together the whole fen ecosystem functioning. This is partly a problem of scale, and also related to the problems in achieving an interdisciplinary approach. These links are being developed through the increasing number of ecohydrological studies of fens incorporating hydrology, peat and water chemistry and vegetation dynamics.

1.3 Fen distribution in Britain

The climate of Britain is highly suitable for the development of peatlands, being cool-temperate with oceanic influences (Taylor 1983). High precipitation rates in the uplands lead to large areas of predominantly ombrotrophic peatlands (blanket bogs), while flat lowland areas with poor drainage and numerous post-glacial hollows and basins have enabled peat formation, typically lowland raised bogs and fens, at lower altitudes. Peatlands cover approximately 6 % of the earth's land surface (Mitsch & Gosselink 1993), and peatlands in Britain account for around 0.4 % of this global total (Immirzi *et al.* 1992). Lindsay (1995) estimates the areas of peatland types, including fens, for England, Scotland and Wales (Table 1.1). Estimates of fen areas in Northern Ireland amount to 4298 ha, but only include sites of European conservation importance (Foss & O'Connell 1996), potentially omitting a far larger area.

Table 1.1 Estimated areas (hectares) of peat soils > 1 m depth in Great Britain.

* indicates incomplete data. Modified from Lindsay (1995).

Country	**Fen**	**Raised Bog**	**Blanket Bog**	**Intermediate Bog**
England	131642	37413	214138	981
Scotland	*1215	27892	1056198	10653
Wales	*2867	4086	158770	85
Total Area	**135724**	**69391**	**1429106**	**11719**

There is often a misconception in Britain that fens are 'The Fens' of East Anglia, including the Norfolk Broads. Although these are probably the largest, and undoubtedly the most well known fens in Britain, fen distribution in Britain is by no means restricted to this region alone. In England individual fen systems such as the Cheshire basin fens (Green & Pearson 1968, Tallis 1972), Blelham Bog and Tarn, Cumbria (Oldfield 1970), Malham Tarn, West Yorkshire (Proctor 1974) and the Broadlands, Norfolk (Wheeler 1978) have been well documented. There have been fewer studies in Wales (the Anglesey fens, Gilman 1994) and Scotland (Gilvear *et al.* 1993, Tratt 1997). These studies have considered specific sites in detail, but with few attempts to put sites in a UK or European context. However, Wheeler and Shaw (1987) and Shaw and Wheeler (1990, 1991) assess the ecological characteristics of a large number of fen sites throughout Great Britain. These studies, along with the work of Tratt (1997) on the fens in the Scottish Borders, show the potential variety and geographical spread of small often isolated fen habitats, particularly in Scotland.

1.4 Fen condition, protection and legislation

1.4.1 Human impacts on fens

Fens are, therefore, found throughout Britain, but are declining in lowland areas through increasingly intensive land use practices (Fojt 1995). The development of more intensive agricultural practices, especially after the First World War, has encouraged the destruction and degradation of many habitats, including fens. An increased use of inorganic fertilizers and lime to increase land productivity has resulted in the seepage of phosphates and nitrates into natural water sources (Burt & Haycock 1993, Heathwaite 1995a,b), which leads to eutrophication. Changes in the catchment can also alter fen nutrient status through, for example, afforestation of primarily unforested catchments (Schot & Van Der Wal 1992). These changes can increase the inputs of major nutrient ions, either through inorganic/organic fertilizer application or by increased mineralisation due to drainage and oxidation (Hill 1976, Klotzli 1987, Burt *et al.* 1990, Howard-Williams & Downes 1993).

Hydrological disturbances in the fen catchment can also have a deleterious impact on the fen. The fen hydrological catchment can be defined as consisting of two main areas, the surface water catchment (adjacent hill slopes and to a greater or lesser extent more distant slopes), and the ground water catchment (shallow and deep aquifers) (Fojt 1991). For example, drainage or abstraction can have dramatic effects such as modifying a fen from a groundwater discharge area to a groundwater recharge area (Boeye & Verheyen 1992). These may affect the fen system in various ways, through changes in the plant species composition or species richness, increases in primary productivity, increases in organic export, and changes in nutrient cycling (Hughes 1992).

Fens appear to be particularly at risk from eutrophication as they are often isolated areas within an agricultural landscape, and they form natural collection points for water from the surrounding catchment. Fens are considered nutrient poor systems, as most of the nutrients are retained within the peat, and available nutrients are tightly cycled within the system (Wassen 1990, Koerselman & Verhoeven 1992). Eutrophic water entering a fen can, therefore, increase the nutrient status and has the potential to alter the character of the fen vegetation and associated fauna (Koerselman & Verhoeven 1995). This type of disturbance is more insidious than the immediate impact of peat cutting or drainage of past decades because it is often difficult to detect in the early stages, and the time lag between the onset of increased nutrient status and changes in the vegetation. Such impacts have been noted in areas of southern Britain such as the Norfolk Broads (Wheeler 1978) and the Somerset Levels (Willis 1967), along with fens on Anglesey, North Wales (Gilman 1994). There is little published work for Scotland or Northern Ireland.

The plant and vegetation response to nutrient changes are not immediate, and there is some time between changes in the chemistry of a site and these changes being reflected in the vegetation of the site (Fojt 1991). There is remarkably little quantitative published information on this time lag. Similarly, there is little quantitative information on the tolerance of fens to increased nutrients before irreversible changes occur. On this basis the chemical analysis of water should provide a better indicator of the potential for enrichment than the monitoring of vegetation alone, allowing conservation measures to be taken before species are lost or the characteristics of the site irreparably altered. Although Proctor (1992) suggests that the distribution of mire plant species and vegetation types has little to do with the direct influence of major ions in solution on ombrotrophic peatlands, but may relate to other factors such as topography and climate. A similar situation may apply to fen species distribution, and base ion concentration along with water level may be more important for species distribution (Walbridge 1994, Boeye & Verheyen 1994) rather than the major nutrients. Base-poor fens in Britain do show a positive linear correlation between species density and base ion concentration (especially in relation to calcium concentrations), and to a lesser degree water level and reduction-oxidation (redox) potential (Shaw & Wheeler 1990).

The impact of human activities on fens and their catchments is not only an issue of recent decades. Humans have long had an intimate relationship with mires, and fens in particular. As early as 2,000 BC evidence for human impacts such as drainage, agriculture, and harvesting (*e.g.* reeds) are found in parts of Europe, with some land use such as fishing dating back to 4,000 BC (Coles 1995, Ingram 1997). Later centuries saw the increasing modification of fenlands through drainage, peat cutting for fuel, marl extraction, hunting and agriculture (Smout 1997). Many of these activities were on a local scale, while others, such as the draining of the Norfolk Broads and the Humberhead Levels in England (Eversham *et al.* 1994), were large scale concerns. These past activities have left their mark not only through the visible drainage patterns, but also by modifying natural vegetation development processes and influencing current vegetation types (Smart *et al.* 1986, 1989, Meade 1992, Tratt 1997). It is obvious, therefore, that humans have been, and continue to be, significant in the development and functioning of fens.

Today, fens, and mires in general, are appreciated for their role in ecosystem functioning. For example, they are important for flood mitigation and sediment trapping (Williams 1990). Peat soils are also effective at trapping pollutants, and this has been utilised through waste water treatment wetlands and reducing pollutants in water courses (Sloey *et al.* 1978, Nichols 1983, Vanek 1992). They may also influence global climate by acting as sources of methane and sinks for carbon dioxide (Lowrance *et al.* 1985), two important greenhouse gases (Gorham 1991). Fens also hold important information on the environmental change through the peat archive (Whitehouse *et al.* 1997, Charman 1997). This record can help reconstruct palaeolandscapes and chart some of the effects of changes in climate and land use (*e.g.* Eversham *et al.* 1994, Tratt 1997).

1.4.2 Fen protection and legislation

Fens have a high conservation value by supporting rare species (Wheeler 1988, 1993). British fens contain a diverse range of species, including some that are common only to that habitat type. A total of 653 plant species have been recorded from British fens, whilst bogs (with only 193 species) are by contrast relatively species poor (Wheeler 1993). They also provide habitats for many animal species including frogs, toads, newts, shrews, birds, and numerous invertebrates (Haslam 1973). Many of these plant and animal species are rare at a national, regional or local level, and are afforded protection through British legislation. The statutory protection afforded to fens of particular 'nature conservation interest' within Britain comes in the form of Sites of Special Scientific Interest, Local Nature Reserves and National Nature Reserves (Ward *et al.* 1997). This protection is awarded under the 1981 Wildlife and Countryside Act. Each of these give various levels of protection from impacts that may affect the nature conservation interest of the site.

The European Union recognizes the importance of fens in relation to species protection and biodiversity. This is formalised in its legislation (European) Council Directive on the Conservation of Natural and Semi-natural Habitats and of Wild Flora and Fauna (92/43/EEC), which developed from the Convention on the Conservation of European Wildlife and Natural Habitats (the Bern Convention). This provides direction on those habitats of priority for conservation, and enables the designation of Special Areas of Conservation. The legislation is generally referred to as the 'Habitats Directive'. A number of fen types are included in this, along with raised and blanket bogs, all of which occur within the UK (Raeymakers 1997).

1.5 Rationale

1.5.1 Aims of the project

The distribution of fens in Scotland is not well studied, although the potential wide distribution and variation in habitat conditions may be inferred from the studies that are available (Spence 1964, Shaw & Wheeler 1991, Charman 1993, Tratt 1997). The potential for threats from artificial nutrient enrichment have not been widely studied in detail on the fens of Scotland (Charman 1993, Grieve & Gilvear 1994, Tratt 1997) despite increasing pressure from agriculturalisation, particularly within lowland areas. Studies from the rest of Britain, especially England, indicates the deleterious effects enrichment can have on these habitats (*e.g.* Boorman & Fuller 1981, Wheeler 1983). European research highlights that extreme measures may be necessary to ameliorate high levels of enrichment if they remain unchecked (Barendregt *et al.* 1995, Beltman *et al.* 1995, Boeye *et al.* 1996). The potential for enrichment in Scottish fens has been largely overlooked. In addition, there are generally few, longer term detailed studies of the nutrient status of British fens. Those carried out often do not consider temporal and spatial changes of hydrology and hydrochemistry on the fen and the implications for vegetation development. The main objectives of this study, therefore, were:

1. a pilot investigation on the distribution of major fen types throughout Scotland to assess the scale and diversity of the fen resource, and highlight potential nutrient enrichment problems at the regional level.

2. to identify the nutrient status of selected fens across Scotland through a scoping survey, and investigate the potential links, at the local level, between nutrient status and land use in the catchment area.

3. to investigate the links between hydrology, hydrochemistry and vegetation patterning of selected fens, with particular reference to spatial and temporal changes in nutrient status at the site level.

1.5.2 Organization of the study

To meet these three objectives the study was organized into three phases, (1) a pilot investigation using a desk study, (2) an initial scoping survey in the field and (3) detailed field investigations using a paired catchment approach. Phases 1 and 2 are presented in chapter 2, while the more detailed work of phase 3 is presented in chapters 3 to 6. Outlines of each phase of the study are as follows:

Phase 1 - desk study to meet objective 1

All available data on fens throughout Scotland were compiled, including unpublished and published reports and OS maps. Fen topographical type was identified from these data sources, and used to assess the distribution of fens types in Scotland, on a regional basis. The most commonly occurring fen topographical type was identified.

Phase 2 - scoping survey to meet objective 2

A small number of fens of the most common topographical type were selected from the phase 1 desk study for investigations to assess nutrient status using a restricted range of hydrochemical and peat soil parameters. The potential links between catchment characteristics, particularly land use, and fen nutrient status were also investigated.

Phase 3 - detailed field investigation to meet objective 3

Two fens selected from the phase two survey were subject to more detailed investigations into links between hydrology, hydrochemistry and vegetation patterning. Monthly monitoring of hydrology and water sampling across the fen allowed spatial and temporal variation, and its implication in vegetation development, to be investigated in detail. Again investigations included catchment characteristics, in particular land use, and their links to hydrologic regimes and fen water nutrient status.

CHAPTER 2

A pilot investigation of the distribution, type and extent of Scottish fens, and their vulnerability to catchment land intensification

2.1 Introduction

Mires are increasingly acknowledged as important habitats both within the UK, and in a wider international context. This is reflected in recent European protective legislation, such as the Habitats and Species Directive (92/43/EEC). Along with other wetlands they are seen as not only having natural functions in the ecosystem, but also as economic resources (Maltby 1986, Barbier 1989). As such they are the focus of increased research, and recent studies have highlighted many such habitats are increasingly under threat, both with regard to 'quality' and 'quantity' of the mire habitat (*e.g.* Fojt 1995).

Ombrotrophic peatlands, or bogs, are well represented in Scotland. They have developed over extensive areas in the north and west of Scotland and to a lesser extent in the east and south at higher altitudes. The majority of these are blanket bogs, which are estimated to cover 1,056,198 ha of Scotland (Lindsay 1995). The second type of ombrotrophic peatland, raised bogs, are less frequent. They occur mainly in lowland conditions where they typically develop over basin fens. The area of raised bog in Scotland is estimated at 27,892 ha (Lindsay 1995), much of this concentrated in Strathclyde.

Scottish fens are less well documented in the literature. Recent figures estimate that fens in Scotland cover approximately 1,215 ha (Lindsay 1995), substantially less than ombrotrophic peatlands, and account for only 11 % of the total peatland resource in Scotland. This figure is likely to underestimate the true extent of fens in Scotland, because there is little available data. Unpublished reports suggest there are fen sites throughout Scotland (Wheeler & Shaw 1987, Shaw & Wheeler 1990 1991, Tratt 1997). Many of these occur as small areas within other habitats, for example, flush fens and spring fens found within the blanket bog landscape that dominates much of Scotland. In addition, small areas of fen develop on the margins of lakes and other water bodies. The discontinuous distribution of much fen vegetation may partially account for the lack of information, but many fens do develop as discrete, readily identifiable and sometimes large areas, most typically basin fens and floodplain fens. For example, Insh Marsh in Scotland is the largest example of a floodplain poor-fen in Britain, and covers approximately 300 ha (Ross *et al.* 1998), accounting for almost 25 % of the Scottish peatland resource when using Lindsay's (1995) data. There is, therefore, an obvious lack of published data on not only the distribution, but also the type of fens in Scotland.

The paucity of information on fens in Scotland may reflect the recent interest and subsequent research on peatland issues such as afforestation of blanket bog and industrial exploitation of lowland raised bogs. Conservation and protection efforts have been concentrated on assessing and ameliorating these more immediate and obvious destructive practices (*e.g.* Wheeler *et al.* 1995, Parkyn *et al.* 1997). In addition, there are few perceived threats to fens in Scotland, although this does not mean that threats do not exist. These threats may be small scale, for example, domestic peat cutting and local drainage. There is also the potential for other more insidious impacts, such as enrichment or acid deposition, that have a time lag between the impact and the subsequent habitat degradation.

One of the main threats to the fen habitat is enhanced nutrient enrichment. This occurs when the nutrient status of the site is increased above the natural state due to human impacts. The impact may happen within the surrounding catchment, and the site is then affected through the water inputs. Changes to the nutrient status ('quality') of inputs can affect biogeochemical processes in peatlands, particularly nutrient cycling (Koerselman *et al.* 1988, Van Dam & Beltman 1992, Sanger *et al.* 1996). This change in nutrient inputs is often linked to changes in land practices in the catchment, such as agricultural intensification or afforestation (Smith & Charman 1988, Schot & Van Der Wal 1992). Wheeler (1993) highlights the potential for increased nutrient inputs to fens through drainage and run-off from agricultural land in the catchment. This can lead to changes in the fen vegetation, and loss of characteristic fen species (Wheeler 1983, Klotzli 1987). In addition, the fen can be affected by more distant impacts through precipitation (Koerselman 1989, Proctor 1994), particularly as peatlands have been reported to retain up to 60 % of the nutrients entering them via precipitation, surface and sub-surface flow (Verry & Timmons 1992). Collectively, these impacts have been described as *external* factors in the nutrient enrichment processes of a site (Koerselman *et al.* 1993).

Nutrient enrichment can also occur as the result of impacts on the fen itself, rather than in the catchment. This has been termed *internal* nutrient enrichment (Koerselman *et al.* 1993). Fens at later stages of development may be susceptible to internal nutrient enrichment due to net accumulation of nutrients in the peat. These nutrients are released if changes in the fen environment allow increased nutrient cycling, and this is summarised by Verhoeven *et al.* (1993). Increased nutrient release occurs within the fen if anaerobic conditions are not maintained and the peat begins to mineralise. This may happen if the water levels falls due to drainage or abstraction (Heathwaite 1992, Ross 1995, Freeman *et al.* 1993a, 1996).

The relationships between fen vegetation and nutrients are complex due to multiple environmental and plant physiological factors acting together (Tilman 1990). Generally, however, increased nutrient availability in fens allows more productive species to proliferate in, or invade the habitat, and outcompete other typical fen plants (Headley & Wheeler 1988, Wheeler 1993). Water and peat chemistry have been studied to characterize the chemical conditions under which a particular vegetation type develops (Golterman *et al.* 1978, Hunt & Wilson 1986, Wheeler & Shaw 1987, Shaw & Wheeler 1990). Peat 'fertility', measured by comparing the growth of a phytometric indicator species (Wheeler 1988, Wheeler & Shaw 1987, Shaw & Wheeler 1990, 1991), also gives an indication of the bioavailability of ions within the peat substrate. Base-poor fens, such as are commonly found in Scotland, are considered sensitive to increased inputs of major nutrient ions. These fens form in relatively acid conditions, and due to their low base status their buffering capacity is reduced (Shaw & Wheeler 1990), *i.e.* the fen has less ability to maintain a *status quo* with regard to ion availability as nutrient inputs fluctuate.

This chapter covers phase 1 and phase 2 of the study (see *chapter 1, section 1.5*). Phase 1 aimed to assess the extent, distribution and variety of Scottish fens using available published and unpublished material, addressing objective 1 of the research. Through this pilot study the most frequently occurring fen hydrotopographical type in the dataset was identified, and a small number of this fen type selected for a more detailed scoping survey. These selected sites formed phase 2 of the study. Phase 2 aimed to assess the nutrient status of selected fen sites by measuring inflow and fen water chemistry, and basic peat soil parameters. The potential role of land use types in affecting the nutrient status of the fens was also assessed, and this addressed objective 2 of the study. Results and conclusions from this chapter were used to identify a pair of fen sites for phase 3 of the study, which looks in detail at the spatial and seasonal variation in hydrologic regime and hydrochemistry in relation to vegetation patterning on the two basin fens (objective 3).

2.2 Methodology

2.2.1 Assessment of the distribution of fen sites in Scotland

Sites with some fen habitat were initially identified from an automated search of the Sites of Special Scientific Interest (SSSI) records held by Scottish Natural Heritage (SNH), using key words '*peatland*', '*mire*', '*fen*' and '*bog*'. This was extended by a manual search of the SSSI records for additional sites. These results gave an indication of the range of fen types currently under SSSI protection in Scotland. Non-designated sites were highlighted by an extensive search of the published literature on fen sites in Scotland, along with unpublished notes and maps held by SNH.

From the large number of sites identified in Scotland (over 700) a simple selection procedure was applied to highlight potential field survey sites:

- *location* - sites were located on mainland Scotland
- *access* - sites had good access both to the site and on the site
- *area* - small (< 50 ha), more or less intact fen sites were preferred
- *hydrology* - freshwater sites with no brackish or tidal influences

The information on the smaller number of sites resulting from this selection were then assessed in more detail. Each site was assigned an hydrotopographical classification, either as a valley bottom floodplain fen, valleyhead fen, basin fen, open water transition fen or hill slope fen, based on the work of Fojt (1989) and Wheeler (1995) (see *section 1.2* for full descriptions of these terms).

2.2.2 Selection of representative fens for survey

A subset of 18 fens with a *basin fen* hydrotopographical classification were selected for a scoping survey from the initial desk study. All sites were found on mainland Scotland on a range of geology and soil types, and at altitudes up to 300 m (Table 2.1). The sites were surrounded by a variety of land use types from improved pasture to semi-natural vegetation, to cover a range of potentially nutrient enriching situations. Data on site morphology and adjacent land types were collected from unpublished reports, OS maps, aerial photographs, SSSI citations and site files, and verified by field survey. Adjacent

Table 2.1 Site and catchment characteristics and survey dates for the 18 Scottish fen sites selected for survey

Site Name	Region	Survey Date	Grid Ref.	Altitude (m)	Peatland Area (ha)	Catchment Area (ha)	Geology	Catchment Soils
Rossie Moor	Tayside	19.07.95	NO 650 540	120	21.5	48	Old Red Sandstone	iron podsols / peaty gleys
Restenneth Moss	Tayside	18.07.95	NO 483 577	65	16.2	160	Old Red Sandstone	iron podsols
Barr Loch Meadow	Strathclyde	04.08.95	NS 347 564	35	3.0	69	Carboniferous Limestone	non calcareous gleys / brown forest soils
Aird's Meadow	Strathclyde	04.08.95	NS 365 585	30	14.0	116	Carboniferous Limestone	non calcareous gleys / brown forest soils
Glen Moss	Strathclyde	02.08.95	NS 368 699	135	11.8	69	Carboniferous Basalt	iron podsols / non calcareous & peaty gleys
Barmufflock Dam	Strathclyde	03.08.95	NS 369 649	50	0.5	73	Carboniferous Basalt	iron podsols / non calcareous & peaty gleys
Heart Moss	Dumfries & Galloway	10.08.95	NX 770 480	120	6.0	133	Silurian Shales	brown forest soils / non calcareous gleys
Torrs Moss	Dumfries & Galloway	11.08.95	NX 780 620	50	10.0	115	Silurian Shales	brown forest soils / non calcareous gleys
Black Loch	Dumfries & Galloway	08.08.95	NX 891 875	200	16.1	92	Permian Sandstone	brown forest soils / non-calcareous gleys
Perchall Loch	Dumfries & Galloway	09.08.95	NY 110 879	70	3.9	74	Old Red Sandstone	brown forest soils / non-calcareous gleys
Hill of Warehouse Mire	Highlands	14.08.95	ND 312 412	120	6.8	56	Old Red Sandstone	peaty podsols / peaty gleys
Newlands of Geise Mire	Highlands	17.08.95	ND 095 674	60	6.8	173	Old Red Sandstone	non-calcareous gleys
Loch of Winless	Highlands	15.08.95	ND 294 545	10	13.8	673	Old Red Sandstone	non-calcareous gleys
Loch Lieurary	Highlands	16.08.95	ND 074 642	50	33.3	320	Silurain Shales	non-calcareous gleys
Brownmoor Heights	Borders	22.08.95	NT 460 254	285	1.0	58	Silurian Shales	peaty gleys / non-calcareous gleys
Greenside Loch	Borders	25.08.95	NT 518 258	80	2.0	166	Silurian Shales	non-calcareous gleys
Long Moss	Borders	24.08.95	NT 480 185	290	6.5	42	Silurian Shales	non-calcareous gleys
Nether Whitlaw Moss	Borders	33.08.95	NT 506 294	270	4.5	76	Silurian Shales	non-calcareous gleys

land was surveyed in the field using Phase 1 survey techniques to classify catchment land type (Nature Conservancy Council 1990).

Results and conclusions from these 18 basin fen sites were used to select two sites for phase three, a paired catchment study, to assess the spatial and seasonal variation in hydrology and hydrochemistry in relation to vegetation patterning (objective 3).

2.2.3 Field survey and sampling

At each site a transect was set-up from the input stream, across the fen to the outflow stream, covering the major vegetation variation on each site. Subsurface water samples (to a depth of 30 cm) were collected at approximately 25 to 50 m intervals along the transect, using a peristaltic pump. In addition, pH and electrical conductivity (EC) were measured in the field on clear but unfiltered subsurface water samples, and peat samples were collected from 0-30 cm depth, and surface vegetation and large root removed prior to analysis. The pH and EC of all inflows (*e.g.* streams, drains) were measured and water samples collected.

Water samples were collected in acid washed 250 ml PVC bottles, filled to the top to exclude air. Samples were stored in the dark at 0-3 ^{0}C and filtered through Whatman GFC prior to analysis. Three laboratory replicates of the filtrate were taken from each field sample, and analysed for nitrate, chloride, phosphate, potassium and calcium. Anions were measured on a sub-sample filtered through 0.5 μm filters (Whatman CA), using a Dionex ion chromatograph fitted with a chemical suppressor and an AS4A analytical column (detection limit 0.02 mg l^{-1}). Sodium hydroxide was used as the eluent, sulphuric acid as the regenerant. Phosphate was determined using the Ammonium Molybdate Ascorbic Acid method (Murphy & Riley 1962), measured colorimetrically at 880 nm (detection limit 0.01 μg l^{-1}). A Corning 400 flame photometer was used to determine potassium concentration (detection limit 0.1 mg l^{-1}). Calcium ions (sample dosed with strontium nitrate hydrochloric acid) were determined by a Pye-Unicam 919 atomic absorption spectrophotometer (detection limit 0.01 mg l^{-1}). Full details of these methods are available in Allen (1989) and Bartram and Ballance (1996).

The peat samples, with the surface vegetation removed, were collected in sealed plastic bags and stored at 0-3 °C. Sample were then sorted to remove large roots, dried at room temperature, ground and analysed for field moisture content using oven drying (105 °C overnight), and inorganic organic matter content using loss on ignition (850 °C for 45 min) (Rowell 1994).

Main changes in vegetation types were noted across each fen. No quantitative data were collected for the vegetation types, therefore descriptions are not included in the main analysis, but presented in site summaries contained in Appendix A2.

2.2.4 Data analysis

The data were normally distributed (Anderson-Darling test for normality), although for nitrate and phosphate the data were first natural Logarithm transformed (Log_e), and statistical analyses were carried out using Minitab 11. In assessing land adjacent to each fen site, phase 1 survey land types (Nature Conservancy Council 1990) were ranked in order of agricultural intensification, assigned a score from +8 (high intensity land type) to -6 (semi-natural land type) (Table 2.2). The catchment land type score was then calculated for each site by adding together rank values for each land type present adjacent to the fen. If higher intensity land types (Phase 1, NCC 1990) were present next to the fen that site obtained a higher score. Variation between the sites in hydrochemistry and peat were analysed using one-way analysis of variance (ANOVA). Pairwise interactions were tested using the Tukey-Kramer multiple comparison test. Correlation coefficients between hydrochemical and peat soil parameters were assessed using Pearson product moment correlation coefficients, and the results checked for linearity. Correlation coefficients were also carried out on the hydrochemistry of different inflows between each site.

The lithotrophic - atmotrophic - thalassotrophic (LAT) model (Van Wirdum 1981) for hydrochemistry was used to determine basic differences between the subsurface water types sampled on the fen sites. The model uses calcium and chloride concentrations of each sample to produce an ionic ratio (IR, *equation 2.1*), which is plotted against electrical conductivity (EC) values of the same sample. The IR and EC together give an indication of the similarity of water types sampled to three reference points; *lithotrophic* water with a higher residence time in the ground, *atmotrophic* water with low residence time in the ground, and *thalassotrophic* water with greater chloride concentrations possibly indicating marine or pollution influences. Additional hydrochemical parameters were compared between each general water type.

$$IR = (0.5\ Ca^{2+}) / ((0.5\ Ca^{2+}) + (Cl^{-})) \qquad \textit{(equation 2.1)}$$

Table 2.2 Rank scores assigned to land use types where +8 = high intensity; -6 = low intensity

Land use type	Rank
Arable	8
Improved pasture	7
Amenity grassland	6
Plantation woodland	5
Semi-improved pasture	4
Artificial exposures/waste tips	3
Industrial	2
Urban	1
Standing water	0
Unimproved pasture	-1
Semi-natural woodland	-2
Scrub	-3
Acid grassland	-4
Wet dwarf shrub heath	-5
Blanket bog	-6

2.3 Results

2.3.1 The distribution of fen types in Scotland

In total 727 sites with some fen component were found (Appendix 1). Their distribution across the Scottish Regions is shown in Fig. 2.1a. The majority of sites occurred in the Highland Region and were often flushes associated with ombrotrophic peatlands. The Borders Region has the next most frequent occurrence, and many of these sites were classified as basin fens. Strathclyde and Tayside also have large numbers of fen sites. The summary by peatland types is shown in Fig. 2.1b. The most commonly found type was basin fen, followed by open water transition fens and valley fens. Flush fens were also well represented, while floodplain, patterned, spring and ladder fens were relatively rare in this dataset. Raised bogs were common in the dataset, attributed to the perimeter fen that often develops in association with the lag stream, while other ombrotrophic peatland sites were rarely included.

Half of the sites (355) were identified as small, accessible fen areas on mainland Scotland, and were, therefore, within the range of this study (see *section 2.2.1*). The remaining sites were either outside the area of this study (*e.g.* flush fens within blanket bog, or fens outside mainland Scotland), or had too few data available to assess. Of these 355 fen sites, four hydrotopographical fen types were identified; *hillslope fen* (4 %), *valley fen* (26 %), *open water transition fen* (27 %), and *basin fen* (43 %), of which basin fens were the most common. Basin fens were therefore considered most representative of fens across mainland Scotland from the dataset, and selected for further research.

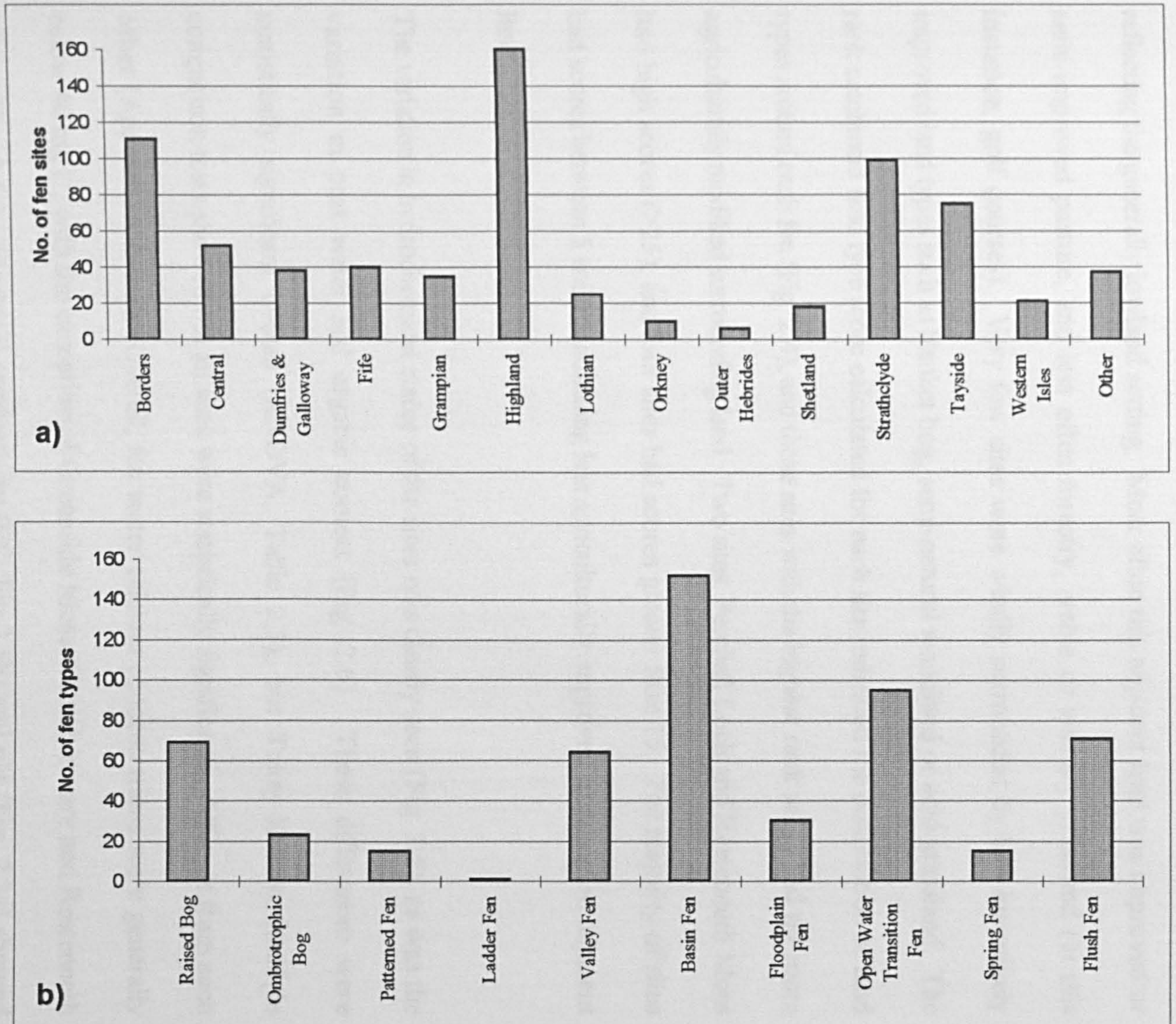


Fig. 2.1 The distribution of a) fen areas in each Region and b) peatland types across Scotland.

2.3.2 Comparison of the 18 selected basin fen sites

Eighteen fen sites were selected from around mainland Scotland (Fig. 2.2). General site descriptions,including vegetation, are presented in Appendix 2. Land adjacent to the fen sites was more likely to be an agriculturally modified, intensive land type (Fig. 2.3), reflecting the generally lowland setting. Most often this adjacent land was improved or semi-improved pasture, and less often forestry, arable or amenity grassland (in this instance, golf courses). Very few sites were wholly surrounded by less intensively improved land types such as blanket bog, semi-natural woodland or acid grassland. The rank catchment land type score calculated for each site indicated the distribution of land types around each fen (Fig. 2.4), and those sites with the highest rank score had the more agriculturally modified surrounding land. Two sites, Perchall Loch and Restenneth Moss had high scores (>25), and four sites had scores greater than 15. The majority of sites had scores between 5 and 15 indicating less agriculturally improved or modified adjacent land.

The variation in hydrochemical status of the sites was clearly seen (Fig. 2.5), as was the variation in peat water and organic content (Fig. 2.6). These differences were statistically significant overall (ANOVA, Table 2.3), but Tukey-Kramer multiple comparison tests showed not all sites were statistically significantly different from each other (Appendix 3.1, 3.2). Overall, fen water calcium concentrations were generally below 40 mg l^{-1}, with the exception of Greenside Moss, Loch Lieurary and Restenneth Moss (Fig. 2.5c). Electrical conductivity (EC, Fig 2.5b) and pH (Fig. 2.5a) showed similar trends. Nitrate concentrations were low (<0.4 mg l^{-1}), except Restenneth Moss

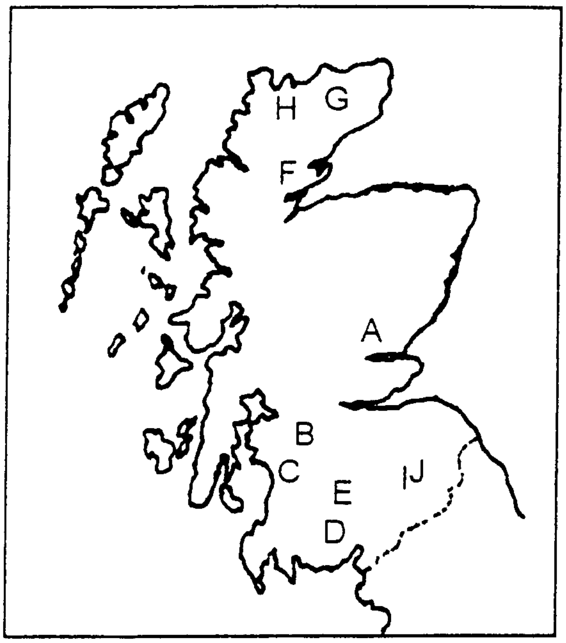


Fig. 2.2 The distribution of 18 basin fen sites across mainland Scotland. See Table 2.1 for site details.

A = Restenneth Moss and Rossie Moor
B = Barr Loch Meadow and Aird's Meadow
C = Glen Moss and Barmufflock Dam
E = Heart Moss and Torrs Moss
F = Black Loch and Perchall Loch
G = Hill of Warehouse Mire
H = Newlands of Geise Mire and Loch Lieurary
I = Brownmoor Heights and Greenside Moss
J = Long Moss and Nether Whitlaw Moss

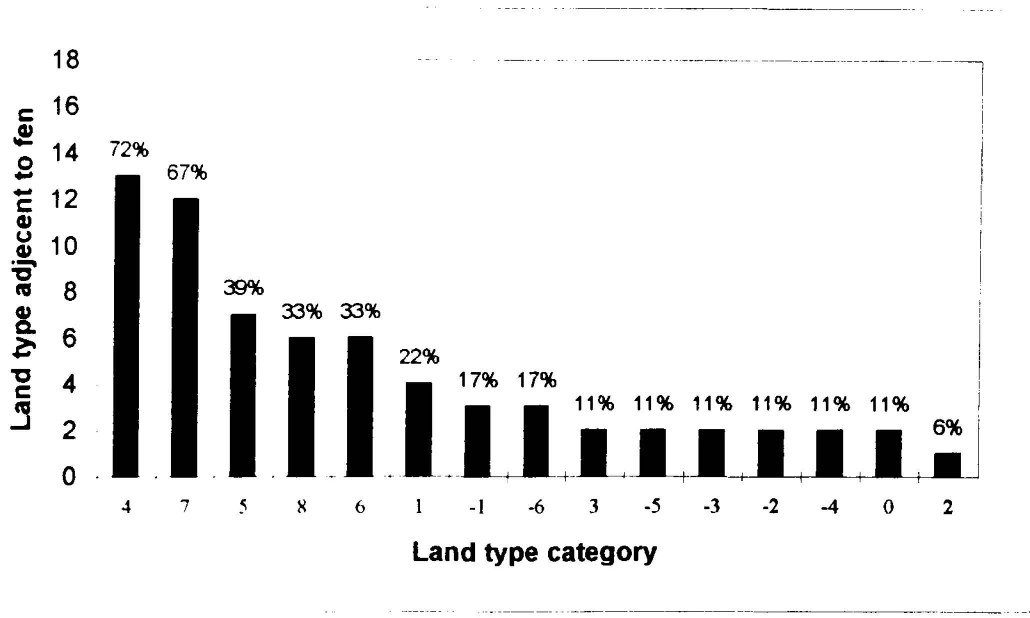


Fig. 2.3 The occurrence of different land type categories found adjacent to the 18 fen sites surveyed. NCC (1990) Phase 1 land use categories have been ranked from higher to lower intensity land use (+8 to -6) as follows:

8 = Arable land
7 = Improved pasture
6 = Amenity grassland
5 = Plantation woodland
4 = Semi-improved pasture
3 = Artificial exposures/waste tips
2 = Industrial
1 = Urban
0 = Standing water
-1 = Unimproved pasture
-2 = Semi-natural woodland
-3 = Scrub
-4 = Acid grassland
-5 = Wet dwarf shrub heath
-6 = Blanket bog

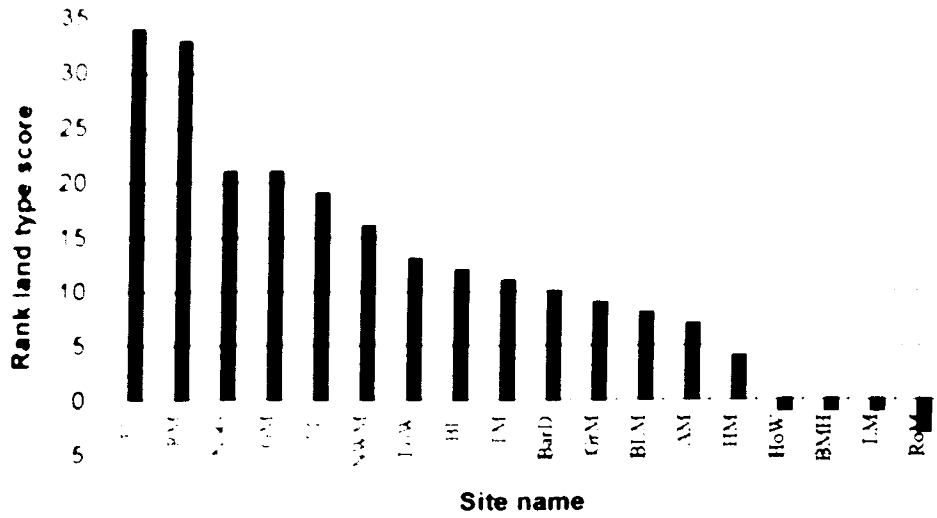


Fig. 2.4 Rank catchment land type scores for the 18 sites surveyed, showing the general intensity of land improvement adjacent to each site. Higher scores represent more intensive land type. Site name abbreviations as follows:

PL = Perchall Loch, Dumfries and Galloway
RM = Restenneth Moss, Tayside
NoG = Newlands of Geise Mire, Highlands
GM = Glen Moss, Strathclyde
LL = Loch Lieuran, Highlands
NWM = Nether Whitlaw Moss, Borders
LoW = Loch of Winless, Highlands
BL = Black Loch, Dumfries and Galloway
TM = Torrs Moss, Dumfries and Galloway
BarD = Barmufflock Dam, Strathclyde
GrM = Greenside Moss, Borders
BLM = Barr Loch Meadow, Strathclyde
AM = Aird's Meadow, Strathclyde
HM = Heart Moss, Dumfries and Galloway
HoW = Hill of Warehouse Mire, Highlands
BMH = Brownmoor Heights, Borders
LM = Long Moss, Borders
RoM = Rossie Moor, Tayside

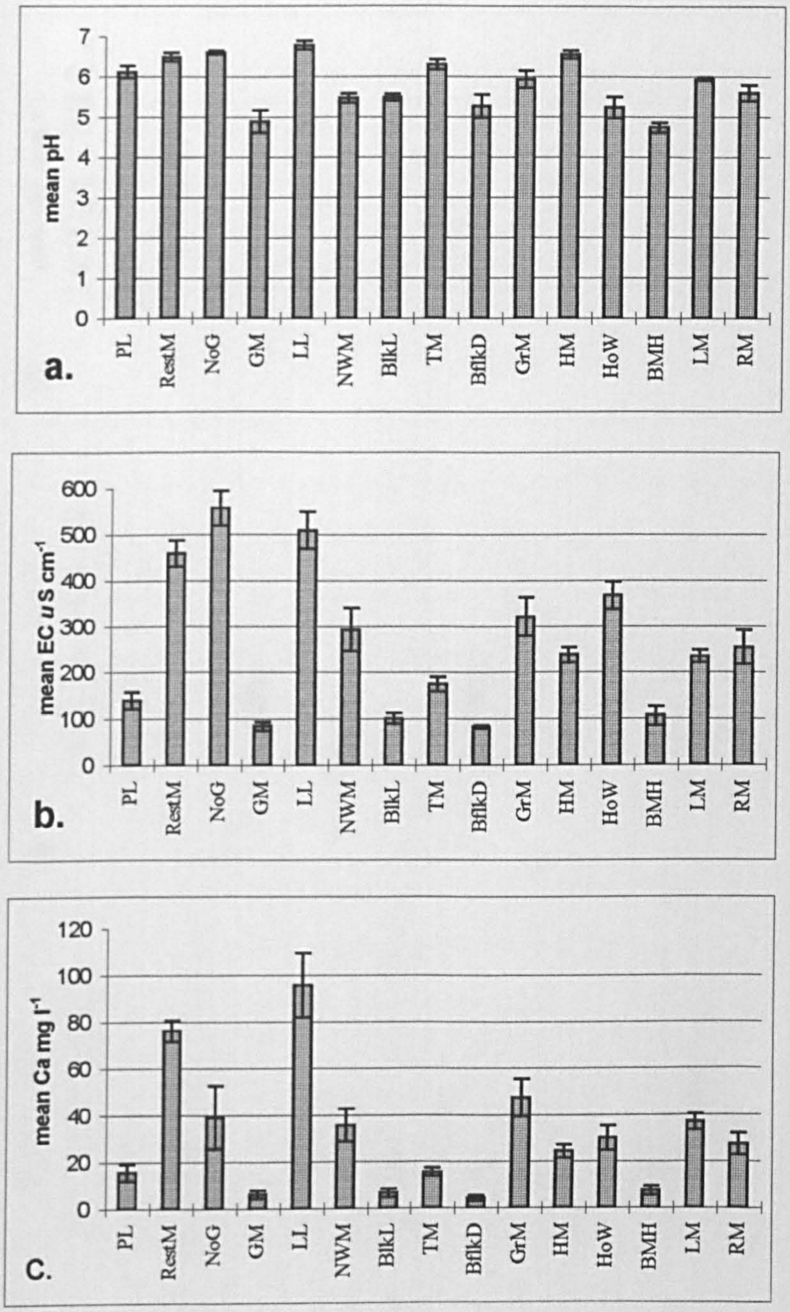


Fig. 2.5 Mean and standard error of the mean for each hydrochemical parameter measured on each site. a. = pH; b = electrical conductivity (EC) u S cm^{-1}; c = calcium mg l^{-1}. Site name abbreviations as follows:
PL = Perchall Loch, RestM = Restenneth Moss, NoG = Newlands of Geise Mire, GM = Glen Moss, LL = Loch Lieurary, NWM = Nether Whitlaw Moss, BlkM = Black Loch, TM = Torrs Moss, BflkM = Barmufflock Dam, GrM = Greenside Moss, HM = Heart Moss, HoW = Hill of Warehouse Mire, BMH = Brownmoor Heights, LM = Long Moss, RM = Rossie Moor.
The three sites Loch of Winless, Barr Loch Meadow and Aird's Meadow were removed from analysis due to the small number of samples collected.

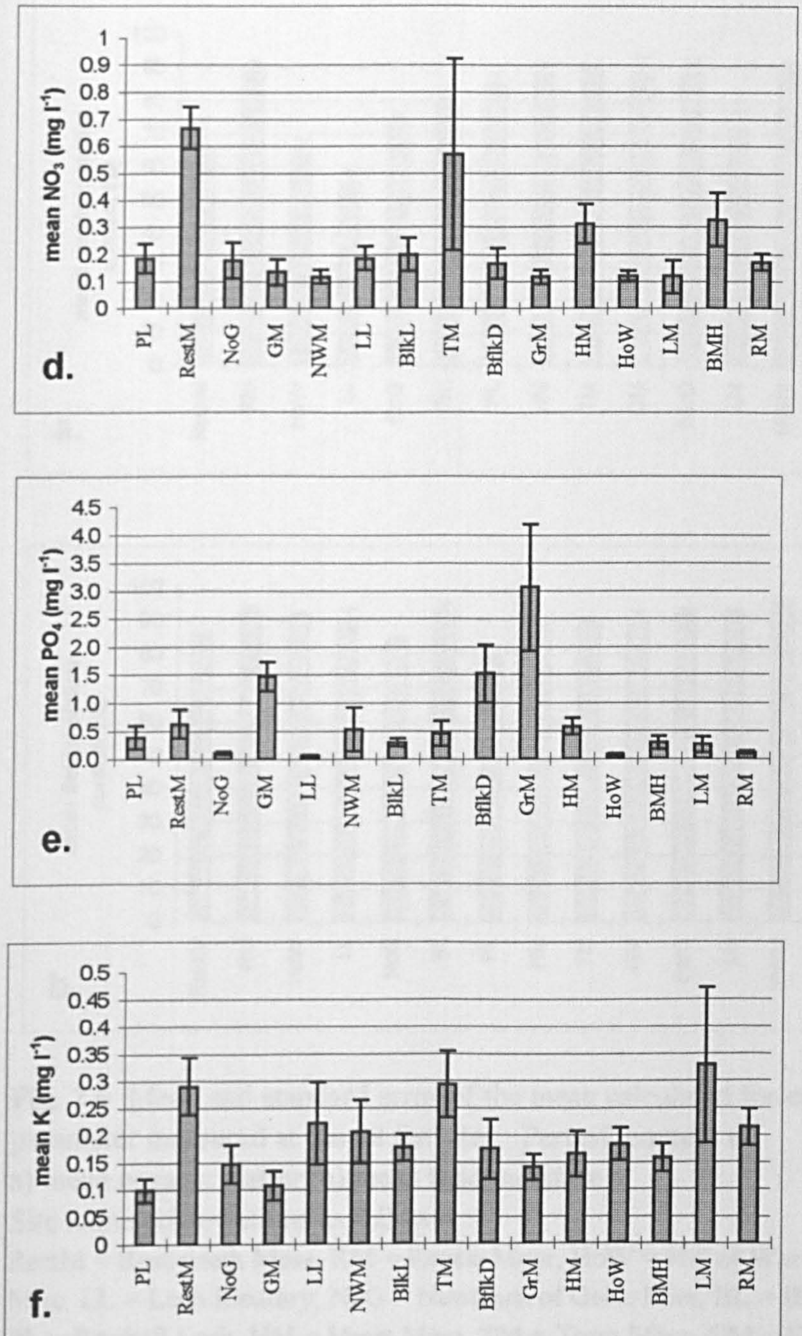
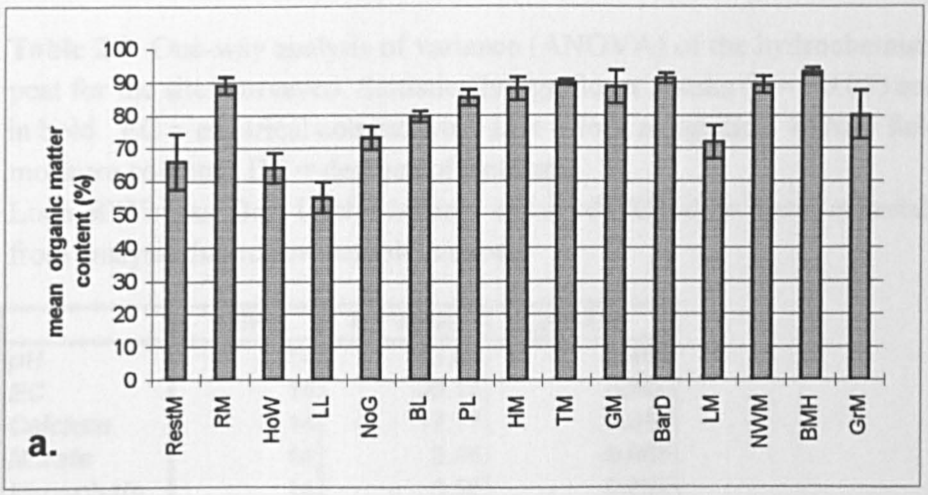


Fig. 2.5 (cont.) Mean and standard error of the mean for each hydrochemical parameter measured at each site. d = nitrate; e = phosphate; f = potassium, all as mg l^{-1}. Site name abbreviations as for Fig. 2.5 a-c



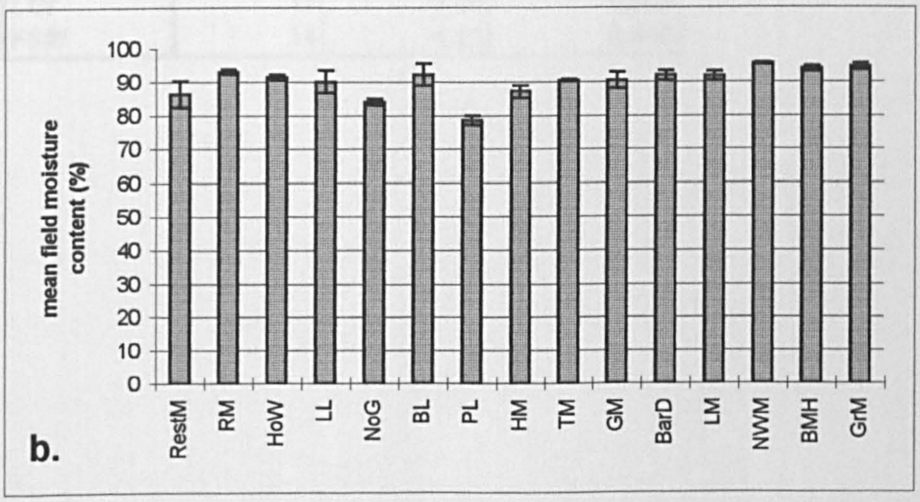


Fig. 2.6 Mean and standard error of the mean calculated for each peat soil parameter measured at the 18 fen sites. Percent content of:
a) mean organic matter; b) mean field moisture
Site name abbreviations as follows:
RestM = Restenneth Moss, RM = Rossie Moor, HoW = Hill of Warehouse Mire, LL = Loch Lieurary, NoG = Newlands of Geise Mire, BL = Black Loch, PL = Perchall Loch, HM = Heart Moss, TM = Torrs Moss, GM = Glen Moss, BarD = Barmufflock Dam, LM = Long Moss, NWM = Nether Whitlaw Moss, BMH = Brownmoor Heights, GrM = Greenside Moss.
Three sites, Loch of Winless, Barr Loch Meadow and Aird's Meadow, were removed from analysis due to the small number of samples collected.

Table 2.3 One-way analysis of variance (ANOVA) of the hydrochemistry and peat for the sites surveyed. Statistically significant results ($p = <0.05$) are shown in bold. EC = electrical conductivity, LOI = loss on ignition, FSM = field soil moisture content, DF = degrees of freedom
Loch of Winless, Barr Loch Meadow and Aird's Meadow were removed from analysis due to low sample numbers

	DF	F - value	*p-value*
pH	14	13.64	**0.000**
EC	14	26.14	**0.000**
Calcium	14	17.17	**0.000**
Nitrate	14	2.46	**0.005**
Phosphate	14	5.58	**0.000**
Potassium	14	1.89	**0.033**
LOI	14	6.45	**0.000**
FSM	14	4.21	**0.000**

and Torrs Moss (Fig. 2.5d). Mean phosphate concentrations were also low (<1.00 mg l^{-1}) except Barmufflock Dam and Glen Moss (Fig. 2.5e). Similarly, potassium concentrations were below 0.25 mg l^{-1}, except for Restenneth Moss and Torrs Moss (Fig. 2.5f). A similar variation was seen between the inflow hydrochemistry of each site (Fig. 2.7). For the inflows, nitrate concentrations were similarly low (<0.25 mg l^{-1}), except for Restenneth Moss which showed a very high concentration (Fig. 2.7b). Mean phosphate concentrations for the inflow were generally <1.00 mg l^{-1} except for Nether Whitlaw Moss which showed mean concentrations at 3.23 mg l^{-1} (Fig. 2.7c). Potassium concentrations were also low (<0.35 mg l^{-1}), other than at Nether Whitlaw Moss (Fig. 27d). Restenneth Moss and Nether Whitlaw Moss both had greater nutrient concentrations in their inflows and on the fen had high catchment land type scores. No site with the lowest catchment land type scores (<5) had greater nutrient concentrations, which included Heart Moss, Hill of Warehouse Mire, Long Moss and Rossie Moor.

Analysing the inflow data between the sites gave an insight into the variation in hydrochemistry of water entering the 18 fen sites. Calcium concentrations were significantly different between sites, whilst potassium and phosphate means were not (ANOVA, Table 2.4). Nitrate means showed an overall significant difference, and the Tukey-Kramer multiple comparison test showed that this was due to the high mean nitrate concentrations at Restenneth Moss (Appendix 3.3).

There were few significant, linear correlation coefficients between fen sub-surface hydrochemistry and fen peats, and the hydrochemistry of the inflows. For both the fen and the inflows (Table 2.5, Table 2.6) calcium, pH and EC were all found to be positively

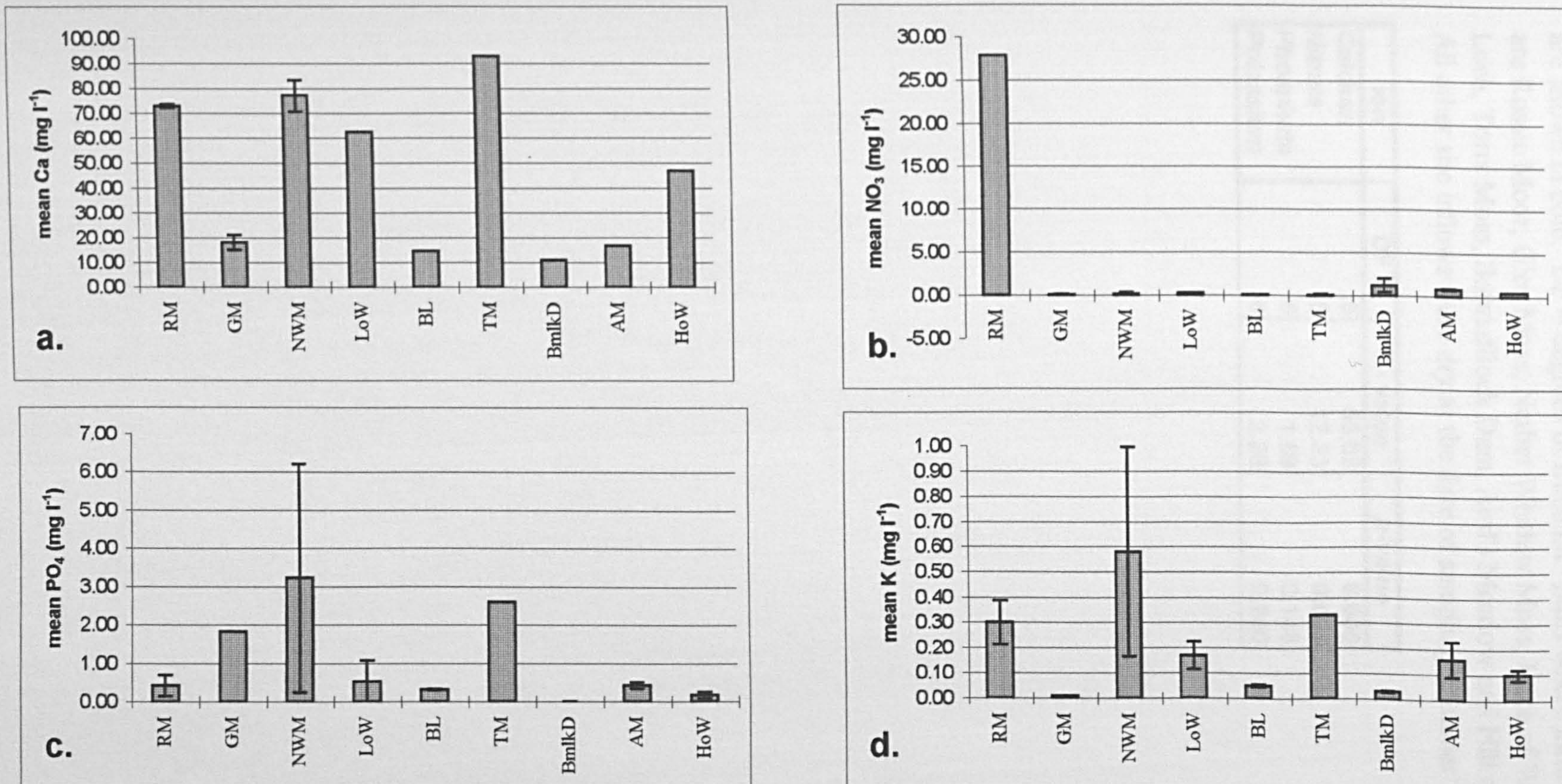


Fig. 2.7 Mean and standard error of the mean for each hydrochemical parameter measured at the inflow stream of the sites surveyed. All other inflow streams were dry at the time of sampling (summer 1995).
a = calcium; b = nitrate; c = phosphate; d = potassium all as mg l^{-1}. Site name abbreviations as follows:
RM = Rossie Moor, GM = Glen Moss, NWM = Nether Whitlaw Moss, LoW = Loch of Winless, BL = Black Loch, TM = Torrs Moss, BmlkD = Barmufflock Dam, AM = Aird's Meadow and HoW = Hill of Warehouse. All remaining sites had dry inflows

Table 2.4 One-way analysis of variance (ANOVA) of the hydrochemistry of the inflow streams of the sites surveyed. Statistically significant results ($p =< 0.05$) are shown in bold. DF = degrees of freedom. Sites where inflows sampled are Rossie Moor, Glen Moss, Nether Whitlaw Moss, Loch of Winless, Black Loch, Torrs Moss, Barmufflock Dam, Aird's Meadow and Hill of Warehouse. All other site inflows were dry at the date of sampling (summer 1995).

Ion	DF	F - value	*p-value*
Calcium	6	55.68	**0.000**
Nitrate	6	12.33	**0.000**
Phosphate	6	1.89	0.148
Potassium	6	2.26	0.940

Table 2.5 Two-tailed Pearson product moment correlation coefficients for fen peat and fen water hydrochemistry for sites surveyed. Statistically significant, linear correlations at 5% level are shown in bold. LOI = loss on ignition, FSM = field soil moisture, EC = electrical conductivity, degrees of freedom = 120. Loch of Winless, Barr Loch Meadow and Aird's Meadow were removed from the analysis due to the small number of samples collected.

	LOI	*FSM*	*pH*	*EC*	*Calcium*	*Nitrate*	*Phosphate*
FSM	**0.461**						
pH	**-0.378**	-0.229					
EC	**-0.372**	-0.086	**0.593**				
Calcium	**-0.468**	-0.031	**0.476**	**0.602**			
Nitrate	-0.272	-0.473	0.141	0.201	0.219		
Phosphate	0.180	0.227	-0.226	-0.245	-0.054	-0.064	
Potassium	-0.073	0.001	0.144	0.183	0.303	0.144	0.063

Table 2.6 Two-tailed Pearson product moment correlation coefficients for inflow stream hydrochemistry for the sites surveyed. Statistically significant, linear correlations at 5% level are shown in bold. EC = electrical conductivity, degrees of freedom = 20. Sites included were Rossie Moor, Glen Moss, Nether Whitlaw Moss, Loch of Winless, Black Loch, Torrs Moss, Barmuflock Dam, Aird's Meadow and Hill of Warehouse Mire. All other site inflows were dry at The time of sampling (summer 1995)

	pH	*EC*	*Calcium*	*Nitrate*	*Phosphate*
EC	**0.439**				
Calcium	**0.489**	**0.921**			
Nitrate	0.622	0.366	**0.546**		
Phosphate	-0.205	0.291	0.314	-0.049	
Potassium	-0.015	**0.452**	**0.526**	0.299	**0.852**

correlated with each other. Fen peat organic matter content was negatively correlated to fen pH, EC and calcium concentrations, and positively correlated to field moisture content of the peat. Inflow potassium concentrations were positively correlated with inflow EC, calcium and phosphate concentrations. Non-linear significant correlations all showed scattered plots with no obvious patterns emerging.

2.3.3 General water types - the LAT Model

Three main groups were distinguished from the LAT model (Van Wirdum 1981) (Fig. 2.8). The first group occurred close to the lithotrophic water type, indicating these fens were dominated by groundwater. Some of the fens found within this group, Restenneth Moss and Nether Whitlaw Moss, had greater nitrate and potassium concentrations. The second group, which contained half the fen sites surveyed, occurred between the lithtrophic and atmotrophic water types, and had a transitional water type between ground water and precipitation. The final group consisted of three fen sites, Glen Moss, Barmufflock Dam and Browmnoor Heights, close to the atmotrophic water type, which suggested fens dominated by precipitation with reduced groundwater influence. These fen sites also had greater mean phosphate concentrations on the fen. No fens were classified close to the thalassotrophic water type.

2.3.4 The selection of two fen sites for phase 3 investigations

The scoping survey of 18 fen sites led to the selection of two fen sites to investigate the

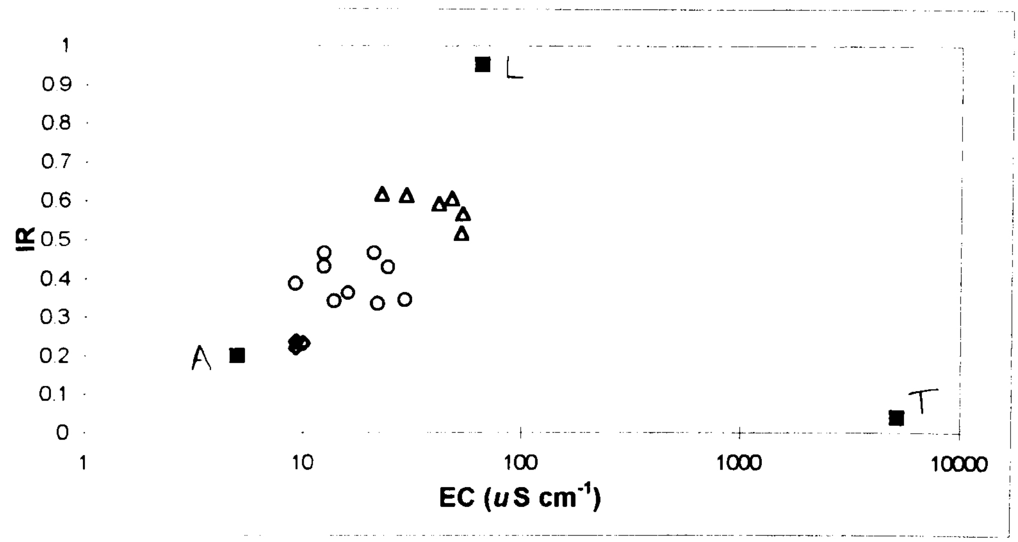


Fig. 2.8 LAT Model (Van Wirdum 1981) with the distribution of 18 fen sites in relation to three reference water types, shown on the graph as L = lithotrophic standard; A = atmotrophic standard; T = thalassotrophic standard. The 18 fen sites produce three clusters: Δ = *group 1* lithotrophic type; ○ = *group 2* transitional between litho- and atmotrophic types; ◇ = *group 3* atmotrophic type.
IR = Ionic Ratio *(equation 2.1)*, EC = electrical conductivity *u* S cm^{-1}

relationships between hydrology, hydrochemistry and vegetation patterning at the site scale (phase 3), to address objective 3 of the research (see *chapter 1, section 1.5.1*). Two basin fens in the Scottish Borders were selected for a paired catchment survey. These were Long Moss SSSI and Nether Whitlaw Moss SSSI. The sites had many catchment characteristics in common (Table 2.1), allowing siters to be compared and contrasted. Both sites occurred on Silurian Shales (Ragg 1960) overlaid with peat deposits of up to 6.5 m deep (Ross, unpublished data). The catchment area geology for both sites was also Silurian Shale overlaid by poorly drained non-calcareous gley soils of the Ettrick Association (Ragg 1960).

The vegetation at both sites range from tall, herb-rich to bryophyte-rich community types, generally developing as floating vegetation rafts over unconsolidated peat, and firmer peat respectively (Tratt 1997). This reflected the vegetation gradient of ombrotrophic bog - species-poor fen - species-rich fen, typical of these habitat types (Sjors 1950, Rodwell 1991, 1995). Both sites are classified as 'transitional fen' by Shaw and Wheeler (1990) with respect to vegetation development and selected hydrochemical and peat characteristics.

Hydrologically the two sites were similar, with small catchments (<100 ha), and a discrete, readily identifiable basin boundary. Each fen was fed by an inflow stream with a single outflow stream at the opposite end.

There were, however, some important differences in the sites and their catchments which added to their value in this detailed paired study. One of the objectives of the research was to investigate the potential effect of increased nutrient inputs to vegetation patterning, and link this to adjacent land types in the catchment. Despite their many similarities Long Moss and Nether Whitlaw Moss had very different land types in their catchment areas, as reflected in their catchment land use scores (Fig. 2.4). Long Moss catchment was dominated by unimproved acid grassland, while Nether Whitlaw Moss catchment was more highly modified, dominated by under-drained, improved grassland, with an adjacent road and reservoir. This enabled an assessment of the potential impacts of the different catchment land types on the fen hydrology, hydrochemistry and vegetation patterning.

2.4 Discussion

Over 700 sites with some fen component were identified across Scotland, and the Highlands, Borders, Strathclyde and Tayside Regions appeared to have the highest numbers. The majority of these sites were designated Sites of Special Scientific Interest (SSSIs). Tratt (1997) studied 68 fen sites in the Borders Region, 45 of which occurred within the Borders Environmentally Sensitive Area. Fojt (1992) estimates that 1062 SSSIs throughout Britain have "some fen interest". This under-estimation of the fens covered by the SSSI series may be the result of smaller fen areas being included in this study, many more fen sites being designated since 1992, or that Scotland holds the majority of designated fen sites. It is difficult from this initial desk study to pin-point why there is such a discrepancy in the SSSI figures on fens, particularly as over half the sites did not have enough information to fully assess the fen habitat. In the light of this, the most likely reason is that this study included areas of fen that formed only a part of a larger habitat (*e.g.* open water transition fen around a large open water area, or flush areas within blanket peatland) which were not included in previous assessments. Spence (1964), for example, identified fen vegetation around 92 of the 102 loch and swamp areas assessed, emphasising that this habitat type is widely associated with fen vegetation, but is often ommited from an assessment of fen habitats in Scotland.

Hydrotopographical classification of 355 fen sites revealed that the majority were basin fens, with other frequently found types being open water transition fens and valley fens. Ombrotrophic peatlands, particularly blanket bog, were under-represented as the study focused on the fen habitat. A large number of blanket peatlands were noted as having flush fens within the landscape, and raised bogs often had a perimeter fen area associated with the lag stream, but these were outside the scope of this study. Within the selection procedures for the study sites basin fens were shown to be most frequently occurring, and these sites were chosen for further study.

Many of the 18 basin fen sites selected from the initial desk study had some improved catchment land type next to them, particularly semi-improved pasture, and also plantation forestry, arable land and amenity grassland. The occurrence of basin fens within agricultural landscapes in Britain has been highlighted (Fojt 1992, Shaw & Wheeler 1992), and Wheeler (1983) found these fens can be subject to nutrient enrichment from fertiliser run-off from the catchment. Studies in other European countries suggest similar effects of enrichment (Verhoeven *et al.* 1983, 1988a, 1993, Barendregt *et al.* 1995). The inflow data indicated that some fen sites were receiving greater nutrient concentrations in water inputs, particularly Restenneth Moss and Nether Whitlaw Moss. However, only nitrate concentrations at Restenneth Moss were statistically significantly greater than inflow concentrations of nitrate at the other sites sampled. Inflow data considered only 'point source' enrichment, and diffuse inputs of nutrients from general sub-surface water percolation was not assessed, although these may be significant (Jorgensen 1994, Heathwaite 1995b).

Fen water pH and electrical conductivity (EC) were highly variable between the eighteen fen sites. The mean pH ranged from approximately pH 4.6 to pH 6.8, with the majority of sites at pH 5.5 or greater. Shaw and Wheeler (1991) observed that poor-fen vegetation tended to have a pH <5.5, while rich fens had a pH >5.5, which has been related to the presence of *Sphagnum* species actively exchanging hydrogen ions (Clymo 1997). Similarly, EC values are often < 300 μS cm^{-1} for poor fens, with greater EC values for rich fens (Shaw & Wheeler 1991). This dataset EC range was approximately 80 - 550 μS cm^{-1}. On the eighteen sites across Scotland pH values suggested typically *rich* fen conditions, while EC (generally <300 μS cm^{-1}) indicated typically *poor* fen conditions. This discrepancy is likely to be the result of limited data being used to create broad hydrochemical classes for fen classification, or limited data collection in this study, and highlights both the need for futher research in this area, and the caution required when applying such classifications.

Tratt (1997) found *poor* fen conditions to be frequent following an extensive survey of the Borders area of Scotland. The more wide-ranging survey, as attempted here, indicated fens in Scotland were more hydrochemically variable than expected. Ratcliffe (1964) developed broader references for fen pH values and calcium concentrations in the water, using the terms *oligotrophic* (pH <5.7, Ca <4 mg l^{-1}), *mesotrophic* (pH 5.7 - 6.5, Ca 4-10 mg l^{-1}) and *eutrophic* (pH >6.5, Ca >10 mg l^{-1}). In these terms the 18 fen sites were generally meso- and eutrophic ranges with regards to calcium concentrations, *not* nutrients, and covered the full range in terms of pH values. Such discrepancies highlight not only the variation in the fen habitat type across Scotland, but also the problems in terminology.

The fen hydrochemical data also suggested that in the water the nutrient concentrations were generally low, with little indication of enrichment, despite the often agricultural catchment land types adjacent. Only four sites showed elevated nutrient concentrations, often related to a specific area sampled rather than an increase across the whole site. These were Restenneth Moss, Torrs Moss, Barmufflock Dam and Glen Moss. Fen sites tended to have elevated concentrations of *either* nitrate or phosphate, rather than both nutrients. This may suggest some nutrient limitation on the sites, with fen sites with greater nitrate concentrations being limited by phosphate availability, and *vice versa*. Nitrate and potassium concentrations often increased toward the edges off the fen, while phosphate concentrations increased in the centre. The edges of the fens may be more susceptible to nutrient enrichment from the catchment (Wheeler 1983, Tratt 1997) where both diffuse and point water sources enter the fen. In contrast, the centre of the fen is often associated with precipitation-dominated water sources, and *Sphagnum*-rich vegetation (Tratt 1997). Increased phosphate concentrations have been reported in these

Sphagnum-rich vegetation types, and may relate to pH and mineralisation rates (Verhoeven & Aerts 1987, Verhoeven *et al.* 1988b).

The variations in fen hydrochemistry and peat moisture and organic matter content between sites were high, and all measured parameters were significantly different. Correlation coefficients indicated that higher peat organic matter content related to greater water content, along with lesser pH, EC and calcium concentrations in associated water samples. Greater pH, EC and calcium concentrations are associated with herbaceous fen vegetation, rather than *Sphagnum*-rich vegetation (Sjors 1950, Wassen *et al.* 1989, Bridgham & Richardson 1993), and this is the case in this study. The peat types produced by these different vegetation communities have different structures (Aaby 1986, Tratt 1997). These differences can also be related to the degree of decomposition and hummification. As decomposition proceeds the amount of mineral material increases (Zoltai 1991), and pore spaces in the peat are reduced which can affect water holding properties (Blackford & Chambers 1993). Herbaceous fen peats with a more hummified structure (lower organic content) may, therefore, be less able to hold water (lower moisture content) than *Sphagnum*-derived peats. Alternatively, the areas with greater inorganic material content may be closer to the edge of the basin and subject to mineral soil input from erosion of adjacent land, or from tall herb vegetation being more effective at filtering out airborne dust particles (Aaby 1986).

For the inflow hydrochemistry, again pH, EC and calcium concentration were all positively correlated. In addition, potassium was positively correlated to EC, calcium and phosphate concentration. There were no significant differences in the concentrations of phosphate and potassium entering the fen as all sites had low concentrations, although Nether Whitlaw Moss showed some increased concentrations. Only Restenneth Moss showed significantly greater nitrate concentrations, and this corresponded to elevated nitrate concentrations on the site.

Three main groups were identified from the LAT model (Van Wirdum 1981). These were related to three different water types; *lithotrophic* (group 1), transitional *litho - atmotrophic* (group 2), and *atmotrophic* (group 3). There were no sites close to the thalassotrophic water type, indicating no marine influence (Van Wirdum 1981) and no pollution associated with elevated chloride concentrations (Kemmers 1986). Group 1 was dominated by fens with more intensive adjacent land use types, and some of these sites had greater nitrate and potassium concentrations. These greater nutrients may be associated with the groundwater (shallow and deep) that dominates these fens, and increased nutrients may originate from adjacent land uses. The second group had a water type transitional between groundwater and precipitation. This may indicate fen sites with a mixing of these water sources on the fen, or sites fed with greater shallow (sub-surface) groundwater that has a lower residence time in the ground. The group contained the largest number of fen sites, both those with relatively intensive agricultural catchment land types, and those with less intensive catchment land use types. The final group was small (three fen sites), but appeared to be dominated by precipitation, with the least influence of groundwater. These fens were also associated with greater phosphate concentrations. Precipitation dominated areas in fens often develop *Sphagnum*-rich vegetation types (Wassen *et al.* 1988, 1989, Verhoeven 1992), and may become isolated from the ground water table for at least part of the year. Studies have shown the relation between increased phosphate concentrations and *Sphagnum* vegetation types (Wilson & Fitter 1984, Wassen 1995), which have been attributed to pH and mineralisation processes (Verhoeven & Aerts 1987, Verhoeven *et al.* 1988b).

Overall, it appears that the selection of basin fens in this study, thought to be generally representative of the larger Scottish dataset, are typically surrounded by intensively modified/ agricultural land of one sort or another. This is perhaps not unexpected as the improvement of moorland, peatland and similarly unproductive land by, for example liming, has been carried out in Scotland since the mid to late 1700s (Dodgshon 1978). Since this date increasing land improvement and agriculturalisation has been continued, particularly after the Second World War and the development of inorganic fertilizers. Very few fen sites assessed were wholly surrounded by less improved land types such as blanket bog, semi-natural woodland and acid grassland. The potential for the enrichment of these basin fens from adjacent land seems apparent. Despite this only one site, Restenneth Moss, had significantly greater concentrations of nutrients in the inflows, and the majority of sites showed low concentration of nitrate, phosphate and potassium. Similarly, although four sites showed elevated concentrations of either nitrogen or phosphate relative to other sites, the concentrations were still low and unlikely to indicate eutrophication. It, therefore, appears that no site was undergoing internal nutrient enrichment, and that only Restenneth Moss appeared to be subject to obvious external nutrient enrichment. This may be attributed to several reasons:

- The adjacent land use types were not having an impact on the fen nutrient status due to low nutrient applications to, and/or low run-off rates from, the adjacent land.

- Management of the fen (*e.g.* mowing) or general grazing reduced nutrients on the fen system through biomass removal (Koerselman *et al.* 1990b, Verhoeven & Schmitz 1991, Kirkham *et al.* 1996). Light grazing was evident on selected sites, but no other management appeared to be widespread.

- The time of survey (summer 1995, see Table 2.1 for survey dates) did not reflect average conditions on the fens. This may be particularly relevant as the summer of 1995 was drier than average (Branson 1995), reducing the availability of water for sample collection. Sampling at different times of the year may have also revealed a different nutrient status (Koerselman *et al.* 1993, Proctor 1994).

- Adjacent land use types may be affecting the nutrient status of the fens, but this is not reflected in the water chemistry because of rapid uptake and/or nutrient transformations in the fen itself. Nutrients are limiting in peatlands, particularly nitrogen and phosphorus (Vermeer 1986a,b, Boyer & Wheeler 1989, Koerselman & Verhoeven 1992, Wassen *et al.* 1995). Any extra nutrient inputs to peatlands, and fens in particular, may be rapidly incorporated into microbial biomass, plant matter, adsorbed onto peat soils and transformed by physiochemical processes (Stutz & Bliss 1975, Vehoeven & Schmitz 1991, Kirkham *et al.* 1996, Koerselman & Meuleman 1996). This may act as a buffer in some cases, maintaining a low concentration of soluble, plant-available nutrients (Boyer &

Wheeler 1989). In other cases the increased nutrients may eventually adversely affect the habitat.

To address some of these issues, and explore the nutrient status and vegetation patterning in detail, a more intensive survey and monitoring of hydrologic regime, hydrochemistry and vegetation patterning was carried out on two fen sites identified from this scoping survey. This formed the major component of the study and addressed objective 3 of the research (*chapter 1, section 5.1*). This phase 3 of the research focused on two fens, Long Moss and Nether Whitlaw Moss, in the Scottish Borders, using the two very similar fens, and their catchments, to compare and contrast the sites in terms of vegetation, hydrology and hydrochemistry. These two sites were geographically close to one another, and were similar in geology, catchment soils, altitude, fen and catchment area. They were also alike in their hydrological characteristics, fed by a single inflow stream with a single outflow stream at the opposite end of the fen basin, and, being at a similar altitude, were likely to be affected by comparable precipitation and evaporative conditions. In terms of the plant cover, both sites showed a range of vegetative types from species-poor to species-rich plant assemblages, with associated substrate types from firm peat to floating vegetation rafts that had developed over unconsolidated peat. This broad range of vegetation types, encompassing the basic diversity of vegetation typical on Scottish fens, enabled some more general, rather than site specific, inferences to be developed.

The major variation in vegetation at these sites, and at many of the 18 fen sites, was found across the fen from the inflow stream to the outflow. Although these data were not presented in the analysis they are available from the author on request. This scoping survey suggested there was also a large amount of variation in hydrochemistry along these vegetation gradients. To further assess this, detailed monthly hydrochemical sampling was carried out along a transect from the inflow to the outflow stream at each site for nine months over the main growing season (March to November 1996). Hydrochemical gradients, particularly change in nutrients, should then be able to be assessed and associated with vegetation changes. In addition, hydrological regimes, including inundation and drying of the fen surface, and water inputs from the inflow stream, were monitored each month over an 18 month period, to incorporate just over the annual hydrological regime (March 1996 - August 1997). The spatial and seasonal variations in hydrology and hydrochemistry could then be assessed in terms of vegetation patterning along the transect.

In addition, increased nutrient input from modified land types adjacent to fen areas was highlighted as a potential factor in vegetation development. This scoping survey indicated that the inflow streams can show elevated nutrients in relation to the general fen environment. These nutrients may increase the fen nutrient status close to the inflow, potentially altering the characteristics of the vegetation found here. The monthly hydrochemical sampling along the transect was also used, therefore, to assess the nutrient status across the fen from the inflow to the outflow. Sampling was more intensive along the 50 m close to the inflow stream in an attempt to pick up any greater concentrations of nutrients, and related to vegetation productivity in terms of species number and above ground biomass production. The full methodologies, results and discussions from the detailed phase 3 research on Long Moss and Nether Whitlaw Moss are presented in chapters three to six.

CHAPTER 3

The classification, characterization and prediction of vegetation types across two basin fens in Scotland

3.1 Introduction

The characterization of vegetation is considered important in defining habitat types, and can contribute to an understanding the ecology of the habitat, both at the species and community level. In terms of conservation and protection, vegetation classification has been used in the management of sites, and more recently for the implementation of legislation (*e.g.* EC Habitats Directive, 92/43/EEC). As such, the development of classification systems to describe vegetation types, both natural, semi-natural and highly modified by human impacts, is important both for understanding systems and for their protection. This is reflected in much of the work on the vegetation of mires, including fens. Within Europe, classification systems broadly characterize mire vegetation as bog, poor fen and rich fen (Du Rietz 1949, 1954, Sjors 1950, Malmer 1962a,b, 1963) predominantly on the basis of plant species number and composition. Similar work was carried out within the UK (Tansley 1939, Holdgate 1955), and later work identified mire vegetation communities within these three broad categories on the basis of more detailed phytosociological assessment (McVean & Ratcliffe 1962, Spence 1964, Daniels 1978, 1985, Wheeler 1980a,b,c, Rodwell 1991, 1994).

Measures of presence/absence or abundance of plant species are used for classification, but on their own may give little insight into vegetation ecology and relationships to environmental conditions. The question of *why* vegetation develops where it does leads to the need to characterize environmental conditions, mainly through measurements of substrate and water chemistry, and exploration of the relationships between environment and vegetation community through statistical analyses. There is also a need to consider the past and present management or use of the area, and the effects this may have on the vegetation development over and above environmental conditions (*e.g.* Green & Pearson 1968, Vermeer & Verhoeven 1987). Some of the early studies defining mire vegetation types and linking these to environmental conditions are the works of Malmer, Sjors and Segal in the 1950s and 60s (*e.g.* Sjors 1950, Malmer 1962a,b, 1963, Segal 1966). Sjors' (1950) study on Swedish mires found that the vegetation groups defined by phytosociological techniques had some correlation to the water pH and electrical conductivity measurements, but there was considerable overlap between groups. Malmer's work extends to a thorough investigation of the chemistry of peat, water and plant biomass to elucidate habitat conditions for particular vegetation communities. Again the correlation between vegetation type and acidity - alkalinity gradients are described using measures of pH, electrical conductivity and calcium concentrations of fen water, but other analyses such as nutrient content of biomass are less conclusive. Similar conclusions are drawn from Segal's (1966) study of mire vegetation groups and environmental characteristics. The basic correlations between acidity - alkalinity gradients and bog - poor fen - rich fen vegetation communities continue to be seen in more recent work (*e.g.* Verhoeven *et al.* 1990, Vitt & Chee 1990), while links between specific vegetation communities and more detailed water and peat chemical analyses are still somewhat inconclusive (*e.g.* Bridgham & Richardson 1993, Tratt 1997).

The use of phytosociological classification as a basis for plant habitat characterization made way for other approaches to studying the vegetation development, using vegetation 'traits' rather than individual species dominance. Early work by Spence (1964), for example, assessed the growth form of plants typical of fens and lochs, classifying them as submerged rosette, submerged linear, floating of emergent forms. In addition, the environmental ranges of these plants were also assessed, including variables such as water depth, temperature and soil nitrogen content. Such techniques are directed more toward an understanding of the species-environment relationship rather than focusing on vegetation classification. The competitor - stress tolerator - ruderal (C-S-R) strategy theory developed by Grime (1974) identifies two main environmental factors influencing vegetation; *stress* and *disturbance*. Stress was defined as any factor that reduces the biomass accumulation rate (*e.g.* drought), while disturbance was any factor that destroyed biomass (*e.g.* grazing). This theory formed the basis for many plant-environment studies, in particular nutrient use and dynamics (Campbell *et al.* 1991, Grime & Sibley 1986, Moore & Keddy 1989), and as a basis for classification (Hills *et al.* 1994).

The C-S-R strategy theory relies on the correct identification of individual species in the field, and is therefore applied at the species level. Recent studies show that plant traits such as height, biomass, stem density, and nearest neighbour distance, that are not species-specific, can be informative in identifying plant 'functional groups' that relate to different survival strategies under different environmental conditions (Tilman 1982, 1988, Hills & Murphy 1996). This trait-based approach can also be applied at the species level, but at the *group* level it allows the vegetation-environment relationship to be explored more holistically. Relationships have been seen between vegetation traits and competitive success (Gaudet & Keddy 1988) and between measures of relative growth rate and relative susceptibility to stress (Shipley & Keddy 1988). To move from the species specific approach towards a functional trait-based approach involving many species opens up the possibility of measuring, analysing and modelling spatial patterns of vegetation development across a broad range of habitat types (*e.g.* Van Der Valk 1981, Keddy & Reznicek 1982, 1986).

This chapter details the study of the vegetation on two fen sites, Long Moss and Nether Whitlaw Moss (Fig. 3.1), selected from the phase 2 survey (*chapter 2*). Both sites occurred in the same region (Scottish Borders) within 20 miles of each other, with identical geology and catchment soil types, and at a similar altitude (approximately 280 m). The fen sites were also of a similar size (Long Moss: 6.5 ha, Nether Whitlaw Moss: 4.5 ha) with a similar catchment area (42 ha and 76 ha respectively). Research focuses on assessing the main vegetation physiognomy and floristics, along with the basic environmental conditions of the fens using phytosociological classification, plant functional traits and simple environmental measurements. The vegetation groups on each site were identified and classified using phytosociological techniques, and compared to National Vegetation Classification (NVC) types (Rodwell 1991, 1995), and similar Scottish-based vegetation classification (Ratcliffe 1964, Spence 1964). The relationship between plant functional traits, simple environmental measurements and the vegetation groups identified was explored using correlation and linear regression. Finally, the ability of the plant functional traits and the environmental variables to predict particular vegetation groups was analysed using multivariate statistical techniques.

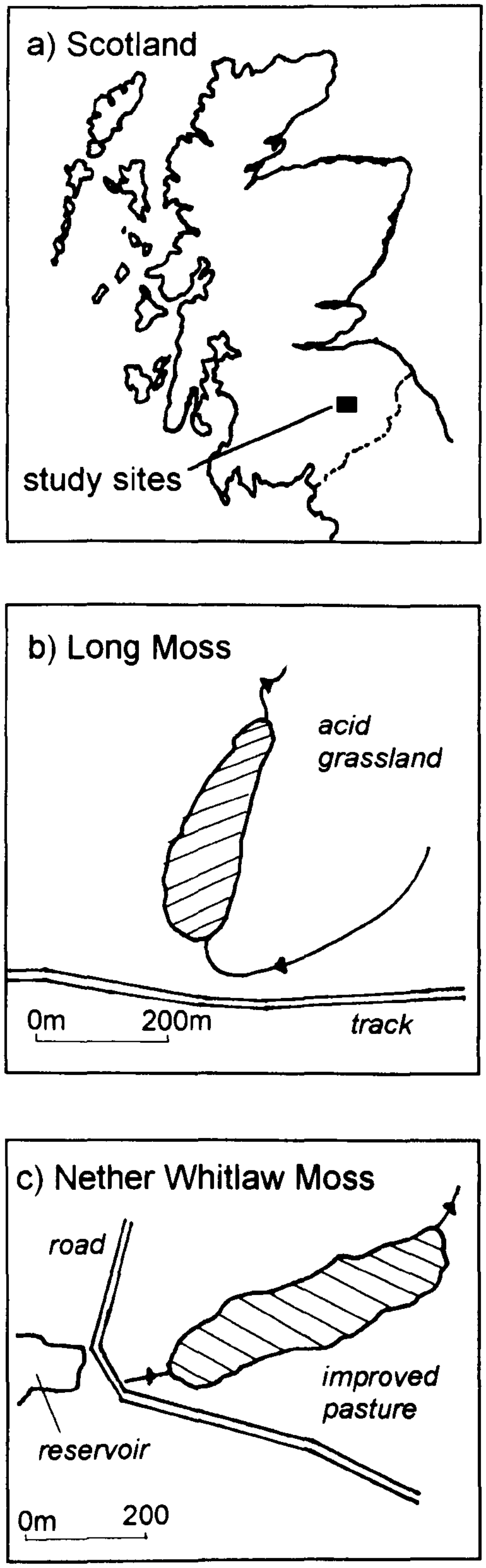


Fig. 3.1 Maps of the fen sites showing a) their location in Scotland, b) Long Moss, c) Nether Whitlaw Moss

3.2 Methodology

3.2.1 Sampling

Vegetation groups for each fen site were characterized using a quadrat survey (July 1997). Stands of visually homogeneous vegetation were identified in the field at each site, and four to six 1 m^2 quadrats randomly placed within each stand. All plant species (higher plants, bryophytes and macrolichens) within the quadrat were identified and cover-abundance scored using the DOMIN scale (Rodwell 1991). Within each quadrat the percentage cover of total bryophytes, herbs, shrubs and trees were recorded as layers, along with their mean height. Shrub and tree cover outside the quadrat area was not recorded. In addition, information on eleven plant functional traits and six environmental variables were recorded for each quadrat. The plant traits measured were shrub height, herb height, moss height, shrub cover, herb cover, moss cover, canopy height, stem width, nearest neighbour distance, stem density (per 25 cm^2) and number of reproductive structures (per 25 cm^2) (after Willby *et al.* 1997). The environmental variables were pH and electrical conductivity (EC) of fen surface water, bare peat/litter cover, open water, standing water depth, and substrate type (measured as a score 1, 2 or 3, where 1 = firm peat and 3 = floating vegetation raft). Environmental variables and plant traits were randomly measured five times for each quadrat and the mean used for further analysis.

3.2.2 Analysis

Quadrat data were analysed using VESPAN (Hill 1979) and MATCH (Malloch 1992) programmes. The VESPAN (Hill 1979) programme was modified to produce statistics on additional plant functional traits recorded for each quadrat. Within the

VESPAN (Hill 1979) programme a standard run Two-way Indicator Species Analysis (TWINSPAN, Hill 1979) was used to produce vegetation groupings. Quadrat data for Long Moss and Nether Whitlaw Moss were analysed as a combined dataset. Once vegetation groups had been finalised the quadrat data from a group were run through MATCH (Malloch 1992) to identify the most appropriate National Vegetation Classification (NVC) vegetation types (Rodwell 1991, 1995). Throughout the thesis vegetation nomenclature follows Clapham *et al.* (1987) for vascular plants, except *Carex* species which follow Jermy *et al.* (1982). *Sphagnum* species nomenclature follows Daniels and Eddy (1985), with all other bryophytes after Watson (1988).

Mean and standard error of the mean was calculated for each plant and environmental variable in each vegetation group identified. One-way analysis of variance (ANOVA) between the vegetation groups identified was carried out on each variable. All pairwise interactions were analysed using the Tukey-Kramer multiple comparison test. All data were tested for normality employing the Anderson-Darling test. Where necessary a natural Log transformation (Log_e) was applied to normalise the data for statistical analysis. Bivariate relationships between environmental variables and plant traits were analysed using Pearson product moment correlation coefficient. Those bivariate relationships with significant, linear correlations were identified, and a number of readily measurable variables that may help to predict a number of other vegetation or environmental characteristics of the vegetation groups were selected for further analysis using simple linear regression. All statistical analyses were carried out on Minitab 11.

Relationships between vegetation and environmental data were explored using

Canonical Community Ordination programme (CANOCO, Ter Braak 1992). The analyses undertaken were principle components analysis (PCA), redundancy analysis (RDA), detrended correspondence analysis (DCA) and canonical correspondence analysis (CCA). Results of the different analysis techniques were compared. A natural Log transformation (Log_e) was applied to all data prior to analysis (see Palmer 1993 and Jongman *et al.* 1995 for a discussion of data transformation for CANOCO analysis). All CANOCO data were displayed using CanoDraw v.3.0 (Smilauer 1992).

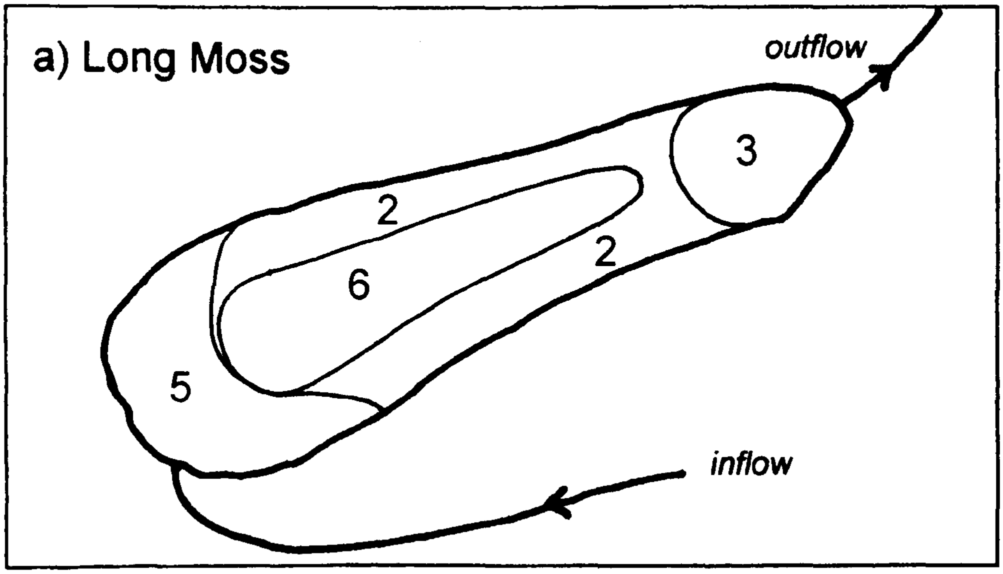
3.3 Results

3.3.1 Vegetation community descriptions

TWINSPAN analysis (Hill 1979) of the combined quadrat data for Long Moss and Nether Whitlaw Moss gave six vegetation groups (Table 3.1). These ranged from *Sphagnum*-dominated mires, sedge-rich fens, through to *Carex rostrata* swamps. The approximate boundaries for each vegetation type on each site were overlain onto aerial photographs (Fig. 3.2). Only two of the six vegetation types contained both Long Moss and Nether Whitlaw Moss samples. These were the *Potentilla palustris* - *Carex rostrata* and the *C. rostrata* - *Menyanthes trifoliata* swamp, although the *Equisetum fluviatile* variant of the *C. rostrata* - *M. trifoliata* swamp only occurred at Nether Whitlaw Moss. Synonymy with the NVC was also explored (Table 3.1) using MATCH (Malloch 1992). The coefficient of similarities showed some high values (>60.0) indicating a good fit with the standard NVC group, but also some much lower values indicating a poorer fit, particularly for the *Carex rostrata*

Table 3.1 The six vegetation groups derived from the TWINSPAN (Hill 1979) analysis of the combined quadrat data from Long Moss and Nether Whitlaw Moss. The synonymous National Vegetation Classification (NVC, Rodwell 1991, 1995) group and coefficient of similarity with the NVC (Match, Malloch 1992) are also shown

Group	Vegetation Type	Twinspan Indicator Species for Group	NVC Type	Coefficient of similarity
1	*Carex rostrata - Menyanthes trifoliata* poor fen, *Sphagnum* subcommunity	*Aulacomnium palustre, Sphagnum squarossum*	M5	43.30
2	*Potentilla palustris - C. rostrata* fen	*Galium palustre, Potentilla palustris, Epilobium palustre*	S27a	66.80
3	*C. rostrata - M. trifoliata* poor fen	*Lemna minor, Eriophorum angustifolium*	S9	48.50
4	*C. rostrata - M. trifoliata* poor fen, *Equisetum fluviatile* subcommunity	*Equisetum fluviatile, Carex diandra, Potamogeton coloratus*	S9	66.20
5	*Carex panicea - C. pulicaris* rich fen	*Carex pulicaris*	M9	54.30
6	*Eriophorum angustifolium - Sphagnum magellanicum mire*	*Sphagnum magellanicum*	M18a	62.30



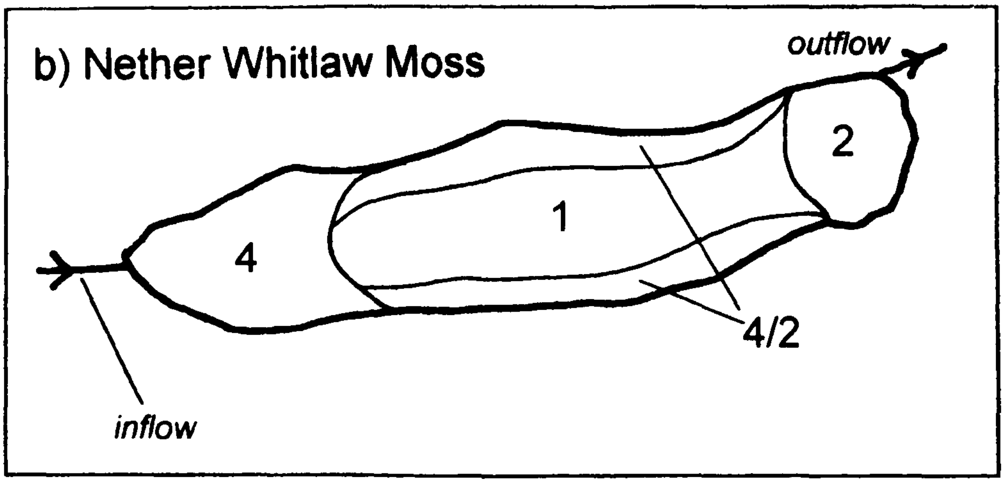


Fig. 3.2 Distribution of the six vegetation types across a) Long Moss and b) Nether Whitlaw Moss. Vegetation types:

1 - Carex rostrata - Sphagnum squarrosum poor fen
2 - Potentilla palustris - C. rostrata transitional fen
3 - C. rostrata - Menyanthes trifoliata poor fen
4 - C. rostrata - M. trifoliata, Equisetum fluviatile poor fen
5 - C. panicea - C. pulicaris rich fen
6 - Eriophorum angustifolium - S. magellanicum mire

vegetation groups 1 and 3. A brief discussion of each vegetation group is presented in *section 3.3.2*, and quadrat details are given in Appendix 4.

3.3.2 Environmental and plant variables for each vegetation group

The mean and standard error of the mean for each environmental variable and plant trait indicated the variation within the dataset (Table 3.2). Shrub height and shrub cover were omitted from futher analysis due to incomplete datasets, as the shrub component was absent from the majority of vegetation types. The main characteristics of each vegetation group are outlined below:

3.3.2.1 Group 1: Carex rostrata - Menyanthes trifoliata *poor fen,* Sphagnum *sub-community (Appendix 4.1)*

The vegetation was dominated by a continuous moss cover characterized by *Sphagnum squarrosum* lawns, giving a tall moss height (mean 9.9 mm) compared to other groups, and a high moss cover (mean 90 %). There was a shrub layer consisting of *Betula pubescens* seedlings (mean height 46.7cm), and a canopy of mature *Betula* and *Salix* species. Many of the species indicated a more acidic environment as the water pH reflected (mean pH 4.6). Both pH and EC of the fen water were the lowest mean values for the six vegetation types. Herb height was reduced, as reflected in lower overall canopy height. The inundation of the *Sphagnum* lawn was shallow during the summer months, giving the shallow water depth measured. The synonymous NVC type was identified as the *Carex rostrata - Sphagnum squarrosum* mire (M5). This group had characteristics similar to both the *C. rostrata - Acrocladium* fen type (Spence 1964), and the *Juncus effusus - Sphagnum* vegetation type (Ratcliffe 1964).

Table 3.2 Calculated mean and standard error of the mean for each plant trait and environmental variables within the six vegetation groups, for Long Moss and Nether Whitlaw Moss. n/a = not applicable; x = variable not found in group. EC = electrical conductivity
Number of observations (N) for each group: group1 = 8, group 2 = 25, group 3 = 8, group 4 = 10, group 5 = 8, group 6 = 8

	Group 1		Group 2		Group 3		Group 4		Group 5		Group 6	
Plant traits	mean	SEM	mean	SEM	mean	SEM	mean	SEM	mean	SEM	mean	SEM
Shrub height (cm)	46.7	13.67	x	x	x	x	x	x	x	x	7.1	0.70
Herb height (cm)	53.8	7.89	69.4	4.72	56.3	4.60	54.0	3.48	33.8	1.25	24.1	2.47
Moss height (mm)	9.9	1.20	7.9	2.70	x	x	1.8	0.80	6.3	4.11	4.4	0.68
Shrub cover (%)	3.0	1.51	x	x	x	x	x	x	x	x	12.0	4.06
Herb cover (%)	40.0	3.89	85.0	3.90	90.0	3.65	85.0	2.77	90.0	5.98	40.0	5.08
Moss cover (%)	90.0	6.11	20.0	5.41	x	x	2.0	0.40	45.0	7.77	85.0	5.90
Canopy height (cm)	34.0	6.01	66.7	4.18	54.9	4.17	61.5	3.11	34.6	3.67	13.0	0.98
Stem width (mm)	2.6	0.38	3.7	0.20	3.4	0.32	3.7	0.26	1.9	0.23	1.1	0.13
Nearest Neighbour (mm)	13.1	3.06	17.2	1.49	24.0	3.16	19.7	0.87	10.0	0.87	95.0	1.04
Stem density (25cm^2)	90.4	16.47	23.1	5.87	10.4	1.35	10.0	2.02	68.9	7.61	134.8	23.66
Reproductive structures (25cm^2)	3.8	0.62	2.8	0.41	1.2	0.17	1.8	0.37	3.3	0.59	2.2	0.98
Environmental measurements												
pH	4.5	0.13	6.3	0.10	6.3	0.10	6.5	0.10	6.4	0.06	x	x
EC (uS cm^{-1})	14.1	5.67	29.9	3.22	17.9	3.70	26.9	1.02	27.4	0.98	3.0	n/a
Bare peat/litter (%)	5.0	3.48	6.0	1.81	6.0	2.82	2.0	n/a	4.0	1.57	9.0	6.02
Open water (%)	x	x	6.0	1.41	15.0	3.07	10.0	2.85	4.0	2.85	x	x
Water depth (cm)	6.6	2.79	8.0	0.71	16.4	2.20	15.6	2.10	1.3	0.25	x	x
Substrate type (1-3)	3	0.00	2	0.10	3	0.00	2	0.17	2	0.19	1	0.13

3.3.2.2 Group 2: Potentilla palustris - Carex rostrata *transitional fen (Appendix 4.2)*

A species-rich fen type transitional between typical rich fen and poor fen groups, developing as floating rafts of vegetation. The tall canopy (mean height 66.7 cm) was dominated by herbs (mean height 69.4 cm), with no shrub component. The bryophyte layer was varied (mean height 7.9 mm, cover 20 %), with *Plagiomnium elatum* and *Calliergon cordifolium* forming some locally dominant patches. Both area and depth of open water were reduced compared to other groups, while EC was the highest value for all six vegetation groups (mean EC 29.9 μS cm^{-1}), with a pH 6.3. The synonymous NVC type was identified as the *Carex rostrata - Potentilla palustris* tall-herb fen, *Carex rostrata - Equisetum fluviatile* sub-community (S27a). The group also had affinities with the *C. rostrata - Acrocladium* community type identified by Spence (1964).

3.3.2.3 Group 3: Carex rostrata - Menyanthes trifoliata *poor fen (Appendix 4.3)*

This was the most species-poor vegetation type identified, dominated by herbs with no shrub or bryophyte components. The canopy height was relatively tall (mean 54.9 cm) compared to other groups, and the plants sparsely distributed (low stem density and greater nearest neighbour distance), but robust (mean stem width 3.4 mm). This vegetation type developed over floating vegetation rafts (substrate type 3), with increased cover of deeper open water (mean cover 15 %, mean depth 16.4 cm). The synonymous NVC type was identified through MATCH (Malloch 1992) as the *Carex rostrata - Menyanthes trifoliata* poor fen (S9), and there were also similarities with the open *C. rostrata* community type of Spence (1964).

3.3.2.4 Group 4: Carex rostrata - Menyanthes trifoliata *poor fen,* Equisetum fluviatile *sub-community (Appendix 4.4)*

This was one of the more species-poor vegetation groups surveyed, with an abundance of *C. rostrata* and *M. trifoliata* that formed floating rafts of vegetation over unconsolidated peat and water (substrate type 3). This was a herb-dominated group (mean herb cover 85 %, height 54 cm) with no shrub component, the only bryophyte frequently recorded was an algae. Compared to other groups the canopy was tall (mean height 61.5 cm) but open (low stem density), with deep water inundation. Typically a poor fen community with a mean pH 6.5. The synonymous NVC type was the *Carex rostrata - Menyanthes trifoliata* poor fen (S9). There were also affinities with the *E. fluviatile - Acrocladium* community type identified by Ratcliffe (1964).

3.3.2.5 Group 5: Carex panicea - Carex pulicaris *rich fen, moss sub-community (Appendix 4.5)*

A *Carex*-dominated fen vegetation group with a high cover of bryophytes creating a species-rich community. The vegetation developed over soft herbaceous peat (substrate type 2), not as floating vegetation rafts. Both herb and moss height were decreased, although percentage cover of both were increased. There were no shrubs. The vegetation was dense (low values for nearest neighbour distance and a high stem density), and plants were less robust (small stem widths and low canopy heights) than other groups. There was no standing water during summer (July 1997), and litter cover was increased. The synonymous NVC group was identified as the *Carex rostrata - Calliergon cuspidatum giganteum mire* (M9). Spence (1964) identifies a similar vegetation community type as the *C. panicea - Campylium stellatum* group.

3.3.2.6 Group 6: Eriophorum angustifolium - Sphagnum magellanicum *mire (Appendix 4.6)*

This vegetation group showed a very different character to the fen vegetation of groups 2 to 5, being dominated by *Sphagnum* with fewer herbs. The vegetation developed over firm peat (substrate type 1) with little vertical movement. Overall canopy height was low (mean 13 cm), the herbs dominated (mean height 24.1 cm) with a sub-layer of ericoid shrubs (mean height 7.1 cm). Herb cover was reduced and replaced by a *Sphagnum*-dominated bryophyte layer. Stem density was extremely high (mean 134.8 stems/25 cm^2), while stem width was the lowest (mean 1.1 mm), reflecting the compact bryophyte growth form. There was no surface water during the time of sampling (July 1997), and bare peat cover increased (mean cover 9 %). The synonymous NVC type identified through MATCH (Malloch 1992) was the *Erica tetralix - Sphagnum papillosum* raised and blanket mire, *Sphagnum magellanicum - Andromeda polifolia* sub-community (M18a). This group has affinities with the *Trichophorum - Eriophorum* mire identified by Ratcliffe (1964).

3.3.3 Results of the one-way analysis of variance

Overall the one-way analysis of variance (ANOVA) gave significant differences for all environmental variables and plant traits (p = <0.05), except for bare peat/litter cover measurements (p = >0.05) (Table 3.3). Six of the pairwise interactions were significantly different for many of the measured variables (Tukey-Kramer multiple comparison test; data available from the author on request). These were interactions between vegetation group 3 and groups 1, 5 and 6, also group 4 and groups 1 and

Table 3.3 Results of one-way analysis of variance (ANOVA) between the six vegetation groups of Long Moss and Nether Whitlaw Moss, for each ariable. DF = degrees of freedom; statistically significant results ($p = <0.05$) are shown in bold. Shrub height, shrub cover and substrate type were omitted from the data set

Variable	DF	F - value	*p-value*
plant traits			
herb height	5	10.28	**0.000**
moss height	5	3.05	**0.030**
herb cover	5	55.38	**0.000**
moss cover	5	60.43	**0.000**
canopy height	5	35.87	**0.000**
stem width	5	17.38	**0.000**
nearest neighbour	5	7.52	**0.000**
stem density	5	32.60	**0.000**
no. reproductive structures	5	3.75	**0.005**
environmental measurements			
pH	4	34.52	**0.000**
electrical conductivity (EC)	5	2.45	**0.046**
bare peat/litter cover	5	1.86	0.114
open water	5	5.05	**0.001**
water depth	5	21.81	**0.000**

6, and finally between group 2 and group 6. In addition, groups 2, 3 and 4 were *not* significantly different from one another in terms of the variables measured (with the exception of water depth). All other pairwise interactions had few significant differences.

Out of those environmental variables and plant traits measured moss cover, canopy height and water depth were most often significantly different between vegetation groups. Other significantly different variables were stem density, stem width, and herb cover. There were little or no significant differences between moss height, number of reproductive structures, conductivity and bare peat/litter cover. Results for each variable are presented in Fig. 3.3 and Fig. 3.4.

3.3.4 Characterizing vegetation - environment relationships

The combined dataset of Long Moss and Nether Whitlaw Moss were subject to four multivariate analysis techniques, Principle Components Analysis (PCA), Redundancy Analysis (RDA), Detrended Correspondence Analysis (DCA) and Canonical Correspondence Analysis (CCA). In terms of the ordination diagrams, all four analyses gave similar results for the separation of species, samples (quadrats) and environmental variables (which here included both environmental measurements and plant functional traits), suggesting a clear separation of vegetation types. The percentage variation in species and sample distribution accounted for by the environmental and plant variables included along the first two synthetic gradients (eigenvalues for axes 1 and 2) differed between the analysis techniques (Table 3.4). DCA and CCA showed the highest eigenvalues, and as CCA includes environmental variables along with species variation in the axes development, this analysis was

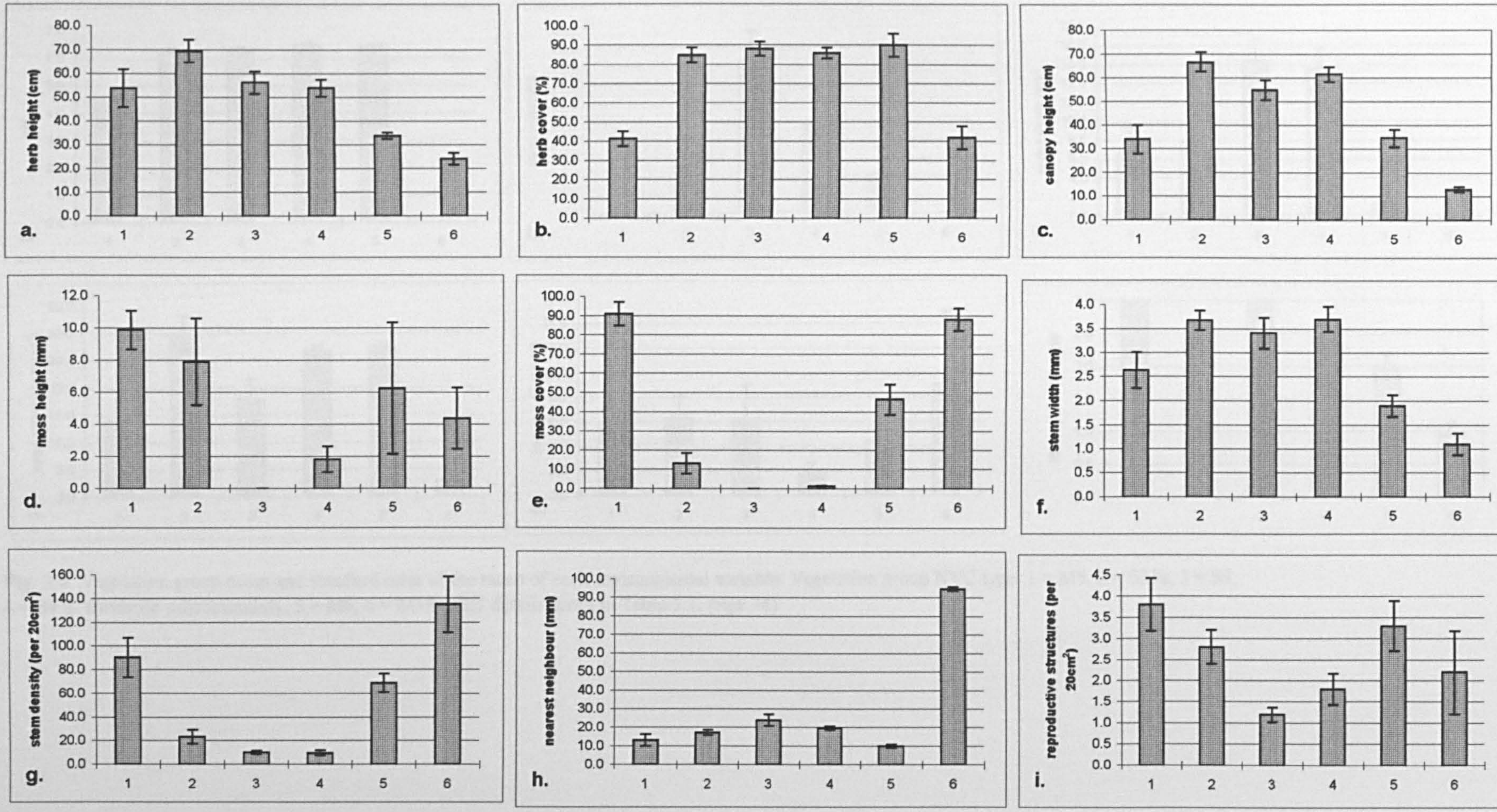


Fig. 3.3 Vegetation group mean and standard error of the mean of each plant trait variable. Shrub height and cover were omitted from analysis due to incomplete data. Vegetation group NVC type: 1 = M5, 2 = S27a, 3 = S9, 4 = S9 *E. fluviatile* subcommunity, 5 = M9, 6 = M18a (full details given in Table 3.1, page 74)

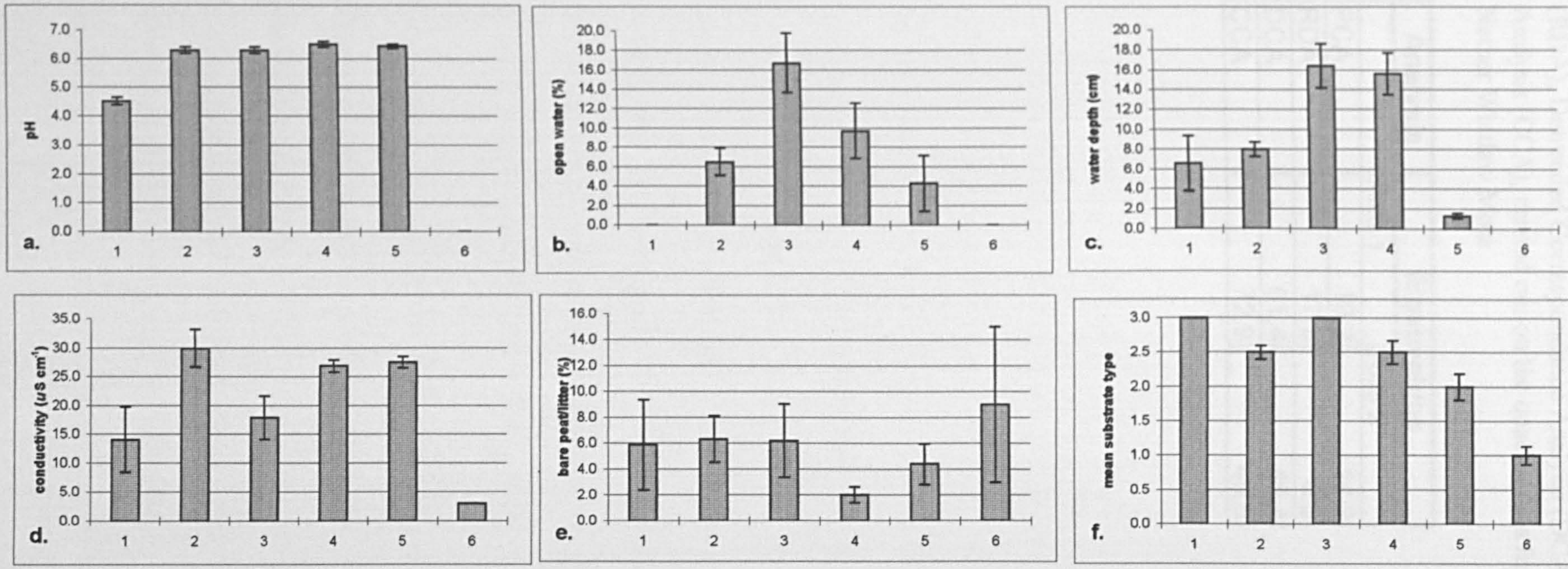


Fig. 3.4 Vegetation group mean and standard error of the mean of each environmental variable. Vegetation group NVC type: 1 = M5, 2 = S27a, 3 = S9, 4 = S9 E. fluviatile subcommunity, 5 = M9, 6 = M18a (full details given in Table 3.1, page 74)

Table 3.4 Eigenvalues for axes 1 and 2 of the ordination using each multivariate analysis techniques, Principal Components Analysis (PCA), Redundancy Analysis (RDA), Detrended Correspondance Analysis (DCA) and Canonical Corespondance Analysis (CCA), carried out on the quadrat data from Long Moss and Nether Whitlaw Moss

Analysis	**Eigenvalues**	
	Axis 1	*Axis 2*
PCA	19.2	14.2
RDA	17.3	8.3
DCA	81.4	45.4
CCA	72.9	49.8

assessed further. As a result, only CCA is discussed in more detail.

Four main groups were identified from the CCA ordination diagram (Fig. 3.5), and reflected the six vegetation types identified through TWINSPAN (Hill 1979) analysis (Table 3.5). The first synthetic gradient (axis 1) separates the quadrats with the more ombrotrophic species from those with more minerotrophic species. The second gradient (axis 2) splits up these minerotrophic quadrats into typically rich-fen and poor-fen species.

The first gradient (axis 1, Fig. 3.5) was positively correlated with bare peat, moss cover, stem density and shrub cover, and negatively correlated with electrical conductivity (EC), pH, canopy height, open water, stem width, herb height, substrate type, water depth and nearest neighbour distance. This gradient separated out the bog vegetation (group 6) from the more minerotrophic vegetation (groups 2, 3 and 4). The second gradient (axis 2) was positively correlated with shrub height, and separated the *Sphagnum*-dominated poor fen (group 1) from the sedge-dominated rich fen (group 5). The poor-fen communities (groups 2, 3 and 4) were difficult to separate, as was separating the samples through TWINSPAN (Hill 1979), which reflects the floristic and environmental similarities of these groups.

Each group could be associated with particular variables according to its position with respect to each variables gradient (represented by the arrow). The *Sphagnum*-dominated poor fen (group 1) was positively associated with shrub height and negatively associated with herb cover. The poor fen types (groups 2, 3 and 4) were positively associated with shrub and canopy height, herb cover, open water cover and stem width, and negatively associated with shrub and moss cover. Rich fen types

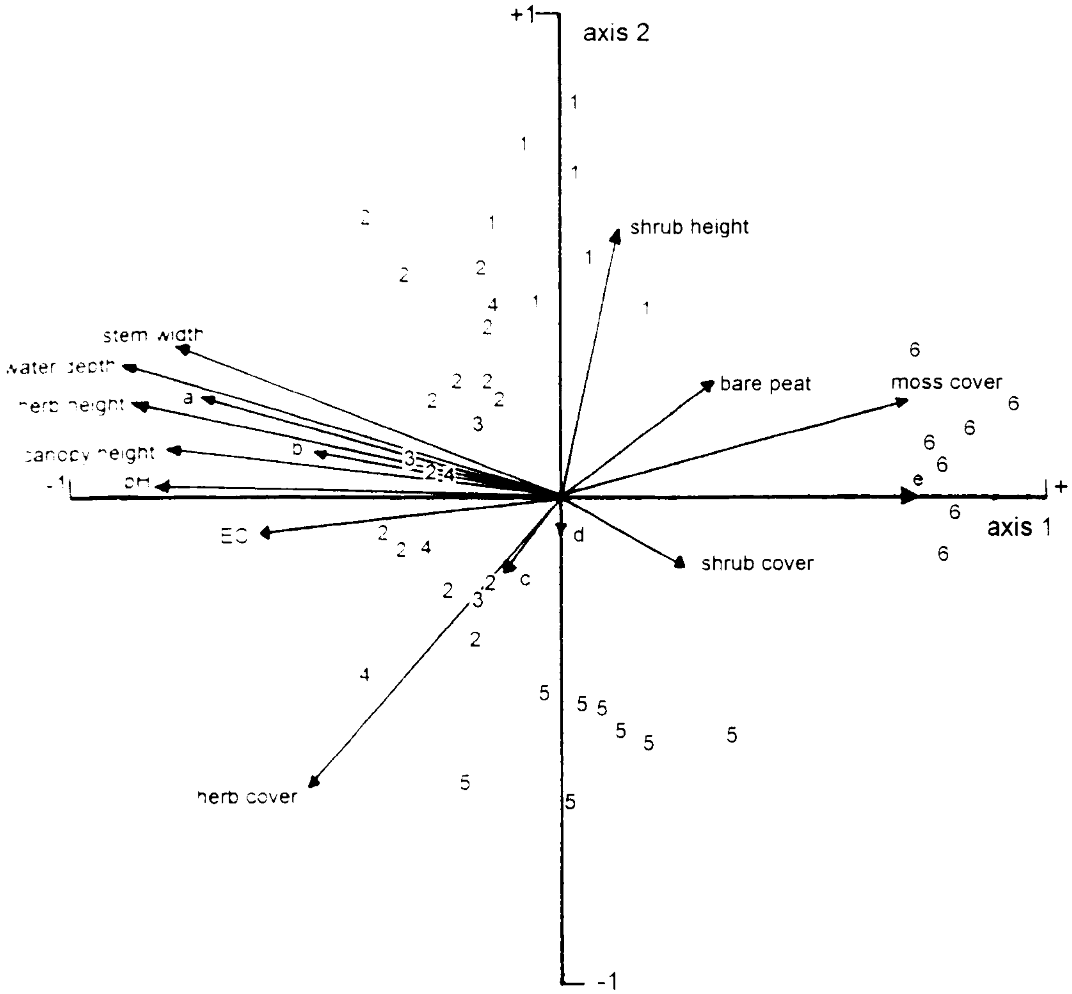


Fig. 3.5 Ordination plot showing plant and environmental variables (arrows) in relation to quadrat samples from each of the six vegetation groups, as detailed in Table 3.1. Coded variables as follows: a) substrate type, b) open water, c) no. reproductive structures, d) moss height, e) stem density.

Table 3.5 The vegetation groups derived from the Canonical Correspondance Analysis (CCA) of quadrat data for Long Moss and Nether Whitlaw Moss, along with associated TWINSPAN (Hill 1979) group and National Vegetation Classification (NVC) type (Rodwell 1991, 1995)

CCA Group	Vegetation Type	TWINSPAN Group	NVC Type
A	*Carex rostrata - Menyanthes trifoliata* poor fen, *Sphagnum* subcommunity	1	M5
B	*Potentilla palustris - C. rostrata* transitional fen	2	S27a
	C. rostrata - M. trifoliata poor fen	3	S9
	C. rostrata - M. trifoliata poor fen, *Equisetum fluviatile* subcommunity	4	S9
C	*Carex panicea - C. pulicaris* rich fen	5	M9
D	*Eriophorum angustifolium - Sphagnum magellanicum* mire	6	M18a

(group 5) were positively associated with herb cover, and to a lesser degree with shrub and moss cover, while negatively associated with shrub height. The final group of ombrotrophic mire species (group 6) was positively associated with moss cover, and negatively associated with stem width, canopy height and open water cover.

3.3.5 Predicting vegetation communities using plant functional traits and simple environmental measurements

The results from the CCA for the data set were used to ascertain a subset of measured variables (plant traits and environmental variables) that were significant in determining the species composition (*see section 3.4*). This subset of variables were identified using 'forward selection' procedures, which determines the effect of a single variable on the first synthetic gradient (axis 1) produced from the CCA (Ter Braak & Verdonschot 1995). The statistical significance of the effect of each variable was analysed by a Monte Carlo permutation test. All analyses were carried out using the CANOCOanalysis programme (Ter Braak 1992).

The environmental variables could be ranked in their order of importance for determining species composition (Table 3.6). These variables could then be reduced to a sub-set that were significant in explaining the variation in species composition. The species become the 'response' variables, and the environmental variables become the 'predictor' variables. This is similar to linear regression except that CCA uses relative abundance values for species, while linear regression uses real abundance values (Jongman *et al.* 1995).

The measured variable acted as the 'predictor' and the expected species composition as the 'response'. Out of the 17 variables measured, six variables well explained the

Table 3.6 Plant and environmental variables ranked by their marginal and conditional effects, as obtained from forward selection. **Li** = fit = eigenvalue with variable j only; La = additional fit = increase in eigenvalue; **cum. La** = cumulative totals of eigenvalues La; p = significance level of the effect (Monte Carlo permutation test with null model of 99 random permutations). EC = electrical conductivity

Marginal effects (forward: step 1)			
j	**variable**	**Li**	***p***
7	pH	0.58	**0.010**
12	canopy height	0.57	**0.010**
6	moss cover	0.52	**0.010**
15	stem density	0.49	**0.010**
13	stem width	0.49	**0.010**
2	herb height	0.47	**0.010**
17	substrate	0.45	**0.010**
10	water depth	0.45	**0.010**
5	herb cover	0.42	**0.010**
11	EC	0.36	**0.010**
1	shrub height	0.33	**0.010**
14	nearest neighbour	0.31	**0.010**
9	open water	0.22	**0.010**
3	moss height	0.17	0.050
8	bare peat	0.17	0.110
16	reprod. structures	0.16	0.040
4	shrub cover	0.13	0.360

Conditional effects (forward: cont.)				
j	**variable**	**La**	***p***	**cum.(La)**
7	pH	0.58	**0.010**	0.58
12	canopy height	0.37	**0.010**	0.95
5	herb cover	0.32	**0.010**	1.27
6	moss cover	0.24	**0.010**	1.51
17	substrate	0.22	**0.010**	1.73
10	water depth	0.20	**0.010**	1.93
15	stem density	0.12	0.510	2.05
13	stem width	0.14	0.140	2.19
2	herb height	0.11	0.700	2.30
11	EC	0.09	0.290	2.39
1	shrub height	0.14	0.220	2.53
14	near neighbou	0.08	0.370	2.61
9	open water	0.08	0.560	2.69
3	moss height	0.19	0.055	2.88
8	bare peat	0.12	0.510	3.00
16	reprod. struct.	0.10	0.120	3.10
4	shrub cover	0.09	0.320	3.19

species composition in the separate vegetation groups (Table 3.6). These were, in rank order of importance, pH, canopy height, herb cover, moss cover, substrate type and water depth. The CCA ordination diagram using only these six variables (Fig. 3.6) gave the same vegetation groups and species compositions as initial analysis using all 17 variables, emphasising the dominant effects of these six variables on species and sample separation.

While CCA interprets the species distributions in relation to measured variables, correlation and linear regression is used to assess the degree of inter-relationships between variables measured within a vegetation group. Again with the goal of clarifying those variables that were significantly related to each other, in an attempt to reduce the number of variables required to give information about a particular vegetation group. Linear regression analysis also assessed if relationships between variables in a single vegetation group ('full model') were the same across all six vegetation groups identified through TWINSPAN (Hill 1979) ('simple model') by calculating the observed test statistic (the F-test). The use of these selected variables in predicting vegetation groups across a range of vegetation types could then be tested statistically. In all analyses shrub height, shrub cover and substrate type were omitted due to incomplete data sets.

There were many significant linear correlations (2-tailed test, $p = <0.05$) between the variables measured for each vegetation group (Table 3.7; Pearson product moment correlation coefficients). Only a few variables showed correlations that may be used to explore predicted variables through linear regression analysis. Herb height was positively correlated with many variables including other plant functional traits (such as herb cover, nearest neighbour distance and stem width), and environmental

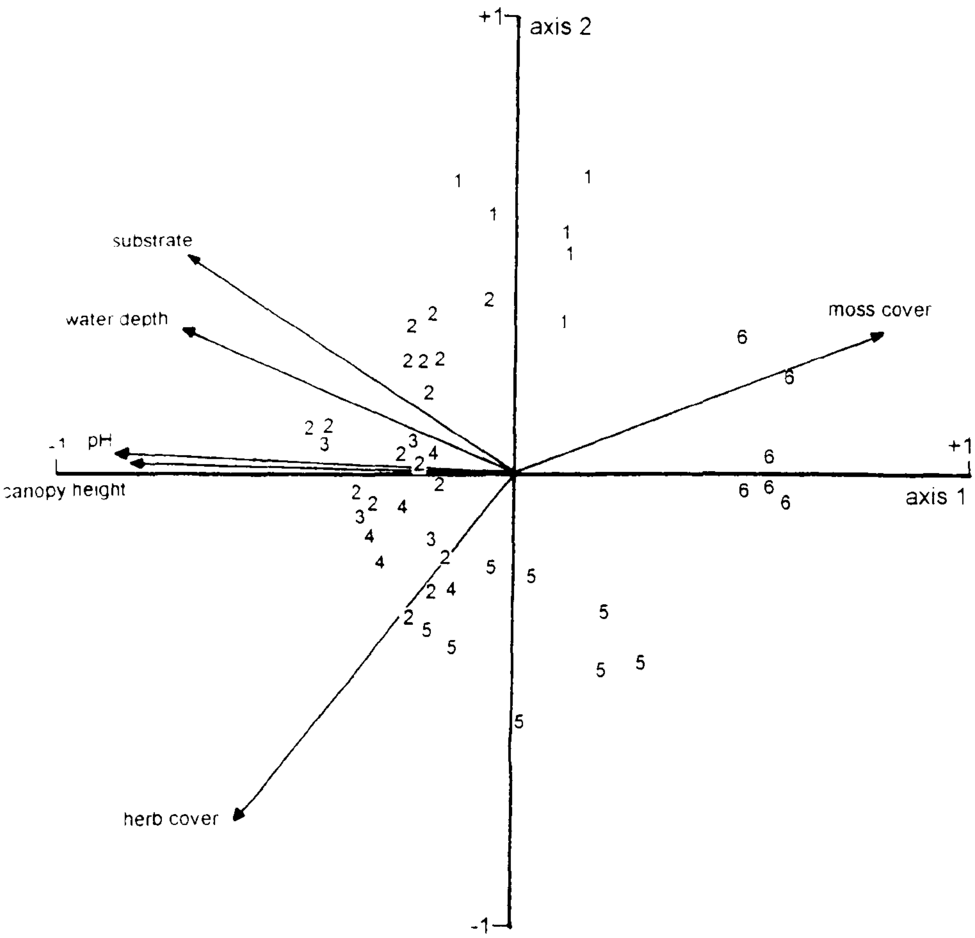


Fig. 3.6 Ordination diagram of the partial CCA using only significant variables, as selected using the Monte Carlo test. Samples from the six vegetation groups (as detailed in Table 3.1) are identified on the ordination.

Table 3.7 Pearson product moment correlation coefficients results for all plant and environmental variables for the combined data of Long Moss and Nether Whitlaw Moss, using a two-tailed test 5% significance level. Significant, linear correlations are shown in bold.
EC = electrical conductivity

	Herb Height	Moss Height	Herb Cover	Moss Cover	Canopy Height	Stem Width	Nearest Neighbour	Stem Density per 20cm^2	Reproductive Structures	pH	EC	Bare Peat/ Litter	Open Water
Moss height	-0.188												
Herb Cover	**0.348**	-0.098											
Moss Cover	**0.562**	**0.377**	**-0.741**										
Canopy Height	**0.871**	-0.200	**0.580**	**-0.754**									
Stem Width	**0.615**	-0.212	**0.467**	**-0.658**	**0.723**								
Nearest Neighbour	**0.373**	-0.127	0.222	**-0.500**	**0.475**	**0.321**							
Stem Density	**-0.502**	0.230	**-0.631**	**0.837**	**-0.684**	**-0.592**	**-0.556**						
Reproductive Structures	0.018	**0.449**	0.006	0.243	-0.050	-0.050	-0.197	0.184					
pH	0.099	**-0.503**	**0.790**	**-0.762**	**0.376**	**0.294**	0.131	**-0.622**	**-0.372**				
EC	**0.337**	-0.087	**0.422**	**-0.333**	**0.408**	0.222	0.021	**-0.310**	0.169	**0.291**			
Bare Peat/Litter	-0.089	0.096	**-0.299**	0.133	-0.121	**-0.312**	0.134	0.017	-0.062	**0.380**	-0.005		
Open Water	0.058	-0.225	0.155	**-0.474**	0.206	**0.289**	**0.469**	**-0.433**	**-0.322**	**0.307**	-0.130	-0.202	
Water Depth (cm)	**0.498**	**-0.360**	**0.331**	**-0.674**	**0.588**	**0.528**	**0.502**	**-0.626**	**-0.280**	**0.333**	0.053	-0.130	**0.457**

variables (such as EC and water depth). Herb cover showed similar significant correlations. Moss cover was negatively correlated with many variables including canopy height, stem width, nearest neighbour distance and pH.

Overall, two variables (herb height and pH) showed significant linear relationships with many other variables. Herb height was positively correlated with herb cover, canopy height, stem width, nearest neighbour distance, conductivity and water depth. It was negatively correlated with moss cover and stem density. The pH value was positively correlated with EC and open water cover, and negatively correlated with bare peat/litter cover, number of reproductive structures and moss height.

Two variables selected as 'predictors' for further analysis through linear regression were herb height and pH. These two variables appeared to be potentially useful as predictors of many other variables measured from the correlation analysis, and were themselves easy to measure in the field.

A great deal of variation in measured variables was found within a single vegetation group using the full linear regression model. Assessing each regression equation for each vegetation group there were many significant results with pH or herb height as the predictor variable (Table 3.8). The greater number of significant regression equations were seen in Groups 1 and 2, few occurred in groups 3, 4 and 6, while no statistically significant interactions were seen in Group 5. The R-squared values, evaluating the fit of the regression line to the data set, for these significant results were relatively high, usually R^2 = >30 %, although some non-significant regression results also gave similar R-squared values.

Table 3.8 Full model linear regression analysis results for combined data for each vegetation group. Non-significant models not shown, significant values ($p = <0.05$) are shown in bold for intercept, slope and F-value. EC = electrical conductivity

Predictor ***x-axis***	**Response** ***y-axis***	**Vegetation Group**	**intercept** ***a***	**slope** ***b***	**R^2** ***(%)***	**ANOVA** ***F-value***
herb height	moss cover	1	127.3	-0.670	75.1	18.05
	canopy height		-0.3	**0.639**	69.9	**13.91**
	nearest neighbour		-4.2	**0.319**	66.8	**12.09**
	EC		-10.3	**0.455**	40.4	**4.06**
	water depth		-8.5	**0.235**	84.6	**33.02**
herb height	moss cover	2	**52.0**	**-0.559**	41.6	**16.41**
	canopy height		12.4	**0.780**	77.6	**79.68**
	stem width		**2.0**	**0.024**	38.0	**14.11**
	water depth		2.2	**0.080**	28.2	**9.02**
pH	bare peat		**40.5**	**-6.038**	41.5	**16.30**
	moss height		**76.3**	**-11.277**	32.9	**11.30**
herb height	canopy height	3	18.7	**0.644**	49.8	**5.96**
	EC		47.5	-0.529	42.5	4.44
herb height	canopy height	4	15.6	**0.847**	88.8	**63.67**
	water depth		-5.9	**0.397**	43.2	**6.08**
herb height	EC	5	**40.6**	-0.401	65.4	5.67
	water depth		**6.3**	-0.164	47.3	5.39
pH	EC		108.9	-12.672	62.2	4.94
herb height	stem density	6	-62.7	**8.184**	73.1	**16.32**

Again, a great deal of variation in measured variables was found between the six vegetation groups using the simple linear regression model. All regression analyses of these simple linear models gave significant results, although not all also had high R-squared values (Table 3.9). Herb height appeared to be a relatively good predictor for moss cover (R^2 = 31.6 %), canopy height (R^2 = 75.8 %), and stem width (R^2 = 37.8 %).

Calculation of the observed test statistic (F-value) allowed statistical comparisons between the complex and the simple models, allowing the complex model to be accepted (p = >0.05), or rejected (p = <0.05) in favour of the simple model. The complex model was rejected in only five out of a possible thirteen cases (Table 3.10). In these five cases the simple model was significantly different to the complex model (p = <0.05), and accepted in favour of it, although the R-squared values were low for these five simple models. In the remaining eight models the complex model could not be rejected (p = >0.05), showing bivariate relationships between predictor and response variables in one group did not hold across the six vegetation groups. Although the regression results were not all statistically significant, there were some high R-squared values, as discussed in the results for the complex model.

3.3.6 Further assessment of the effects of plant functional traits and environmental conditions on species compositions - partial CCA.

The effects of some variables are known to influence species composition, such as pH and electrical conductivity (EC), and may have obscured the more subtle effects of other measured variables. Similarly, some variables were not of particular interest in terms of predicting vegetation types. In this case moss, herb and shrub cover, bare

Table 3.9 Simple model linear regression results for all vegetation groups combined Only significant models shown. Significant ($p = <0.05$) results for slope, intercept and F-value are shown in bold. EC = electrical conductivity

Predictor *x-axis*	Response *y-axis*	intercept *a*	slope *b*	R^2 *(%)*	ANOVA *F-value*
herb height	herb cover	**59.3**	**0.342**	12.1	**8.94**
	moss cover	**82.3**	**-0.932**	31.6	**30.04**
	canopy height	1.7	**0.900**	75.8	**203.53**
	stem width	**1.2**	**0.033**	37.8	**39.58**
	nearest neighbour	**9.3**	**0.137**	13.9	**10.53**
	stem density	**108.9**	**-1.156**	25.2	**21.91**
	conductivity	**12.4**	**0.215**	11.4	**7.07**
	water depth	-0.5	**0.153**	24.8	**21.40**
pH	conductivity	-8.0	**5.447**	8.4	**4.98**
	bare peat/litter	**19.9**	**-2.812**	14.4	**9.10**
	open water	-12.3	**2.973**	9.4	**5.62**
	reproductive structures	**8.4**	**-1.008**	13.8	**8.67**
	moss height	**34.3**	**-4.978**	25.3	**18.25**

Table 3.10 Comparison of the complex and simple linear models, using the F-test. Bold figures show models significant at the 5% level ($p = <0.05$). EC = electrical conductivity, N = number of observations

Regression equation	N	F-value
herb cover = a + (b**herb height*)	67	24.147
moss cover = a + (b**herb height*)	67	31.354
canopy height = a + (b**herb height*)	67	6.727
stem width = a + (b**herb height*)	67	5.038
nearest neighbour = a + (b**herb height*)	67	2.240
stem density = a + (b**herb height*)	67	13.289
EC = a + (b**herb height*)	57	**1.660**
water depth = a + (b**herb height*)	67	12.858
EC = a + (b**pH*)	56	**0.778**
bare peat = a + (b**pH*)	56	**0.616**
open water = a + (b**pH*)	56	6.233
reproductive structures = a + (b**pH*)	56	**2.004**
moss height = a + (b**pH*)	56	**1.718**

peat cover, and substrate type were shown to have non-significant effects on plant distribution, or be less useful in the field (*see section 3.5*). The effects of both types of variables were eliminated ('partialled out') by treating them as covariables, a procedure known as partial CCA. The effects of the remaining variables were singled out from the known background variation imposed by the covariable, and their significance on species distribution tested using the Monte Carlo permutation test.

Covariables eliminated were pH, EC, moss cover, herb cover, shrub cover, bare peat cover and substrate type. The remaining ten variables were included in the partial CCA. The partial CCA ordination diagram (Fig. 3.7) showed axis 1 to be positively correlated with shrub height, herb height, stem width and nearest neighbour distance, and axis 2 to be positively correlated with moss height and reproductive structures, and negatively correlated with water depth and open water. Within the ordination diagram the six vegetation groups were difficult to separate out as all samples occurred close together toward the centre of the ordination diagram. Some general patterns could be seen with respect to the separate variables. *Carex rostrata - Menyanthes trifoliata* poor fen, *Sphagnum squarrosum* sub-community (group 1) was positively correlated to moss height, shrub height and number of reproductive structures, and negatively correlated to water depth and open water cover. *Potentilla palustris - C. rostrata* transitional fen (group 2) showed a similar pattern, but also occurred along a range of herb heights and stem widths. *C. rostrata - M. trifoliata* poor fen types (groups 3 and 4) showed positive correlations with open water, and negative correlations with shrub and herb height. Group 4 (the *Equisetum fluviatile* sub-community) also showed a positive correlation with water depth. *Carex*-dominated rich fen (group 5) again showed a positive correlation with open water,

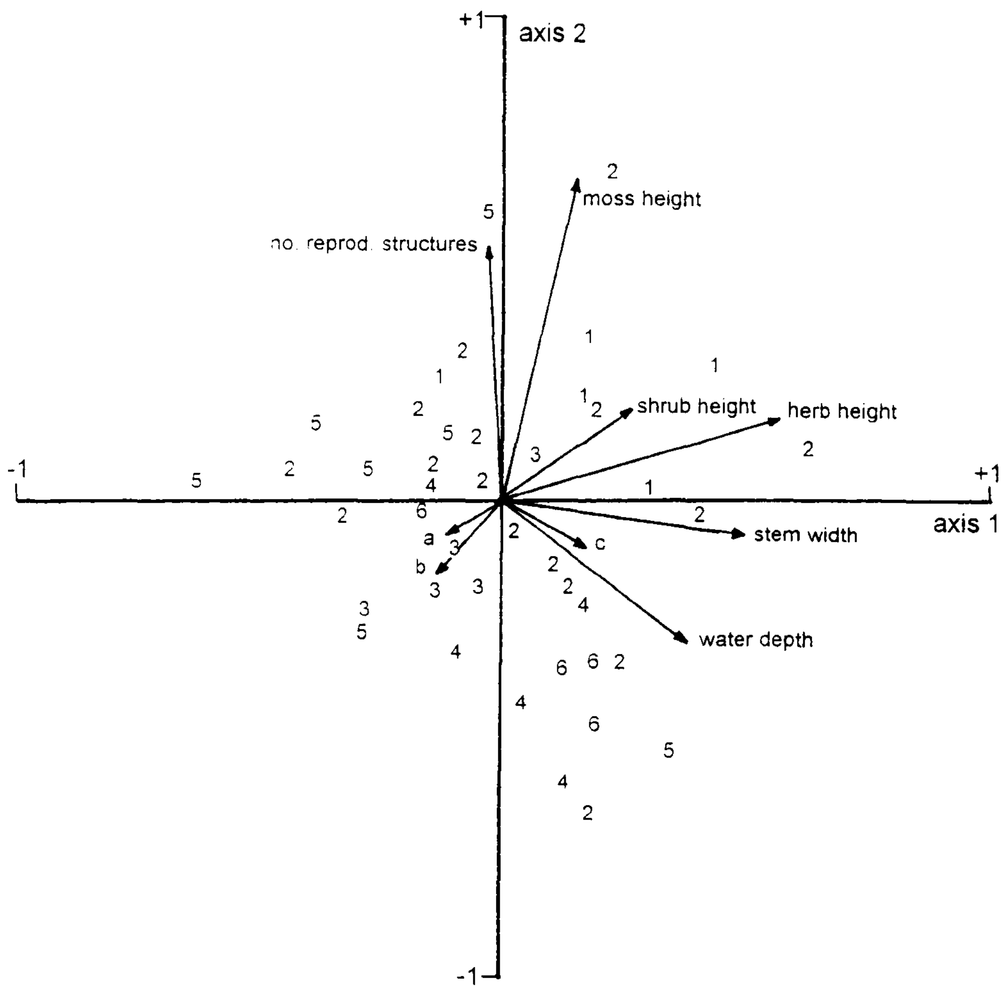


Fig 3.7 Ordination plot of the partial CCA results using selected variables to predict vegetation types. a = nearest neighbour distance and stem density, b = open water cover. The samples relating to the six vegetation groups (as detailed in Table 3.1) are shown.

and a negative correlation with herb height and additionally stem width. The final group *Eriophorum angustifolium - Sphagnum magellanicum* mire (group 6) was scattered over the ordination although it appeared to be negatively associated with herb and moss height.

The influence of each of the ten variables was assessed using forward selection procedures, which determined the effect of a single variable on the first synthetic gradient (axis 1) produced from the partial CCA. Their statistical significance was tested using a Monte Carlo permutation procedure. The measured variable acts as the 'predictor' and the expected species composition as the 'response'. Out of the ten variables measured, four variables well explained the species composition in the separate vegetation groups (Table 3.11). These were, in rank order of importance, canopy height, water depth, moss height and stem width. All four variables significantly influenced the species distribution in the previous CCA (see *section 3.6*), and this second CCA allowed the influence of these four specific variables to be studied in greater detail. In the CCA ordination diagram (not illustrated) axis 1 was positively correlated with canopy height, while axis 2 was positively correlated with water depth and negatively correlated with moss height. Again the samples were not well separated by the partial CCA ordination, and groups were not obvious, but some links to individual variables were seen. *Carex rostrata - Menyanthes trifoliata* poor fen, *Sphagnum squarrosum* sub-community (group 1) was positively associated with canopy height, *C. rostrata - M. trifoliata* poor fen (group 3) was positively associated with water depth and negatively associated with moss height. *Carex*-dominated rich fen (group 5) was negatively associated with canopy height and water depth. The *Potentilla palustris - C. rostrata* transitional fen (groups 2), *C. rostrata* -

Table 3.11 Selected plant and environmental variables as used in partial CCA ranked by their marginal and conditional effects, as obtained from forward selection.
Li = fit = eigenvalue with variable *j* only; **La** = additional fit = increase in eigenvalue; **cum. La** = cumulative totals of eigenvalues La; **p** = significance level of the effect (Monte Carlo permutation test with 99 random permutations)

Marginal effects (forward: step 1)			
j	**variable**	**Li**	***p***
12	canopy height	0.26	**0.010**
2	herb height	0.26	**0.010**
13	stem width	0.22	**0.010**
10	water depth	0.21	**0.010**
3	moss height	0.21	**0.010**
1	shrub height	0.15	0.030
16	reprod. structures	0.14	0.030
15	stem density	0.13	0.100
14	nearest neighbour	0.12	0.070
9	open water	0.10	0.210

Conditional effects (forward: cont.)				
j	**variable**	**La**	***p***	**cum.(La)**
12	canopy height	0.26	**0.010**	0.26
10	water depth	0.20	**0.010**	0.46
3	moss height	0.19	**0.010**	0.65
13	stem width	0.14	**0.010**	0.79
16	reprod. struct.	0.11	0.070	1.00
1	shrub height	0.13	0.060	1.03
2	herb height	0.12	0.070	1.15
15	stem density	0.11	0.120	1.26
14	near neigh.	0.09	0.270	1.35
9	open water	0.08	0.270	1.43

M. trifoliata poor fen, *Equisetum fluviatile* sub-community (group 4) and *Eriophorum angustifolium - Sphagnum magellanicum* mire (group 6) all appeared to be scattered over the ordination diagram with no identified trends with respect to these four variables.

3.3.7 Separating the poor fen vegetation types using CCA

Analysis of the quadrat data effectively separated out the three distinct mire types (*C. rostrata - M. trifoliata* poor fen, *E. fluviatile* sub-community; *Carex*-dominated rich fen; *Eriophorum - Sphagnum* mire), but the poor fen vegetation types were more difficult to define despite partial CCA using significant variables only. The strong effects of these three vegetation types may mask the subtle differences between the poor fen types, therefore an analysis of the quadrats from the poor fen vegetation types only was carried out. The CCA used all 17 variables measured and forward selection was used to determine those variables that were significant (Monte Carlo permutation test) in the species distribution. The CCA ordination diagram (Fig. 3.8) showed axis 1 was weakly positively correlated with pH, and negatively correlated with canopy height, herb cover and EC. Axis 2 was positively correlated with stem density, moss height and moss cover, and negatively correlated with substrate type and herb height. The three vegetation types were identified but the groups occurred close together. The *P. palustris - C. rostrata* transitional fen (group 2) was scattered over the ordination, but samples appeared to be associated with increased canopy height, herb cover, stem density and moss height. Group 3, the *C. rostrata - M. trifoliata* poor fen, was associated with increased shrub height and a floating substrate type, and negatively correlated to stem density, moss height and moss cover. The *C. rostrata - M. trifoliata* poor fen, *Equisetum* sub-community (group

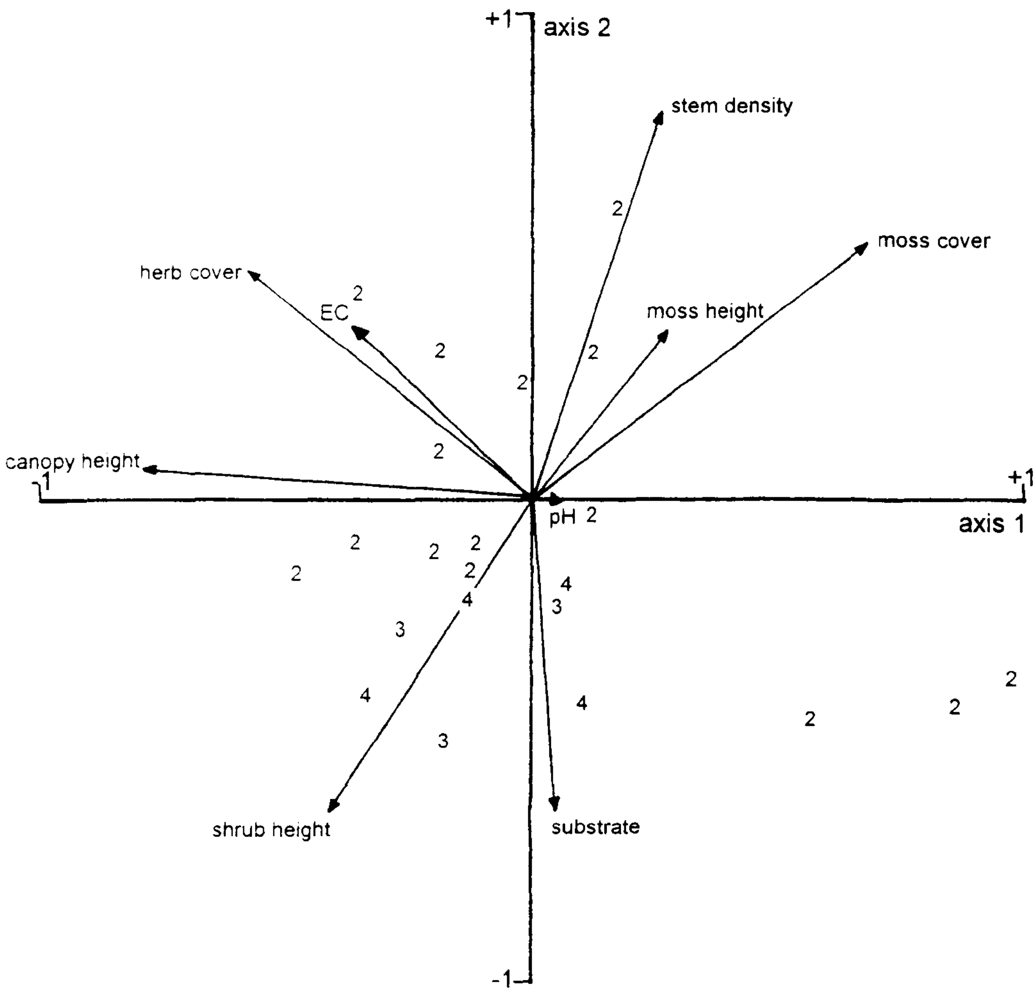


Fig. 3.8 Ordination of CCA of poor fen and transitional fen samples only (groups 2.3 and 4), showing plant and environmental variables.

4) was also associated with the same variables as group 3, but to a lesser degree.

Analysis of each of the seventeen variables (using forward selection and Monte Carlo permutation tests) gave 7 variables that were significant in determining species distribution in the CCA (Table 3.12). These are, in rank order of importance, moss cover, stem density, canopy height, substrate type, pH, moss height and water depth. The remaining variables had no significant effect. A second CCA ordination (not illustrated) using only these 7 significant variables gave similar species-sample separation and the similar variables showed the same trends. Here the *P. palustris* - *C. rostrata* transitional fen (group 2) was associated with increasing stem density, pH and canopy height, and *C. rostrata* - *M. trifoliata* poor fen types (groups 3 and 4) with increasing shrub height and floating mat formation and decreasing moss cover, stem density and pH.

3.4 Discussion

The use of TWINSPAN (Hill 1979) in classification of vegetation community data is widespread in vegetation ecology (*e.g.* Smith & Charman 1988, Chapman & Rose 1991). It has been suggested (Gauch and Whittaker 1981) that because it is a divisive cluster analysis technique, and uses all information to produce the initial division, it is a more robust analysis method for large, complex and variable datasets than agglomerative cluster analysis techniques, such as Ward's analysis (Ward 1963, Orloci 1967). The TWINSPAN (Hill 1979) analysis of the combined Long Moss and Nether Whitlaw Moss quadrat data produced clearly identifiable and ecologically meaningful vegetation classifications. Six main vegetation groups were identified

Table 3.12 Selected plant and environmental variables ranked by their marginal and conditional effects, as obtained from forward selection of poor fen samples (quadrat) only. **Li** = fit = eigenvalue with variable j only; **La** = additional fit = increase in eigenvalue, **cum. La** = cumulative totals of eigenvalues La; **p** = significance level of the effect (Monte Carlo permutation with null model of 99 random permutations). EC = electrical conductivity

Marginal effects (forward: step 1)			
j	**variable**	**Li**	***p***
6	moss cover	0.32	**0.010**
15	stem density	0.32	**0.010**
12	canopy height	0.32	**0.010**
2	herb height	0.29	**0.010**
17	substrate	0.26	**0.010**
10	water depth	0.25	**0.010**
5	herb cover	0.24	0.050
3	moss height	0.22	0.150
13	stem width	0.21	**0.010**
16	reprod. structures	0.21	0.040
8	bare peat	0.21	0.070
14	nearest neighbour	0.20	0.010
11	EC	0.19	0.030
7	pH	0.18	0.080
9	open water	0.16	0.020

Conditional effects (forward: cont.)				
j	**variable**	**La**	***p***	**cum.(La)**
6	moss cover	0.32	**0.010**	0.32
15	stem density	0.31	**0.010**	0.61
12	canopy height	0.25	**0.010**	0.87
17	substrate	0.21	**0.010**	1.08
7	pH	0.21	**0.010**	1.29
3	moss height	0.17	**0.010**	1.46
10	water depth	0.16	**0.010**	1.62
5	herb cover	0.12	0.080	1.74
11	EC	0.11	0.080	1.85
8	bare peat	0.08	0.090	1.93
9	open water	0.08	0.090	2.01
16	reprod. struct.	0.08	0.060	2.09
14	near neigh.	0.07	0.120	2.16
2	herb height	0.07	0.120	2.23
13	stem width	0.07	0.150	2.30

which together encompassed a range from bog, species-poor fen to species-rich fen characteristics. Subtle changes in species dominance were used for TWINSPAN division after these six main groups, but were more difficult to judge whether they reflected ecologically significant changes in floristic composition. These latter splits may be a consequence of the artificial divisions enforced by the TWINSPAN analysis standard run, and not actually ecologically significant. TWINSPAN (Hill 1979) is not without its problems with regard to data distortion (Van Groenewoud 1992, Tausch *et al.* 1995), and this may be particularly problematic in small datasets as when analysing discrete sites, or a small number of sites.

Canonical correspondence analysis (CCA) reflected the same directions of vegetation change. The analysis effectively separated off the ombrotrophic species from the minerotrophic species, and the species-rich fen from the species-poor fen. The six TWINSPAN (Hill 1979) vegetation groups could be identified in the CCA ordination diagram, although the *Carex rostrata* species-poor fen types (TWINSPAN groups 2, 3 and 4) were less clearly separated both in the full CCA, and the partial CCA using only poor fen quadrats. This may reflect the similarities in floristic composition of these three fen types. Problematic groups may also represent vegetation ecotones that are highly variable transition zones between main vegetation types, and therefore more difficult to classify successfully, or they may represent separate vegetation groups that have not been adequately sampled in the field (Tausch *et al.* 1995).

The difficulty in separating the poor fen vegetation groups was also reflected in assigning National Vegetation Classification (NVC) types (Rodwell 1991, 1994) to these groups. Particularly in assigning the *C. rostrata - Potentilla palustris* tall herb fen, the *C. rostrata* swamp and the *E. fluviatile* swamp vegetation groups (NVC types S27a, S9 and S10). Rodwell (1994) notes the floristic similarities between these three vegetation types including the development of ecotones. Problems in satisfactorily dividing and assigning NVC types to fen vegetation types in the Borders Region have been reported elsewhere (Tratt 1997). For the remaining three vegetation groups the analysis of similarities with the NVC was on the whole useful, with some high values of coefficients of similarities that indicated a good match between the vegetation group and the standard NVC group. Vegetation types were also found to be similar to the vegetation communities identified in Scotland by Ratcliffe (1964) and Spence (1964), and these communities often had more similarities to the six TWINSPAN (Hill 1979) vegetation groups than the equivalent NVC type. This was particularly noticable for groups 2, 3 and 4, where the dominant species were better represented by the Spence (1964) and Ratcliffe (1964) vegetation communities, whereas they were typically treated as indicators of sub-communities by the NVC.

Phytosociological techniques and the NVC require knowledge of the habitat along with expertise in species identification. The basis of these techniques is the selection of homogeneous vegetation types, which is essentially subjective and heavily reliant on the expertise of the individual. Multivariate techniques such as CCA are not based on the initial selection of homogeneous vegetation areas, but still require plant species identification skills. Techniques employing plant traits and simple environmental variables are not dependent on species identification. This approach amalgamates species into functional groups which share the same ecological traits, and these ecological traits are reflected in the measured plant traits (Boutin & Keddy 1993). The vegetation and environment are characterized using measurements such as plant height, stem density and moss cover. As such they are simpler and quicker to apply, and this makes them potentially useful as conservation management tools. Regular monitoring of selected plant traits and environmental variables could provide a means of tracking the subtle changes in environmental conditions, some of which (*e.g.* eutrophication or changes to the hydrological regime) may be deleterious to the vegetation type (Keddy & Shipley 1989, Verhoeven *et al.* 1994).

The seventeen environmental variables and plant traits measured in this study were highly correlated to each other. This multicollinearity of environmental variables is often seen in vegetation community datasets (Palmer 1993), and can make it difficult to distinguish the important environmental variables governing species composition. Overall, some trends were distinguished, and each vegetation group could be typified by a number of environmental and plant variables. These are outlined below:

- The *Sphagnum squarrosum* species-poor fen (group 1) main characteristics are sparse herbaceous vegetation, taller bryophyte growth, greater bryophyte cover dominated by *Sphagnum*, and a low surface water pH and electrical conductivity.

- The *Carex*-dominated species-rich fen (group 5) was characterized by an almost complete cover of low growing herbs, predominantly *Carex* species. In addition there was around a 50 % bryophyte cover that lacked *Sphagnum* species. Many other variables measured were in the mid-range of the dataset.

- The *Sphagnum*-dominated ombrotrophic mire (group 6) was characterized by a low herb cover, an understorey of ericoid shrubs, and a dense low cover of *Sphagnum*. There was also little open water on the surface.

- The species-poor and transitional, herbaceous fen types (groups 2, 3 and 4) were again more difficult to separate out on the basis of their environmental and vegetation variables. For all three groups taller, more robust herbaceous vegetation forming more open canopies was found in conjunction with more open water and deeper inundation levels.

These general trends lead to the hypothesis that taller more robust, open herb canopies are linked to greater open water area and depth. Conversely shorter herbs with increasingly dense bryophyte development are linked to shallow water depths and reduced open water cover (Fig. 3.9). While spatial patterning of vegetation on fens is readily described through classification, to assess the functions of these patterns, and hypothesise on underlying processes is more difficult (Keddy & MacLellan 1990). A common theme amongst vegetation patterning in many habitats is the role of competitive success. Keddy and Shipley (1989) and Givnish (1982) highlight plant height as a useful plant trait in predicting competitive success. The taller, robust species usually suppressing smaller ones, and obtaining more of a resource such as light or nutrients. In this study plant/canopy height and stem width recur as significant variables in separating vegetation groups. Yet the taller, more robust vegetation types are found in some of the more inhospitable conditions subject to frequent, deeper inundation and the problems that brings with anoxic conditions and waterlogging. Referring to Grime's (1974) theory these conditions would encourage vegetation that can tolerate these environmental stresses, and this usually reduces competitive ability. Here the function of taller, more robust vegetation structure may be to withstand frequent inundation, rather than increase competitive ability in terms of resource capture.

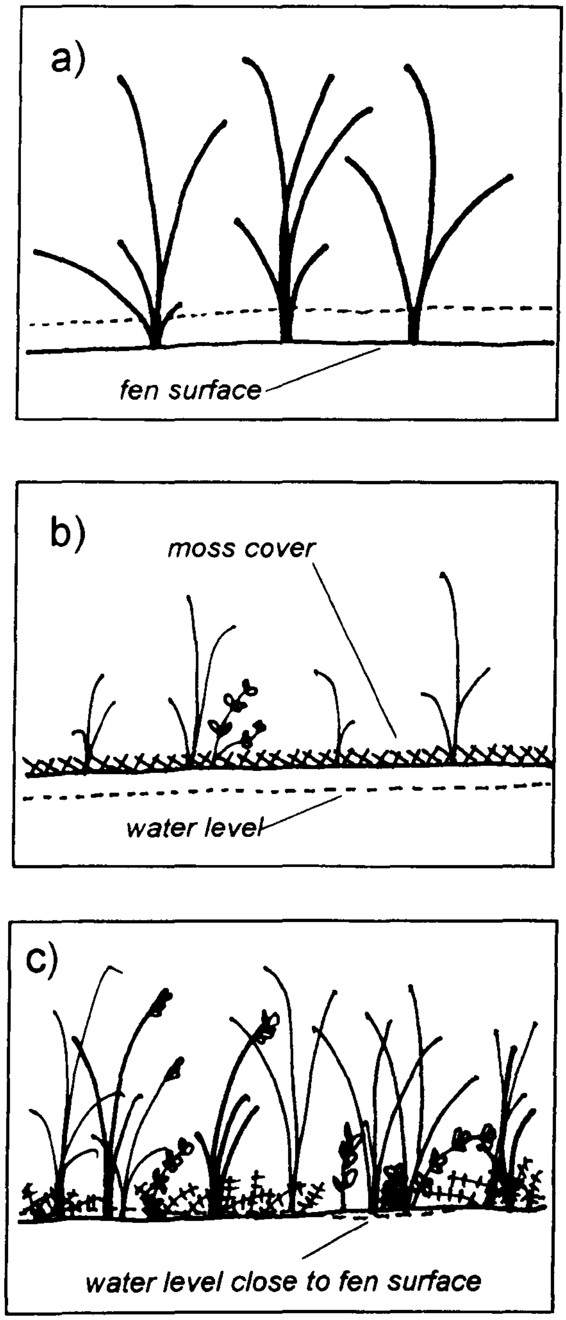


Fig. 3.9 Three main types of fen vegetation cover found; a) tall, open herbs, b) sparse herbs with dense moss cover, c) short, dense herbs with patchy moss cover.

Other variables important in vegetation group separation were stem density and bryophyte cover/height These three variables appear to be linked. The close, compact growth of *Sphagnum* species was separated from the more lax, taller growth of other bryophytes, such as the mosses of the rich fen. In addition the *Sphagnum* species tended to grow as large uninterrupted expanses, while other bryophytes grew as smaller patches interspersed with herbaceous cover or open water. Percent cover values reflect this. Fen environmental variables were also linked to these plant traits, with *Sphagnum* present in more acidic, low solute concentration water, or where no free water was present at all.

The strong directional gradients of water pH and electrical conductivity may obscure more subtle effect of other variables. Partial CCA was also used to remove these two variables and explore underlying trends (Ter Braak 1987, Jongman *et al.* 1995). Removing the strong ombrotrophic - minerotrophic gradient reflected in pH and electrical conductivity did not reveal any underlying, less obvious gradients in the vegetation. Few groups could be distinguished on the ordination, as species and sample points were clustered together.

One approach to dealing with multicollinear data is to reduce the number of collinear variables down to just two or three that are representative (Ter Braak 1987). Correlation coefficient results suggested that fen water pH and plant canopy height may be useful predictors of many other vegetation variables, and plant height has been noted as an important functional trait in wetlands in recent studies (Keddy & Shipley 1989, Willby *et al.* 1997). The linear regression models developed could not be successfully applied across vegetation groups. Results indicated that although surface water pH and/or plant height may be an effective predictor in some vegetation groups, it is unlikely to be so across all groups. There are problems recognised with this approach that may account for the poor relationships. Firstly, relationships between species distributions and environmental variables are generally non-linear, more usually a unimodal response curve, and so not suited to linear regression techniques (Ter Braak 1987). Secondly, reducing multicollinear variables to just one or two may remove variables that are significant in affecting species composition, even if they are not significant in variance-covariance structure of the environmental data (Palmer 1993).

The exploratory data analyses carried out using simple linear regression models and CCA were useful in presenting some hypotheses for future research, but, of course, the relationships between plant and environmental variables and the associated vegetation groups identified in this study were preliminary. The potential use of variables such as canopy height, water depth, stem density, *etc.* on other fen sites has not been explored. More data are required before conclusive relationships can be identified, and for fens these data are scarce. Many studies have focused on individual plant species responses to environmental factors in mire habitats (reviewed by Gignac 1994), but far fewer studies have taken a functional approach to mire vegetation community ecology. Encouragingly, for those studies that have taken a functional approach, some of the same variables (plant height and water depth) have been noted as being important in distinguishing between vegetation types in wetlands (Menges & Waller 1983, Keddy & Shipley 1989, Willby *et al.* 1997). Also at a larger scale, across distinct wetland types, the use of plant functional techniques appears potentially useful in evaluating wetlands (Verhoeven *et al.* 1994). There are, of course, many environmental variables that can potentially be assessed as indicators of mire type, not least hydrochemical variables such as calcium and nutrient concentrations (Willby *et al.* 1997). This is explored further in chapter 6.

CHAPTER 4

Hydrological functioning of two Scottish basin fens in relation to catchment and site characteristics

4.1 Introduction

Basin fens, like all mires, are influenced by their catchment hydrology. They also affect water movement within the catchment through their storage abilities. Although they are often small elements within a larger landscape, they form an important link in the hydrological cycle of an area. To conserve the integrity of this cycle, and to understand the fen system itself, a knowledge of the hydrodynamics of the fen and the catchment is fundamental.

Catchment hydrology influences the volume, timing and chemistry of water input. This varies with water-source, which depends on catchment characteristics such as regional climate, geology, soil type, slope and land use. Different sources bring in different amounts of solutes, and their quality influences the fen nutrient status (Van Wirdum 1981, Verhoeven 1986, Howard-Williams & Downes 1993). Site characteristics influencing the rate of water flow through a fen will affect nutrient loading, and may also influence aeration (Gosselink & Turner 1978). In addition, outflow rates will influence nutrient export and through flow, an area that has had little study. Storage and movement of water through the fen system relate to these water inputs and outputs (Howard-Williams 1985), and determines the water table regime. This in turn affects the drought and flooding episodes that affect the vegetation.

At the site level hydrology affects many biogeochemical processes within fen systems through water inflows and outflows, and through effects on physiochemical and biological processes (Gosselink & Turner 1978, Heathwaite 1995a). It is a major factor in the development of characteristic fen vegetation types, and necessary for peat development. The link between hydrology and vegetation development has long been studied (*e.g.* Rutter 1954). Studies have shown hydrology influences plant growth form (Rutter 1954, Ingram 1992), seed germination (Baskin *et al.* 1996), species dominance (David 1996) and plant functional group (Runhaar 1997), and in turn plant evapotranspiration affects water losses from the system. Many wetland plant classification systems relate indirectly to hydrology (*e.g.* Rodwell 1991, 1994, Wheeler 1980a,b,c), although the precise forms of these relationships are not always known (Wheeler & Shaw 1995b). Peatland classifications are also based directly on hydrology, particularly in relation to water sources, flow paths and inundation frequency (*e.g.* Gilvear *et al.* 1994, Gilvear & McInnes 1994, Gore 1983).

Hydrological parameters also affect the physiochemical and biological processes that release, transform or remove ions from the fen (Bowden 1988, Koerselman *et al.* 1993, Verhoeven *et al.* 1993). Low water inputs and/or high outputs draw-down water levels, increasing the aeration of the peat at the surface. This influences fen biogeochemistry, including trace gas emissions (Freeman *et al.* 1993a, Martikainen *et al.* 1993, 1995, Nykanen *et al.* 1995, Regina *et al.* 1996) and nutrient status (Heathwaite 1990, Lundin & Bergquist 1990, Freeman *et al.* 1993b). Subsequent saturation with water level rise will reverse these processes, leading to different nutrient dynamics that follow seasonal hydrological fluctuations.

Studies in hydrology often take the form of calculated hydrological budgets, where all inputs and outputs are measured, along with changes in storage (Verry & Timmons 1992, Owen 1995). These studies are often the basis for hydrological modelling (Bakker 1994, Bradley 1996, Walton *et al.* 1996, Spieksma & Schouwanaars 1997), and the development of hydrologic indices (Lent *et al.* 1997). These quantitative studies are relatively rare, particularly on mires, and many studies concentrate on partial measurements, qualitative assessments, and/or indirect assessment through water chemistry (Van Wirdum 1981) and plant indicator species (Newbould & Mountford 1997, Wierda *et al.* 1997, Gowing *et al.* 1998). These are often site-specific studies addressing particular problems (Siegal & Glaser 1987, Schot & Molenaar 1992, Gilman 1994, De Mars *et al.* 1997), and can also provide useful information for more general model development (Bradley 1996).

The aim of this chapter was to assess the hydrological functioning of two basin fen sites, Long Moss and Nether Whitlaw Moss, particularly in relation to vegetation development. This was done through measuring inflow stream discharges, fen water table fluctuation, fen surface movement and rainfall over an 18 month period (March 1996 - August 1997). In addition, detailed rainfall and evapotranspiration data were obtained from a nearby MORECS station. These data were used to characterise catchment run off and water-sources, and to compare their impact on fen hydrologic regime. The effects of water level draw-down and fen surface inundation on vegetation were discussed.

4.2 Methodology

4.2.1 Site selection

Based on the phase two scoping survey (*chapter 2*) two basin fen sites in the Scottish Borders were selected for a paired catchment study, Nether Whitlaw Moss SSSI and Long Moss SSSI. Vegetation on both sites range from tall herb-rich to bryophyte-rich community types, generally developing as floating vegetation rafts over unconsolidated peat, and firmer peat respectively (*chapter 3, section 3.3.2*). This reflected a vegetation gradient of ombrotrophic bog - species-poor fen - species-rich fen (*chapter 3, section 3.4*). These two sites formed the study area on which the rest of the research in the thesis is based (*phase 3*) addressing objective three, to investigate the links between hydrology, hydrochemistry and vegetation patterning with particular reference to spatial and temporal variation (see *chapter 1, section 1.5*).

Hydrologically the two sites appeared similar. Their catchments were small (<100 ha) and each basin fen was fed by an input stream, with a single outflow stream at the opposite end (Fig. 4.1). At Nether Whitlaw Moss there were additional water inputs from drains along the northeast boundary of the site, diverting surface water off adjacent farmland. In addition, at Nether Whitlaw Moss a reservoir spill weir was connected to the inflow stream via a culvert. The extent of diffuse sub-surface and surface water input from the surrounding catchment was difficult to assess, although the catchment area was dominated by poorly drained soils (Ragg 1960), which suggests rapid surface and sub-surface water run off. Basin fens are often isolated from groundwater influences

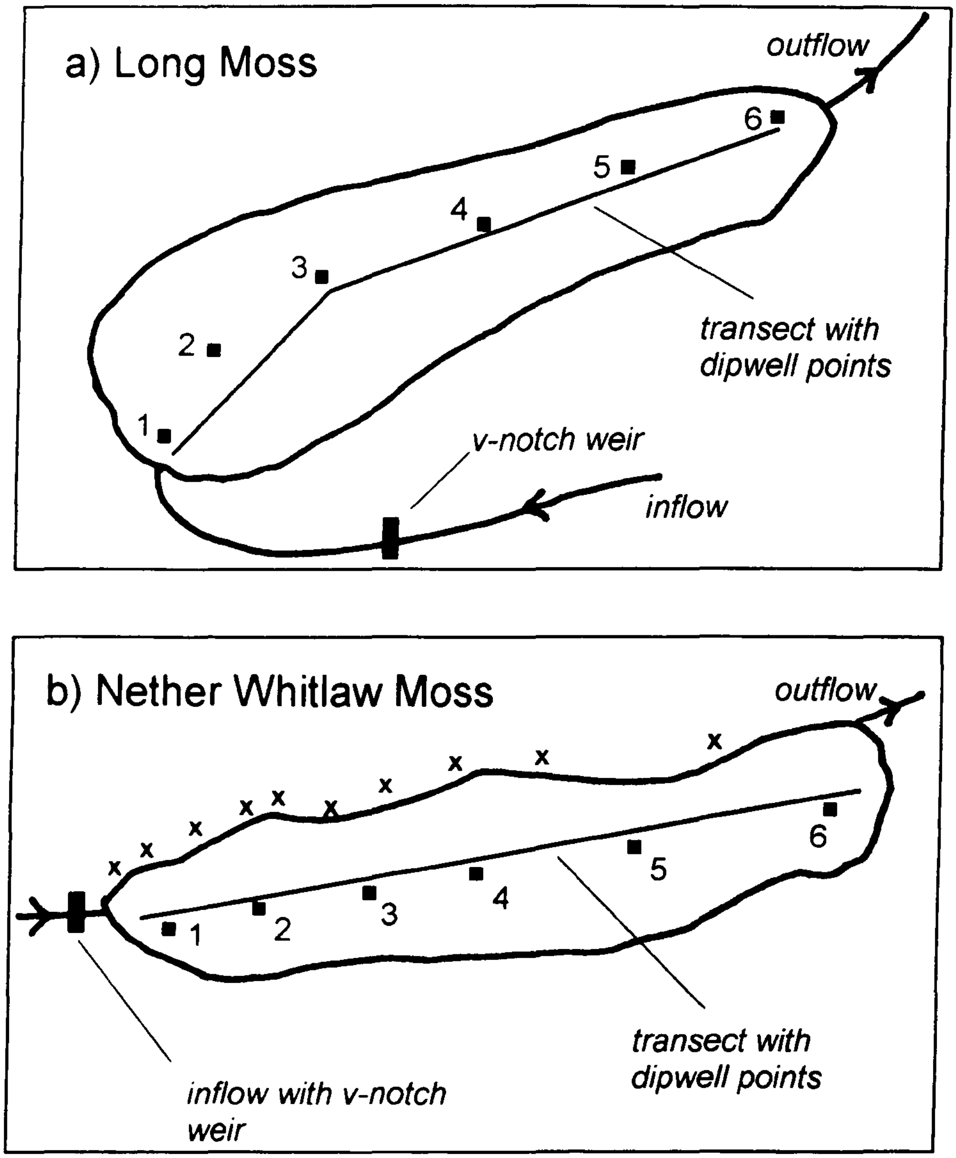


Fig. 4.1 Dipwell locations along each transect on a) Long Moss and b) Nether Whitlaw Moss. V-notch weir locations and drains (x) also shown

(Hughes & Heathwaite 1995), and no groundwater upwelling was expected due to the impervious blue-grey clay lining both basins (Tratt 1997, peat core data held by the author and available on request).

4.2.2 Data collection

Inflow streams were identified as the main water inputs, together with direct precipitation, and a possible point source of nutrient inputs at Nether Whitlaw Moss (*section 2.3.2*). Stream inputs were measured from April 1996 to August 1997 using a v-notch thin-plate weir suitable for the low flow ranges expected (B.S. 3680 1965, Shaw 1991). At Long Moss the v-notch was a 45° angle, and at Nether Whitlaw Moss a 60° angle. Water levels behind the weir were automatically logged every hour using a stilling well, float and data logger. The ranges of measurable flows were for Long Moss approximately 0.1 l s^{-1} to 116 l s^{-1}, and for Nether Whitlaw Moss approx. 0.1 l s^{-1} to 20 l s^{-1}. A second potential point source for water and nutrient inputs was identified as the drain inputs at Nether Whitlaw Moss. Here several attempts were made to monitor the input using a box-weir, float and a continuous data logger, but none succeeded because of highly sporadic flow leading to continual corrosion of the float mechanism.

Rainwater inputs were measured each month (June to November 1996) using a standard rain gauge (12.5 cm diameter) at each site. In addition daily rainfall data were obtained for the closest meteorological station (Bowhill; NGR 3428E 6278N) for March 1996 to August 1997. Daily open water potential evaporation was also obtained from Bowhill for this period.

Water level and fen surface fluctuations were measured every month (March 1996 - August 1997) using a transect of six dipwells at each site. Half these dipwells (numbers 2, 4 and 6) were modified to record minimum and maximum water levels over the month between site visits (Bragg *et al.* 1994). Each dipwell was placed within different vegetation types close to where sub-surface water samples were taken, and anchored to the fen surface vegetation (Gilman 1994). A datum post at each measuring point, embedded into basal clay, enabled both water movement and corresponding fen surface movement to be measured (Fig. 4.2). All measurements were taken at a distance using binoculars to prevent displacement of the fen surface or water levels by trampling. The levels of the fixed datum posts were surveyed in using a Wild TC1010 total survey station, and related to altitude above sea level using Ordnance Survey benchmarks.

4.2.3 Data analysis

Hourly discharges (Q) from the v-notch weir were calculated for the inflow streams (*equation 4.1*, B.S. 3680 1965), and then converted to mean daily discharge rates.

$$Q = 8/15 \,.\, \sqrt{2g} \,.\, C_e \,.\, \tan\theta/2 \,.\, h_e^{5/2} \qquad (equation\ 4.1)$$

Q = discharge ($m^3\ s^{-1}$)

g = gravitational acceleration = 9.80665 m s^{-2}

C_e = coefficient of discharge

θ = angle of the v-notch

h_e = $h + K_h$

where h = the head of water measured behind the v-notch (m)

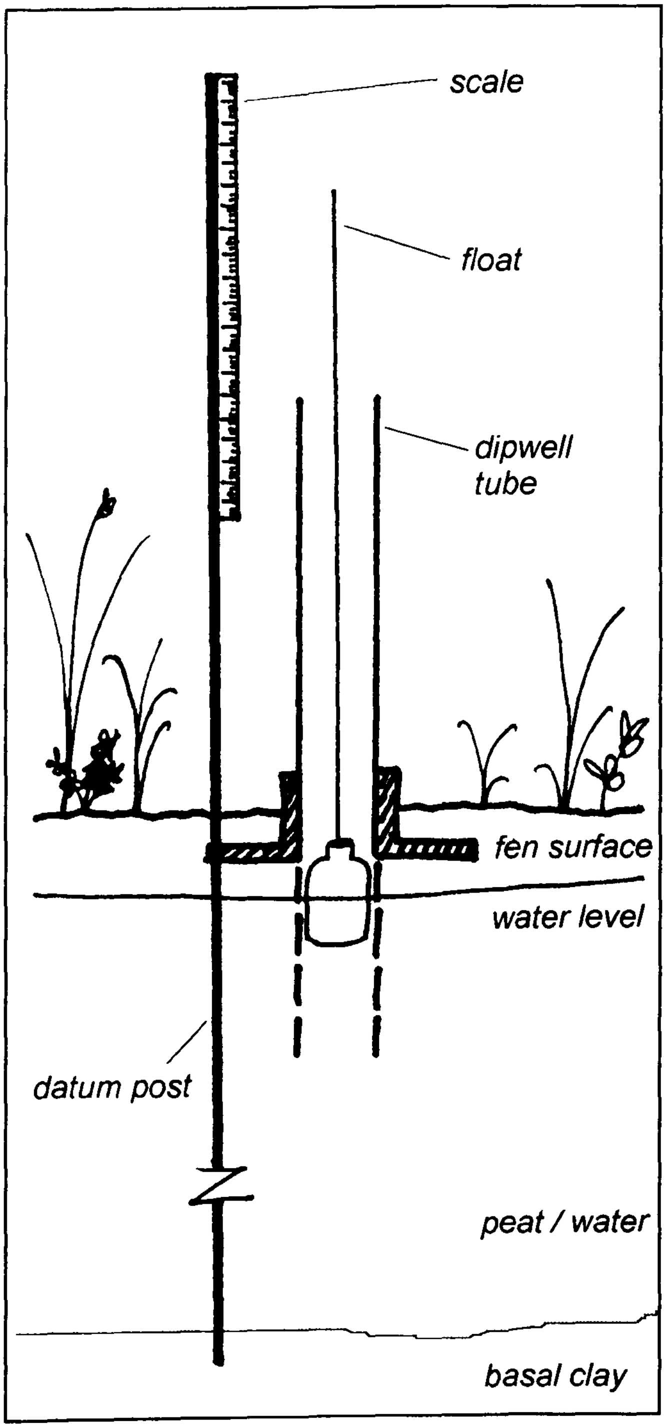


Fig. 4.2 Dipwell embedded in fen surface, with float and scale enabling water level and fen surface movement to be measured against the datum post embedded in basal clays

K_h = empirical adjustment for the influence of fluid properties

Long Moss	$C_e = 0.580$	$\theta = 45°$	$K_h = 0.0015$ mm
Nether Whitlaw Moss	$C_e = 0.576$	$\theta = 60°$	$K_h = 0.0011$ mm

Due to the low flows measured all flows were expressed as l s^{-1} by multiplying by 1000. The annual flow regime (April 1996 - March 1997) of each stream was expressed using mean monthly flow (Qm) as a ratio of mean annual flow (Q).

Rainfall data collected at each site were compared to each other, and to rainfall data (PPT) from Bowhill meteorological station for the same period (Mann-Whitney *U*-test). Daily potential evapotranspiration (PE) data based on open water surfaces are considered an underestimation of evapotranspiration from vegetated surfaces (Verry 1988), although the precise relationships between open water PE and wetland evapotranspiration are heavily debated. Koerselman and Beltman (1988) propose an equation to describe evapotranspiration (ET) from temperate region fens in relation to potential evapotranspiration (*equation 4.2*). This was used to estimate daily fen evapotranspiration using Bowhill meteorological data, plotted as mean daily figures.

$$ET = 0.73\ PE + 0.16 \qquad (equation\ 4.2)$$

Effective rainfall was calculated as rainfall minus evapotranspiration (PPT - ET).

Water and fen level fluctuations (March 1996 - August 1997) at each dipwell were plotted to show water level draw down and fen inundation. Differences between 1996 and 1997 water levels were analysed for each site using the Mann-Whitney *U*-test. Profiles of water and fen surface levels at each site were plotted for three months representing spring, summer and autumn/winter periods.

4.3 Results

4.3.1 Inflow stream discharge rates

The inflow stream at Long Moss (Fig. 4.3a) showed a higher maximum flow (approx. 40 l s^{-1}) than that at Nether Whitlaw Moss (approx. 14 l s^{-1}) (Fig. 4.3b). Both streams showed low flow levels between rainfall events. Long Moss inflow stream had a series of large peaks after rainfall events showing a rapid response to surface and sub-surface run off. The inflow stream at Nether Whitlaw Moss showed an almost constant low-level base flow, except short summer periods (during June to September 1996) when the flow was below the minimum recorded by the weir (<0.1 l s^{-1}). There were fewer and lower peak flows at Nether Whitlaw Moss, suggesting less surface and sub-surface run off to the stream during rainfall events. The peaks recorded at Nether Whitlaw Moss occurred at Long Moss at a similar size, but at Long Moss they were surrounded by additional larger peaks. There appeared to be some discrepancies in the data recording of the loggers at the weir for Long Moss, with continuous high levels recorded over much of December (Fig. 4.3a). This produced a flat discharge hydrograph rather than the expected peaks, which may indicate a problem with the mechanism such as the float sticking at a high level between high flow events. Annual flow regimes for Long Moss

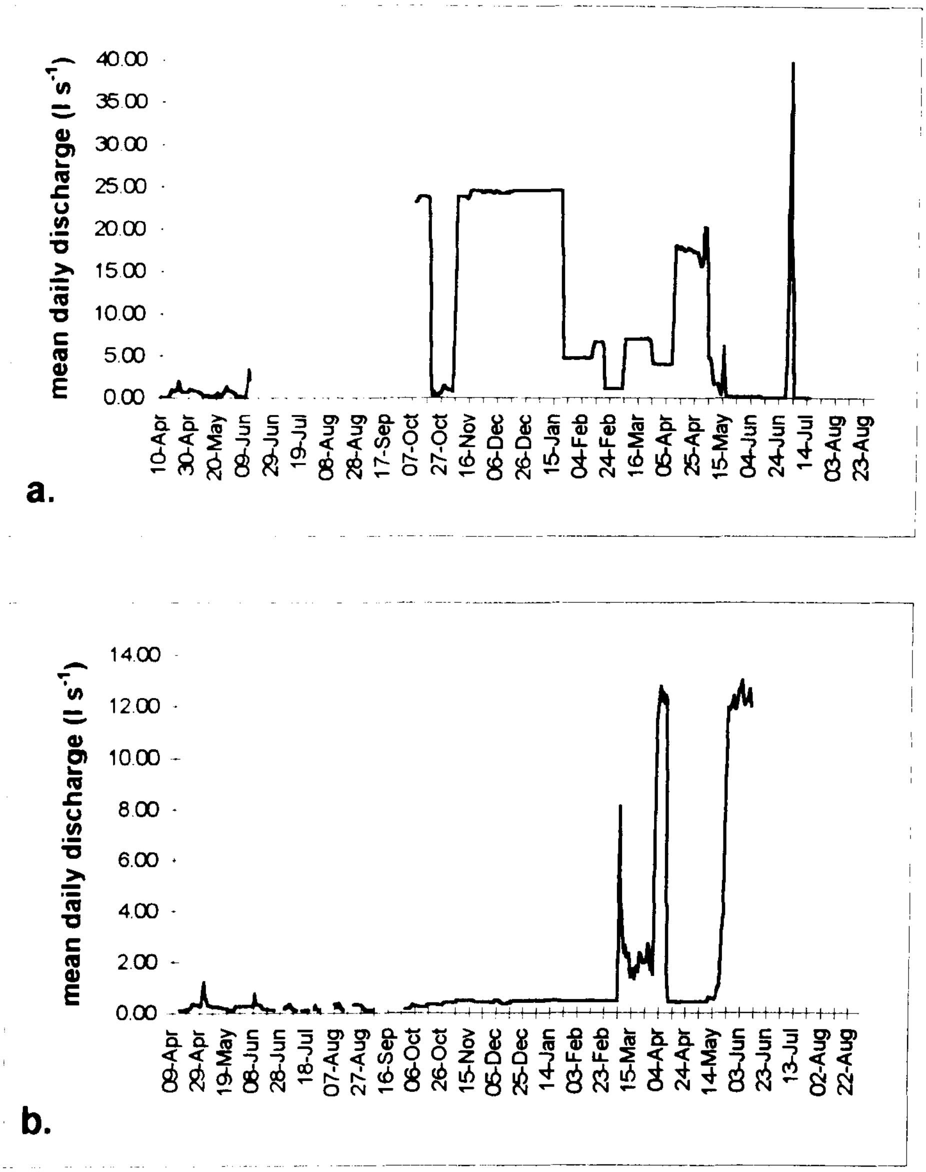


Fig. 4.3 Discharge hydrographs for inflow streams at a) Long Moss and b) Nether Whitlaw Moss, with mean daily discharge calculated as l s^{-1} Data unavailable at Long Moss for June to Sept. 1996, and at both sites for July - Aug. 1997.

may, therefore, over-estimate winter 1996/1997 mean flows (Fig. 4.4a).

Annual flow regimes, expressed as a curve based on mean monthly flows highlighted the difference in base flow and peak flow influences on each input stream. At Long Moss (Fig. 4.4a) the flow regime showed an early winter peak (December) showing rapid run off dominated by quick flow. The very low summer values suggested the lack of base flow. Nether Whitlaw Moss, in contrast, showed monthly flows that were similar to the annual mean, with no winter peak (Fig. 4.4b). This suggested reduced quick flow and a more sustained base flow. No measurements were collected at Long Moss in July, August and September 1996, and at Nether Whitlaw Moss in August and September 1996 due to damaged equipment.

4.3.2 Rainfall and evapotranspiration

There was no significant difference between the monthly rainfall recorded on site at Long Moss and that at Nether Whitlaw Moss (Mann-Whitney *U*-test: $W_{11} = 138.5$; $p = 0.450$) showing both sites were subject to similar rainfall patterns. Similarly there was no significant difference between the rainfall recorded at each site, and the meteorological station data for the same periods (Mann-Whitney *U*-test: Long Moss: $W_{11} = 133.0$; $p = 0.6936$, Nether Whitlaw Moss: $W_{11} = 124.0$; $p = 0.8955$). The Bowhill meteorological station data was then taken as a good approximation of the rainfall at both fen sites.

Daily rainfall data from Bowhill (Fig. 4.5a) showed continuously wetter periods in October and November 1996, and February and June 1997, with rainfall peaking between

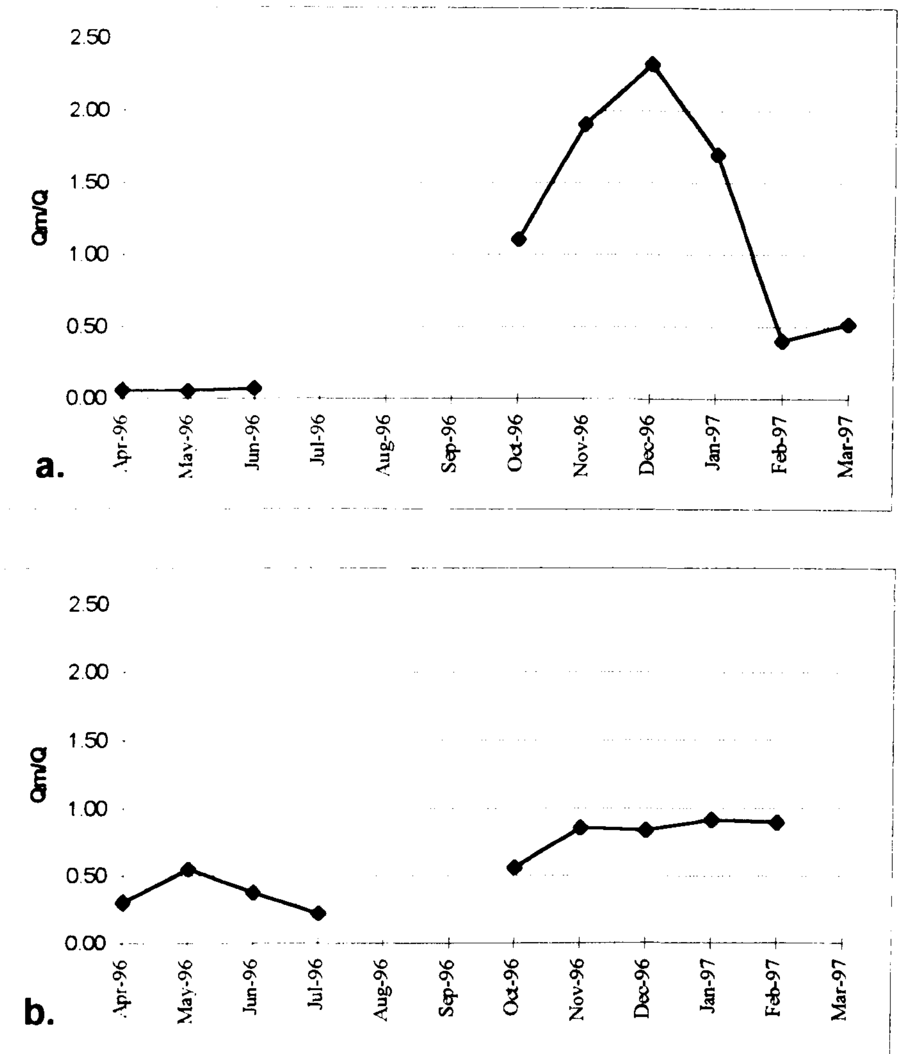


Fig. 4.4 Annual flow regimes of inflow streams at (a) Long Moss and (b) Nether Whitlaw Moss. Mean monthly flow (Qm) is given as a ratio of annual mean (Q)

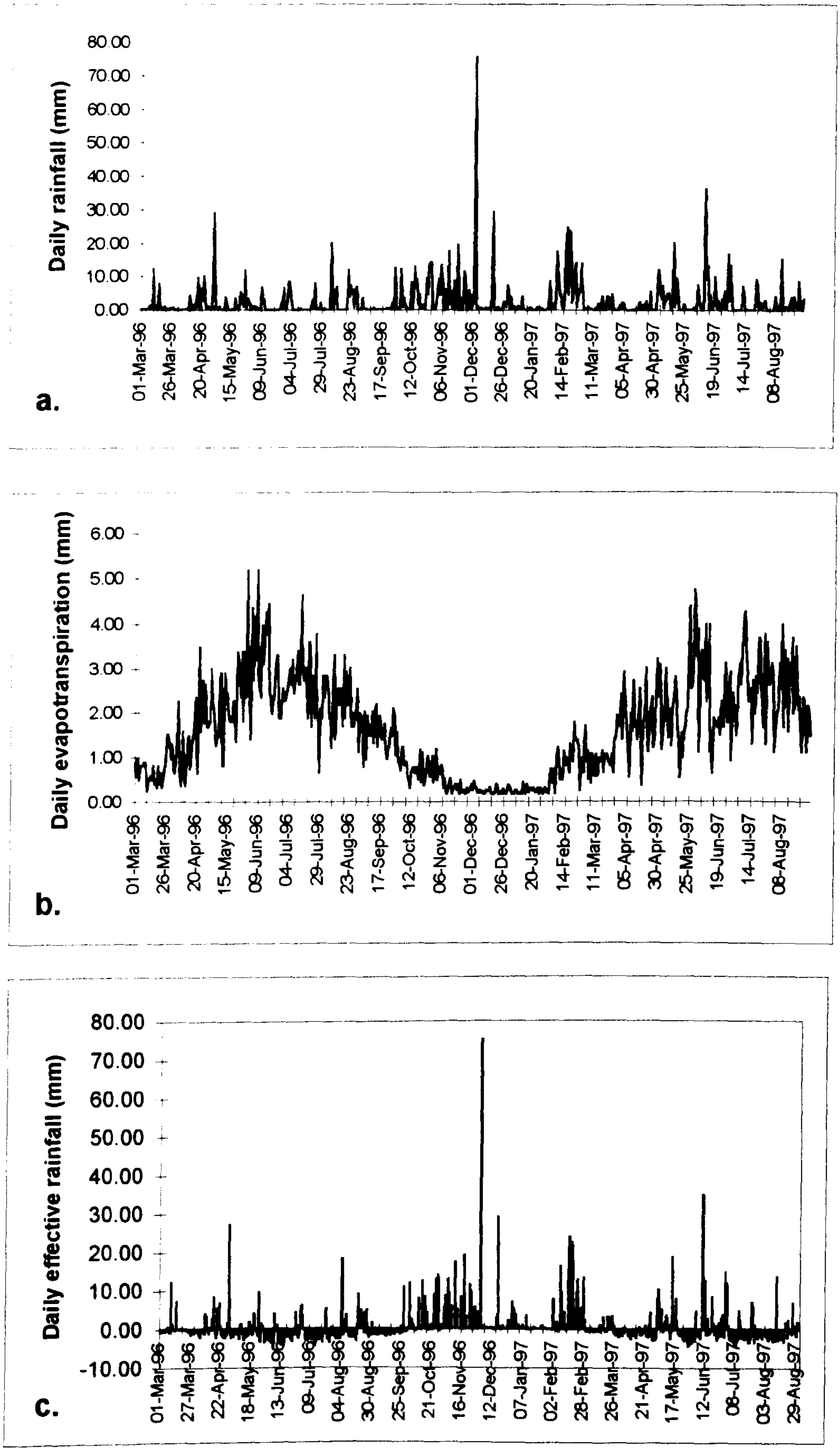


Fig. 4.5 Data from Bowhill MORECS station, presented as a) daily rainfall (PPT), b) daily evapotranspiration (ET) and c) effective rainfall (PPT - ET)

10 and 40 mm day^{-1}. Other wet periods had fewer peaks at lower levels. December 1996 showed two high intensity rainfall events, but was relatively dry for the rest of the month. Drier periods occurred in September 1996, January and April 1997. Overall, the data for spring/summer 1997 showed more rain than 1996, although there was no significant difference in mean monthly values (Mann-Whitney *U*-test: $W_6 = 36.0$; $p = 0.6884$).

Daily evapotranspiration was usually less than rainfall values, the maximum values at around 5 mm day^{-1} in the summer (Fig. 4.5b). Evapotranspiration levels were slightly lower in spring/summer 1997 than 1996, although statistically there was no significant difference between 1996 and 1997 mean monthly values (Mann-Whitney *U*-test: $W_6 = 39.0$; $p = 1.000$).

Daily effective rainfall (PPT - ET, Fig. 4.5c) was greatest in October and November 1996, and February 1995. These are similar to the rainfall figures (Fig. 4.5a).

4.3.3 Water level and fen surface fluctuations

All six dipwells at Long Moss, including those modified to show minimum - maximum water levels (Bragg *et al.* 1994), showed a similar spring/summer decline and autumn/winter rise in water levels over the 18 month monitoring period (Fig. 4.6), relating to the seasonality of effective precipitation. The lowest water levels were recorded in June, July and August 1996. Water levels in 1997 appeared greater that levels in 1996, although no significant difference was found (Mann-Whitney *U*-test: $W_{17} = 268.0$; $p = 0.3173$). The maximum water level draw down was around 25 to 30 cm

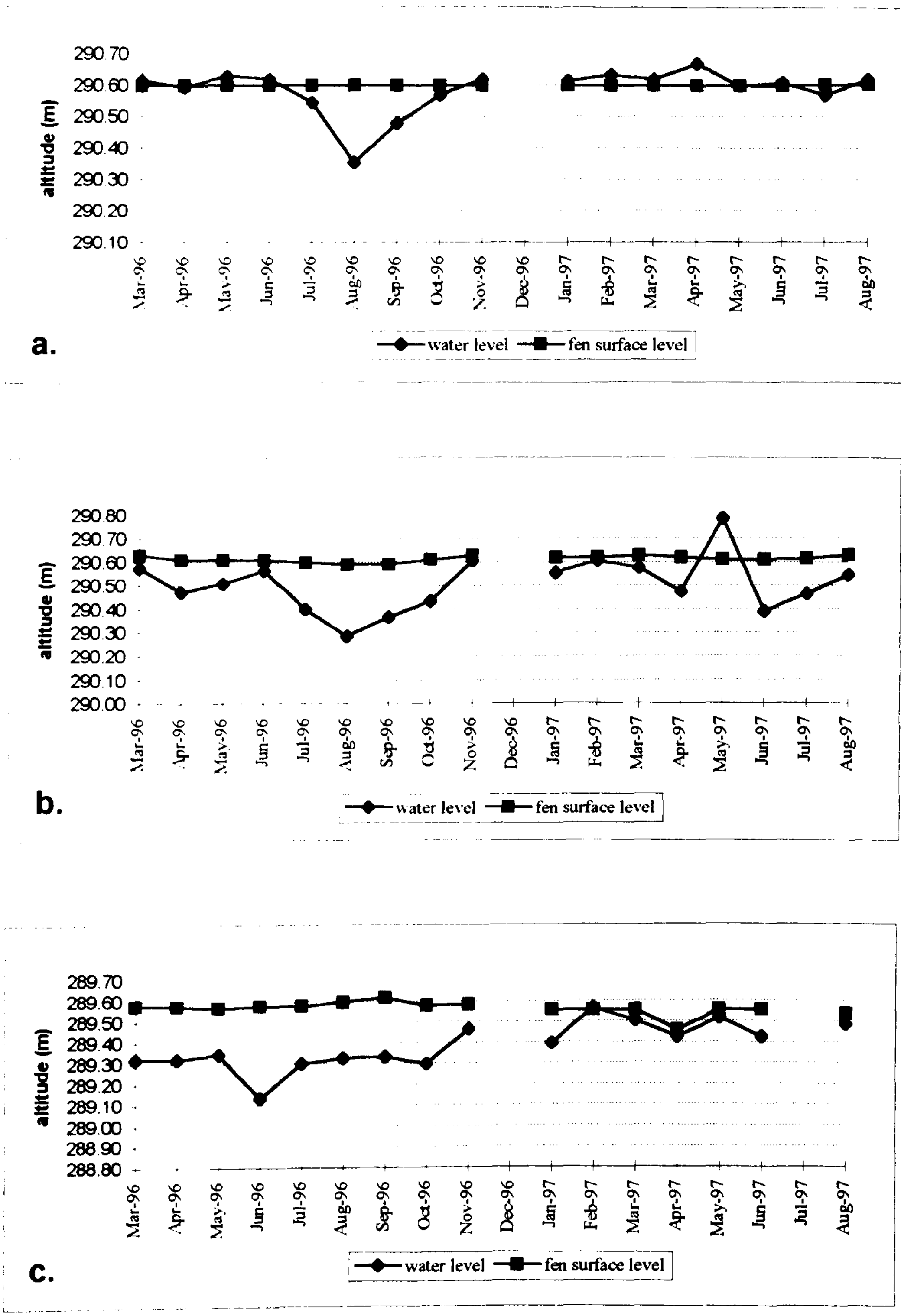
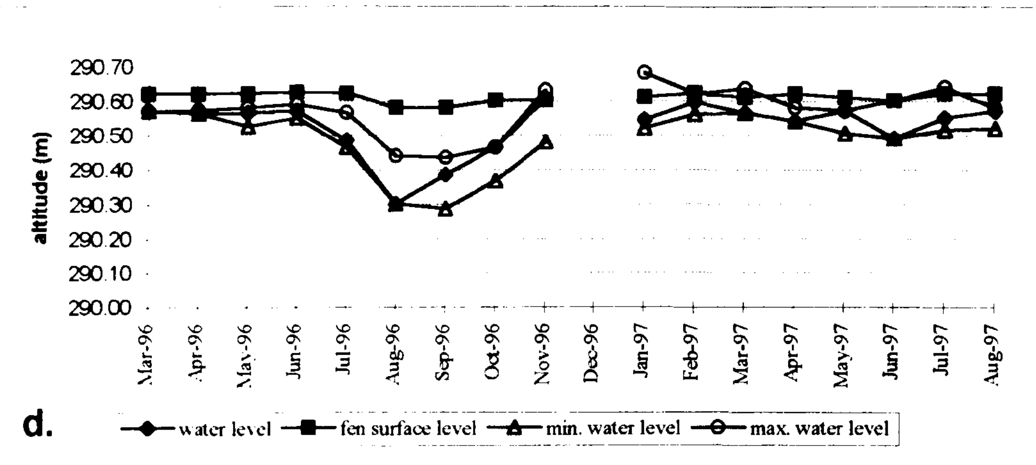
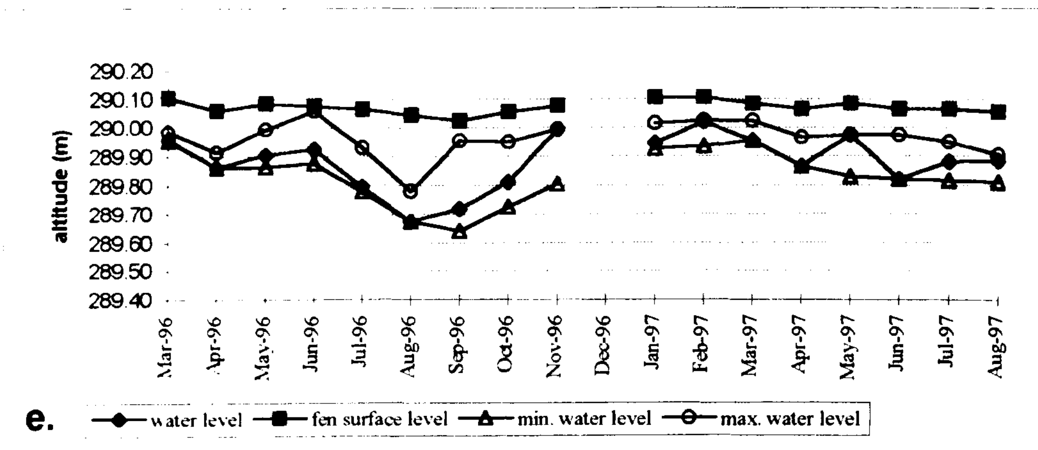


Fig. 4.6 Water level and fen surface fluctuations at Long Moss for a) dipwell 1, b) dipwell 3 and c) dipwell 5





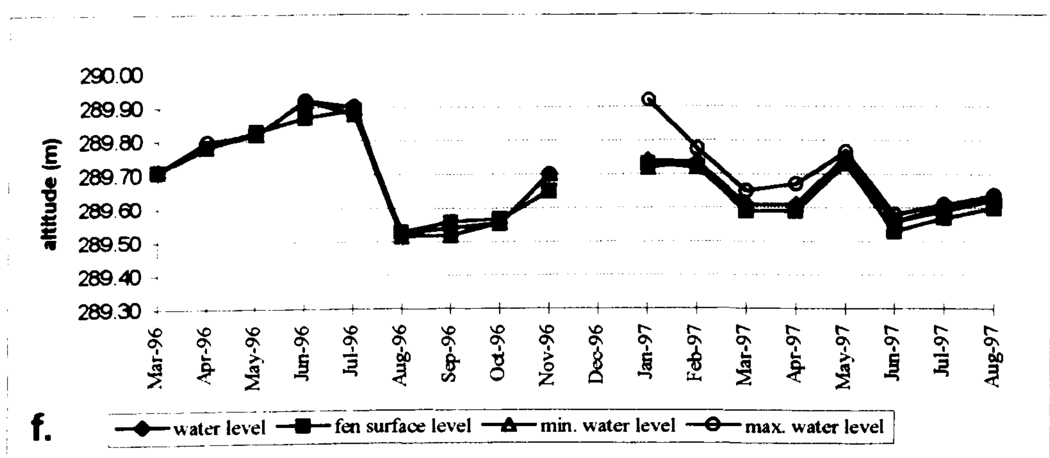


Fig. 4.6 (concl.) Water level and fen surface fluctuations at Long Moss, with additional data on monthly minimum and maximum water levels for d) dipwell 2, e) dipwell 4 and f) dipwell 6

below the fen surface in 1996, although this was reduced to approx. 20 cm in 1997. The maximum inundation depth was around 20 cm above the fen surface in 1997, with lower levels in 1996. The variation in water levels measured by the dipwells 2, 4 and 6 could be large, up to a 35 cm change in water level over the month.

Similar seasonal fluctuations in water level were observed for Nether Whitlaw Moss as seen for Long Moss (Fig. 4.7). There was a drop in water levels during summer months, the lowest levels being reached slightly later in July, August and September 1996. Water levels appeared more consistent between the two years, and 1997 levels were not significantly different to 1996 levels (Mann-Whitney *U*-test: $W_{15} = 236.0$; $p = 0.9009$). Inundation periods were more frequent on Nether Whitlaw Moss, as seen at dipwells 1, 2, 4 and 6. At the same points fen surface vertical movement was also greater. At the remaining dipwells (1 and 3) there was little fen surface movement recorded, and water levels were consistently further below the fen surface level. Maximum water level draw down below the fen surface was approximately 30 to 40 cm, and maximum inundation depth between 15 and 20 cm above fen surface level. Variations in water levels within a month were reduced compared to Long Moss, with a maximum change of approximately 20 cm over one month. These variations in water and fen surface fluctuations were seen in both 1996 and 1997.

At both sites the dipwells showed a similar variation in the range of water levels over the 18 month monitoring period (Table 4.1), where water level fluctuations ranged from 13 to 59 cm. There were large variations in the range of fen surface level fluctuation across both sites (Table 4.2), from no measured movement in firm peat areas, to between 20 and

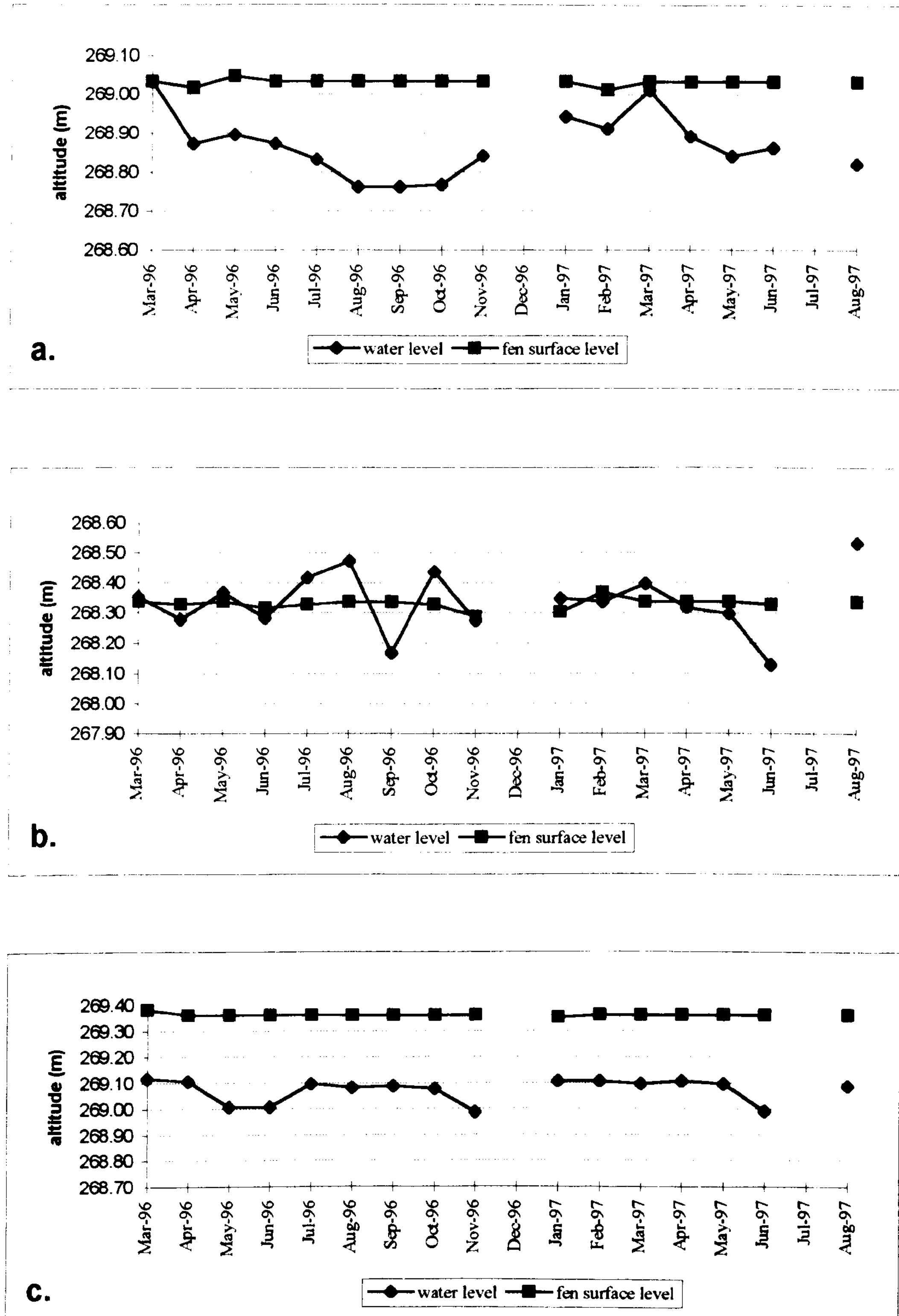


Fig. 4.7 Water level and fen surface fluctuations at Nether Whitlaw Moss for a) dipwell 1, b) dipwel 3 and c) dipwell 5

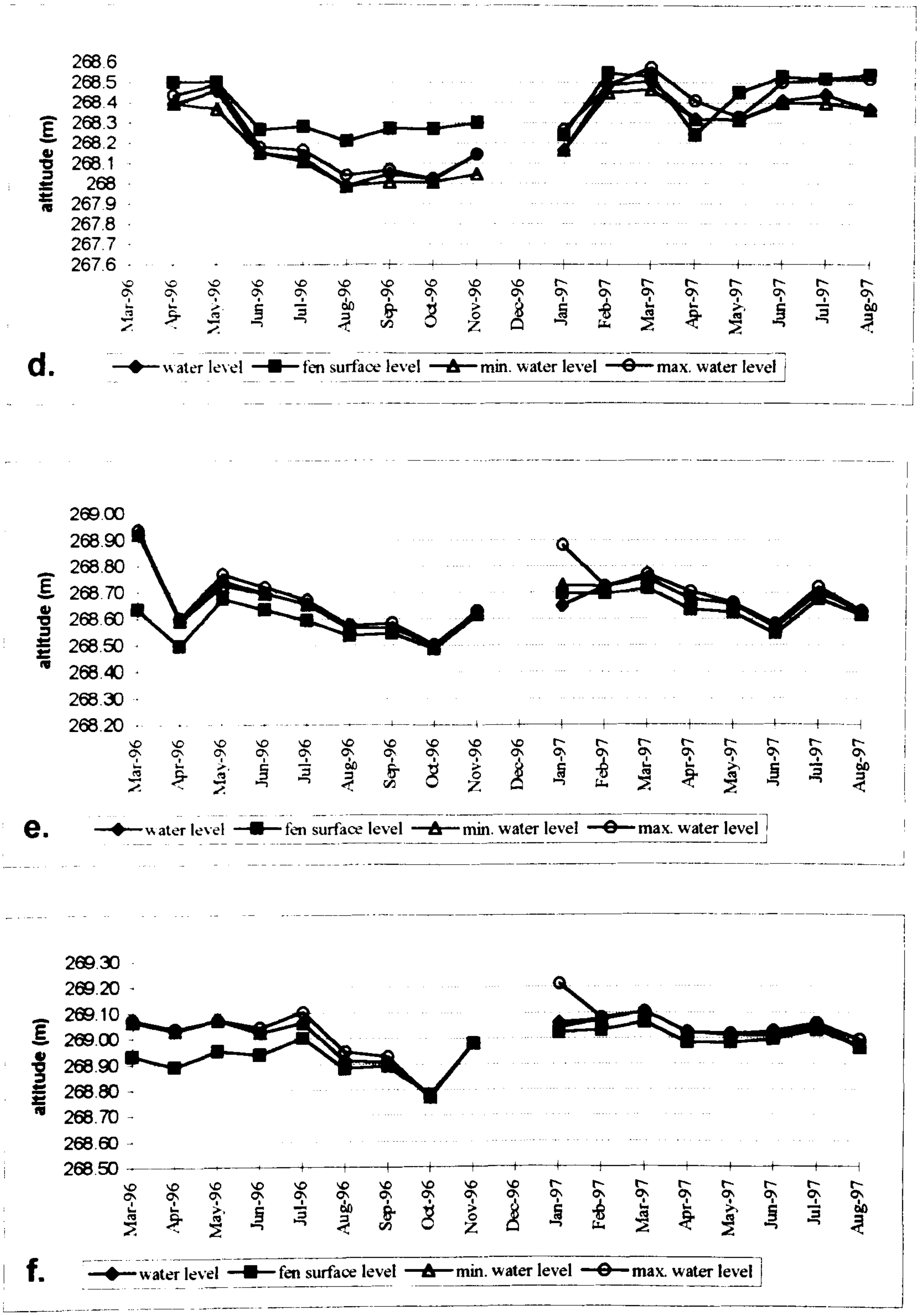


Fig. 4.7 (concl.) Water level and fen surface fluctuations at Nether Whitlaw Moss, with additional data on monthly minimum and maximum water levels for d) dipwell 2 e) dipwell 4 and f) dipwell 6

Table 4.1 Water level fluctuations for each of the six dipwells on Long Moss and Nether Whitlaw Moss. N = number of observations over the 18 month sampling period (March 1995 - Aug. 1996)

Dipwell	Water levels (m)				N
	mean	minimum	maximum	range	
Long Moss					
1	290.58	290.35	290.67	0.32	17
2	290.53	290.29	290.68	0.39	51
3	290.50	290.28	290.78	0.50	17
4	289.89	289.64	290.06	0.42	51
5	289.38	289.13	289.56	0.43	16
6	289.69	289.51	289.69	0.18	48
Nether Whitlaw Moss					
1	268.87	268.76	269.03	0.27	16
2	268.28	267.98	268.57	0.59	48
3	268.34	268.13	268.53	0.40	16
4	268.67	268.50	268.93	0.43	51
5	269.07	268.99	269.12	0.13	16
6	269.01	268.77	269.21	0.44	51

Table 4.2 Fen surface level fluctuations for each of the six dipwells on Long Moss and Nether Whitlaw Moss. N = number of observations over the 18 month sampling period (March 1995 - Aug. 1996)

Dipwell	Fen surface levels (m)				N
	mean	minimum	maximum	range	
Long Moss					
1	290.60	290.60	290.60	0.00	17
2	290.61	290.58	290.63	0.05	51
3	290.61	290.59	290.63	0.04	17
4	290.07	290.02	290.10	0.08	51
5	289.56	289.45	289.61	0.16	16
6	289.67	289.51	289.69	0.18	48
Nether Whitlaw Moss					
1	269.03	269.01	269.05	0.04	16
2	268.39	268.21	268.55	0.34	48
3	268.33	268.29	268.37	0.08	16
4	268.61	268.48	268.71	0.23	51
5	269.36	269.35	269.38	0.03	16
6	268.96	268.78	269.06	0.28	51

30 cm ranges in the areas where floating vegetation has developed. The greater fen surface movements were seen at Nether Whitlaw Moss, with three out of six sample points showing ranges >20 cm. At Long Moss the ranges were reduced, with only two sample points showing ranges >10 cm.

4.3.4 Seasonal changes in fen surface and water levels across each site

A profile of each site was drawn using the measurements at all six dipwells across one site for three months; representing spring fen levels (April 1996), summer fen levels (July 1996), and autumn/winter fen levels (October 1996). Corresponding water levels were also plotted. At Long Moss (Fig 4.8 a-c) the firmer peat and *Sphagnum*-dominated vegetation were clearly seen as higher areas at the beginning of the transect (dipwells 1 and 2). Levels dropped by around 50 to 100 cm toward the herb-rich, floating vegetation types toward the outflow (dipwells 3 to 6). Over all three months the profiles of both the fen surface and the water levels remained similar.

For Nether Whitlaw Moss the profile was different (Fig. 4.9 a-c), showing a drop of around 50 cm from firmer edge peat at the inflow (dipwell 1) to the floating vegetation herb-rich found at dipwells 2, 3 and 4. After this (dipwell 5) the surface rose to the highest point recorded on the fen. This area was dominated by firmer peat and *Sphagnum*-rich vegetation type. The area dominated by floating vegetation types (dipwell 6) dropped down to a similar level to dipwell 1. Again, the profile was similar for all three months.

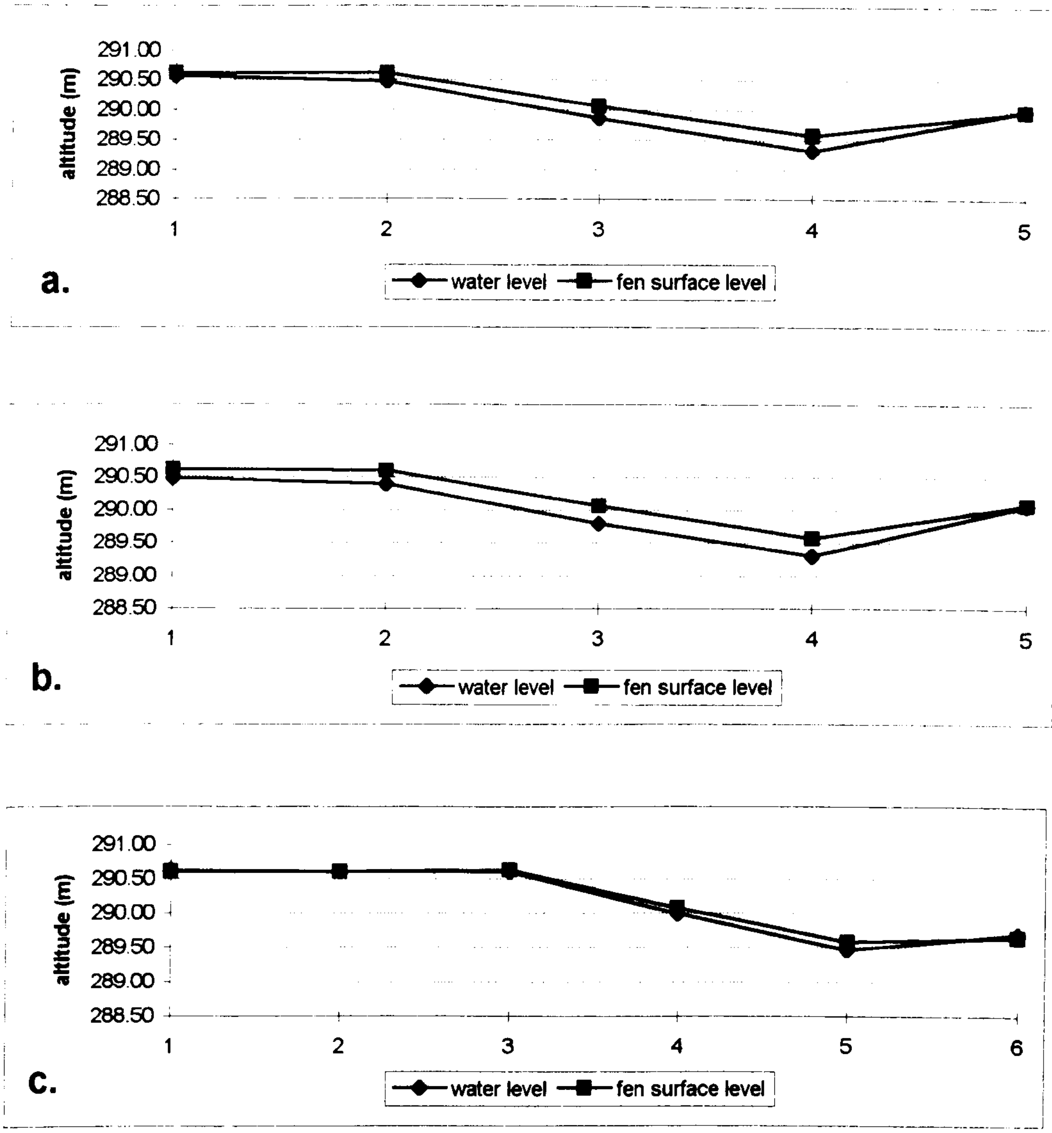


Fig. 4.8 Profiles of the water level and fen surface of Long Moss in a) April 1996, b) July 1996 and c) October 1996 at dipwells 1 to 6

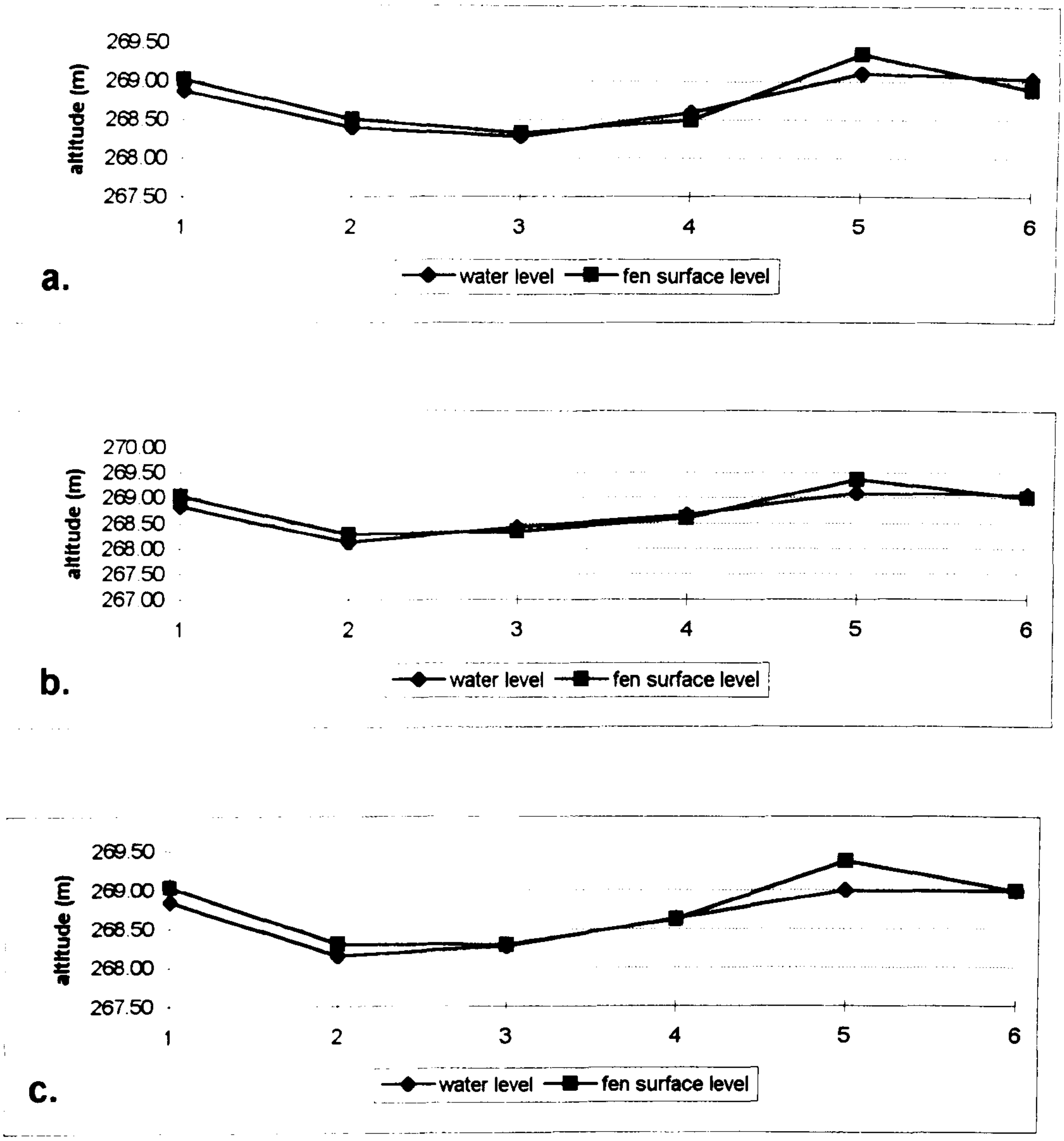


Fig. 4.9 Profiles of the water level and fen surface of Nether Whitlaw Moss in (a) April 1996, (b) July 1996 and (c) October 1996, at dipwells 1 to 6

4.5 Discussion

Catchment run off is closely related to regional climate, and is also modified by the specific physical characteristics of each individual catchment (Ward 1968). The regional climate and catchment characteristics at Long Moss and Nether Whitlaw Moss were similar in terms of geology, soils, altitude and general climate. Despite this, stream flow regimes for each fen were different. At Long Moss the flow regime was dominated by quick flow from the catchment area giving a rapid response to rainfall events, and early winter peak flows (December), although problems with equipment may artificially increase the actual levels of flow over December, so the results should be interpreted with some caution. There was no evidence of base flow, leading to very low summer levels and long dry periods in the summer. In contrast, Nether Whitlaw Moss inflow stream had an almost continuous, although low base flow that rarely dried-up over the summer. Quick flow was reduced and winter peaks appeared later in February and March. This stream appeared less affected by rapid run off from the surface catchment, with a more constant water-source percolating from elsewhere.

In southern Scotland maximum run off generally occurs in December and minimum run off in June (Ward & Robinson 1990). Long Moss appears to conform to this, but Nether Whitlaw Moss shows a later minimum and maximum flow. Later flows are often attributed to increased water-holding capacity of the underlying rock that leads to a later release of accumulated water (Ward & Robinson 1990). At both sites the catchment geology is characterised by folded Silurian shales, mudstones and greywakes that are associated with the rounded hills and smooth slopes of the Southern Uplands (Brown &

Shipley 1982). Shales have a porosity of approximately 0 - 10 %, and an effective porosity of around 0.5 - 5 % (Gregory & Walling 1973, Ward & Robinson 1990, Baird 1997). This is lower than porosity ranges for sandstone, limestone, and unconsolidated materials, but higher than material such as granite and schists of the Highland areas of Scotland. The geology and soils indicate that this area will be generally poorly drained. Nether Whitlaw Moss is slightly different as it occurs in the 'corrugated hills', a particular geomorphological feature of the area. These tightly folded hills alternate hard greywakes and shales with softer rocks. The differential erosion of these rock types leads to a small scale relief of ridges and hollows (Ragg 1960, Brown & Shipley 1987). This small scale change in topography may nevertheless have an effect on the hydrology, particularly in a small catchment such as Nether Whitlaw Moss.

The local topography of each site may, therefore, subtly alter stream flow regimes. Long Moss had a long, sinuous stream, and much of the catchment appeared to drain into the stream and then enter the fen. In contrast, Nether Whitlaw Moss had a short, straight inflow fed by only a small area of the surface catchment and connected to a spillweir of the nearby Lindean Reservoir. This spillweir was not overtopped during the 18 months, the reservoir having additional outflow points elsewhere, and therefore reservoir water was an unlikely input source for the fen, although the presence of the resevoir may still affect the fen hydrology in more subtle ways not detected in this study. Hydrochemical differences between the inflow stream and the reservoir also suggest there was no reservoir input (Ross unpublished data). The inflow stream appeared to be less influenced by catchment surface run off, this entering the fen diffusely from the surrounding land. The inflow stream has a base flow, a reduced peak flow and a later winter peak. These characteristics suggest that part of the inflow source may be from beyond the surface catchment, possibly as precipitation falling elsewhere and percolating to the inflow stream some time later.

Another main difference between the two catchments was the type of land use next to the site and dominant within the catchment. This can affect catchment characteristics such as run off (Farley & Werrity 1989, Globevnik & Sovinc 1998). At Long Moss the whole catchment is unimproved acid grassland. There are no sub-surface drains and the grassland is lightly grazed by sheep and cattle. The wet climate and poorly-drained gley soils of the area, combined with the lack of artificial drainage, may keep water levels close to the surface throughout most of the year. Infiltration of rainwater over the catchment area is reduced if the water level is already high, and this can result in increased, rapid surface run off (Dunne & Black 1970a,b). This may be linked to the quick flow responses of Long Moss inflow stream. At Nether Whitlaw Moss the catchment is mainly improved pasture, more heavily grazed by sheep and cattle. One field next to the fen is under-drained, and these drains enter the fen. Other fields in the catchment are also likely to be drained. Drainage does not reduce the amount of water coming from a catchment, but can alter the drainage patterns (Armstrong 1984). It reduces the amount of surface run off (Harris *et al.* 1984), often redirecting flow as drain flow and percolation through sub-surface soils. At Nether Whitlaw Moss the surface flow may be reduced because of these drainage effects, with flow redirected through the sub-surface onto the fen edge rather than the inflow stream. This may account for the limited quick flow response of the inflow stream, and again highlights the potential importance of diffuse water flow into the fen from surrounding land. The flood hydrology of such drained land is, however, complex with variable affects according to soil types and antecedent conditions, and more detailed measurements are required before water flow paths can be determined.

The effect of vegetation cover on run off rates is well documented, with increased biomass reducing run off (Globevnik & Sovinc 1998). This is attributed to factors such as interception and increased evapotranspiration (Dabney 1998, Globevnik & Sovinc 1998). The catchment areas of Long Moss and Nether Whitlaw Moss were vegetated by different plant species, acid grassland and improved pasture respectively. The effects of these different vegetation types were not assessed in this study, but may be potential factors in the different flow regimes of the two input streams.

Water is obviously fundamental to fen formation, but the type of hydrologic regime can affect the development on the fen, particularly its vegetation (Gosselink & Turner 1978, Beltman & Rouwenhurst 1991, De Mars *et al.* 1997). How the water arrives at the fen is important, but equally how the water flows on the fen is also important. Basin fens, and other peatland types, are often seen as a hydrologic unit responding uniformly to water inputs and outputs, but at smaller scales hydrological variation may be greater. Increasingly the scale of hydrological study is recognised as important, from micro-relief of topography through to regional scales (Carter & Novitzki 1988, Baird 1997, Spieksma & Schouwanears 1997). In this study the heterogeneity of hydrologic responses within a site was clear. There were underlying responses that were similar across a fen and between the two fen sites. These related to general summer water level draw down and autumn/winter rises. This could be attributed to seasonal changes in evapotranspiration and rainfall. These data alone were not enough to describe the degree of flooding and drying of the fen surface, *i.e.* the water level fluctuations that are important in vegetation development.

Plants must be adapted to frequent water level fluctuations to grow in fen conditions, not necessarily continuous flooding (Crawford 1996). Wheeler (1993) suggests this may develop as a tolerance of fluctuating water levels rather than a requirement for flooding, as many species will grow in drier conditions if competitor species are excluded. Flooding also has specific effects on plants, increasing germination success of some *Carex* species (Baskin *et al.* 1996) and affecting the whole plant both physically and chemically (Rutter 1954, Vosenek *et al.* 1996, Weber & Brandle 1996). The timing of the flood is also important and species composition has been linked to the hydroperiod (David 1996), and the groundwater level (Barendregt *et al.* 1992, Hald & Peterson 1992, Runhaar *et al.* 1997, Wierda *et al.* 1997).

Water level fluctuation in relation to the fen surface on Long Moss and Nether Whitlaw Moss appeared to be connected to peat type and vegetation development. There were three main types of vegetation development that affected depth of inundation or drying, and all three were present on both sites. First, the formation of floating vegetation rafts allowed the fen surface and the water level to move together. This kept the water close to the fen surface and reduced the severity of inundation and drying. Other areas had partially floating vegetation mats developed over unconsolidated peat. These enabled limited fen surface movement as water levels fluctuated. Drying was less severe, but flooding depth and frequency were increased. These areas appeared to be where vegetation would be most affected by fluctuating water levels. Alternatively, vegetation that developed over firm peat had limited vertical movement and water levels fluctuated independently. This led to more severe water level draw-down (up to 40 cm below the surface), but fewer flood events.

Where vegetation developed over firmer peat there was a sub-division depending on the peat type. In *Sphagnum*-dominated areas the peat was almost entirely formed from the remains of this moss, developing a typically ombrotrophic peat. In herbaceous *Carex*-dominated areas the peat was more typically herbaceous minerotrophic fen peat. The structural differences between these peat affects their hydraulic properties. Ombrotrophic type peat are described as having two layers ('diplotelmic'), the top area being loose and open (the acrotelm) and below this in the permanently saturated zone is a more dense peat (the catotelm) (Ingram 1978, 1983, Ingram & Bragg 1984). This diplotelmic structure is heavily based on the structure of *Sphagnum* and its effect on water flow (Ingram & Bragg 1984, Clymo 1992, 1997). In the acrotelm water can flow rapidly through the peat allowing excess water to be readily and quickly shed. This will reduce flooding episodes, and flooding in these *Sphagnum* peat areas of the fen was limited or did not occur. As water levels drop the water flows through the more dense peat of the catotelm. Here hydraulic conductivity is reduced and water flows more slowly. This should reduce water loss in drier times, but in this case water level draw-down at these *Sphagnum* peat areas was similar to other dipwell points on the fen, at around 30 cm below the fen surface.

In fen peat there is little or no diplotelmic development because of the limited growth or the complete absence of *Sphagnum* species (Ingram 1992). Generally, therefore, fen peats are expected to have lower hydraulic conductivities than *Sphagnum* peats, reducing water flow rates through them. There will still be some reduction in hydraulic conductivity in fen peat at greater depths, related to changes in hummification levels (Bloeman 1983), but the change down the fen peat profile is likely to be less marked. The dipwell measurements indicated more frequent flooding in fen peat areas than in the areas of *Sphagnum* peat. This may be explained by lack of acrotelm development reducing rapid water shed, leading to greater and more frequent inundation, and Schoewenaars (1993) found that increased hummification levels in peat have been related to increased water level fluctuation. Fen peat does show a range of hydraulic conductivities, largely due to the inherent variability in the peat structure but also because of the difficulties in obtaining accurate measurements (Baird & Gaffney 1994, 1995, Baird 1995, Ours *et al.* 1997), and more research is needed in this area.

In summary, the catchment hydrology of the sites were found to differ slightly despite their similarities in climate, altitude, geology, soils and area. This was demonstrated through the flow regimes of the inflow streams. At Long Moss the regime was dominated by run off from the catchment drainage network, while at Nether Whitlaw Moss water appeared to enter the stream from outwith the surface catchment through channelised inflows. The run off was likely to enter the fen through more diffuse flow from surrounding land rather than via the stream. This may be related to local variation in topography, resevoir development and differences in land use within the catchment. In addition to the effects of diffuse surface/sub-surface water and stream inflows on each site, groundwater upwelling on the fen itself could potentially influence site hydrology. Groundwater upwelling has been noted on fen sites in the Border Region, developing as unvegetated 'well-eyes'. Tratt (1997) in a detailed study of fen vegetation development in the Border mires, indicates the presence of well-eyes on many fens, particularly on Murder Moss which is in the vicinity of Nether Whitlaw Moss. Well-eyes were not noted on Long Moss or Nether Whitlaw Moss in this study, or by Tratt (1997). There is, however, the potential for fissures in the impervious blue-grey clay lining these fen basins, which could enable some groundwater upwelling, and locally influence hydrological and hydrochemical conditions.

It was clear from dipwell data that the basin fens did not function as a single hydrologic unit. Although the water entering the site followed typical seasonal patterns, the responses to water inputs were different across the fen. This was related to peat structure and to vegetation raft development. It may also be a function of basin morphology with steeper-sided basins linked to the formation of floating rafts (Tratt 1997). The relationships between these hydrological responses and the vegetation and hydrochemical heterogeneity of the fens are further discussed in chapter 6.

Chapter 5

Hydrochemical variation in two small basin fens in Scotland, and associated vegetation and nutrient status.

5.1 Introduction

As discussed in previous chapters, the hydrochemistry of fens, and wetlands generally, is closely linked to the hydrological influences on an individual site (Richardson *et al.* 1978, Wilcox *et al.* 1986, Verhoeven & Aerts 1987, Grieve *et al.* 1995). Apart from influencing water table movement and wetting/drying of the peat surface, water inputs are an important external source of nutrients for plants. The hydrochemistry of these external water inputs depends on geology, soils and land use of the catchment (Ross *et al.* 1998). Fen hydrochemistry is also affected by the internal nutrient dynamics driven by physiochemical or biological interactions (Verhoeven 1986). This has been demonstrated in other wetland systems (*e.g.* Gale *et al.* 1992). Some major plant nutrients, namely nitrogen and phosphorus, within a fen system are sequestered in peat soils as organic material unavailable to plants. Processes within the fen release these organic nutrients as inorganic species (such as nitrate and phosphate). These processes are decomposition and mineralisation, and along with inputs from external sources (*e.g.* precipitation and groundwater) control the availability of major plant nutrients.

The relative influence of external nutrient inputs and internal nutrient dynamics on a fen depends on its development stage. An 'open' nutrient cycle with high water flow-through rates dominate early successional fens (Howard-Williams 1985, Howard-Williams & Downes 1993). Peat development is limited and the fen nutrient status is determined by external inputs (Koerselman *et al.* 1990a). These nutrient inputs, particularly nitrogen, may drive early successional changes (Berendse *et al.* 1989). Later successional fens become more isolated from the influence of its environment (Verhoeven 1986), as peat development 'locks away' nutrients. Nutrient dynamics in later successional phases are dominated by internal processes of mineralisation, decomposition and ion exchange (Bowden 1988), and these processes can modify external inputs. To begin to understand the cycling and redistribution of nutrients and the manner in which they are influenced by hydrological processes, a number of processes that can occur in these systems need to be considered, along with the interactions between these processes.

Peat soils have a greater cation exchange capacity (CEC) than mineral soils because of their high organic content (Clymo 1983, Ellis & Mellor 1995), and physiochemical reactions include adsorption and release of solutes on peat colloid surfaces (ion exchange). For example, the release of hydrogen ions through acidification of the peat causes dissociation of base cations, such as potassium (Hemond 1980, Boeye & Verheyen 1994). These base cations are readily leached away (Ellis & Mellor 1995). The high ion exchange capacity of peat also enables it to adsorb cations such as potassium and ammonium (Cuttle 1983).

Anion exchange can also occur in peat soils, and iron and aluminium oxides are particularly important in this (Ellis & Mellor 1995). Iron and aluminium oxides adsorb soluble orthophosphate at pH 4.5 to 6.5 (Stumm & Morgan 1981), and make them unavailable to plants. Conversely, above pH 6.5 release of soluble orthophosphate may occur. In addition, D'Angelo & Reddy (1994) found that the reduction of iron oxides under flooded conditions releases phosphate, and is likely to elevate phosphate concentrations in peat soil water. Khalid *et al.* (1977) also found that in flooded soils phosphate release was significantly positively correlated to amount of iron in the soil.

At greater pH, calcium concentration can affect the availability of phosphates (Stumm & Morgan 1981), forming insoluble (and therefore plant unavailable) calcium phosphates, such as hydroxyapatite (Boyer & Wheeler 1989). These physiochemical processes may control phosphate availability within fens (*e.g.* Verhoeven *et al.* 1985, Wassen & Barendregt 1992, Koerselman *et al.* 1993). Sites with low concentrations of calcium may be more sensitive to additional phosphate inputs as they lack this mechanism that converts soluble phosphates into insoluble, plant unavailable forms, and buffer increased phosphate concentrations (Boyer & Wheeler 1981).

Ion transformations can also occur in response to reduction - oxidation potential of the soil and water. This redox measurement is a combination of peat aeration and soil moisture content, and may change seasonally. Phosphate is adsorbed onto iron oxides making them plant unavailable (Borggard 1983), and this adsorption is strongest to iron (Fe^{3+}) oxides that occur under oxidising conditions (Patrick & Khalid 1974), so iron may remove soluble phosphate in aerated, acidic conditions. The redox potential is often a main contributor to differences between rich fen and poor fen hydrochemistry, and has been linked to the oxidation of pyrite (FeS^{2-}) under high redox conditions (Kemmers & Jansen 1988). The subsequent release of iron from the pyrite may increase the potential for phosphate to be adsorbed onto the iron, reducing its solubility.

Biological interactions are involved in nutrient transformations such as decomposition and mineralisation (Verhoeven 1986, Verhoeven *et al.* 1993). These processes are predominantly mediated by microbial activity in the peat soil. Decomposition of plant litter occurs at different rates depending on environmental conditions (*e.g.* temperature, oxygen availability). In temperate climate fen (and bog) decomposition rates are slow because of the prevailing anoxic conditions and low temperatures, therefore organic matter accumulates as peat (Chamie & Richardson 1978). Rates also depend on the type of plant material (Rastin *et al.* 1988, Lahdesmakii & Piispanen 1988, Updegraff *et al.* 1995), and even within the same genus, different plant species can have very different decomposition rates (Verhoeven & Aerts 1992). The nutrient content of the peat and the plant litter (*i.e.* substrate quality) can, therefore, affect the rates of decomposition, with increasing nutrient contents leading to increased rates of decomposition (Coulson & Butterfield 1978, Aerts & Ludwig 1997).

Substrate quality can, therefore, affect decomposition rates, and it might be expected that different vegetation types will exhibit different rates due to the differences in litter nutrient content. Verhoeven and Toth (1995) found that *Carex* litter decomposed more rapidly than *Sphagnum* litter, and suggest *Sphagnum* litter may contain a phenolic substance that reduces decomposition rates. Koerselman and Verhoeven (1992) found that although parts of the *Sphagnum* plant are slow to decompose, there is an initial rapid release of nutrients from the cell cytoplasm. These would be expected to increase nutrient concentrations in *Sphagnum*-dominated areas, yet in reality they can be quickly incorporated into microbial or plant biomass and not detected in the field. In addition, living *Sphagnum* can actively scavenge ions such as potassium (Hemond 1980, Boeye & Verheyen 1994) and nitrate (Lee & Woodin 1988, in Verhoeven *et al.* 1990) and prevent their loss from the system. Similar nutrient loss prevention can be seen in the internal retranslocation and storage of ions in some vascular plants (*e.g.* Prentki *et al.* 1978, Jonasson & Chapin 1985).

Decomposition and the mineralisation of peat nutrients is therefore crucial in the availability of nutrients to plants (Verhoeven *et al.* 1983). The nutrients are also readily taken up by microbial populations, leading to competition for a scarce resource. The mineralisation of the major plant nutrients nitrogen, phosphorus and potassium is carried out through different processes. Potassium is leached quickly from litter and rapidly available for biological uptake (Braekke 1981), but may be adsorbed onto the peat matrix through ion exchange (Richardson *et al.* 1978). It involves little microbial breakdown as potassium is present in ionic form in the plant cell (Verhoeven *et al.* 1983). Nitrogen (N) and phosphorus (P) are both found within complex organic material which relies on microbial decomposition for release as an inorganic ion. In mires, like other natural and semi-natural systems where nutrients are limiting, N and P are also quickly taken up by microbes. Nutrient mineralisation is, therefore, often rapidly followed by incorporation into the microbial biomass, again making it unavailable for plant uptake. Although where anaerobic microbial activity dominates the resulting microbial requirement for N and P is reduced, leading to more nutrients in solution (Wetzel 1983, in D'Angelo & Reddy 1994).

Indirect measurements of nitrogen and phosphorus mineralisation rates in peat have also been used to decide the nutrient status of a fen (Verhoeven *et al.* 1983, Verhoeven & Aerts 1987, 1992). Fen nutrient assessment is becoming increasingly widespread, not just to describe the natural variation within fen habitats, but also to identify potential artificial nutrient enrichment. Agricultural intensification has increased nutrient inputs into groundwater, surface water and precipitation that may enter a fen (Wheeler 1983, Verhoeven *et al.* 1988a,b, Verhoeven *et al.* 1996). Enrichment can cause changes to the internal nutrient cycling of the fen, which lead to changes in plant productivity (Sanville 1988, Van Oorschot 1994), and/or changes in species composition (Wheeler 1993). This may be a particular problem in fens within an agricultural landscape (Shaw & Wheeler 1990).

The aim of this chapter is to assess the hydrochemical variation on two small basin fens in Scotland, and to highlight the effect this may have on nutrient availability to plants, nutrient status and vegetation development. Four main approaches were taken in assessing hydrochemical variation. First, data for both fens were split using the vegetation types identified through TWINSPAN (Hill 1979) analysis (detailed in *section 3.3.2*), and variations between vegetation groups were analysed. Second, these data were classified according to a water type model using ionic concentrations to identify different basic water types (LAT Model, Van Wirdum 1981). The hydrochemical variation between these water types was then assessed. Third, the two sites were compared on a month by month basis, in particular to identify any increased nutrients at Nether Whitlaw Moss (surrounded by improved grassland) as compared to Long Moss (surrounded by unimproved acid grassland). Finally, temporal (monthly) and spatial hydrochemical variation was assessed in some detail at each site separately.

5.2 Methodology

5.2.1 Collection of water samples

Sub-surface waters were sampled at monthly intervals from March to November 1996 along a transect that ran from the inflow stream to the outflow stream across each fen (Fig. 5.1), equivalent to the transect for monthly dipwell measurements (*chapter 4*). Ten sample points were located on the transect at approximately 0m, 0.25m. 1m, 5m, 10m, 25m, 50m, 100m, 200m and 300m at each site. In addition, water samples were collected from inflow streams, outflow streams, lag streams (Long Moss only) and next to drains entering the fen (Nether Whitlaw Moss only), and rain gauges installed at each site. Samples along the transect were extracted from perforated PVC tubes sunk to a depth of 30 cm (the main rooting depth of the higher plants), into 250 ml acid-washed PVC bottles, using a peristaltic pump. At each sampling point on the transects five replicate water samples were extracted and analysed individually (detailed in *section 5.2.2*). Electrical conductivity, pH and reduction-oxidation potential (at a depth of 30 cm), and pH of surface waters was measured in the field at each sampling point, using clear but unfiltered water. Further samples were taken from input streams, drain inflows, rain gauges, outflow streams, and lag streams around the perimeter of the fen, and subjected to the same analyses.

5.2.2 Laboratory analysis of water samples

Water samples were stored over-night at 0-3 ^{0}C and filtered through Whatman GF/C filter paper the following day. To ensure precision each sample was replicated three times for cation analysis, and three random samples replicated three times at the beginning of anion analysis. Accuracy was checked using blanks and standard

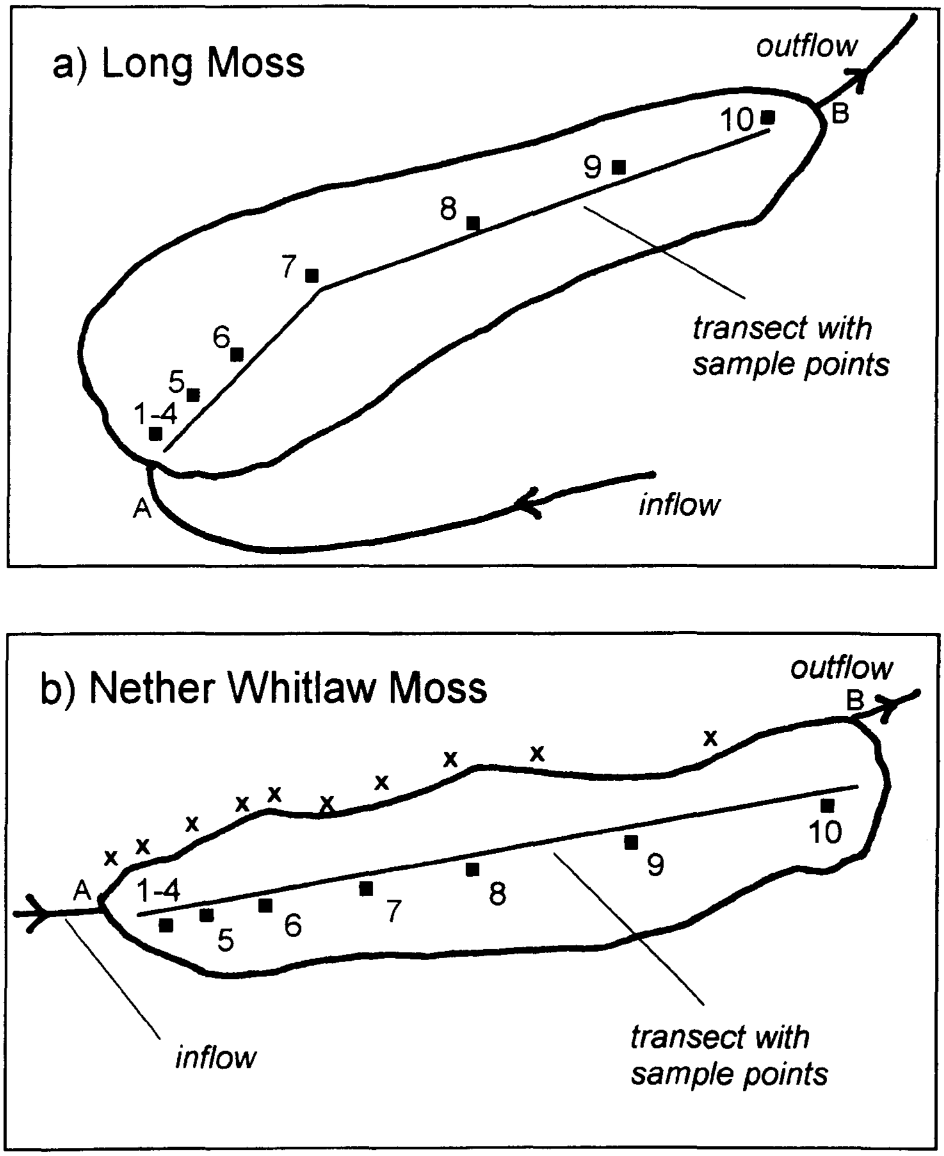


Fig. 5.1 Sample locations along each transect on a) Long Moss and b) Nether Whitlaw Moss. Sample locations for inflow (A), outflow (B) and drains (x) also shown. Sample positions along transect;
1 - 0m, 2 - 0.25m, 3 - 1m, 4 - 5m, 5 - 10m, 6 - 25m,
7 - 50m, 8 - 100m, 9 - 200m, 10 = 300m

solutions, and systematic error was reduced by randomising samples, blanks and standards during each analysis.

Three replicates of each filtrate were analysed for ammonium, phosphate, potassium and calcium. Ammonium was determined colorimetrically at 640 nm following the phenate method (Eaton *et al.* 1995), detection limit 0.01 mg l^{-1}. Phosphate was determined using the Ammonium Molybdate/Ascorbic Acid method of Murphy & Riley (1962), detection limit 0.01 $\mu g\ l^{-1}$. In addition, potassium was determined using a Corning 400 flame photometer, detection limit 0.1 mg l^{-1}, and calcium (samples dosed with strontium nitrate/hydrochloric acid) by a Pye-Unicam 919 atomic absorption spectrophotometer (Allen 1989), detection limit 0.01 mg l^{-1}. Sub-samples were filtered through 0.5 μm Whatman CA and Dionex On-Guard-Ag filters before analysis for nitrate, sulphate and fluoride using a Dionex ion chromatograph fitted with a chemical suppressor and an AS4A analytical column. Sodium hydroxide was used as the eluent, sulphuric acid as the regenerant. Three replicates of three randomly chosen samples were analysed at the beginning of the analysis run to check precision. Additional sub-samples were analysed for chloride after filtering through Whatman CA only, in July 1996. Detection limits at 0.02 mg l^{-1}. Full details of these methodologies are presented in Allen (1989) and Bartram and Ballance (1996).

5.2.3 Data analysis

In general, to highlight underlying trends and achieve a normal distribution, the data were transformed using natural Logarithmic (Log_e) transformation, and removal of outlying data points. Outlier data points were identified by carrying out analysis of the fits and residuals resulting from the one-way analysis of variance tests on samples from each transect point. In addition, data distribution was assessed using the Anderson-Darling test for normality. Original (un-transformed) data were used where subsets showed a normal distribution, or where nonparametric statistical analyses were used. All analyses were carried out using Minitab 11 and Excel 5.0.

The six vegetation groups identified through TWINSPAN (Hill 1979) analysis (*section 3.3.2*) formed the basis to compare hydrochemical variation between and within each vegetation group over the nine-month sampling period. The vegetation groups were as follows:

Group 1 - *Carex rostrata - Menyanthes trifoliata* poor fen, *Sphagnum* sub-community

Group 2 - *Potentilla palustris - C. rostrata* transitional fen

Group 3 - *C. rostrata - M. trifoliata* poor fen

Group 4 - *C. rostrata - M. trifoliata* poor fen, *Equisetum fluviatile* sub-community

Group 5 - *Carex panicea - Carex pulicaris* rich fen

Group 6 - *Eriophorum angustifolium - Sphagnum magellanicum* mire

Mean and standard errors of the mean (SEM) were calculated for each hydrochemical parameter for each vegetation group. A two-way analysis of variance (2-way ANOVA), using a General Linear Model (GLM) to account for unbalanced designs, was carried out on each hydrochemical parameter using vegetation group and month as the variables. Multivariate analysis of variance (MANOVA) was also carried out, which combined all seven hydrochemical parameters by vegetation group and by month. The site by month interaction was not assessed due to incomplete datasets.

The lithotrophic - atmotrophic - thalassotrophic (LAT) model (Van Wirdum 1981) for hydrochemical classification was used to highlight similarities and differences between the sub-surface water types sampled on the two fen sites. The model used calcium and chloride concentrations of each sample to produce an ionic ratio (IR, *equation 5.1*), which was plotted against electrical conductivity (EC) values of the same sample.

$$IR = (0.5\ Ca^{2+}) / ((0.5\ Ca^{2+}) + (Cl^{-})) \qquad \textit{(equation 5.1)}$$

The IR and EC together suggested the similarity of sampled water types to three reference points; *lithotrophic* waters with a higher residence time in the ground, *atmotrophic* water with low residence time in the ground, and *thalassotrophic* water with greater chloride concentrations possibly showing marine or pollution influences.

The groups identified from the LAT water type classification were used as a basis for analysing hydrochemical variation over the nine-month sampling period. Mean and SEM were calculated to compare between LAT groups. Again a two-way ANOVA, using a GLM, assessed each hydrochemical parameter, while a MANOVA combined all seven parameters. Datasets were analysed by LAT water type and by month, and the interaction (LAT group x month) also assessed.

Differences between the nutrient status of the two sites were analysed using descriptive statistics and a two-sample t-test. The hydrochemical data gathered over the nine month sampling period from transects across the fen, inflow, outflow, and rainwater were used. In addition, the hydrochemical composition of the water entering from land drains on the north side of Nether Whitlaw Moss (see Fig. 4.1) was assessed, as were samples from the perimeter lag stream of Long Moss.

Temporal variation in the nutrient status of each fen site was compared for each month, using hydrochemical data from the transect (descriptive statistics). Differences between and within each site, for each month, were analysed using a two-way ANOVA (incorporating a GLM) for each hydrochemical parameter, and a MANOVA analysis for all parameters combined. Mean and SEM were calculated for the inflow, outflow, rainfall, land drain and lag stream data, and differences assessed using Mann-Whitney *U* and Kruskal-Wallis tests.

Spatial and temporal variations were analysed together, on a site by site basis, using a two-way ANOVA test (incorporating a GLM). In addition, overall differences between all hydrochemical parameters were tested using MANOVA. The interaction between spatial and temporal variation (site x month) was not analysed due to an unbalanced dataset.

5.3 Results

5.3.1 Hydrochemical variation between and within vegetation groups

Significant differences were seen in the means of hydrochemical parameters between the vegetation groups (Table 5.1 and Fig. 5.2). Measurements of pH were greatest in the three herb dominated *Carex rostrata* species-poor and transitional fens, and the *Carex panicea* - *Carex pulicaris* species-rich fen (groups 2 - 5), and lesser in the *Eriophorum* - *Sphagnum* bog and *C. rostrata* - *M. trifoliata, Sphagnum squarrosum* species-poor fen (groups 1 & 6) (Fig. 5.2a). Electrical conductivity and calcium concentrations showed similar patterns, greater in herb-dominated groups 2 and 4,

Table 5.1 Two-way analysis of variance (ANOVA incorporating a GLM), and multiple analysis of variance (MANOVA) for vegetation group and month. EC = electrical conductivity, DF = degrees of freedom

	Vegetation Group			Month		
	DF	F-value	*p-value*	DF	F-value	*p-value*
pH	5	519.68	**0.000**	7	22.44	**0.000**
EC	5	247.03	**0.000**	7	8.74	**0.000**
Calcium	5	408.52	**0.000**	7	38.52	**0.000**
Nitrate	5	8.18	**0.000**	7	21.82	**0.000**
Ammonium	5	5.36	**0.000**	7	7.66	**0.000**
Phosphate	5	30.81	**0.000**	7	54.63	**0.000**
Potassium	5	31.78	**0.000**	7	33.52	**0.000**
MANOVA	35 ; 2194	74.50	**0.000**	49 ; 2649	30.29	**0.000**

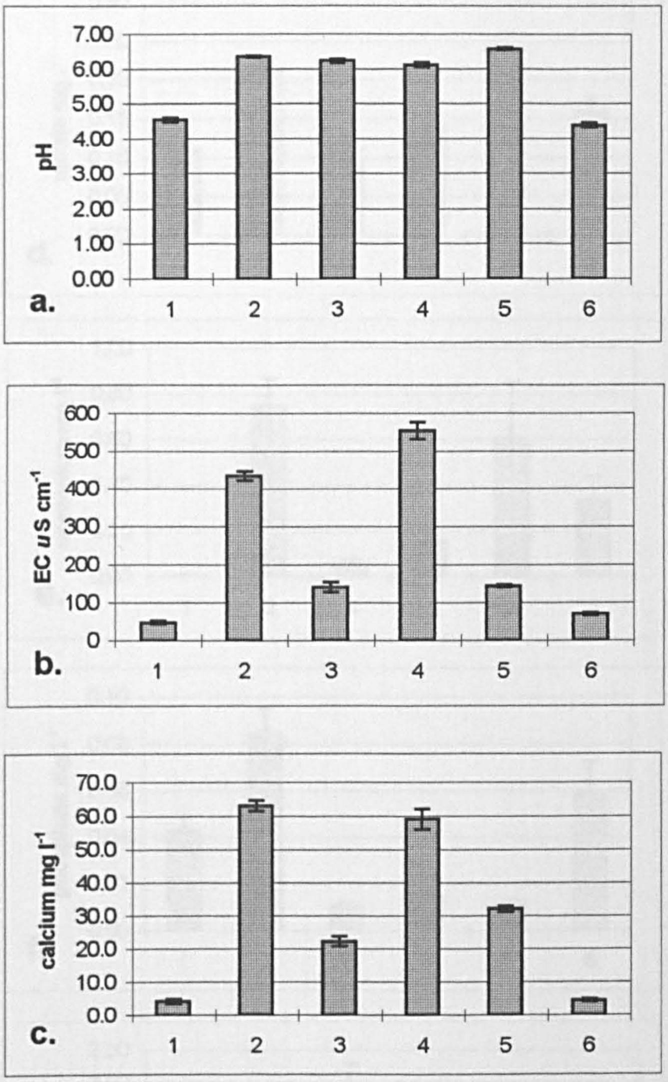


Fig. 5.2 Mean and standard error of the mean for a) pH, b) electrical conductivity (EC) and c) calcium for water samples from vegetation groups 1 to 6, as detailed below:

1 = *Carex rostrata - Menyanthes trifoliata* poor fen, *Sphagnum squarrosum* subcommunity

2 = *Potentilla palustris - C. rostrata* transitional fen

3 = *C. rostrata - M. trifoliata* poor fen

4 = *C. rostrata - M. trifoliata* poor fen, *Equisetum fluviatile* subcommunity

5 = *Carex panicea - Carex pulicaris* rich fen

6 = *Eriophorum angustifolium - Sphagnum magellanicum* mire

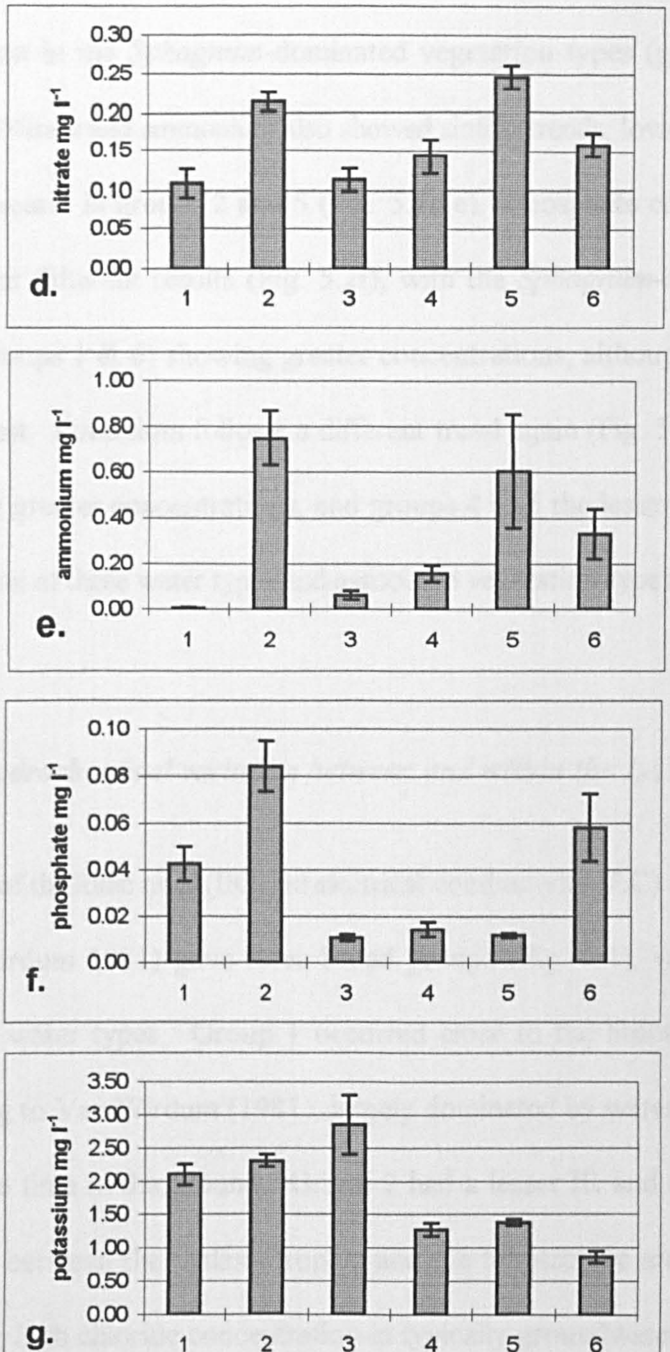


Fig. 5.2 (concl.) Mean and standard error of the mean for d) nitrate, e) ammonium, f) phosphate and g) potassium for water samples from vegetation groups 1 to 6

and lowest in the *Sphagnum*-dominated vegetation types (groups 1 and 6) (Fig. 5.2b,c). Nitrate and ammonium also showed similar trends, lowest in groups 1, 3 and 4, and greater in groups 2 and 5 (Fig. 5.2d,e). Phosphate concentrations showed somewhat different results (Fig. 5.2f), with the *Sphagnum*-dominated vegetation types (groups 1 & 6) showing greater concentrations, although group two showed the highest. Potassium follows a different trend again (Fig. 5.2g) with groups 1 to 3 having greater concentrations, and groups 4 to 6 the lesser concentrations. The distribution of these water types and associated vegetation types are presented in Fig. 5.3.

5.3.2 Hydrochemical variation between and within the LAT water types

Analysis of the ionic ratio (IR) and electrical conductivity (EC) using the LAT model (Van Wirdum 1981) gave three broad groups (Fig. 5.4), which related to three different water types. Group 1 occurred close to the lithotrophic standard and, according to Van Wirdum (1981), largely dominated by water with a typically long residence time in the ground. Group 2 had a lesser IR and a greater EC, so was situated between the thalassotrophic and the lithotrophic area. This suggested a relatively high chloride concentration in typically groundwater-dominated samples. The third group was close to the atmotrophic standard, with a low IR and EC, and can be assumed to be dominated by precipitation. The distribution of these LAT water types across each fen is presented in Fig. 5.5.

Both two-way ANOVA (using a GLM) and MANOVA analyses showed a significant interaction between IR group and month (Table 5.2), along with significant differences for IR group and month separately (except for no significant difference

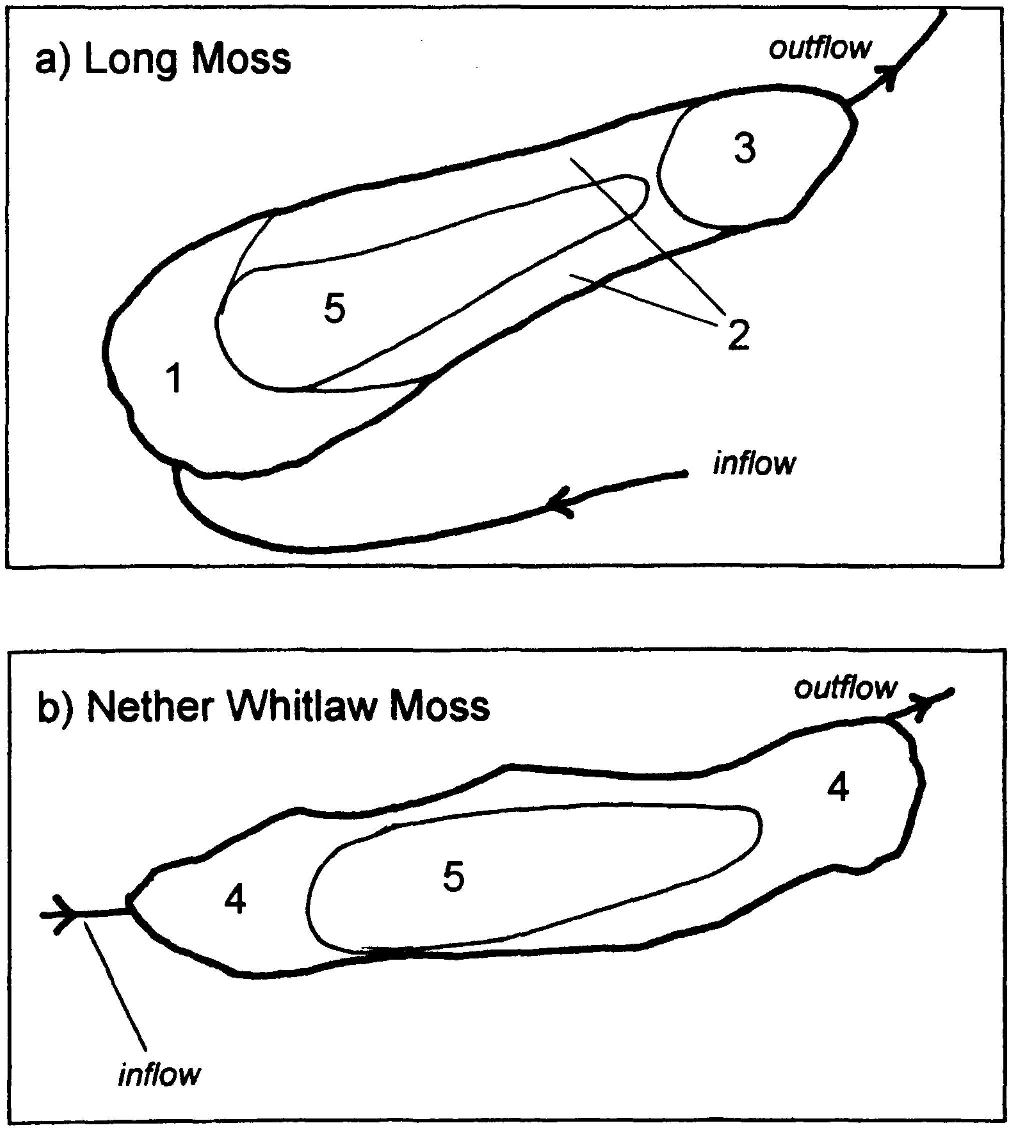


Fig. 5.3 Distribution of the different water type across a) Long Moss and b) Nether Whitlaw Moss, and associated vegetation groups (as detailed in section 5.3). Water types:

1- high pH, EC, higer nitrate / ammonium concentrations
2 - high pH, EC, higher overall nutrient concentrations
3 - high pH, lower overall nutrient concentrations
4 - high pH, EC and calcium, higher overall nutrient concentrations
5 - low pH, EC and calcium, high phosphate concentrations

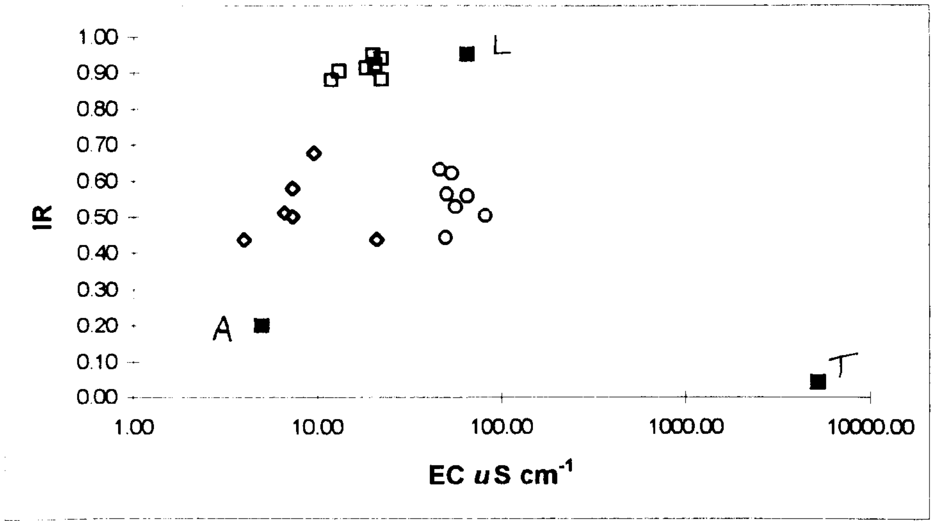


Fig. 5.4 LAT Model (Van Wirdum 1981) showing the distribution of water samples from both sites in relation to three reference water types, shown on the graph as L = lithotrophic standard, A = atmotrophic standard, T = thallasotrophic standard. The samples produced three clusters: □ = *group 1* lithotrophic type; ○ = *group 2* transitional litho- thalassotrophic type; ◇ = *group 3* atmotrophic type
IR = Ionic Ratio (see *equation 5.1*), EC = electrical conductivity *u* S cm^{-1}

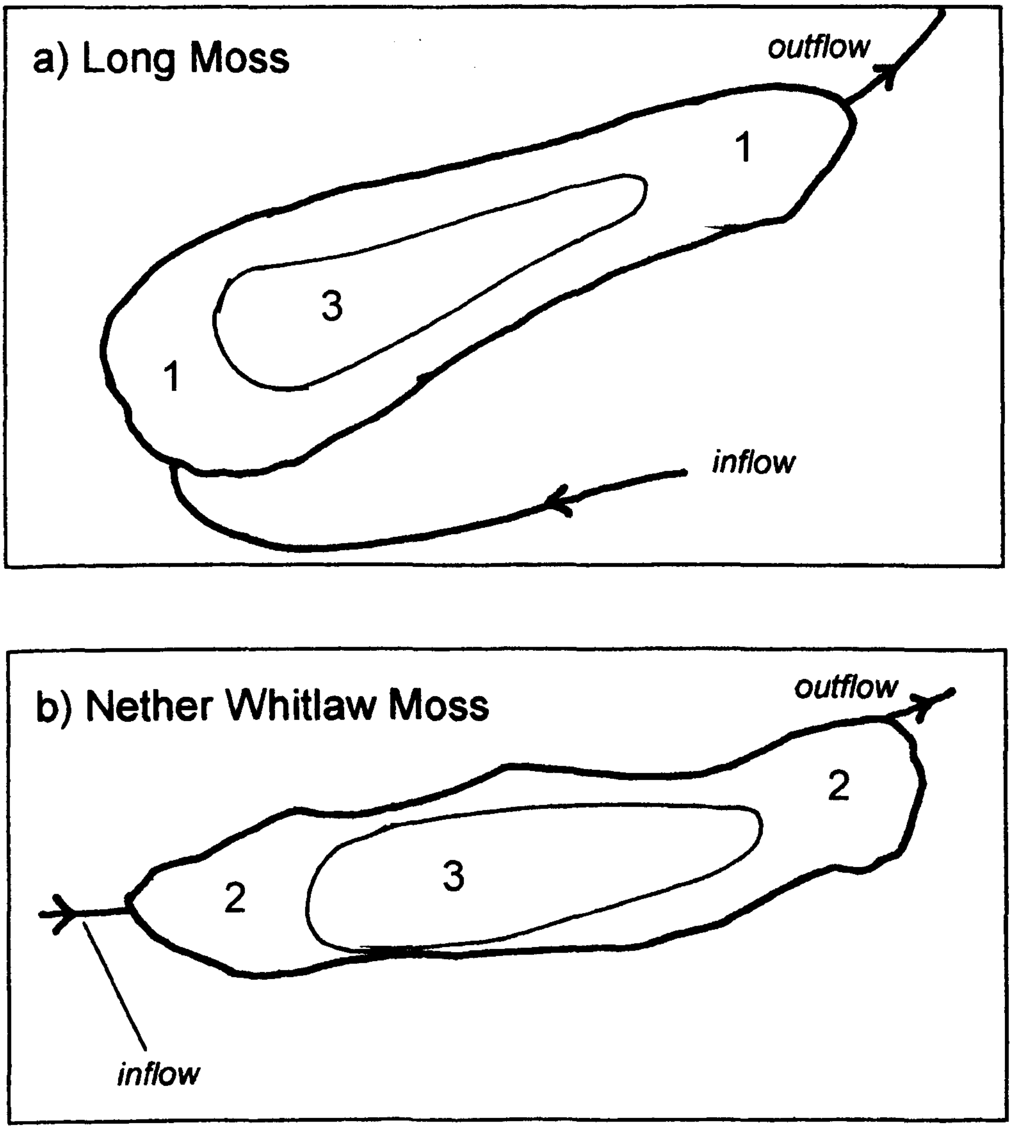


Fig. 5.5 Distribution of the three LAT water type across a) Long Moss and b) Nether Whitlaw Moss. Water types:
1 - lithotrophic water
2 - litho - thalassotrophic transitional water type
3 - atmotrophic water type

Table 5.2 Two-way ANOVA (incorporating a GLM) and MANOVA for ionic ratio group (IR) as identified by the LAT Model (Van Wirdum 1981), month and the interaction IR group x month, for each hydrochemical parameter
EC = electrical conductivity, DF = degrees of freedom

	Ionic Ratio Group			Month			IR GroupxMonth		
	DF	F-value	*p-value*	DF	F-value	*p-value*	DF	F-value	*p-value*
pH	2	853.67	**0.000**	7	3.84	**0.006**	14	10.43	**0.000**
EC	2	1231.47	**0.000**	7	14.80	**0.000**	14	9.13	**0.000**
Calcium	2	1098.01	**0.000**	7	57.55	**0.000**	14	9.11	**0.000**
Nitrate	2	0.65	0.522	7	9.99	**0.000**	14	7.29	**0.000**
Ammonium	2	9.80	**0.000**	7	13.81	**0.000**	14	10.68	**0.000**
Phosphate	2	0.06	**0.000**	7	0.04	**0.000**	14	3.70	**0.000**
Potassium	2	3.52	**0.030**	7	27.83	**0.000**	14	1.73	**0.046**
MANOVA	14 ; 1020	290.10	**0.000**	49 ; 2593	26.66	**0.000**	98 ; 3234	8.29	**0.000**

in nitrate concentration between IR groups). It appeared, therefore, that monthly differences in hydrochemical parameters were dependant on IR group.

The hydrochemical means calculated by IR group showed some distinct groups (Fig. 5.6). Measurements of pH, EC, calcium, nitrate and ammonium were lowest in Group 3, the atmotrophic dominated water type, whilst phosphate concentrations were greater. In the lithotrophic - thalassotrophic transitional water type (Group 2) EC, calcium, nitrate, ammonium and phosphate concentrations were all high. Group 1 (lithotrophic water type) had intermediate concentrations of all parameters, except phosphate which was low. Concentrations of potassium were similar across all three groups.

5.3.3 Comparison of two fen sites - evidence for nutrient enrichment

Overall, significant differences between Nether Whitlaw Moss (surrounded by improved grassland) and Long Moss (surrounded by unimproved acid grassland) were measured in pH, EC, calcium, potassium and phosphate concentrations (Table 5.3). No significant differences were observed in nitrate and ammonium concentrations, although ammonium concentrations were slightly elevated at Nether Whitlaw Moss (Table 5.4).

These results can be contrasted with the comparison of inflow and outflow data between sites, which gave few significant differences (Table 5.5). Nether Whitlaw Moss inflow stream had significantly greater EC and calcium concentrations than Long Moss (Table 5.5 & 5.6). The outflow stream at Nether Whitlaw Moss had significantly greater EC than the Long Moss outflow stream, although the pH was significantly lesser. There were no significant differences in the nitrate, ammonium,

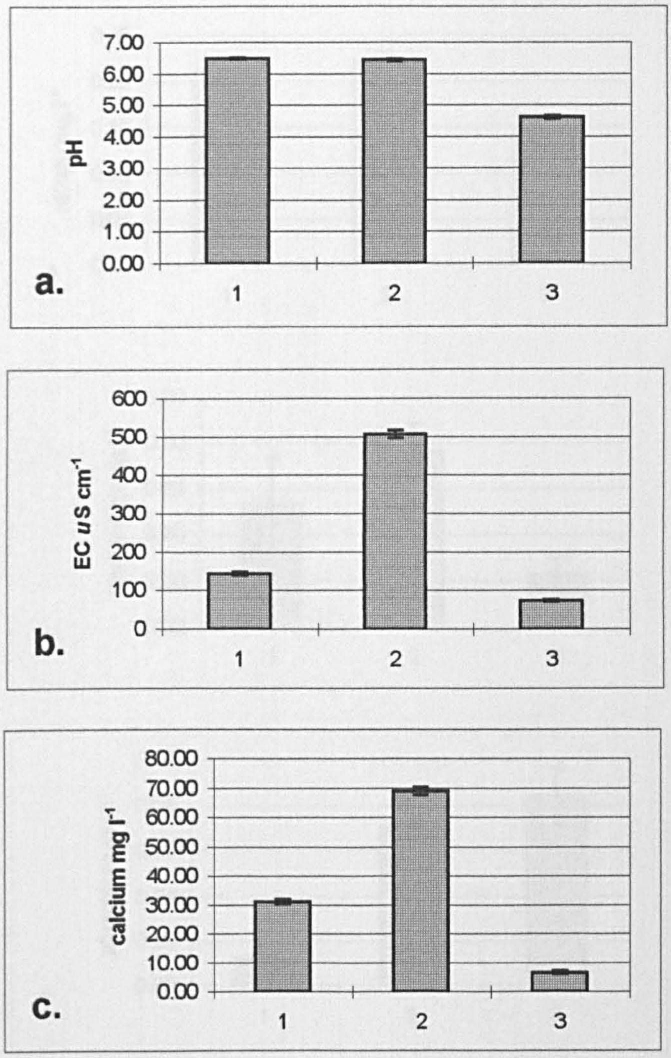


Fig. 5.6 Mean and standard error of the mean for a) pH, b) electrical conductivity (EC) and c) calcium mg l^{-1} for each water type group identified through the LAT model

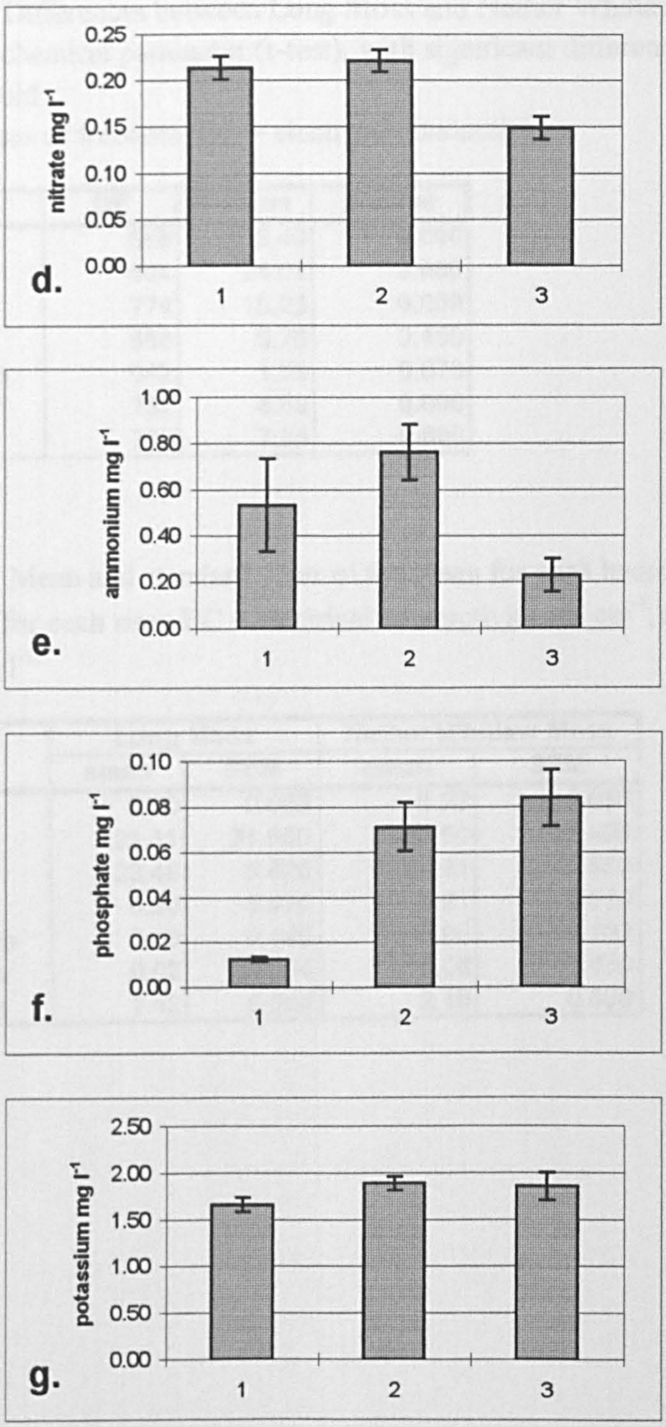


Fig. 5.6 (concl.) Mean and standard error of the mean for a) nitrate b) ammonium, c) phosphate and d) potassium for each water type identified through the LAT model

Table 5.3 Differences between Long Moss and Nether Whitlaw Moss for each hydrochemical parameter (t-test), with significant differences ($p = <0.05$) shown in bold.
DF = degrees of freedom, EC = electrical conductivity

	DF	T-value	*p-value*
pH	658	5.40	**0.000**
EC	694	24.03	**0.000**
Calcium	774	15.23	**0.000**
Nitrate	658	0.76	0.450
Ammonium	642	1.79	0.073
Phosphate	732	8.69	**0.000**
Potassium	776	7.55	**0.000**

Table 5.4 Mean and standard error of the mean for each hydrochemical parameter for each site. EC = electrical conductivity u S cm^{-1}, all ions as mg l^{-1}

	Long Moss		Nether Whitlaw Moss	
	mean	SEM	mean	SEM
pH	5.90	*0.053*	6.22	*0.036*
EC	121.11	*31.900*	438.50	*11.400*
Calcium	23.48	*0.826*	60.51	*1.530*
Nitrate	0.20	*0.010*	0.21	*0.010*
Ammonium	0.48	*0.149*	0.65	*0.103*
Phosphate	0.02	*0.004*	0.08	*0.010*
Potassium	1.42	*0.064*	2.16	*0.080*

Table 5.5 Comparison of inflow and also outflow stream hydrochemical data between sites (t-test), significant differences ($p = <0.05$) shown in bold
EC = electrical conductivity, DF = degrees of freedom

	Inflow			Outflow		
	DF	T-value	*p-value*	DF	T-value	*p-value*
pH	8	0.34	0.740	11	5.07	**0.000**
EC	8	-7.77	**0.000**	11	-6.23	**0.000**
Calcium	8	-5.53	**0.001**	7	0.88	0.150
Nitrate	8	-0.61	0.560	6	-1.02	0.350
Ammonium	8	-1.86	0.100	11	-0.33	0.750
Phosphate	11	-1.68	0.120	5	-1.45	0.210
Potassium	11	-1.35	0.210	9	0.72	0.490

Table 5.6 Mean and standard error of the mean for each hydrochemical parameter at the inflow and outflow streams at each site.
EC = electrical conductivity u S cm^{-1}, all ions in mg l^{-1}

	Inflow				Outflow			
	Long Moss		*Nether Whitlaw Moss*		*Long Moss*		*Nether Whitlaw Moss*	
	mean	SEM	mean	SEM	mean	SEM	mean	SEM
pH	7.34	*0.250*	7.23	*0.191*	6.60	*0.100*	5.91	*0.091*
EC	144.00	*16.900*	552.50	*49.800*	108.57	*6.340*	170.00	*7.560*
Calcium	27.06	*2.030*	81.96	*9.710*	27.09	*8.040*	25.77	*3.240*
Nitrate	0.62	*0.313*	0.87	*0.253*	0.10	*0.060*	0.60	*0.482*
Ammonium	0.03	*0.014*	0.23	*0.107*	0.09	*0.069*	0.13	*0.088*
Phosphate	0.01	*0.003*	0.02	*0.005*	0.01	*0.003*	0.04	*0.021*
Potassium	0.98	*0.299*	1.57	*0.318*	1.09	*0.236*	0.89	*0.144*

phosphate and potassium concentrations between the sites for the either the inflow or the outflow streams.

Comparing the inflow hydrochemistry with the outflow hydrochemistry at each site (Table 5.6), pH was significantly greater in the inflow stream at both sites, and at Nether Whitlaw Moss conductivity and calcium concentrations were also greater in the inflow than the outflow stream. At each site no significant differences were seen between the inflow and outflow concentrations of nitrate, ammonium, phosphate or potassium (Table 5.7).

Rainfall hydrochemistry showed no significant difference between the two sites (Table 5.8). At Long Moss the lag stream was sampled to give an indication of the hydrochemistry of diffuse water inputs from the surrounding unimproved acid grassland. No significant difference was seen in the hydrochemistry over the sampling period (Mann-Whitney *U*-test, Table 5.8), and mean values gave no indication of enriched water run off from the acid grassland (Table 5.9). At Nether Whitlaw Moss the nutrient status of the water entering from the improved pasture was assessed using samples where land drains entered the fen, taken in June, August, September and October 1996. Most of the hydrochemical parameters showed no increase in their mean concentrations close to the drains (Table 5.10) compared to mean values for the fen (Nether Whitlaw Moss, Table 5.4), but there was an increase in the concentration of phosphate, and to some extent nitrate. There were also significant differences in all the monthly hydrochemical parameters measured in these samples (Table 5.10), with September and October showing the greatest changes (Fig. 5.7). Electrical conductivity and calcium concentrations declined in October (Fig. 5.7b,c), while nitrate concentrations increased (Fig. 5.7d). Ammonium,

Table 5.7 Comparison of the inflow and outflow stream hydrochemical parameters for each site (t-test), significant differences (p = <0.05) shown in bold. EC = electrical conductivity, DF = degrees of freedom

	Long Moss			Nether Whitlaw Moss		
	DF	T-value	*p-value*	DF	T-value	*p-value*
pH	5	-2.75	**0.040**	11	-6.22	**0.000**
EC	5	-1.96	0.110	7	-7.60	**0.000**
Calcium	6	0.00	1.000	9	-5.49	**0.000**
Nitrate	4	-1.64	0.180	9	-0.51	0.620
Ammonium	6	0.87	0.420	13	-0.40	0.470
Phosphate	9	0.41	0.690	5	1.09	0.320
Potassium	8	-6.22	0.790	11	-1.95	0.077

Table 5.8 Mean and standard error of the mean for precipitation hydrochemistry at each site, and a comparison of the sites using Mann-Whitney *U*-test (M/W U-Test), where no significant differences (p = <0.05) were found. N = number of samples, EC = electrical conductivity u S cm^{-1}, all ions as mg l^{-1}

	Long Moss			Nether Whitlaw Moss			M/W U-Test
	N	Mean	SEM	N	Mean	SEM	*p-value*
pH	5	6.46	*0.234*	5	6.54	*0.175*	0.674
EC	4	37.50	*2.500*	4	82.50	*15.500*	0.065
Calcium	5	3.46	*1.150*	5	4.18	*0.877*	0.600
Nitrate	4	1.75	*0.401*	4	2.29	*0.287*	0.471
Ammonium	5	1.63	*0.423*	5	3.10	*1.010*	0.210
Phosphate	5	0.29	*0.199*	5	0.36	*0.117*	0.403
Potassium	5	2.58	*0.656*	5	4.28	*1.220*	0.296

Table 5.9 Mean and standard error of the mean of each hydrochemical parameter for lag stream samples (Long Moss). EC = electrical conductivity *u* S cm^{-1}, all ions as mg l^{-1}, N = number of samples.

	Lag stream		
	N	Mean	SEM
pH	14	6.97	*0.119*
EC	14	157.10	*25.600*
Calcium	14	32.69	*6.060*
Nitrate	12	0.15	*0.052*
Ammonium	14	0.06	*0.037*
Phosphate	14	0.01	*0.002*
Potassium	14	0.98	*0.174*

Table 5.10 Mean and standard error of the mean of hydrochemical parameters for samples close to field drains (Nether Whitlaw Moss). Statistically significant differences between months (Kruskal-Wallis test, $p = <0.05$) are shown in bold. EC = electrical conductivity *u* S cm^{-1}, all ions as mg l^{-1}, N = number of samples

	Field Drains			
	N	Mean	SEM	*p-value*
pH	26	6.69	*0.104*	**0.000**
EC	26	176.90	*15.200*	**0.002**
Calcium	24	42.53	*4.260*	**0.001**
Nitrate	20	0.45	*0.131*	**0.002**
Ammonium	23	0.54	*0.167*	**0.001**
Phosphate	23	0.10	*0.027*	**0.001**
Potassium	21	1.75	*0.455*	**0.024**

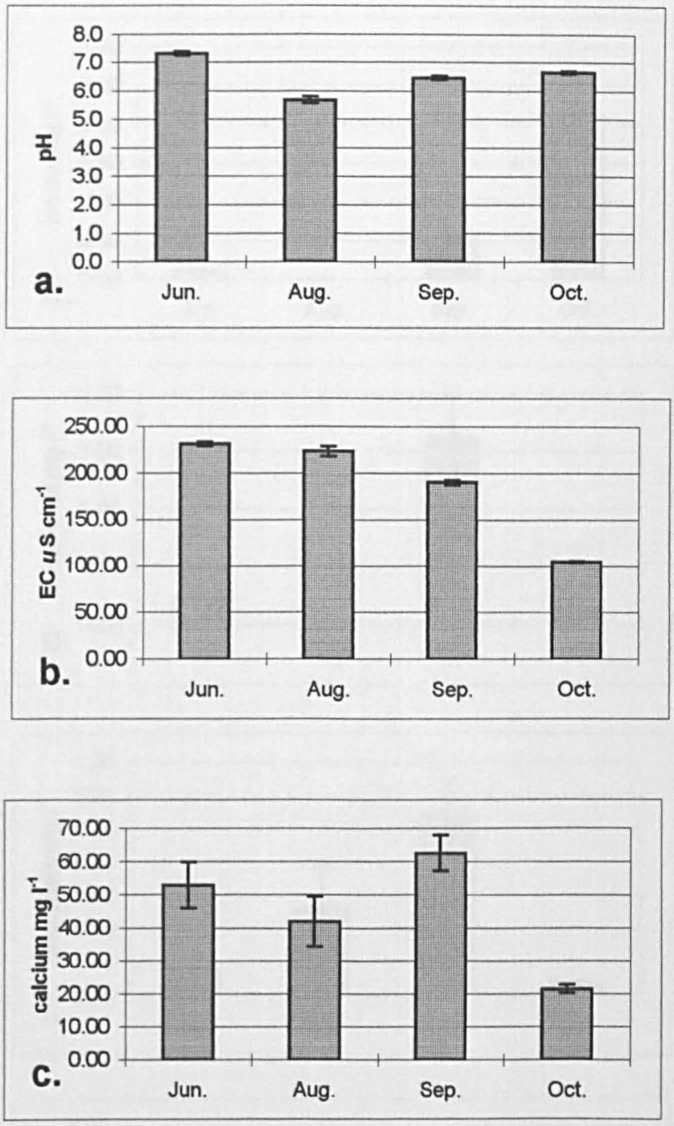


Fig. 5.7 Mean and standard error of the mean for a) pH, b) electrical conductivity (EC) and c) calcium as measured in water samples close to the field drain inflows at Nether Whitlaw Moss in June, August, September and October

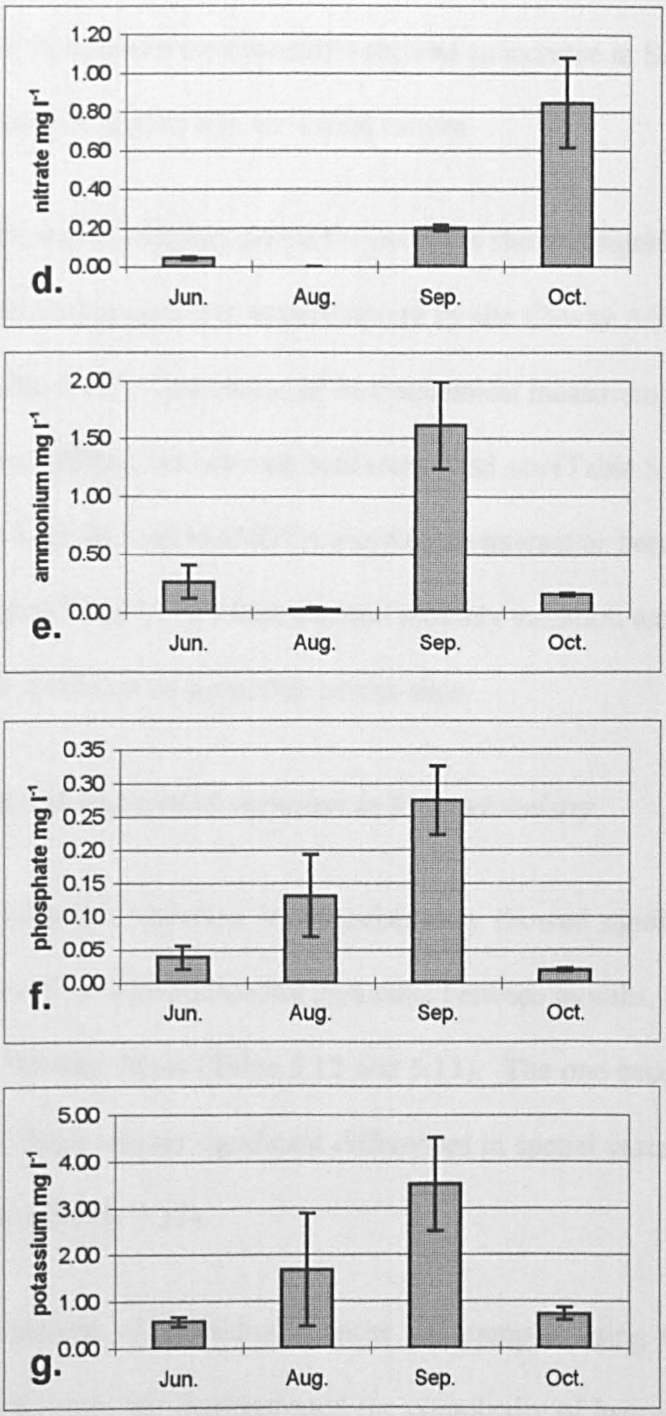


Fig. 5.7 (concl.) Mean and standard error of the mean of d) nitrate, e) ammonium, f) phosphate and g) potassium measured in water samples taken close to the field drains at Nether Whitlaw Moss

phosphate and potassium concentrations showed an increase in September (Fig. 5.7e-g), as did calcium, and to a lesser extent nitrate.

Over the nine-month sampling period the two sites showed significant differences for all hydrochemical parameters, except nitrate by site (2-way ANOVA incorporating a GLM; Table 5.11). Combining all hydrochemical measurements in a MANOVA gave significant differences between both month and site (Table 5.11). For both two-way ANOVA (GLM) and MANOVA analyses the interaction between month and site was significant (Table 5.11), which showed monthly variation was dependent on site which made it difficult to generalise across sites.

5.3.4 Temporal and spatial variation in hydrochemistry

Temporal and spatial variation in hydrochemistry showed significant differences in measurements of each hydrochemical parameter between months, at both Long Moss and Nether Whitlaw Moss (Table 5.12 and 5.13). The one exception was at Long Moss where there was no significant differences in spatial variation of ammonium concentrations (Table 5.12).

Closer examination of individual months and samples using the Tukey-Kramer multiple comparison test demonstrated the complexity of hydrochemical temporal variation underlying these overall significant differences (data available from the author on request). This was reflected in the mean values for each parameter, and monthly and sample variations for Long Moss and Nether Whitlaw Moss are presented below.

Table 5.11 Two-way ANOVA (using a GLM) and MANOVA showing differences in the hydrochemistry of the two sites over the nine month sampling period. The interaction between month and site (MonthxSite) is also shown. Significant differences (p = <0.05) are shown in bold. EC = electrical conductivity, DF = degrees of freedom

	Month			Site			MonthxSite		
	DF	F-value	*p-value*	DF	F-value	*p-value*	DF	F-value	*p-value*
pH	7	11.55	**0.000**	1	36.58	**0.000**	7	4.20	**0.000**
EC	7	7.52	**0.000**	1	477.26	**0.000**	7	8.70	**0.000**
Calcium	7	13.58	**0.000**	1	165.29	**0.000**	7	3.99	**0.000**
Nitrate	7	8.66	**0.000**	1	0.76	0.384	7	11.33	**0.000**
Ammonium	7	23.72	**0.000**	1	12.06	**0.000**	7	14.30	**0.000**
Phosphate	7	52.00	**0.000**	1	111.20	**0.000**	7	7.10	**0.000**
Potassium	7	34.56	**0.000**	1	47.22	**0.000**	7	3.92	**0.000**
MANOVA	49 ; 2634	29.70	**0.000**	7 ; 518	136.59	**0.000**	49 ; 2634	8.41	**0.000**

Table 5.12 Two-way ANOVA (with GLM) and MANOVA showing month and sample variation at Long Moss, with significant differences (p =<0.05) shown in bold. EC = electrical conductivity, DF =degrees of freedom

	Month			Sample		
	DF	F-value	*p-value*	DF	F-value	*p-value*
pH	8	15.29	**0.000**	9	312.29	**0.000**
EC	8	21.60	**0.000**	9	56.34	**0.000**
Calcium	8	111.57	**0.000**	9	533.32	**0.000**
Nitrate	7	15.44	**0.000**	9	5.70	**0.000**
Ammonium	8	6.11	**0.000**	9	1.83	0.062
Phosphate	8	67.52	**0.000**	9	10.62	**0.000**
Potassium	8	28.76	**0.000**	9	21.26	**0.000**
MANOVA	42;1180	28.95	**0.000**	54;1284	23.12	**0.000**

Table 5.13 Two-way ANOVA (with GLM) and MANOVA showing month and sample variation at Nether Whitlaw Moss, with significant differences (p =<0.05) shown in bold. EC = electrical conductivity, DF =degrees of freedom

NW Moss	Month			Sample		
	DF	F-value	*p-value*	DF	F-value	*p-value*
pH	8	81.42	**0.000**	9	264.38	**0.000**
EC	8	17.24	**0.000**	9	291.19	**0.000**
Calcium	8	57.63	**0.000**	9	616.76	**0.000**
Nitrate	7	11.66	**0.000**	9	14.23	**0.000**
Ammonium	8	24.70	**0.000**	9	13.57	**0.000**
Phosphate	8	34.75	**0.000**	9	21.48	**0.000**
Potassium	8	35.55	**0.000**	9	53.46	**0.000**
MANOVA	42;1213	24.35	**0.000**	54;1320	35.01	**0.000**

For Long Moss pH measurements were highest in August (Fig. 5.8a), significantly greater than May, July, October and November. Electrical conductivity showed greater variation, the mid to late summer months (July - September) having significantly greater measurements than the spring/early summer months (March - June) (Fig. 5.8b). Calcium concentrations showed a similar trend (Fig. 5.8c), with July and September having significantly greater calcium concentrations.

Nitrate, ammonium, phosphate and potassium concentrations on Long Moss were generally low throughout the sampling period (Fig. 5.8d-g). Some peaks in concentrations were seen in early spring and mid summer for nitrate (Fig. 5.8d) and phosphate (Fig. 5.8f), and in late summer for ammonium (Fig. 5.8e). These peaks were often significantly different from the lesser concentrations seen at other times, except for ammonium where the large variation in August samples (high standard error of the mean) obscures this pattern. Potassium concentrations were relatively constant except for significantly reduced measurements in May and June (Fig. 5.8g).

At Nether Whitlaw Moss pH was often significantly different between months, and decreased in mid to late summer and autumn (Fig. 5.8h). Electrical conductivity showed a similar trend, despite a peak in August (Fig. 5.8i), but few of these pairwise comparisons were statistically significant. Calcium concentrations showed a similar summer and autumn drop (Fig. 5.8j) with some autumn values being significantly reduced compared to the spring values.

Nutrient concentrations at Nether Whitlaw Moss were generally low throughout the sampling period, with some mid summer (June/July) peaks in nitrate, ammonium and phosphate concentrations (Figs. 5.8k-m). There were also significantly greater April

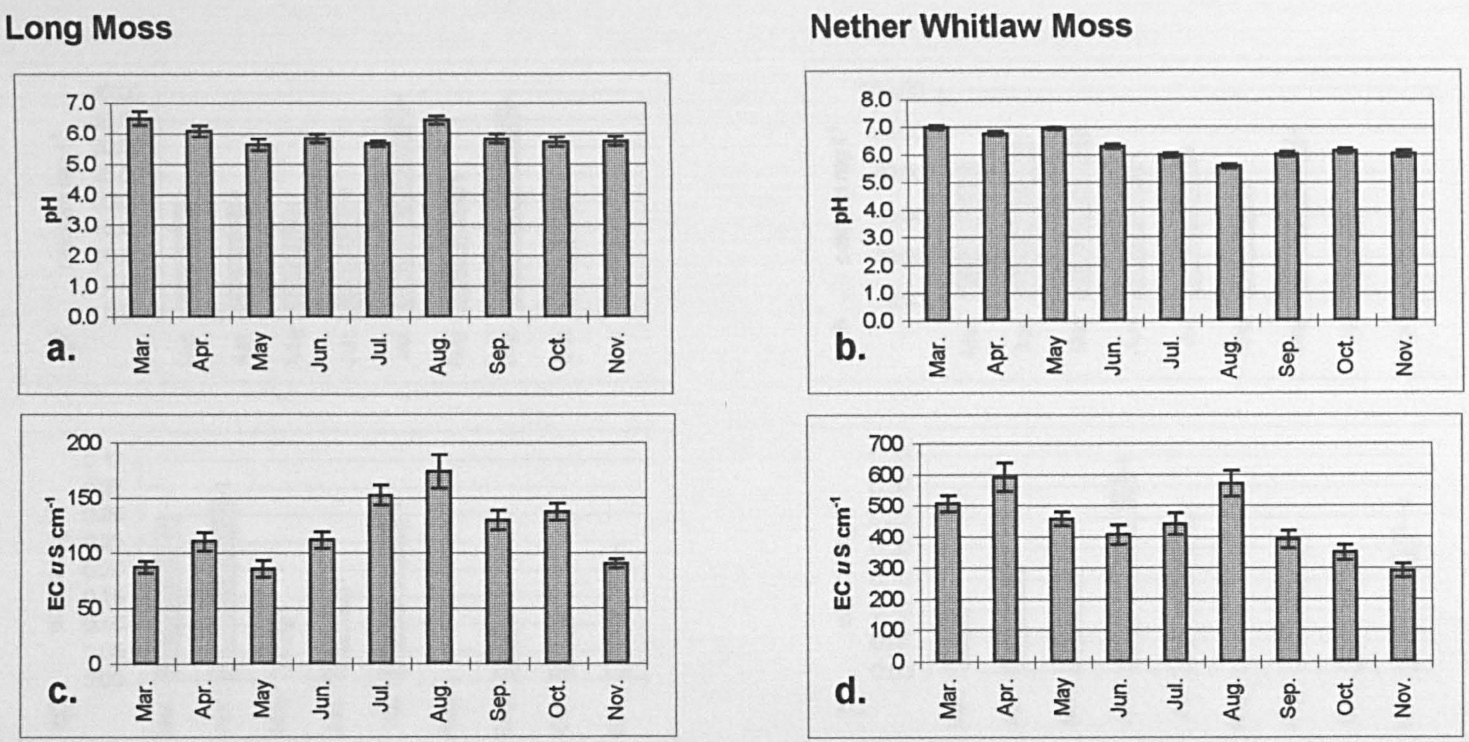


Fig. 5.8 Monthly mean and standard error of the mean of pH at a) Long Moss and b) Nether Whitlaw Moss, and electrical conductivity (EC, *u* S cm^{-1}) at c) Long Moss and d) Nether Whitlaw Moss

Long Moss　　　　Nether Whitlaw Moss

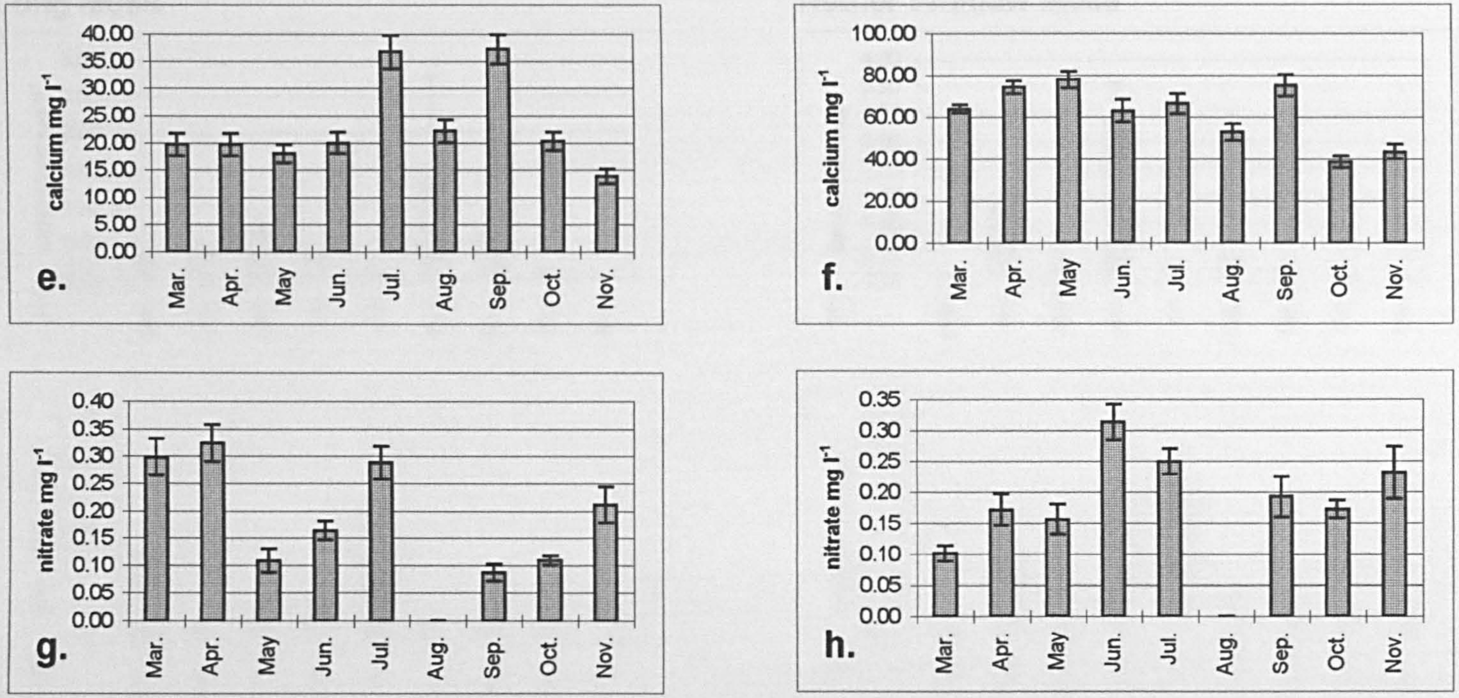


Fig. 5.8 (cont.) Monthly mean and standard error of the mean for calcium at e) Long Moss f) Nether Whitlaw Moss, and nitrate at g) Long Moss h) Nether Whitlaw Moss, as mg l^{-1}

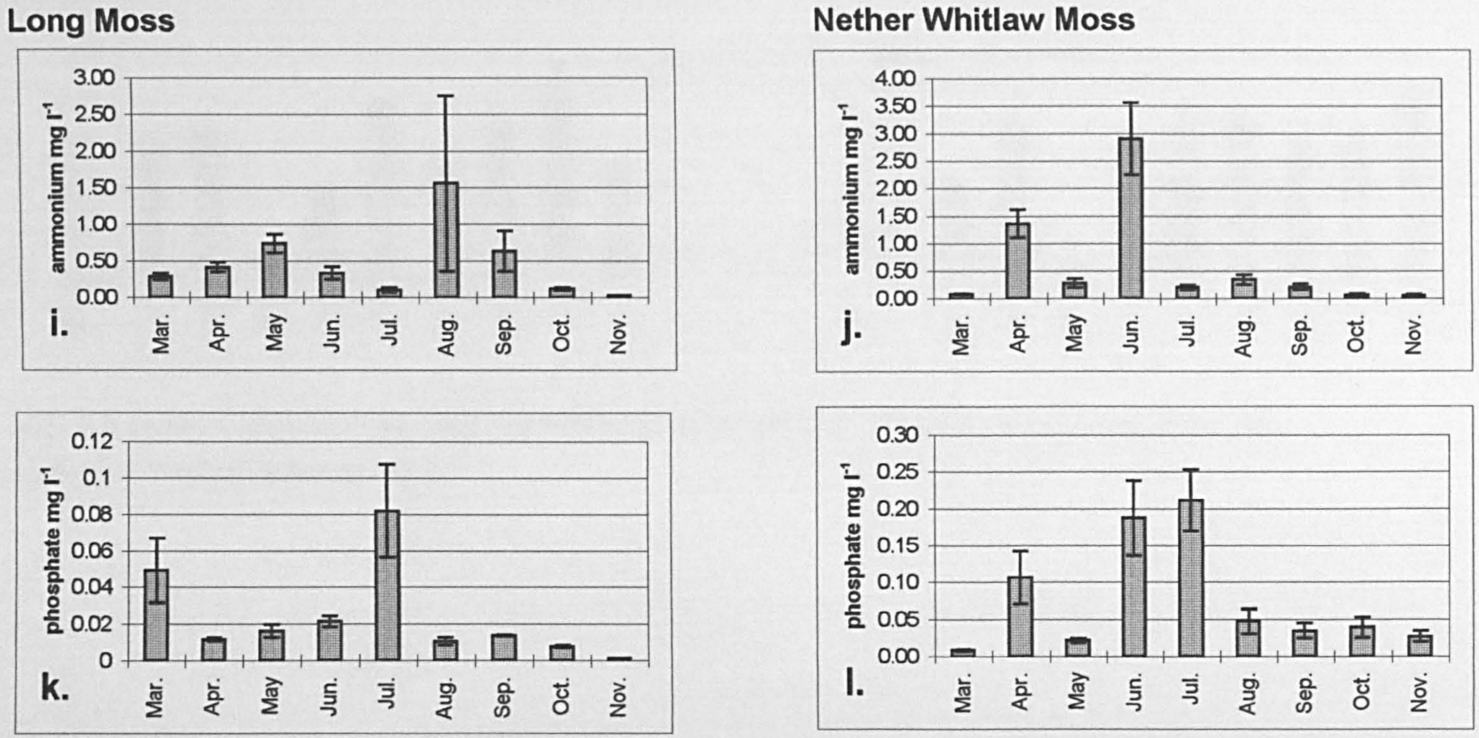


Fig. 5.8 (cont.) Monthly mean and standard error of the mean for ammonium at i) Long Moss j) Nether Whitlaw Moss and phosphate at k) Long Moss l) Nether Whitlaw Moss, as mg l^{-1}

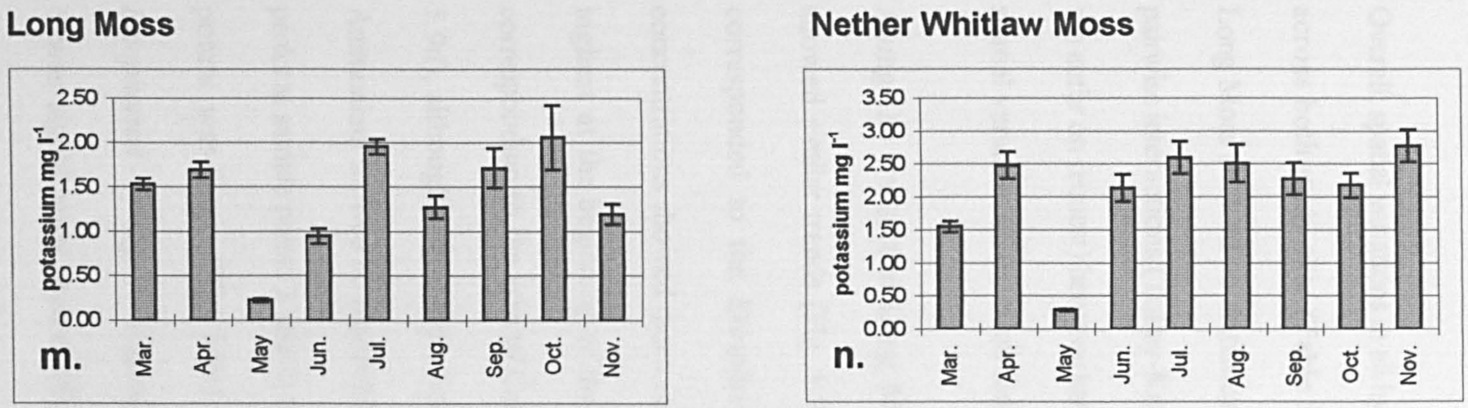


Fig. 5.8 (concl.) Monthly mean and standard error of the mean of potassium at m) Long Moss and n) Nether Whitlaw Moss, as mg l^{-1}

values for ammonium and phosphate. Potassium concentrations were constant over the sampling period, with few statistically different means, except for a markedly reduced May value (Fig. 5.8n).

Overall, spatial variations in all hydrochemical parameters were significantly different across both study sites (Table 5.12 and 5.13). Only ammonium concentrations at Long Moss showed no statistical differences between sampling points. Analyses of pairwise interactions (Tukey-Kramer multiple comparison tests, data available from the authr on request) between sample sites at each fen highlighted the high degree of spatial variation across each fen, underlying these general trends.

Along the transect at Long Moss water pH, electrical conductivity and calcium showed similar trends (Fig. 5.9a-c), declining at sample points 6, 7 and 8, which corresponded to the *Eriophorum - Sphagnum* vegetation type. The nutrient concentrations showed more variation across the site. Nitrate concentrations were highest at the beginning of the transect close to the inflow (sample points 1 - 5), corresponding to the area of *Carex panicea - Carex pulicaris* species-rich fen (Fig. 5.9d), although only sample point 5 was statistically significantly greater in nitrate. Ammonium showed no significant differences in concentrations, although there were peaks at sample points 2 and 8, but the variation across the sampling period at these points was large (Fig. 5.9e). Phosphate concentrations were greater in the *Eriophorum - Sphagnum* vegetation type (sample points 6 & 8), although only point 6 was significantly greater (Fig. 5.9f). Potassium concentrations developed an opposite trend (Fig. 5.9g), increasing toward the end of the transect in the *Carex rostrata - Menyanthes trifoliata* species-poor fen close to the outflow.

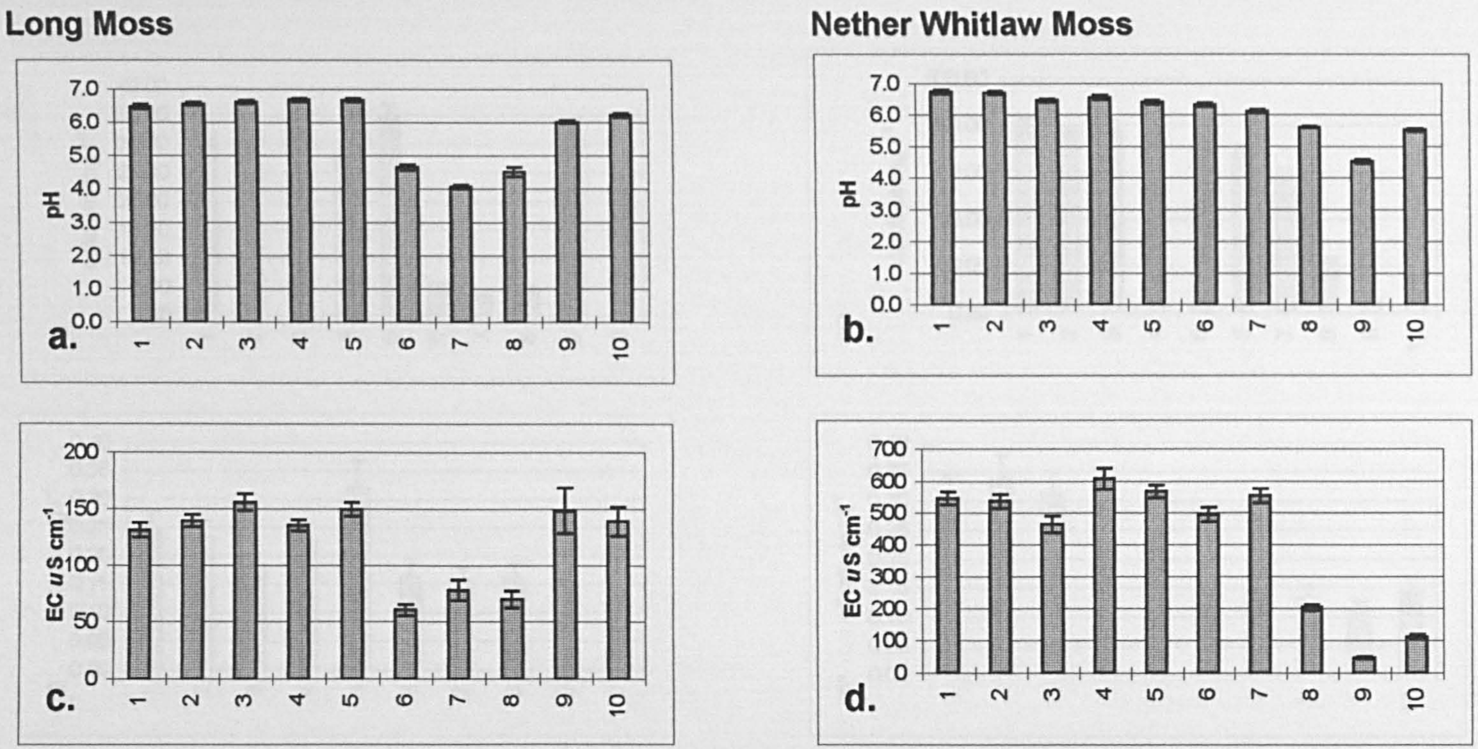


Fig. 5.9 Sample mean and standard error of the mean of pH at a) Long Moss and b) Nether Whitlaw Moss, and electrical conductivity (EC) at c) Long Moss and d) Nether Whitlaw Moss, as *u* S cm^{-1}

Long Moss **Nether Whitlaw Moss**

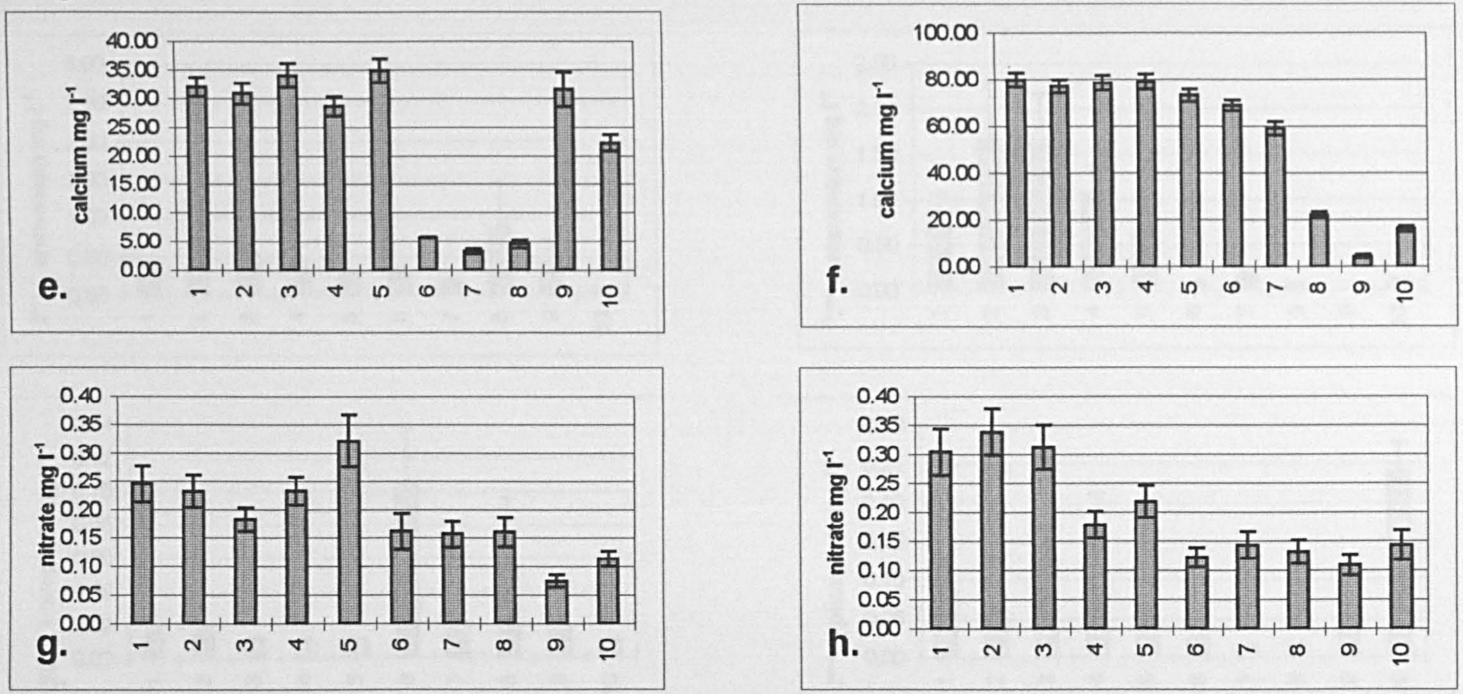


Fig. 5.9 (cont.) Sample mean and standard error of the mean for calcium at e) Long Moss f) Nether Whitlaw Moss, and nitrate at g) Long Moss h) Nether Whitlaw Moss, as mg l^{-1}

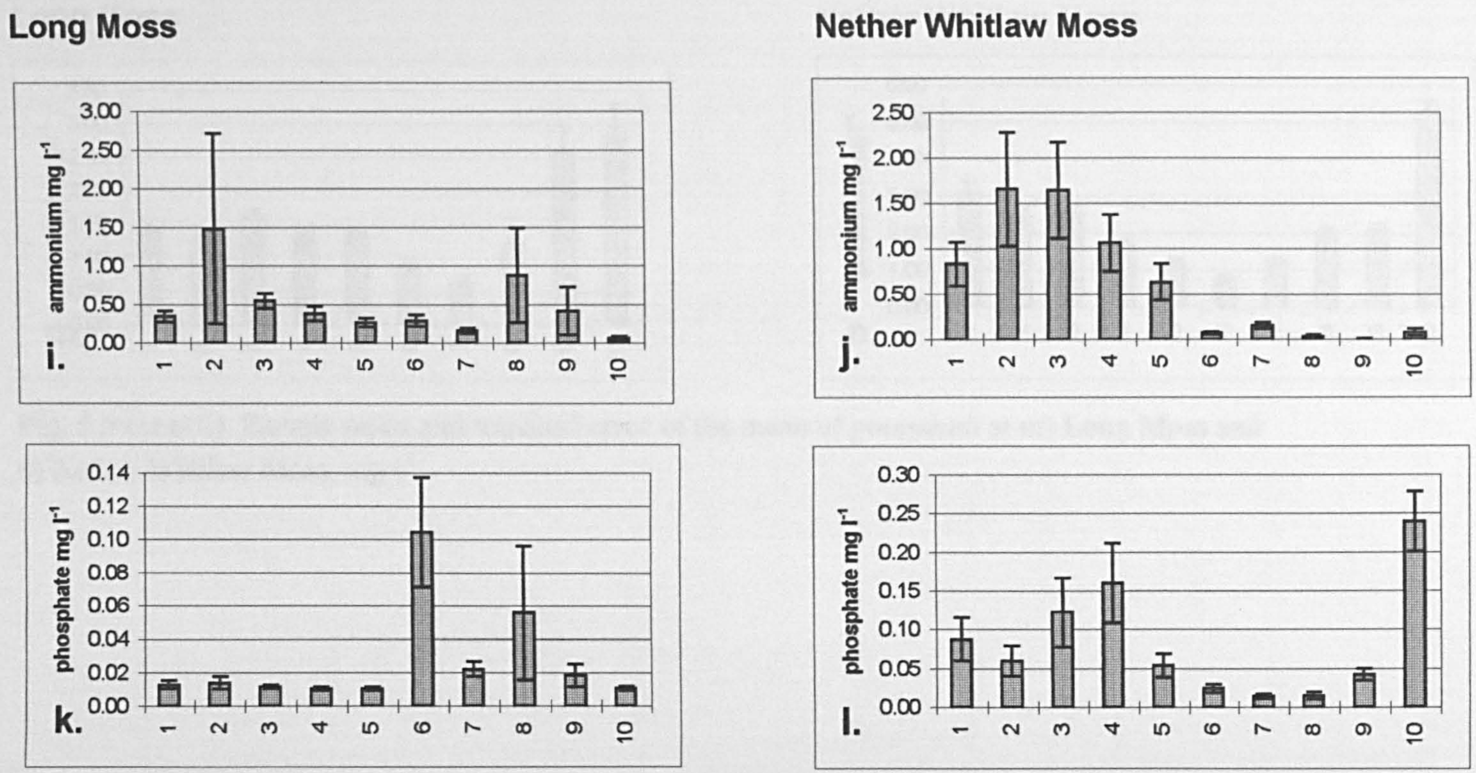


Fig. 5.9 (cont.) Sample mean and standard error of the mean for ammonium at i) Long Moss j) Nether Whitlaw Moss and phosphate at k) Long Moss l) Nether Whitlaw Moss, as mg l^{-1}

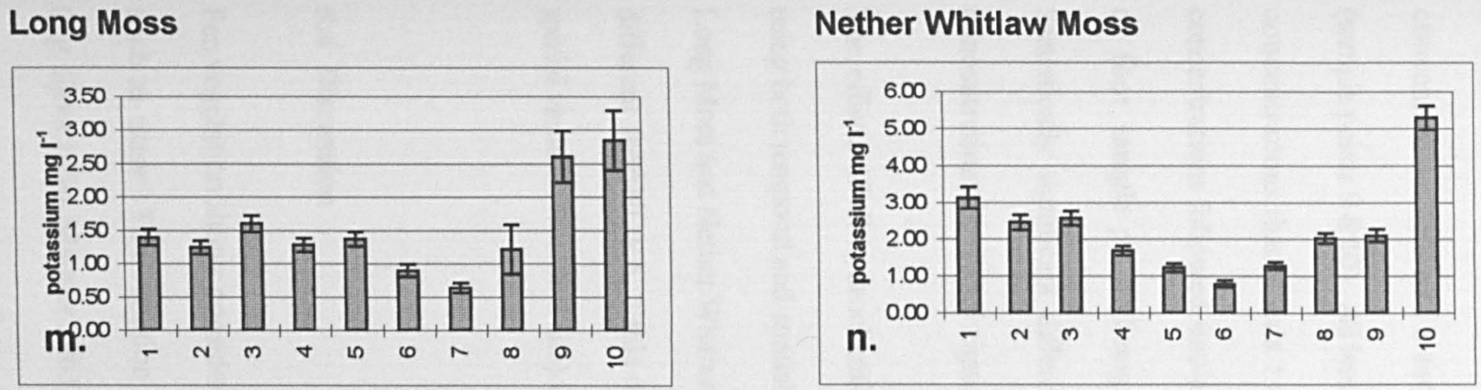


Fig. 5.9 (concl.) Sample mean and standard error of the mean of potassium at m) Long Moss and n) Nether Whitlaw Moss, mg l^{-1}

At Nether Whitlaw Moss pH and electrical conductivity of the water showed a similar pattern as at Long Moss (Fig. 5.9h,i), declining towards the end of the transect in both the *Sphagnum* and *C. rostrata* poor fen vegetation types. Calcium concentrations followed a similar trend (Fig. 5.9j) with a slight increase at the end (sample points 9 & 10). All later sample points were significantly reduced in calcium concentrations than points 1 to 5. Nitrate, ammonium, phosphate and potassium concentrations followed similar trends to calcium (Fig 5.9k - n), with the first three or four sample points being significantly greater than the last points (6 - 10). Statistically significant differences in phosphate and potassium were fewer, but concentrations increased significantly at the last sample point.

The effects of all hydrochemical parameters combined was assessed for each site using both temporal and spatial variation (month and sample MANOVA). For both Long Moss and Nether Whitlaw Moss spatial and temporal variation was significantly different (MANOVA, Table 5.12 & 5.13). The interaction between temporal and spatial variation (month x site) was not able to be carried out due to unequal datasets.

5.4 Discussion

Fen vegetation shows considerable spatial variation, even over relatively small sites such as these. This variation has been attributed to differences in water chemistry (*e.g.* Sjors 1950, Malmer 1963, Verhoeven *et al.* 1990). Fens receive water inputs, and associated nutrients, from many different sources; groundwater, sub-surface and surface hill-slope run off, rivers and precipitation. These chemically different water sources enter the fen, interact and mix, and are modified by internal nutrient cycling processes, plant litter decomposition, ion exchange and plant uptake (Koerselman & Verhoeven 1992). Water flow through fens and water table fluctuations can also be an important influence (Cooper & Andrus 1994). It is difficult to detect how these hydrologically and hydrochemically dynamic water types relate to plant species composition, but plant functional traits may provide a means to identifying some of these relationships. This chapter assessed the hydrochemical variation of two small basin fens in relation to vegetation development and water type (LAT model, Van Wirdum 1981). The nutrient status of the two sites was also compared in relation to adjacent land use, to look for evidence of nutrient enrichment. Finally, the temporal and seasonal variation within and between sites was assessed.

The vegetation groups, based on TWINSPAN (Hill 1979) classification (*section 3.3.2*), and the water types derived from the LAT model (*section 5.3.2*), formed a useful basis for the classification of fen hydrochemistry in relation to base status (pH, EC and Ca^{2+} concentrations) and nutrient status (NO_3^-, NH_4^+, PO_4^{2-} and K^+ concentrations). The two classifications distinguished facets of the internal hydrochemistry in different ways. The first approach using vegetation characteristics to imply environmental characteristics, the second using major ionic concentrations in the water (Ca^{2+}, Cl^- and EC) as a measure of environmental conditions. Yet there were similarities in the resulting groups.

Species-rich *Carex panicea - Carex pulicaris* fen vegetation type (group 5) dominated the LAT water type 1 (a lithotrophic water type). The species-poor *Carex rostrata - Menyanthes trifoliata* and the *Potentilla palustris - C. rostrata* transitional fen vegetation (groups 2, 3 and 4) were found in all three LAT groups, but the majority occurred in LAT group 2. This transitional water type was found toward the lithotrophic - thalassotropic LAT type, which showed calcium concentrations typical of waters with a longer residence time in the ground, and high chloride concentrations that may suggest artificial nutrient inputs (Kemmers 1986, Koerselman *et al.* 1990b, Schot & Wassen 1993). The ombrotrophic *Eriophorum - Sphagnum* mire (group 6) and the species-poor *C. rostrata - M. trifoliata, Sphagnum squarrosum* (group 1) fen vegetation types were found in LAT group 3, the atmotrophic water type, low in calcium and typical of precipitation-dominated water.

The mean nutrient concentrations showed similar patterns in both the corresponding vegetation and LAT groups. There were relatively high concentrations of nitrate and ammonium, and low concentrations of phosphate and potassium in LAT group 1 and the associated *C. panicea - C. pulicaris* species-rich vegetation (group 5). Wassen (1995) found a similar phosphate-poor water type for rich-fen vegetation in Poland. In this study these water and vegetation types dominated the fen edge, and were also close to the inflow stream at Long Moss, and nitrogen inputs from the stream may increase nitrate and ammonium concentrations on these areas of the fen.

Water type 1 (LAT group 1) was also present in the species-poor fen areas of Long Moss close to the edges (*Potentilla palustris - Carex rostrata* transitional fen, group 2) and towards the outflow stream (*Carex rostrata - Menyanthes trifoliata* poor fen/swamp, group 3). Although both vegetation types were species-poor fen, and had a similar water type, the species compositions and nutrient characteristics were different in detail. The *P. palustris - C. rostrata* transitional fen (group 2) showed greater concentrations of nitrate, phosphate and potassium. The *C. rostrata - M. trifoliata* fen (group 3) showed reduced concentrations of nutrients. The greater nutrient concentrations at the fen edge may be the influence of diffuse surface run off and sub-surface seepage, particularly on the south eastern side where there is a steep mineral slope with noticeable soil erosion. Peat cores from the fen close to this slope showed increased mineral content (data held by the author and available on request) suggesting active soil erosion onto the fen. Analysis of the perimeter lag stream water, which might be expected to be a good indicator of diffuse run off did not reveal any increase in nutrients, and the water was chemically similar to the inflow. Another possible explanation for these differences in nutrient concentrations may be due to internal nutrient processes, *e.g.* the release of unavailable nutrients, such as organic nutrients or insoluble inorganic complexes, through biological and physiochemical processes, occuring or increasing toward the fen edge.

Lesser concentrations of nutrients were measured in the LAT water type 1 associated with the species-poor *C. rostrata - M. trifoliata* fen/swamp vegetation type (group 3), found towards the outflow at Long Moss. These concentrations were consistent with nutrient concentrations in a *C. rostrata* species-poor fen type identified in the Scottish Borders (Tratt 1997, see Appendix 5). The nutrient concentrations may be reduced as the water flows through the system and biological and physiochemical processes transform or remove them, as in this study this vegetation type was found close to the outflow.

In LAT water type 2 (lithotrophic - thalassotrophic dominated) nitrate, ammonium and phosphate concentrations were all relatively high, with slightly elevated potassium. High chloride concentrations (as present in this water type) have been associated with elevated artificial nutrients, along with greater sulphate concentrations (Kemmers 1986, Shot & Wassen 1993). Other studies have found that these same ions may also be associated with increasing nutrient release within the fen (internal eutrophication) through physiochemical processes (Beltman & Rowenhurst 1991). This water type was associated with the species-poor *Carex rostrata - Menyanthes trifoliata* fen (group 4) dominant over much of Nether Whitlaw Moss. The water type was dominant toward the inflow stream (the first 50 m of the transect) and around the edges of the fen, where the main areas of *C. rostrata - M. trifoliata* fen area were found. Influence of the inflow stream, and perhaps surface and sub-surface flow from the surrounding land (particularly the land drains entering the fen on the north side), undoubtedly influence the properties of this water type, and may account for the increase in calcium and chloride. Similarly high calcium concentrations were noted for the inflow stream.

Schot and Wassen (1993) found that although calcium-rich waters were often associated with species-rich fen types (as in the *C. panicea - C. pulicaris* species-rich fen vegetation group 5 at Long Moss), the response to an increase in nutrient concentrations, along with increased calcium concentrations, is associated with a typically species-poor, but more productive, vegetation. The tall *Equisetum fluviatile* dominated the *C. rostrata - M. trifoliata* fen vegetation close to the inflow and the edges at Nether Whitlaw Moss, and this species has been classed as a competitor-ruderal species (Grime 1988). This vegetation type appeared to be similar, in both floristics and hydrochemistry, to the calcium-rich, species-poor, high productivity fen described by Schot and Wassen (1993).

The fen edges at Nether Whitlaw Moss were influenced by the land drains from adjacent agricultural fields, and these areas had slightly increased phosphate concentrations. Increased phosphate concentrations in water samples close to the land drains suggest that intensive land use surrounding the site is a factor in the development of the *E. fluviatile*-dominated *C. rostrata - M. trifoliata* species-poor fen. This contrasts with the low concentrations of phosphate at Long Moss with adjacent unimproved acid grassland. Although inorganic phosphate is considered less mobile than nitrate in agricultural systems, and so less susceptible to leaching (Tivy 1987), high concentrations of phosphate have been measured in hillslope run off in fen catchments (*e.g.* Grieve & Gilvear 1994). In addition, organic and particulate phosphorus may be readily transported in sub-surface flow (Heathwaite 1995b). These insoluble materials may be mineralised to soluble inorganic phosphates within the fen. Alternatively the fen itself may be a source of these increased phosphates. Changes toward a lower reduction-oxidation (redox) potential and more acidic pH can release phosphates from insoluble complexes such as those formed with iron and aluminium (Kemmers & Jansen 1988). Measured pH values close at the fen edge (mean pH 6.7) were generally greater than on the fen (mean pH 6.46), and fluctuated significantly over the sampling time. These seasonal increases in pH and redox potential may cause dissolution of phosphate in this edge area increasing its availability to plants.

The third LAT water type was classified as atmotrophic water, which suggested precipitation inputs were dominant over the ground and surface water inputs. This water type was represented in the central areas of each fen, furthest from the potential influence of surface and sub-surface water inputs. Although the vegetation that had developed in this setting was different at each site, both were characterized by the dominant bog mosses (*Sphagnum* species), typical of ombrotrophic areas. At Long Moss the vegetation was an ombrotrophic *Eriophorum angustifolium - Sphagnum magellanicum* mire type (group 6) dominated by *Sphagnum capillifolium,* *S. magellanicum* and *S. papillosum*. The development of a lag stream around this ombrotrophic vegetation type may further reinforce the isolation from the influence of lithotrophic (minerotrophic) water (Sallantaus 1988). At Nether Whitlaw Moss the vegetation was a species-poor *C. rostrata - M. trifoliata* fen (group 1) but dominated by *Sphagnum squarrosum*. This bog moss species usually suggests minerotrophic water influence (Daniels & Eddy 1985), and in this extent may reflect possible seasonal inundation of parts of this vegetation type with lithotrophic water, although the limited monthly water level measurements did not indicate this (see *section 4.3.3*).

The LAT water type (group 3) associated with the *Sphagnum*-rich areas were typically low in nutrients, particularly in nitrate and ammonium, but concentrations of phosphate were greater than the other two water types. Microbial activity can increase phosphate availability, but it is generally accepted that this activity is attenuated in anaerobic and acidic conditions (Given & Dickson 1975, Brinson *et al.* 1981, DeLaune *et al.* 1981). This leads to less inorganic soluble phosphate, as lowered microbial activity reduces phosphate release from organic matter (Wilson & Fitter 1984). Some studies have shown increased mineralisation can occur on peat. This may result in greater soluble phosphate associated with *Sphagnum* vegetation developing in ombrotrophic conditions (Verhoeven & Aerts 1987), and in poor fens with infiltrating rainwater (Wassen 1995). Daughtrey *et al.* (1973) showed that peat soils have a greater potential for phosphorus mineralisation, *i.e.* they have a store of phosphorus that can potentially be released. If conditions for mineralisation are improved (greater oxygen concentrations) then peat may release phosphate. The firmer *Sphagnum* peat may be more susceptible to seasonal increases in mineralisation as they have lower a water table compared with surface levels in the summer (while floating fen areas can maintain a high water table, and more anoxic conditions, through vertical movement of the vegetation mat - see *section 4.3.3*). More acidic conditions, as found in *Sphagnum*-dominated vegetation types, can also release physicochemically bound phosphates (Waughman 1980, Verhoeven *et al.* 1988b, Beltman & Rowenhurst 1994), as can high sulphate concentrations (Koerselman & Verhoeven 1995), increasing the availability of soluble phosphate.

In both classifications the separation of groups was mainly influenced by base status (pH, EC and calcium concentration), which reflected the bog - species poor fen - species rich fen gradient. This is seen in many mire studies (*e.g.* Sjors 1950, Malmer 1963, Wassen *et al.* 1989, Vitt & Chee 1990, Bridgham & Richardson 1993). In this study there was a greater discrimination along this vegetation gradient, with the inclusion of an additional species-poor productive fen type (vegetation group 4), similar to that reported by Schot and Wassen (1993). This resulted in the extended gradient bog - species poor (unproductive) fen - species poor (productive) fen - species rich fen, dependant on both base status and nutrient availability.

The above analysis suggests a reasonable correspondence between some water types and vegetation. The vegetation/LAT groups with increased nutrient concentrations could be found on both sites. The effects, therefore, of potential enrichment from surrounding improved land use at Nether Whitlaw Moss were not clear. A comparison of the two sites identified whether Nether Whitlaw Moss, surrounded by improved arable land, had significantly increased nutrient concentrations.

The *Sphagnum*-dominated vegetation types at both Long Moss and Nether Whitlaw Moss were relatively high in phosphates. Their position in the centre of each fen, and the higher elevation of these areas compared to the fen margins (see *section 4.3.4*) isolated them from the adjacent mineral land. The water type (group 3) also indicated these areas were dominated by precipitation inputs. Precipitation inputs have been shown to increase the nutrient status of fens in the Netherlands (Koerselman *et al.* 1989a,b), where inputs from precipitation are high (N = 40 kg ha^{-1} yr^{-1}). Similar estimates of nitrogen inputs are given for south east England (Goulding 1990), although in Scotland total nitrogen input estimations are reduced (N = 10 kg ha^{-1} yr^{-1}) and unlikely to cause the same degree of enrichment (Barrett *et al.* 1987 cited by Heathwaite *et al.* 1993). The phosphate concentrations in rainwater are similar to the *Sphagnum* vegetation types (Long Moss 0.29 mg l^{-1}; Nether Whitlaw Moss 0.36 mg l^{-1}), and greater than those found on the rest of the fen, and in the inflows and drains. Groundwater and surface water inputs may dilute these phosphate inputs on the remaining vegetation types, along with rapid uptake by vegetation and microbial activity. Contamination of precipitation samples from plant and insect matter was also a possibility, although other nutrients were not elevated.

Overall, Nether Whitlaw Moss had significantly greater concentrations of calcium, phosphate and potassium in subsurface water, but there was no significant difference in concentrations of nitrate and ammonium. Increased phosphate concentrations were found close to the field drain inflows, which suggests nutrient inputs from surface run off and sub-surface seepage channelled by the drains, rather than inputs from the inflow stream. The potential impact of additional diffuse pollution from the catchment was not able to be estimated in this study, although it is often important in eutrophication of waters (Jorgensen 1994), particularly in relatively low intensity agricultural systems (Heathwaite 1995b) such as those in much of Scotland.

These *relative* increases in nutrients at Nether Whitlaw Moss may not be high enough to suggest active enrichment problems. Published data from other northern temperate mire systems (UK, Netherlands, Poland, USA, Canada), including the bog - poor fen - rich fen transition (Appendix 5), suggests that all of the measured variables are within the expected ranges of fen vegetation types. The pH values suggest Nether Whitlaw Moss (mean pH 6.22) to be somewhere between rich and poor fen types, i.e. a transitional fen type. Long Moss is more towards the poor fen range (mean pH 5.9). As to nutrients (N, P, K), Nether Whitlaw Moss has a greater mean potassium concentration (2.16 mg l^{-1}). Only a few Netherlands sites showing greater concentrations (max. 6.5 mg/l^{-1}), while most of the sites had concentrations below 1.00 mg l^{-1}. Both Nether Whitlaw Moss and Long Moss show low concentrations of nitrate (0.21 mg l^{-1} and 0.20 mg l^{-1} respectively) compared to other published data. Most sites were below 2.00 mg l^{-1}, except for some Netherlands and Scottish (Tratt 1997) sites. Ammonium concentrations were around mid-range for both sites (0.65 mg l^{-1} and 0.48 mg l^{-1} respectively), again with most sites below 2.00 mg/l^{-1}. Phosphate concentrations, although relatively high compared to Long Moss (mean 0.024 mg l^{-1}), were in mid-range for Nether Whitlaw Moss (mean 0.104 mg l^{-1}) when compared to other data. The majority of sites were below 1.00 mg l^{-1} phosphate, except a few Netherlands sites. Comparing Nether Whitlaw Moss nutrient concentrations to the other Scottish sites only (Appendix 5; Grieve *et al.* 1995, Tratt 1997, and this study), potassium and ammonium concentrations are slightly greater, but nitrate and phosphate concentrations are below other measured concentrations.

Vegetation and LAT group classifications, and site by site comparisons showed that Nether Whitlaw Moss has increased pH, EC, calcium and phosphate concentrations in the mire sub-surface waters, usually related to a vegetation and/or water type. In these analyses the associations between some variables (MANOVA tests) suggested a more complex pattern of hydrochemical variation underlay these general conclusions, although patterns were dependant on site. Additional analysis of the hydrochemical data of sites, both spatially and temporally, showed there was a considerable amount of variation within one site, even within a single vegetation or LAT group on that site. Although the interaction of month and sample was not analysed, these two variables may also be dependant. There were many statistically significant differences both between sites and within sites for all hydrochemical parameters measured. These variations and interactions make it difficult to assess general trends within the dataset, and highlights the difficulty in attempting to classify the hydrochemical nutrient status of a fen even with an intensive, longer term sampling regime. The inherent variability in fens, and in peatland systems generally, have been highlighted by other studies. These draw on spatial variation both horizontally (as measured in this study) and vertically within the peat soils and/or water column, along with temporal/seasonal variation (*e.g.* Hemmond 1980, Lembrechts & Van Stratten 1982, Wierder 1985, Proctor 1992,1994, Jean & Bouchard 1993, Boeye *et al.* 1994, De Mars & Garritsen 1997). Most of this variation has been attributed to the dynamic hydrological and hydrochemical processes occurring in a fen, particularly related to seasonality. The influences of geology, topography and oceanicity are also factors in regional and geographical variation (Daniels 1985).

CHAPTER 6

Vegetation assemblages in relation to hydrologic regimes and nutrient gradients on basin fens

6.1 Introduction

Hydrology and hydrochemistry have been shown to be a major influence on vegetation development in fen systems (*e.g.* La Baugh 1986, Hemond 1980). Although individual biological and physiochemical processes have been defined within fens, and can be correlated to hydrodynamic processes linking specific hydrochemical conditions to particular vegetation types can prove problematic (Shaw & Wheeler 1990, 1991, Tratt 1997). Several studies have attempted to characterize the chemical environment of existing vegetation types and relate this to hydrology, peat and water chemistry, and plant community dynamics. The results, discussed below, are somewhat inconclusive. They include studies that show relationships between peat chemistry and vegetation type (Bridgham & Richardson 1993), between general water chemistry and vascular and non-vascular plant distributions (Vitt & Chee 1990), and between vascular plant distribution and water table regimes (Vermeer 1986b).

Bridgham and Richardson (1993) found that only differences in total nitrogen (N) and phosphorus (P) and N:P ratios of the peat could be distinguished between two types of poor fen, herbaceous vegetation (short and tall pocosin). Other chemical parameters, including hydrochemical measurements, were not significantly different between the two vegetation types. Such links between soil and vegetation along gradients may be easier to identifiy because they show both reduced temporal variation compared to hydrochemical gradients (Karlin & Bliss 1984, in Boeye *et al.* 1994). However, Bridgham and Richardson (1993) concluded that seasonal variations in hydrological functioning may be more important in determining the development of these similar vegetation types, rather than the nutrients assessed. When comparing the two extremes of the poor to rich fen gradient in the same study, Bridgham and Richardson did find links between peat nitrogen, phosphorus and potassium content of the biomass and vegetation development. They concluded that potential hydrochemical indicators such as pH and exchangeable cations do not necessarily reflect the nutrient content of the vegetation biomass, and hence the nutrient status of the fen. This agrees with the idea that calcium is a main regulator of pH, particularly in fen (Kemmers 1986). The pH does not, therefore, necessarily reflect nitrate, phosphate and potassium availability to and uptake by plants, although there are thresholds of pH above and below which certain chemical processes only occur, as discussed in *chapter 5, section 5.1*.

The lack of direct relationships between pH and nutrients is further emphasised by Vitt and Chee (1990). They propose that vascular plants are distributed in relation to available N and P, while bryophytes are influenced by alkalinity and acidity gradients. This implies that bryophytes are associated with tolerance of acidic conditions, rather than nutrient availability (Clymo & Hayward 1982, in Bridgham & Richardson 1993, Verhoeven *et al.* 1990). In a similar approach Vermeer (1986b) shows that grasses and most herbs flourish under a low water table, while *Carex* and *Juncus* species grew better under flood conditions. This was thought to be linked to nitrogen and phosphorus availability under different hydrological regimes.

Vegetation has some ability to alter its own environment through positive feedback, and this is usually discussed in terms of autogenic processes. Water entering a fen site can be altered chemically by the vegetation once in the fen itself. In addition, therefore, to the possibility of more than one main water type on the fen (*e.g.* precipitation, surface water, groundwater, *etc.*) there is also scope for any water type to be modified and altered once in the fen system. Processes responsible for this are often physiochemical or microbiological as discussed in *sections 5.1* and *5.5*. Some of these vegetation-driven autogenic processes are linked to microbial populations, such as root zone aeration increasing aerobic microbial activity and mychorrizal interactions (Weber & Brandle 1996). Others involve the plant alone causing chemical changes. In particular, Clymo (1997) demonstrates the ability of *Sphagnum* species to acidify their environment through cation exchange and the release of hydrogen ions. Plants may also facilitate the development of other species. For example, other bryophytes may facilitate the invasion of *Sphagnum* species by providing suitable sites for initial *Sphagnum* colonisation (Glime *et al.* 1982).

Plants have different environmental requirements (Grime 1988), and it is too simplistic to assume that all species within a community type are present because their growth is optimal under the prevailing physiochemical conditions. Interspecific competition plays an important role in the distribution of species within peatlands (Gignac 1994). The ombrotrophic central areas that often develop in fens allow *Sphagnum* species to colonise in favour of the more typical fen bryophytes (Beltman *et al.* 1995). This is important in the transition from minerotrophic fen to ombrotrophic bog. Such advantage may come from the ability to exploit nutrients available (Lee & Woodin 1988 in Verhoeven *et al.* 1990), or the ability to exude chemicals that actively prevent vascular plant growth (Verhoeven and Schmitz 1991, in Beltman *et al.* 1995) both ideas which imply a competitive advantage, or to withstand the increasing acidity (Vitt & Chee 1990), which implies a tolerance to stress. Differences in vascular plant competitive success has also been studied on peatlands (Vermeer 1986b, Ohlsen & Malmer 1990, Aerts 1993).

Annual biomass production has also been linked to plant species richness, with low and high productivity giving low species richness, and intermediate productivity giving greater species richness. Grime (1973, 1979a,b) attributed such species richness patterns to niche differentiation within a habitat. Similar ideas are seen in the work of Wheeler & Giller (1982), Vermeer (1986a,b) and Verhoeven *et al.* (1993), but not all studies give clear results. For example, Vermeer and Verhoeven (1987) found no links between biomass production (measured as above ground biomass) and species diversity.

This chapter further examines the relationships between the vegetation on two fen sites, Long Moss and Nether Whitlaw Moss, and the hydrochemical and hydrological variation, as detailed in chapters four and five. This brings together the hydrology, hydrochemistry and vegetation assemblage analyses into a more ecohydrological approach, assessing the effect of environmental conditions on vegetation development. Each fen vegetation type was characterized in terms of their hydrochemical and hydrological parameters, above ground biomass and species number. In addition multivariate statistics were used to elucidate the main environmental gradients underlying the vegetation community changes.

6.2 Methodology

6.2.1 Sampling

Vegetation communities for each fen site were characterised using a quadrat survey (July 1997). Methods, TWINSPAN analysis (Hill 1979) and resulting vegetation types are detailed in *section 3.2*. The six resulting vegetation groups were as follows:

Group 1 - *Carex rostrata - Menyanthes trifoliata* poor fen, *Sphagnum squarrosum* sub-community

Group 2 - *Potentilla palustris - C. rostrata* transitional fen

Group 3 - *C. rostrata - M. trifoliata* poor fen

Group 4 - *C. rostrata - M. trifoliata* poor fen, *Equisetum fluviatile* sub-community

Group 5 - *Carex panicea - Carex pulicaris* rich fen

Group 6 - *Eriophorum angustifolium - Sphagnum magellanicum* mire

The effect of nutrient inputs from the catchment, and from internal cycling in the fen, on above ground biomass was assessed by collecting pak standing crop (end of July 1996). Vegetation was clipped to ground level in three replicate 25x25 cm quadrats within the 1x1 m quadrat at 0 m, 10 m, 25 m, 50 m, 125 m, 225 m and 275 m sampling point at Long Moss. The procedure was repeated at equivalent sample points on Nether Whitlaw Moss. Biomass samples were identified and sorted to species, washed in double distilled water to remove peat/soil feargments, dried (70°C for 48 hours) and weighed. Average July standing crop was calculated for each species for each sampling point as grams of dry matter per m^2. The average number of species per 25x25 cm was calculated from the three replicate samples for each sampling point, based on the number of different species found in the biomass collections.

Hydrochemical data were collected an analysed as detailed in *section 5.2*. In this analysis only sample points with associated vegetation and biomass data were selected for direct, rather than inferred, comparison between hydrochemical parameters and vegetation types. These were Long Moss sample points 1, 5 - 10, and equivalent sample points on Nether Whitlaw Moss.

Hydrological data used were dipwell measurements, collected from each area as detailed previously (*section 4.2*). Each dipwell was sited next to each hydrochemical sampling point and reflected hydrological fluctuations within the area.

6.2.2 Data analysis

The biomass of each vegetation type was assessed using July standing crop data. These figures were split into bryophyte biomass and herbaceous biomass to represent the different plant strategies. The herb biomass figures were used to identify the fertility of each vegetation type using a fertility index (Koerselman pers. comm.). In addition, fertility indices (*e.g.* Ellenberg 1958, 1988, Clausman *et al.* 1987) have been developed to predict the biomass of species using linear regression models, and give an indication of environmental conditions (Melman *et al.* 1988). The reliability of these indicator systems on low productivity vegetation types, such as fens, has not been thoroughly assessed. To assess the potential of these fertility indices and linear models to indicate environmental conditions, biomass data for individual species collected in the field were compared with biomass figures derived from Clausman indicator values (Clausman *et al.* 1987), using *equation 6.1* (Koerselman pers. comm.)

$$\textbf{Biomass}\ (g/m^2) = (238 * \text{Clausman optimum value}) - 480 \quad (\textit{equation 6.1})$$

The hydrochemical and hydrological measurements for each vegetation type were assessed using descriptive statistics, and one-way analysis of variance was carried out (ANOVA). Pairwise interactions were investigated using Tukey-Kramer multiple comparison test. Where data were not normally distributed, even after natural logarithmic (Log_e) transformation, Kruskal-Wallis analysis was carried out, and pairwise interactions were assessed using Q-value multiple comparison analysis (Heath 1995). Bivariate relationships between all hydrochemical parameters were analysed using Spearman's rank correlation coefficient, and checked for linearity. This gave an indication of more general trends between parameters across all six groups. All analyses were carried out on Minitab 11.

For hydrological data the overall (18 month) fen surface level fluctuation range and the water level fluctuation range were calculated for each dipwell (*section 4.3*), and associated with each of the six vegetation groups. In addition, maximum inundation depth above fen surface, and maximum water level drop below fen surface were calculated for each dipwell point, and again associated with each of the vegetation groups.

Relationships between vegetation and environmental data were explored using canonical correspondence analysis (CCA) (CANOCO program, Ter Braak 1992) using the combined dataset. Variables were assessed for their influence on the species distributions using forward selection procedures, and the statistical significance of these influences tested using the Monte Carlo permutation test. All CANOCO data were displayed using CanoDraw v.3.0 (Smilaur 1992).

Initially, the overall mean of each hydrochemical parameter, total plant above-ground biomass (July standing crop), herbaceous plant biomass, bryophyte biomass and species number were used as environmental variables in the CCA. The significant variables in species distribution from the first CCA were then combined with more detailed hydrological variables, fen surface level range, water level range, maximum inundation depth and maximum water level drop, in a second ordination to assess both the effects of hydrology and hydrochemistry on species distribution.

6.3 Results

6.3.1 Characterizing hydrochemical and hydrological variation in relation to biomass and species diversity

Above ground biomass (July standing crop per m^2) was greatest in the herb-dominated transitional and species-poor fen vegetation types (groups 2, 3 and 4), and lowest in the species-rich fen and *Sphagnum*-dominated vegetation types (groups 1, 5 and 6) (Fig. 6.1). Using herb biomass data only a fertility index (Koerselman pers. comm., Table 6.1) was used to indicate the likely nutrient status of each vegetation group (Table 6.2). The majority of vegetation groups (2 to 5), including the species-rich, species-poor and transitional fen types, were classified as oligo- to mesotrophic fertility. The *Sphagnum*-dominated vegetation types (groups 1 and 6) were both classified as having lower fertility. The *Carex rostrata - Sphagnum magellanicum*

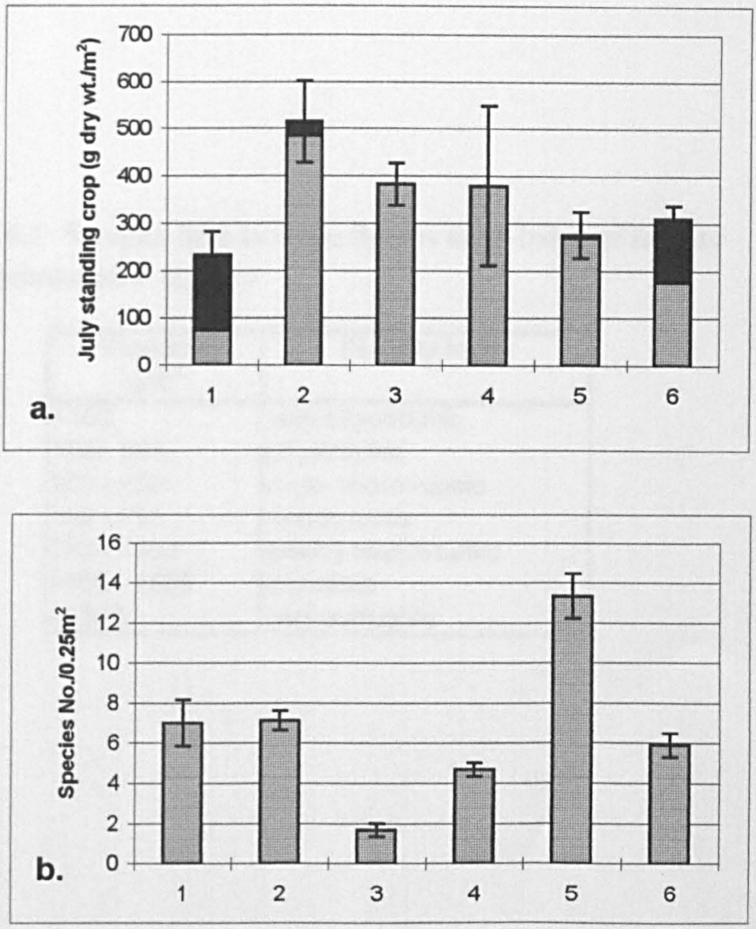


Fig. 6.1 Mean and standard error of the mean for a) standing crop divided as bryophyte (dark) and herb (light) totals, and b) species number for each of the six vegetation groups.

1 = *Carex rostrata* - *Menyanthes trifoliata* poor fen, *Sphagnum squarrosum* subcommunity

2 = *Potentilla palustris* - *C. rostrata* transitional fen

3 = *C. rostrata* - *M. trifoliata* poor fen

4 = *C. rostrata* - *M. trifoliata* poor fen, *Equisetum fluviatile* subcommunity

5 = *Carex panicea* - *Carex pulicaris* rich fen

6 = *Eriophorum angustifolium* - *Sphagnum magellanicum* mire

Table 6.1 Summer herb biomass figures as an index of fertility (Koerselman pers. comm.)

Biomass g/m^2	Fertility Index
<100	very oligotrophic
100 - 250	oligotrophic
250 - 450	oligo- mesotrophic
450 - 750	mesotrophic
750 - 1100	weekly mesotrophic
1100 - 1500	eutrophic
>1500	very eutrophic

Table 6.2 mean herb biomass (July standing crop) for each of the six vegetation groups, and associated fertility index (see Table 6.1).
N = number of samples, SEM = standard error of the mean

Group	Vegetation type	Herb biomass (g/m^2) mean	SEM	N	Fertility Index
1	*C. rostrata - M. trifoliata* poor fen, *Sphagnum* sub-community	73.8	34	3	very oligotrophic
2	*P. palustris - C. rostrata* transitional fen	484.9	82.1	18	oligo- mesotrophic
3	*C. rostrata - M. trifoliata* poor fen	382.6	45.4	3	oligo- mesotrophic
4	*C. rostrata - M. trifoliata* poor fen, *Equisetum* sub-community	379	169	3	oligo- mesotrophic
5	*C. panicea - C. pulicaris* rich fen	265.5	49.6	6	oligo- mesotrophic
6	*E. angustifolium - S. magellanicum* mire	175.9	50.6	9	oligotrophic

poor fen being very oligotrophic, whilst the *Eriophorum angustifolium - Sphagnum squarrosum* mire being oligotrophic. No vegetation groups were classified by the fertility index as having mesotrophic to eutrophic fertility status.

Total biomass was not significantly different between vegetation types (ANOVA test, $F_5 = 1.52$; $p = 0.209$), and there were no significant pairwise interactions (Tukey-Kramer test, data available on request). Separate ANOVA of the herb and bryophyte components of the total biomass both gave significant differences between the vegetation groups (herb biomass: $F_5 = 4.62$; $p = 0.002$, bryophyte biomass: $F_5 = 6.07$; $p = 0.000$). For pairwise interactions for herb biomass data group 2 was significantly greater than groups 1 and 6 (data on request), while for bryophyte biomass data group 1 and 6 were significantly greater than all other groups.

Using the ecological optimum values for particular species, derived by Clausman *et al.* (1987), can provide an alternative to using biomass to indicate fertility. Only 12 species that were dominant in this data set had associated Clausman-values, so the dataset was limited. Four species (*Carex pulicaris, Equisetum fluviatile, Galium palustre and Menyanthes trifoliata*) had calculated biomass figures which were greater than the biomass figures recorded in the field, while one species (*Carex nigra*) had a lower calculated biomass (Table 6.3). The remaining seven species with low Clausman-values (<2) gave negative calculated biomass figures.

Species number (per 25x25 cm) varied between vegetation groups, showing lower species numbers in herb-dominated poor fen types, and greater numbers in the rich fen vegetation type. Overall, there was a significant difference between species numbers of vegetation types (ANOVA test, $F_5 = 17.46$; $p = 0.000$). Pairwise

Table 6.3 Dominant species from each of the six vegetation groups showing the Clausman optimum value (Clausman *et al.* 1987), calculated biomass using *equation 6.1* (Koerselman pers. comm.), and mean biomass figures collected in the field (g/m^2). N = 3 per sample, x = species not present

Species	Clausman optimum value	Biomass g/m^2						
		calculated	Gp. 1	Gp. 2	Gp. 3	Gp. 4	Gp. 5	Gp. 6
Calluna vulgaris	1.1	-218.20	x	x	x	x	x	9.81
Carex nigra	2.2	43.60	x	x	x	x	76.19	x
Carex panicea	1.9	-27.80	x	x	x	x	27.60	x
Carex pulicaris	2.7	162.60	x	x	x	x	3.49	x
Carex rostrata	1.9	-27.80	56.53	73.36	358.35	147.20	29.65	x
Equisetum fluviatile	4.5	591.00	x	429.67	x	69.71	x	x
Erica tetralix	1.1	-218.20	x	x	x	x	x	14.48
Eriophorum angustifolium	1.0	-242.00	13.76	43.01	x	x	13.44	39.61
Galium palustre	3.8	424.40	x	47.04	x	x	x	x
Menyanthes trifoliata	2.7	162.60	x	93.53	24.21	26.08	15.79	x
Sphagnum spp.	0.9	-265.80	101.07	x	x	x	x	67.52
Sphagnum squarrosum	1.9	-27.80	25.44	x	x	x	x	x

interactions showed group 5 had significantly more species per 25x25 cm than all other groups (Tukey-Kramer multiple comparisons, data available on request). Also group 3 was significantly poorer in species than groups 1, 2, 5 and 6.

The general hydrochemical indicators (pH, electrical conductivity (EC) and calcium concentrations) showed large differences between the six vegetation types (Fig.6.2a-c). Generally, the concentrations of nutrients (nitrate, ammonium, phosphate and potassium) were low in all vegetation groups (Fig. 6.2d-g), and showed considerable variation within a single vegetation type. Calcium concentrations and EC values showed similar trends, as did nitrate and ammonium concentrations. These trends are discussed in more detail below.

The pH range of the vegetation groups was broad, ranging from approx. pH 4.5 to pH 6.5 (Fig. 6.2a). The lesser values were found in the *Sphagnum*-dominated vegetation types (groups 1 and 6), while the greater values were measured in the rich fen type (group 5). All three poor fen vegetation types (group 2, 3 and 4) had pH values around 6.0. There was little overlap between these three divisions indicating a low amount of variation in pH values within a vegetation type.

Electrical conductivity (EC) values ranged from approx. 50 to 600 $\mu S\ cm^{-1}$ (Fig. 6.2b), the lesser values (median approx. 50 $\mu S\ cm^{-1}$) in the *Sphagnum*-rich vegetation types (group 1 and 5). The greater values (median >400 $\mu S\ cm^{-1}$) were measured in poor fen types, the *Potentilla palustris* - *Carex rostrata* fen and the *C. rostrata* - *Menyanthes trifoliata* fen, *Equisetum fluviatile* subcommunity (groups 2 and 4). The values varied considerably in group 2, while group 4 showed more consistently high EC.

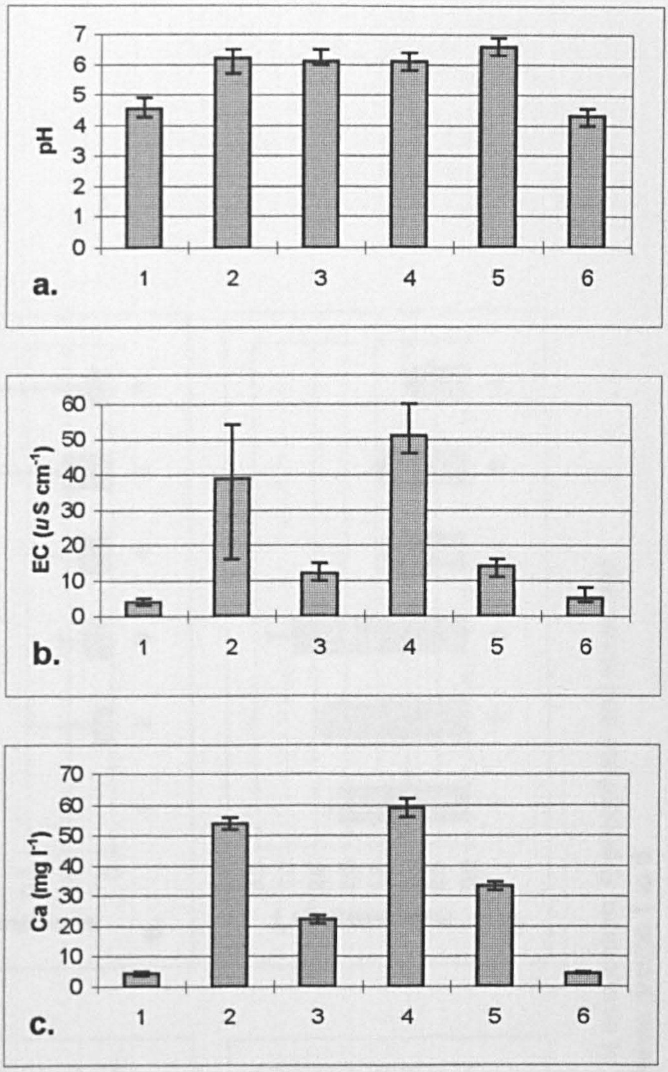


Fig. 6.2 Sample mean and standard error of the mean for a) pH, b) electrical conductivity (EC) and c) calcium for vegetation groups 1 to 6 as follows:

1 = *Carex rostrata - Menyanthes trifoliata* poor fen, *Sphagnum squarrosum* subcommunity
2 = *Potentilla palustris - C. rostrata* transitional fen
3 = *C. rostrata - M. trifoliata* poor fen
4 = *C. rostrata - M. trifoliata* poor fen, *Equisetum fluviatile* subcommunity
5 = *Carex panicea - Carex pulicaris* rich fen
6 = *Eriophorum angustifolium - Sphagnum magellanicum* mire

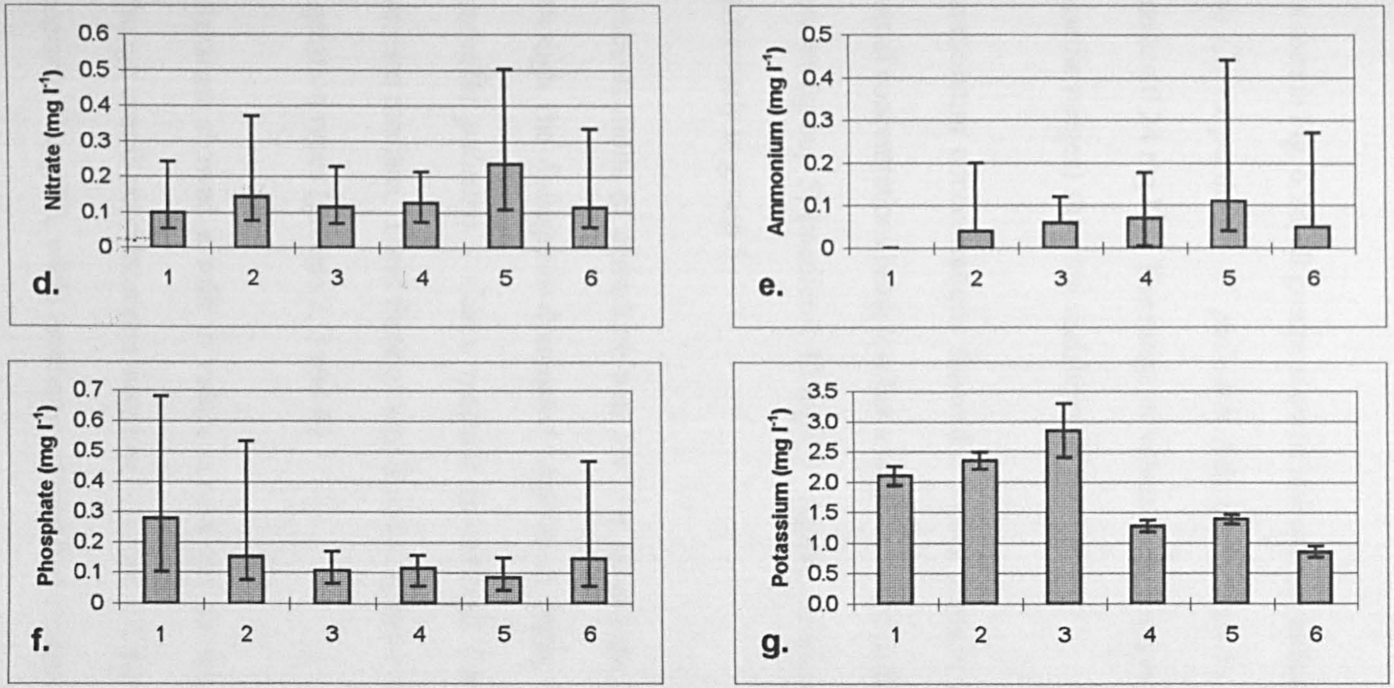


Fig. 6.2 (concl.) Median and Q-values for d) nitrate, e) ammonium, f) phosphate and mean and standard error of the mean for g) potassium for vegetation groups 1 to 6

The calcium concentrations showed similar trends to EC (Fig. 6.2b), with the lowest values in the *Sphagnum*-dominated vegetation types (mean <5 mg l^{-1}), and the greater values in groups 2 and 4 (mean >50 mg l^{-1}). Variability within the groups is low as indicated by the low standard error of the mean.

As seen in Fig. 6.2d, all groups showed low nitrate medians (<0.15 mg l^{-1}), except for the *Carex panicea - C. pulicaris* rich fen (group 5) which was slightly greater (median 0.24 mg l^{-1}). The range of values in each vegetation group was high (large quartile ranges) showing variability in the dataset.

Ammonium concentrations showed a similar pattern to nitrate (Fig. 6.2e), with overall concentrations being low but a slight increase in the *C. panicea - C. pulicaris* rich fen (group 5) (median 0.11 mg l^{-1}). Again, the variability in the data was high, particularly in group 5.

Concentrations of phosphate was low for all groups, median 1.5 mg l^{-1} or less, although the *Sphagnum*-dominated vegetation types (groups 1 and 6) and the *Potentilla palustris - Carex rostrata* transitional fen (group 2) had relatively increased medians. These three groups also had greater variability than the poor fen vegetation types (groups 2, 3 and 4).

Potassium showed a split in values across the six vegetation types (Fig. 6.2g), although overall concentrations were low. Groups 1, 2 and 3 all had increased values (medians >2 mg l^{-1}), while remaining groups had reduced values (medians <1.5 mg l^{-1}).

Overall, the ANOVA and Kruskal-Wallis analyses of hydrochemical parameters between the six vegetation groups gave significant differences for all hydrochemical variables ($p = <0.05$) (Table 6.4). However, pairwise interactions between vegetation groups for pH, EC, nitrate, ammonium and phosphate (using the Q-value test statistic) were not statistically significant ($Q = <2.936$, 5% significance level, data available on request). Significant differences were seen for the pairwise interactions for calcium and potassium (Tukey-Kramer test, data available on request). For calcium all groups were significantly different to one another except groups 6 and 1, and groups 2 and 4. This followed a similar pattern to EC and pH results (Fig. 6.2) with groups 1 and 6 showing the lesser values and groups 2 and 4 the greater values. For potassium groups 2 and 3 were significantly greater than groups 4 and 5, and group 1 was also greater than group 4.

There were many significant correlations (Spearman's rank correlation coefficient, 2-tailed test, 5% significance level) between the hydrochemical variables measured in each vegetation group (Table 6.5), although most of these relationships were non-linear. The only significant linear relationships were positive correlations between pH, EC and calcium values.

The range of variation in both the fen surface level and the water level were calculated for each sample point over the 18 month sampling period (Table 6.6). There were large variations in the range of fen surface level fluctuation, from no measured movement in firm peat areas, to between 20 and 30 cm ranges in the areas where floating vegetation has developed. The greater fen surface movements were seen at Nether Whitlaw Moss, with three out of six sample points showing ranges >20 cm. At Long Moss the ranges were reduced with only two sample points

Table 6.4 One-way ANOVA and Kruskal-Wallis test results for hydrochemical parameters for each of the six vegetation groups. EC = electrical conductivity, DF = degrees of freedom. Significant differences (p = <0.05) shown in bold.

Variable	**DF**	**F-value**	***p-value***
One-way ANOVA test			
Calcium	5	279.02	**0.000**
Potassium	5	23.82	**0.000**
Kruskal-Wallis test			
Nitrate	5	14.11	**0.015**
Ammonium	5	52.04	**0.000**
Phosphate	5	37.54	**0.000**
pH	5	307.09	**0.000**
EC	5	342.75	**0.000**

Table 6.5 Spearman's rank correlation coefficients for hydrochemical parameters between the six vegetation groups, using a 2-tailed test at 5% significance level. Significant, linear correlations are shown in bold. EC = electrical conductivity.

	pH	EC	Calcium	Nitrate	Ammonium	Phosphate
EC	**0.543**					
Calcium	**0.662**	**0.864**				
Nitrate	0.118	-0.052	0.030			
Ammonium	0.334	0.233	0.246	0.040		
Phosphate	-0.126	0.039	0.118	-0.067	0.136	
Potassium	0.114	0.084	0.103	0.178	0.024	0.271

Table 6.6 Summary of the hydrological characteristics of Long Moss and Nether Whitlaw Moss, including water and fen level range, and maximum and minimum water levels over the 18 month sampling period. N = number of observations

Dipwell	water level range (cm)	fen surface level range (cm)	Max. inundation depth above surface (cm)	Max. water level drop below surface (cm)	N
Long Moss	32.0	0.0	7.0	36.0	17
2	39.0	5.0	7.0	36.0	51
3	50.0	4.0	17.0	16.0	17
4	42.0	8.0	0.0	37.0	51
5	43.0	16.0	1.0	43.0	16
6	18.0	18.0	19.0	23.0	48
Nether Whitlaw Moss	27.0	4.0	0.0	37.0	16
2	59.0	34.0	4.0	43.0	48
3	40.0	8.0	19.0	37.0	16
4	43.0	23.0	19.0	31.0	51
5	13.0	3.0	0.0	19.0	16
6	44.0	28.0	19.0	20.0	51

showing ranges >10 cm. Water level fluctuations range from 13 to 59 cm over the 18 month sampling period. Both sites showed similar variation in water levels ranges.

Maximum inundation levels and maximum water level drop below the fen surface were calculated for each sample point (Table 6.6), indicating extreme flooding and drying events. Inundation levels varied greatly over both sites, between 1 and 20 cm above the fen surface. Water levels dropped below the fen surface by 16 to 43 cm. Spearman's rank correlation coefficients showed fen surface level and water level ranges to be significantly positively correlated (2-tailed test, 5% significance level). No other variables were significantly correlated (Table 6.7).

6.3.2 Characterizing vegetation - environment relationships through Canonical Correspondence Analysis (CCA)

The initial CCA included total biomass, herb biomass, bryophyte biomass and mean hydrochemical parameters as environmental variables. Three main groups were identified from the ordination diagram (Fig. 6.3) reflecting the divisions between ombrotrophic bog, species-poor fen and species-rich fen vegetation types. The first gradient (axis 1) was positively correlated with bryophyte biomass, and negatively correlated with most other variables including mean values of pH, EC, nitrate, calcium and herb biomass. The second gradient (axis 2) was negatively correlated to mean values of species number, phosphate and ammonium. Axis 1 split off the ombrotrophic species from the more minerotrophic species, while axis 2 separated the rich fen species from the poor fen. These three ordination groups were related to corresponding Twinspan groups. The ombrotrophic species were represented by

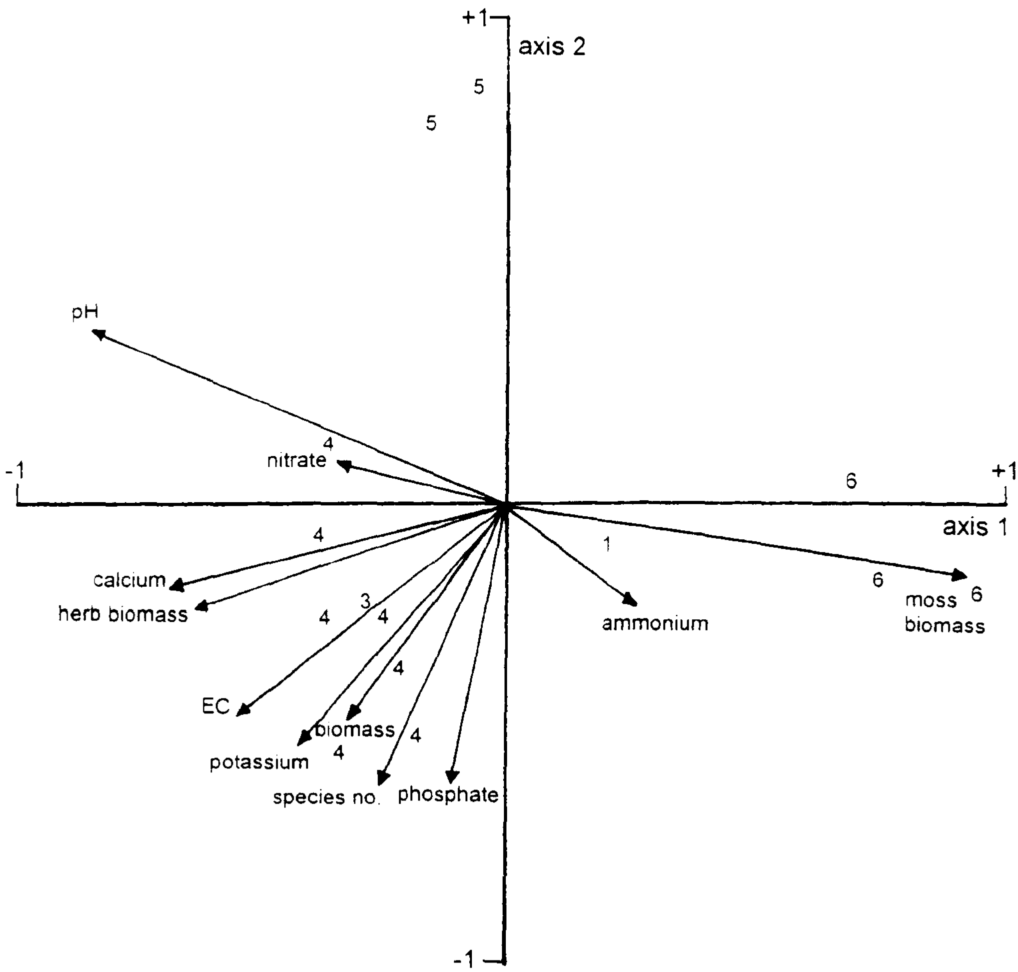


Fig. 6.3 Ordination biplot from CCA showing the six vegetation types in relation to mean hydrochemical and biomass values along with species number. Vegetation groups:
1 - Carex rostrata - Sphagnum squarrosum poor fen
2 - Potentilla palustris - C. rostrata transitional fen
3 - C. rostrata - Menyanthes trifoliata poor fen
4 - C. rostrata - M. trifoliata, Equisetum poor fen
5 - C. panicea - C. pulicaris rich fen
6 - Eriophorum angustifolium - S. magellanicum mire

Table 6.7 Spearman's rank correlation coefficients between mean hydrological measurements for each dipwell on Long Moss and Nether Whitlaw Moss. Significant, linear correlations (2-tailed test, 5% significance level) shown in bold. Number of observations = 14.

	fen surface range	water level range	inundation depth
water level range	**0.468**		
inundation depth	0.454	0.437	
water level drop	0.159	0.257	-0.408

groups 1 and 6, while the species-rich fen species were represented by group 5. The poor fen species were represented by groups 2, 3 and 5, which all occurred close together in the ordination showing the floristic similarity of these three groups.

Each species/sample group can be associated with particular variables according to the group's position with respect to the variable's gradient (represented by the arrow). The ombrotrophic species were positively associated with bryophyte biomass and, to a lesser degree, ammonium. Many other variables were negatively associated with this group. Poor fen species were positively associated with calcium, EC, potassium, phosphate, herb biomass and species number. This group was also negatively associated with ammonium and bryophyte biomass. The rich fen species were generally negatively associated with many variables, while positively associated with pH.

Relationships between variables in the ordination diagram can assessed using the angle between two variables as a guide. An acute angle suggests a positive relationship between the two variables, while an obtuse angle represents a negative relationship. Ammonium and bryophyte biomass are generally negatively associated with most other variables, with the exception of positive correlation between ammonium and phosphate, total biomass and species number. Also positive correlations existed between bryophyte biomass and ammonium and phosphate. Also positive correlations between max. water level drop and pH, calcium, nitrate, and herb biomass. In addition there are negative associations between phosphate and pH, and phosphate and nitrate.

The results from the CCA for the combined data set can be used to ascertain a subset of measured variables that were significant in determining the species composition. This subset of variables were identified using forward selection procedures, which determined the effect of a single variable on the primary synthetic gradient (axis 1) produced from the CCA. The statistical significance of the effect of each variable was tested by a Monte Carlo permutation test, using 99 permutations in the null hypothesis.

The environmental variables were than ranked in order of importance in determining species composition in the ordination diagram, as indicated by forward selection procedures, and their statistical significance on species distributions along axis 2 analysed using the Monte Carlo permutation procedure ('marginal effects', Table 6.8). Out of the twelve separate variables assessed, three variables (bryophyte biomass, total biomass and pH) well explained the species composition in the separate vegetation groups combined along the primary axis ('conditional effects', Table 6.8). The CCA ordination using only these three variables showed similar groups to the ordination using all twelve variables, emphasising the dominant effect of these variables on species separation.

The second CCA was carried out using the environmental variables total biomass, bryophyte biomass and pH of sub-surface water (all significant in the first CCA), along with general hydrological measurements of the magnitude of fen surface movement, water level range, maximum inundation level and maximum water level drop. From the ordination diagram (Fig. 6.4) axis 1 was positively correlated with bryophyte biomass, water level range and maximum inundation level, and negatively correlated with total biomass, pH, magnitude of fen surface movement and maximum

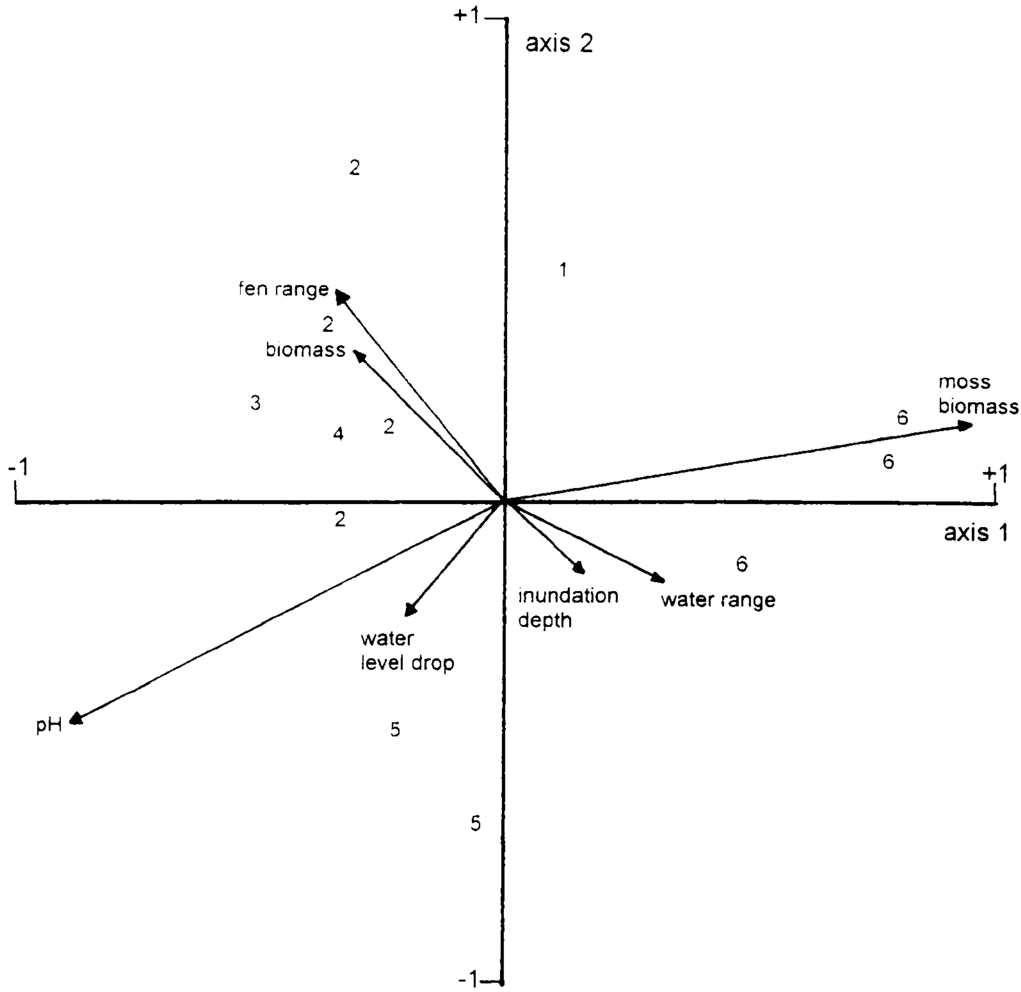


Fig. 6.4 Ordination biplot from CCA showing the six vegetation groups in relation to general hydrological parameters, along with the significant variables of pH, moss biomass and total biomass.

Table 6.8 Environmental variables ranked by their marginal and conditional effects, as obtained from forward selection. **Li** = fit = eigenvalue with variable j only; **La** = additional fit = increase in eigenvalue; **cum. La** = cumulative totals of eigenvalues La; **p** = significance level of theeffect (Monte Carlo permutation test with null model of 99 random permutations). EC = electrical conductivity

Marginal effects (forward: step 1)			
j	**variable**	**Li**	***p***
10	bryophyte biomass	0.75	**0.010**
6	pH	0.72	**0.010**
1	calcium	0.59	**0.010**
9	herb biomass	0.56	**0.020**
7	EC	0.54	**0.010**
8	total biomass	0.47	**0.050**
2	potassium	0.44	0.180
3	ammonium	0.41	0.180
5	phosphate	0.39	0.320
11	species number	0.37	0.270
12	max. water level drop	0.35	0.320
4	nitrate	0.24	0.710

Conditional effects (forward: cont.)				
j	**variable**	**La**	***p***	**cum.(La)**
10	bryo. biomass	0.75	**0.010**	0.75
8	total biomass	0.46	**0.030**	1.21
6	pH	0.40	**0.050**	1.61
2	potassium	0.37	0.080	1.98
7	EC	0.31	0.220	2.29
3	ammonium	0.26	0.330	2.55
9	herb biomass	0.26	0.320	2.81
11	species no.	0.19	0.230	3.00
1	calcium	0.16	0.590	3.16
5	phoshate	0.15	0.390	3.31
4	nitrate	0.23	0.800	3.54
12	max. water drd	0.23	0.350	3.77

water level drop. The second axis was positively correlated to fen surface level range and total biomass, and negatively correlated to pH and maximum water level drop.

The main vegetation groups were again identified on the ordination plot, with the more ombrotrophic species (groups 1 and 6) associated with increased bryophyte biomass and a greater water level range, along with lower pH values and reduced fen surface movement. The sedge-rich vegetation (group 5) were associated with higher pH and, to a lesser extent, greater water level drop. The poor fen vegetation types (groups 2, 3 and 4) were all associated with increased total biomass and greater magnitude of fen surface fluctuations.

Forward selection of the seven variables showed that five variables, when combined in the CCA, were statistically significant in separating out the species and samples along the axes. These were, in rank order, bryophyte biomass, total biomass, pH, magnitude of fen surface movement and water level range ('conditional effects', Table 6.9). The final two variables, maximum water level range and maximum inundation level, were not statistically significant in the ordination. This was reflected in the short length of the arrows for these variables on the ordination plot (Fig. 6.4).

6.4 Discussion

In this chapter relationships between vegetation groups and environment were assessed using the multivariate analysis technique Canonical Correspondence Analysis (CCA). Previous work highlighted the large variability in both the hydrology (*sections 4.3 and 4.4*), and the hydrochemistry (*sections 5.3 and 5.4*) of the two

Table 6.9 Environmental variables ranked by their marginal and conditional effects, as obtained from forward selection. **Li** = fit = eigenvalue with variable j only; **La** = additional fit = increase in eigenvalue; **cum. La** = cumulative totals of eigenvalues La; **p** = significance level of the effect (Monte Carlo permutation test with null model of 99 random permutations).

Marginal effects (forward: step 1)			
j	**variable**	**Li**	*p*
2	bryophyte biomass	0.75	**0.010**
3	pH	0.72	**0.010**
1	total biomass	0.47	0.120
4	fen surface range	0.40	0.180
5	water level range	0.37	0.280
7	max. water level drop	0.35	0.330
6	max. inundation depth	0.28	0.660

Conditional effects (forward: cont.)				
j	**variable**	**La**	*p*	**cum.(La)**
2	bryo. biomass	0.75	**0.010**	0.75
1	total biomass	0.45	**0.050**	1.20
3	pH	0.46	**0.050**	1.66
4	fen range	0.41	**0.010**	2.07
5	water range	0.40	**0.050**	2.47
7	water drop	0.29	0.23	2.76
6	inundation	0.23	0.32	2.99

study sites. This appeared to relate to the different vegetation types found on the sites, but precise relationships were difficult to elucidate. These relationships were highlighted by analysing some general hydrological parameters and mean hydrochemical concentrations that were related directly to plant species data using CCA. In addition, plant biomass (July standing crop) was included in the analyses as in indicator of potential nutrient availability.

A brief analysis of hydrochemical parameters showed this subset of samples had equivalent trends in hydrochemistry over the six vegetation groups as found in the analysis of the full hydrochemical dataset (*section 5.4*). Hydrological parameters also appeared to give a similar picture as for previous analysis (*section 4.4*). The *Sphagnum*-dominated vegetation types on firmer peat deposits showing reduced fen surface fluctuations, and greater water level ranges. In contrast, areas of *Carex rostrata* fen vegetation were associated with greater fen surface movement, and lower water level ranges. Maximum inundation level and the maximum water drop below fen surface did not reveal clear trends between vegetation groups. The species-rich *Carex* vegetation type appeared to have a low inundation level, and a high water level drop below surface, but the remaining groups showed highly variable results. It therefore appears that these data relating to extreme hydrological conditions were not an important factor in vegetation differentiation in this study. Factors such as duration and frequency of flooding and drought may be more useful, but such detail was not available from the current dataset.

The two CCA ordinations both gave species/sample groups that were comparable with the ordinations and Twinspan-derived vegetation groups developed from vegetation classification (*sections 3.3 and 3.4*). The ombrotrophic species were separated from the more minerotrophic species along the first axis, and the species-rich *Carex* fen separated from the species-poor fen along the second axis. Again, the species-poor *Carex rostrata* fen vegetation types (groups 2, 3 and 4) were not readily separated by the ordination, indicating their floristic similarities.

The initial ordination assessed the associations between species distribution and mean hydrochemical parameters, along with information on above ground biomass and plant species numbers. High bryophyte biomass was a significant factor in the separation of the *Sphagnum*-dominated vegetation groups in the ordination diagram, along with reduced values for pH and mean calcium concentration. This is similar to the suggestion that bryophyte distribution may be more affected by acidity - alkalinity gradients than by nutrient concentrations, proposed by Vitt and Chee (1990). In contrast, the species-poor *Carex rostrata* fen types are positively associated with increased levels of nutrients and higher biomass (both herb and total). The species-rich *Carex* fen is only associated with increased pH, and negatively associated with nutrients and biomass. Similarly, Vitt & Chee (1990) found that vascular plant distribution was related to the availability of nitrogen and phosphate. Hydrochemical variables such as calcium and nutrient concentrations have been found to be significant in separating out fen vegetation types (Willby *et al.* 1997). Statistical analysis suggested that in this dataset only bryophyte biomass, pH and total biomass were significant in separating out the samples and species in the initial ordination diagram. Mean nutrient values appeared to be less significant, although clearly associated with particular vegetation types.

The second ordination showed that in addition to bryophyte biomass, pH and total biomass, two additional hydrological parameters were important in the separation of species and samples. These were the magnitude of fen surface level fluctuation and the range of water level fluctuation over the 18 month sampling period. These two factors were also positively correlated to one another. It appears that the *Sphagnum*-dominated vegetation types were influenced by an large overall water level range but a small fen surface fluctuation. This may relate to the firm peat found in these *Sphagnum*-dominated vegetation types, particularly group 1, reducing fen surface movement. Additionally, these vegetation types are found within the centre of the fen system, and slightly elevated, encouraging surface water and ground water to flow around them (Sallantus 1988), and potentially reducing water inputs leading too greater water level drops particularly in summer. Conversely, the *Carex rostrata* species-poor fen vegetation types were associated with a high fen surface movement range and a low water table movement range. This may reflect the development of floating vegetation mats and more constant water inputs. Species-rich *Carex* vegetation were associated with a low magnitude of fen surface fluctuation, but a more constant water table. This reflects the firmer herbaceous peat the vegetation has developed over, and their situation around the edge of the fen close to the lag stream where water levels are maintained through preferential flow patterns. The remaining hydrological parameters of maximum inundation level and maximum water table drop below surface were, suprisingly, not statistically significant in the ordination. This may reflect the high degree of variability within this dataset, particularly relating to seasonal variation, which can obscure any relationships across vegetation types.

Above ground biomass has been associated with productivity, and hence nutrient availability to a vegetation type (*e.g.* Kirkham *et al.* 1996). In this study the above ground biomass (July standing crop) was separated into herb and bryophyte biomass, along with the total biomass figure. In the *Sphagnum*-rich vegetation types (groups 1 and 6) bryophyte biomass was highest. In the *Carex rostrata* transitional and species-poor fen vegetation types (groups 2, 3 and 4) herb biomass was the highest. In contrast, the species-rich *Carex* fen was low in total biomass, incorporating both bryophytes and herbs. Bryophyte biomass represents more of a problem in assessing productivity than herbaceous biomass. Herbaceous species die back every year so their biomass is representative of that years growth. However, bryophyte species do not die back each winter, so their biomass is the accumulation of many years growth rather than one season.

When assessing herb biomass only, the transitional and species-poor *Carex rostrata* fens had the greater biomass, indicating a more productive environment, while the *Sphagnum*-rich vegetation types had the lowest biomass indicating unproductive conditions. The species-rich *Carex* fen appeared in the middle of these two extremes. Including only herb biomass may somewhat under-estimate the potential productivity of vegetation types with a significant bryophyte component. Including bryophyte biomass in the analysis can distort the results, and lead to misinterpretation in relation to other published data. The fertility index based on herb biomass (Koerselman pers. comm.) indicated that the *C. rostrata* transitional fen with the highest herb biomass (group 2) was at about the same overall fertility as the other herb-dominated vegetation types (groups 3, 4 and 5), within the oligo-mesotrophic fertility range. The *Sphagnum*-dominated vegetation types (groups 1 and 6) were of a lower fertility, in the highly oligotrophic and oligotrophic fertility index groups respectively. A large moss component, as observed in these two *Sphagnum*-dominated vegetation types, can act as a reservoir of nutrients accumulated in the vegetation that are not released through annual die-back (Koerselman *et al.* 1988) leading to the low fertility status. These results suggest that none of the fen vegetation types are subject to increased fertility, and that the sites, overall, are of a low general fertility. The range of herb biomass found at these two sites (between approximately 70 - 380 g/m^2) is within the range of biomass figures presented for other fen sites. Wheeler and Shaw (1991) found a range of 80 - 2900 g/m^2 above ground biomass at rich fen sites, while Vermer and Verhoeven (1987) found 300 - 1000 g/m^2 on fens surrounded by heavily fertilized agricultural land, and Willby *et al.* (1997) found 250 - 2800 g/m^2 on a floodplain fen. In comparison Long Moss and Nether Whitlaw Moss are toward the lower end of these ranges, again indicating overall reduced fertility.

Predicting plant species biomass using Clausman indicator values (Clausman *et al.* 1987) through linear regression models (Melman *et al.* 1988, Koerselman pers. comm.) was not successful in this dataset. Calculated biomass figures were often above that observed in the field, predicting a greater trophic status than expected, or produced negative values for low productivity species. This may be due to the limited number of species able to be assessed, but it also seems to indicate that for these very low-productive, species-poor environments such models may not be successful in predicting trophic status.

Above ground biomass has been linked to species diversity, with lower biomass associated with higher species numbers (Grime 1973, Wheeler & Giller 1982, Vermeer 1986a,b, Verhoeven *et al.* 1993, Kirkham *et al.* 1996). This association has been presented as a generalised model for herb-dominated vegetation communities, where high species diversity is found at moderate above ground biomass, and low species richness at extreme low and high biomass (Grime 1973, 1979a,b). In this study herb-dominated vegetation groups, the *Carex rostrata* poor fens (groups 2, 3 and 4) and the *Carex* rich fen (group 5) adhered to this hypothesis. The *Carex* fen having greater species numbers and lower biomass than the three *Carex rostrata* vegetation types. Difficulties arise when including the *Sphagnum*-dominated vegetation types (groups 1 and 6). The significant amount of bryophytes increase the biomass figures, despite these vegetation types being relatively poor in plant species. Similar high values for bryophyte biomass have been reported in similar poor fen and bog environments (Koerselman *et al.* 1990b, Wassen *et al.* 1995). When removing the bryophytes, the biomass figures for these two vegetation types are extremely low, while the species number remains low. It appears that while the association between high biomass and low species number holds for herb-dominated fen vegetation types, the relationship is less well defined for bryophyte-rich fen and bog vegetation types. This may account for the lack of relationship between the species-rich *Carex* fen vegetation type and species number on the first CCA ordination diagram.

Vermeer and Verhoeven (1987) found no links between biomass and species diversity in fens in the Netherlands, and suggest the lack of litter production (due to annual mowing) may be important. In addition, Solander (1983) showed that in extreme environments the productivity of both *Equisetum fluviatile* and *Carex rostrata* are not only affected by nutrient availability, but also temperature. Similar results of environmental factors being associated with species numbers, rather than biomass alone, are seen (Grillas 1990, Gough *et al.* 1994). Although Long Moss and Nether Whitlaw Moss were not subject to any management or extreme conditions, the results of these two studies highlight that the general association between species number and above ground biomass can be modified by other environmental factors. In this study the nutrient poor, acidic conditions prevalent in the *Sphagnum*-dominated vegetation types may complicate the association between above ground biomass and species number.

One problem with associating above ground biomass with trophic status and nutrient availability is that below ground biomass is not considered. Heathland species have been found to allocate varying amounts to above and below ground biomass (Aerts 1993), so a high above ground biomass may not necessarily indicate a high below ground biomass, or *vice versa*. Doyle (1982) measured both above and below ground biomass in an ombrotrophic mire, and found that a large proportion of the vascular plant biomass was below ground, and this accounted for almost all of the total biomass of that vegetation type. Similarly, low productive *Carex* species (*Carex diandra* and *C. rostrata*) appeared to invest more into below ground biomass (Aerts *et al.* 1992). No data were collected on below ground biomass in this study, but there remains the possibility that this will account for a substantial part of each vegetation types total biomass.

In summary, CCA produced almost identical ordination diagrams to those produced in chapter 3, separating off the samples and species into similar groups despite using different environmental variables. In this analysis bryophyte biomass, pH, total biomass, the magnitude of fen surface movement and water level range were all significant in separating out the samples and species in the ordination diagrams. The *Eriophorum - Sphagnum* mire (group 6) and the *Carex rostrata - Sphagnum squarrosum* poor fen (group 1) were associated with high bryophyte biomass and low pH, along with a large water level range, but a small fen surface movement. The *C.*

rostrata transitional and species-poor fen types (groups 2, 3 and 4) were associated high total biomass, along with a large fen surface movement and therefore reduced inundation and drought severity. In addition, these vegetation groups was associated with increased nutrients. Finally, the species-rich *Carex panicea - C. pulicaris* fen was associated with higher pH, lower total biomass, and reduced fen and water level fluctuation.

CHAPTER 7

General discussion and conclusions

7.1 Summary of the research aims and objectives

Studies of fens in Britain to date have primarily focused on site specific studies, most often in England (Wheeler 1983, Gilvear *et al.* 1997), but less often in Wales (Gilman 1994) and Scotland (Charman 1993, Ross *et al.* 1998). In addition, few of these studies have attempted to put these site studies in a wider UK or European context. Despite the lack of published information on fens in Scotland, unpublished work indicates that there is a wide distribution and variety of fens in Scotland (Wheeler & Shaw 1991, Tratt 1997). This study assessed both the distribution and hydrotopographical type of a large number of fens found in Scotland. It also attempted to place the study sites in a European context through comparison with a large number of published data on fens.

Despite this lack of research on fens in Scotland, there are many studies on the vegetation, hydrology and hydrochemistry of mires, and fens in particular, in Europe and worldwide. The spatial vegetation changes that occur across mires are often obvious, and therefore have been the focus of a great deal of research, both in terms of vegetation classification (*e.g.* Wheeler 1980a,b,c,) and ecological understanding (*e.g.* Vitt & Chee 1990, Wassen *et al.* 1992). Studies have tried to assess why vegetation develops where it does with regard to environmental characteristics such as topography (De Mars *et al.* 1997), water source (Bridgham & Richardson 1993), hydrochemistry (Beltman & Verhoeven 1988) and substrate type (Boeye & Verheyen 1994). In this study a number of basin fens were studied across Scotland to assess ecological variability, particularly in terms of nutrient status. In addition, two sites were studied in detail with regard to vegetation patterning and its relationship to fen hydrology and hydrochemistry.

Fens are "largely dependent on water provided by the mineral catchment" (Fjot 1991), and as such are likely to be subject to pollution through ground water and surface water (Heathwaite 1995b). Nutrient enrichment is one of the more widespread and increasing forms of water pollution, related to land improvement and increasingly intensive agricultural practices particularly since the Second World War (Burt & Haycock 1993). As fens are naturally nutrient poor habitats (Verhoeven *et al.* 1990), with nutrients sequestered within peat (Howard-Williams & Downes 1993), these habitats are vulnerable to nutrient enrichment *i.e.* eutrophication (Wheeler 1983, Boeye *et al.* 1996). This is exacerbated by their often isolated situation within agricultural landscapes, particularly basin fens (Fojt 1995). The potential for increased nutrient inputs to a fen from adjacent land was assessed on a number of sites across Scotland. The site nutrient status was assessed through the hydrochemistry of both the inflows and the fen area.

Overall, this study has shown that fens in general were widespread throughout Scotland, and that basin fens were a frequently occurring hydrotopographical type. Within basin fens there was a great deal of variation in vegetation, hydrology, hydrochemistry and peat types. This variation occurred both between fens and across a single fen site. The vegetation patterning across two basin fens was related to water chemistry, hydrology and substrate type, but relationships were often difficult to elucidate due to inherent spatial and temporal variation of the fen environment.

Nevertheless, some generalised vegetation - environment relationships were defined for northern temperate basin fens.

7.2 The distribution and type of fens in Scotland, their nutrient status, and vulnerability to enrichment

This is the first study to take a comprehensive view of fens throughout Scotland to assess their distribution and hydrotopographical type. Fens were found to be widespread throughout Scotland, occurring either as discrete sites, or associated with a larger habitat such as blanket bog or open water bodies (*section 2.3.1*). A large number of sites (over 700) with some fen habitat were found within Scotland, with the highest numbers being found in the Highlands, Borders, Strathclyde and Tayside Regions. The majority of sites were under SSSI notification, but this no doubt reflects the bias of the search toward these sites, as very little data are held on other fen areas. From the subset of 355 sites, basin fens (43 %) were the most frequently occurring fen hydrotopographical type, followed by open water transition fens (27 %), floodplain/valley fens (26 %) and, lastly, hillslope fens (4 %). Fen areas within blanket bog, or associated with raised bog lag streams were not included in this subset.

A scoping survey of eighteen basin fens from across mainland Scotland found that the majority of sites (72 %) were surrounded by land types that were agriculturally improved or modified in some way (*section 2.3.2*). These land types were typically semi-improved pasture, plantation forestry, arable or amenity grassland (golf courses). There was, therefore, potential for these basin fen sites to be affected by increased nutrient inputs from catchment water inputs.

Water inputs, including streams and drains from adjacent land, showed that some fen sites received slightly elevated nutrient concentrations, particularly Restenneth Moss and Nether Whitlaw Moss (*section 2.3.2*). However, not all sites with agriculturally improved or modified catchments showed significantly greater nutrient concentrations in their inflows. This may be due to sampling during dry periods, insufficient sampling at each site, both in terms of space and time, or no detectable nutrient input from the catchment area.

Analysis of fen sub-surface water found there were significant differences between the fen hydrochemical status for all parameters, including nutrient and calcium concentrations, pH and electrical conductivity (EC) (*section 2.3.2*). Overall, the hydrochemical data suggested that nutrient status of the majority of fens was low, with few detectable signs of enrichment. However, four fens did show elevated nutrient concentrations. Restenneth Moss and Torrs Moss had greater nitrate and potassium concentrations, while Barmufflock Dam and Glen Moss had greater phosphate concentrations. The concentrations of these nutrients were not, however, outwith the range published for similar fens throughout Britain and Europe (Appendix 3).

There were significant variations in organic matter content and field moisture content in the peat sampled over the 18 fen sites (*section 2.3.2*). This was attributed to the formation of different peat types. Greater inorganic matter and lower moisture content was associated with herbaceous, minerotrophic peat which generally have higher hummifictation rates (Aaby 1986, Zoltai 1991) and lower water holding capacities (Blackford & Chambers 1993). Conversely, *Sphagnum*-derived ombrotrophic peat with greater organic matter and moisture content generally has reduced hummification rates and hence greater water holding properties.

Elevated nitrate and potassium concentrations in sub-surface fen water samples were associated with fens dominated by deep and shallow ground water (lithotrophic water type) (*section 2.3.3*). Contrary to this, fens with dominant precipitation inputs (atmotrophic water type) had elevated phosphate concentrations. Over half of the 18 fens had a transitional litho-atmotrophic water type, indicating they received relatively equal inputs of both ground water, surface water and precipitation. These mixed hydrological inputs were, therefore, more typical of basin fens in Scotland. These transitional sites, although hydrochemically variable, did not show elevated nutrient concentrations.

Despite the apparent vulnerability of these basin fen sites to nutrient enrichment from the surrounding improved land types, there were only two sites with elevated nutrients concentrations in their inflows. In addition, the majority of fens also showed low concentrations of nutrients in their sub-surface waters. The four fens with elevated nutrients showed concentrations within the range published for similar sites in Britain and Europe, with little indication of nutrient enrichment.

7.3 Linking vegetation patterning with hydrological and hydrochemical variation

7.3.1 Vegetation patterning

Six vegetation types were identified on the two basin fens through phytosociological classification, ranging from ombrotrophic bog, to species-poor fen, and species-rich fen (*section 3.3.1 and 3.3.2*).

The seventeen plant and environmental variables measured in this study were highly correlated to each other. This multicollinearity of variables made it difficult to distinguish the important variables governing species composition. Multicollinearity is, though, characteristic of vegetation community data sets (Palmer 1993). Overall, each vegetation group could be typified by a number of plant and environmental variables (*section 3.3.4*), which led to the following hypotheses:

- Taller, robust, species-poor, open herb canopies with no bryophyte cover were associated with deeper inundation and greater areas of open water.
- Short herbs with a dense, continuous cover of short bryophytes were associated with shallow inundation level and reduced open water areas. In addition, these areas had reduced pH and EC values for the water.
- Short, dense, species-rich herb canopies with a patchy cover of taller, lax bryophytes were associated with mid range inundation and open water cover.

In this study the taller, inundated, species-poor herb-dominated vegetation type related to the *Carex rostrata - Menyanthes trifoliata* fen and the *Potentilla palustris*

- *C. rostrata* fen. The short herb, drier, bryophyte-dominated vegetation related to the *Eriophorum angustifolium - Sphagnum magellanicum* mire and the *C. rostrata - Sphagnum squarrosum* poor fen. Finally, the species-rich, short herb vegetation type with patchy bryophyte cover related to the *Carex panicea - Carex pulicaris* fen. The three general vegetation types presented here are somewhat extremes of the continuum of vegetation characteristics found across the site. Some samples, particularly within the *P. palustris - C. rostrata* transitional fen, fall between these types or show more variable characteristics. This is inevitable in any attempt to simplify the range of vegetation types, and there will always be highly variable ecotonal zones between main vegetation types (Tausch *et al.* 1995). These main vegetation types do, however, provide a summary of the important plant and environmental variables that occur together and characterize a vegetation type.

Ordination analysis showed that the distribution of the bog and fen species was related to sub-surface water pH, canopy height, herb cover, moss cover, substrate type and standing water depth (*section 3.3.4*). The importance of pH as strong directional gradients in species mire composition has been noted by many authors (*e.g.* Sjors 1950, Malmer 1963, Verhoeven *et al.* 1990, Vitt & Chee 1990). As has the importance of flooding and substrate type.

Unlike phytosociological classification, predicting vegetation types from plant traits and environmental variables, such as canopy height, nearest neighbour distance and inundation depth, does not rely on species identification. Instead species with similar plant and environment variables are hypothesised to share the same ecological traits (Boutin & Keddy 1993). Measuring plant and environment variables may then provide a simpler and quicker alternative to phytosociological classification. As such, plant traits are potentially useful as a conservation management tool. In this study it was difficult to identify plant or environmental variables that could predict vegetation groups, due to multicollinearity of the variables (*section 3.3.5*). One approach to dealing with multicollinear data is to reduce the number of collinear variables to just two or three that are representative of the whole dataset (Ter Braak 1987). This was achieved through multivariate linear regression and simple linear regression analyses. Both highlighted pH and herb/canopy height as effective predictors of vegetation types, although simple linear regression was generally less effective. Herb height has been shown as significant in predicting the competitive ability of a species (Givnish 1982, Keddy & Shipley 1989) and characterizing environmental conditions (Willby *et al.* 1997). In this case the greater herb height may reflect stress tolerance to flooding (*sensu* Grime 1979a,b), rather than more effective resource capture.

7.3.2 Hydrological variation

Despite the similar regional climate and catchment characteristics of the two basin fens, the flow regimes for each inflow stream were quite different (*section 4.3.1*). Long Moss inflow stream was dominated by quick flow from the catchment, indicating a rapid response to rainfall. Conversely, Nether Whitlaw Moss inflow stream showed a more continuous base flow that rarely dried up during the summer. The stream was less affected by rapid run off from the catchment. This may be attributed to the different land use types of the two fen catchments. The unimproved, undrained acid grassland surrounding Long Moss may have water levels close to the surface most of the year, increasing quick flow. Nether Whitlaw Moss catchment has, by contrast, improved pasture which is under-drained. The drainage reduces surface flow, redirecting it as drain flow and percolation through the soil, thereby reducing quick flow to the stream.

In addition small scale changes in the geology around Nether Whitlaw Moss, achieved by the local formation of the 'corrugated hills' (Ragg 1960), may enable this fen to receive ground water from outwith the surface catchment. This could explain the base flow of the inflow stream. Long Moss does not occur within the 'corrugated hills' formation, and appeared to be solely reliant on precipitation, surface and subsurface inputs to the inflow stream, hence the long, dry periods in the summer.

Water levels on the fen themselves were subject to seasonal changes related to effective precipitation, showing a summer decline and an autumn increase (*section 4.3.3*). At both sites the overall rise and fall of water levels were very similar, but the basin fens did not function as a hydrological unit. At a smaller scale the inundation and drying regimes of the fen surface differed greatly across each fen, and the effect on vegetation was likely to be different, too. The following hydrological regimes were found on each fen:

- The formation of floating vegetation rafts allowed the fen surface and the water level to move together. This kept water levels close to the fen surface, reducing the severity of inundation and drought. These areas were generally at the lower parts of the fen, such as close to the outflow.

- Those areas that had semi-floating (partially anchored) vegetation rafts over unconsolidated peat had limited surface movement as the water levels fluctuated. Drying occurred, along with deeper and more frequent flooding.

- Firm peat areas on the fen had little vertical movement and water levels fluctuated independently. This led to greater water level draw-down, but far fewer inundations. These firm peat areas could either represent a continuous peat profile to the bottom of the basin, as at Long Moss, or a thick, stable peat raft developed over unconsolidated peat/water, as at Nether Whitlaw Moss (Tratt 1997).

- Firm peat areas dominated by ombrotrophic *Sphagnum* peat had no recorded inundations, while firm minerotrophic herbaceous peat were subject to some flooding. This may be explained in terms of the diplotelmic structure of the *Sphagnum* peat, with greater hydraulic conductivity at the peat surface (acrotelm) encouraging excess water to be shed rapidly and preventing flooding (Clymo 1992, 1997). The diplotelmic structure is not clearly present in minerotrophic peat (Ingram 1992), and hydraulic conductivity at the surface is reduced.

7.3.3 Variation in hydrochemistry

Each fen had a variety of water types, identified through the LAT Model (Van Wirdum 1981), indicating the heterogeneity of water types on each fen (*section 5.3.2*). These indicated the dominance of either ground water (lithotrophic), precipitation (atmotrophic) or a chloride-rich ground water (litho-thalassotrophic). Each water type was related to particular vegetation types and nutrient concentrations.

- The ground water dominated (lithotrophic) areas of the fen related to the species-rich *Carex panicea* - *C. pulicaris* fen vegetation type. Schot &

Wassen (1993) describe a similar species-rich fen vegetation type associated with calcium-rich water

- The species-poor, productive *Carex rostrata - Menyanthes trifoliata* fen, *Equisetum fluviatile* sub-community was found in all three water types, but the majority of samples occurred in association with the chloride-rich ground water (transitional litho-thalassotrophic water type). The high chloride concentrations can indicate artificial nutrient inputs (Kemmers 1986), and nutrient concentrations were generally elevated in these samples.

- The species-poor, unproductive *C. rostrata - M. trifoliata* fen and the *Potentilla palustris - C. rostrata* transitional fen were mainly found in the lithotrophic water type. Nutrient concentrations differed between the two vegetation types, being exceptionally poor in the unproductive poor fen.

- Precipitation-dominated (atmotrophic) water types were associated with the *Eriophorum vaginatum - Sphagnum magellanicum* mire and the species-poor *C. rostrata - S. squarrosum* fen vegetation types. Nutrient concentrations were typically low in this water type, except for phosphate. These increased phosphate concentrations may be related to the dissolution of insoluble calcium phosphates in acidic conditions releasing phosphate (Verhoeven & Aerts 1987, Wassen 1995). Alternatively, the release of phosphates from aluminium and iron compounds under anaerobic or acidic conditions may also occur (Kemmers & Jansen 1988, D'Angelo & Reddy 1994, Koerselman & Verhoeven 1995).

The separation of water types was predominantly on the basis of pH, EC and calcium concentrations, which is reflected in the bog - species-poor fen - species-rich fen vegetation gradient Species separation via CCA ordination was also based primarily on these environmental characteristics (*section 7.3.1*). This gradient is seen in many mire studies (*e.g* Verhoeven *et al.* 1990, Vitt & Chee 1990). Here, though, we see greater discrimination in the species-poor fen vegetation types, giving an *unproductive* species-poor fen, and a *productive* species-poor fen. This reflects the elevated nutrient concentrations present in the latter group, leading to a more productive but less diverse fen vegetation type.

7.3.4 Synthesis

The *Eriophorum vaginatum - Sphagnum magellanicum* mire and the *Carex rostrata - S. squarrosum* poor fen were both typically associated with nutrient-poor, atmotrophic (base-poor) water. There was, although, an increase in phosphate concentrations. Similar phosphate increases in *Sphagnum*-dominated areas have been observed previously, and attributed to physiochemical processes releasing bound phosphates (*e.g.* Borggard 1983, D'Angelo & Reddy 1994). Another possibility is the reduction of microbial activity in these areas leads to more phosphate in solution, but preliminary studies found some evidence for this (Appendix 4). These areas had firmer *Sphagnum*-derived peat that were subject to a low water level in summer, but was not subject to inundation. The peat was either continuous to the bottom of the basin, or formed a sturdy, stable peat raft (Tratt 1997) with minimal movement. The vegetation was dominated by short herbs and dense bryophyte cover.

The *Carex panicea* - *C. pulicaris* species-rich fen was associated with the lithotrophic (base-rich) water type, with slightly elevated nitrate concentrations. This may relate to the vegetation's position close to the inflow at Long Moss where nitrate inputs may be greater. Although no elevated nitrate concentrations were recorded in the inflow stream. Alternatively, these areas may be phosphate-limited leading to an excess of nitrate present in the water (Koerselman *et al.* 1988, Koerselman & Verhoeven 1992, Kirkham *et al.* 1996). The firm, minerotrophic peat that developed here was subject to lower water levels in dry periods, as was the *Sphagnum*-derived firm peat. In contrast, these minerotrophic peat were subject to more frequent flooding, attributed to the lack of acrotelm development which, in ombrotrophic peat allows rapid water-shed from the peat surface. The inherent low hydraulic conductivity of minerotrophic peat reduces water flow through the peat and prevents high water levels from being rapidly shed.

The *Carex rostrata* - *Menyanthes trifoliata* fen, *Equisetum fluviatile* sub-community, was associated with litho-thalassotrophc water that was rich in both calcium and chloride. Nutrient concentrations were generally high, leading to a species-poor but highly productive vegetation type. This vegetation type developed over floating vegetation rafts where water levels were almost constantly at or above the fen surface. The close proximity of this vegetation type to the fen edge and inflow at Nether Whitlaw Moss probably leads to increased water flow in the area, as the water is directed around the central higher area. Increased water flow has been shown to increase aeration, thereby increasing mineralization processes, which may be a factor in increasing soluble nutrients, and in reducing peat formation giving a thin, highly mobile vegetation raft. In addition, nutrient inputs from the adjacent land may also be a factor, not only by adding nutrients to the system, but also by ameliorating conditions for mineralization processes.

The *Carex rostrata - Menyanthes trifoliata* poor fen was associated with base-rich lithotrophic water with lesser concentrations of nutrients. The vegetation developed over floating vegetation rafts. This vegetation type was found close to the outflow at Long Moss.

The transitional vegetation type, the *Potentilla palustris - Carex rostrata* fen, was associated with both floating and semi-floating rafts. The water type was typically base-rich (lithotrophic), with increased nutrient concentrations. This vegetation type was associated with the edge and outflow areas of Nether Whitlaw Moss (floating rafts), and the edges of Long Moss (semi-floating rafts).

Nether Whitlaw Moss was surrounded by improved pasture, and hypothesised to have greater nutrient inputs than Long Moss surrounded by unimproved acid grassland. Overall, Nether Whitlaw Moss was found to have greater concentrations of calcium, phosphate and potassium in the subsurface water, but there were no significant differences in nitrate and ammonium. Greater calcium and potassium concentrations were associated with the inflow stream suggesting they were related to ground water inputs. Greater phosphate concentrations were associated with the field drain inflows along one side of the fen, suggesting inputs from catchment sub-surface and surface run off.

The nutrient concentrations at Nether Whitlaw Moss are greater only in relation to Long Moss. Comparison of both Long Moss and Nether Whitlaw Moss hydrochemistry with a variety of fen sites across UK, The Netherlands, Poland, USA and Canada suggests that nutrient concentrations at Nether Whitlaw Moss are not high enough to suggest active enrichment problems. Comparing the study sites to other Scottish site indicates that potassium and ammonium concentration are slightly elevated, but phosphate and nitrate concentrations are below other published data. Using a fertility index derived from above ground herbaceous biomass (Koerselman pers. comm) both sites were classed as oligotrophic to mesotrophic, with no indication of any eutrophic conditions.

7.4 Conclusions

- Fens were widespread throughout Scotland, either as discrete habitats (*e.g.* basin fens) or within a larger habitat type (*e.g.* small hillslope fens within blanket bog).
- Fen distribution was greatest in the Highlands, Borders, Strathclyde and Tayside Regions.
- Within these more discrete habitat types, basin fens were the most frequently occurring hydrotopographical type across mainland Scotland.
- Basin fens were often surrounded by improved land types, more specifically semi-improved pasture, plantation forestry, arable or amenity grassland (golf courses). They were, therefore, potentially vulnerable to nutrient inputs from these adjacent land types.

- Despite that improved land types adjacent to the sites often increase the nutrient status of fens (Wheeler 1983), few basin fens showed increased nutrient concentrations in their inflows. Similarly nutrient concentrations on the fens were increased in only four sites. These sites were elevated in potassium and nitrate OR phosphate, and never all three major plant nutrients.

- A comparison of the hydrochemistry of two fen sites, Long Moss and Nether Whitlaw Moss, found that Nether Whitlaw Moss surrounded by improved pasture had significantly greater concentrations of calcium, potassium and phosphate than Long Moss. The calcium and potassium was associated with ground water inputs, while the phosphate was associated with catchment surface and sub-surface inputs.

- The sub-surface water nutrient concentrations at Nether Whitlaw Moss were not outwith the range of nutrients reported for similar fens throughout UK, The Netherlands, Poland, USA and Canada. Similarly, a fertility index showed the trophic status of both Long Moss and Nether Whitlaw Moss as oligotrophic to mesotrophic, with no indication of eutrophic conditions. There was, therefore, no evidence of active enrichment.

- Detailed, long term studies on the two basin fens showed the large variation across fens in terms of vegetation patterning, hydrology and hydrochemistry. Spatial changes in vegetation were considerable, showing a gradient from ombrotrophic bog, to species-poor fen (unproductive), species-poor fen (productive), and species-rich fen. Both hydrology and hydrochemistry showed temporal and spatial variation, and such data has rarely been collected for fens in Scotland.

- Spatial hydrological variation at both sites was related to substrate development. Floating vegetation rafts ameliorated the effects of flooding and drought, while firmer peat reduced inundations. Semi-floating vegetation rafts were subject to a highly variable regime, with frequent flooding along with water level fall in the summer.

- Both temporal and spatial hydrochemical variation was found at the two fen sites. Spatial variation related to vegetation patterning, and both base-richness and nutrient concentrations were important in species distributions. This was not obvious from the initial analysis of these two sites during the scoping survey, and highlights the need for greater long term studies of fens.

- From these two basin fens, which encompassed a variety of vegetation types typical of fens in Scotland, some general associations between vegetation types and hydrological and hydrochemical conditions can be presented:

    - Species-rich *Carex panicea - C. pulicaris* occurred on base-rich waters with generally low nutrients, although slightly elevated nitrate was found. Substrate type was firmer, herbaceous peat leading to water level drop in summer, and flooding in autumn/winter.

    - The distribution of the species-poor, high productivity *C. rostrata - Menyanthes trifoliata* fen, *Equisetum fluviatile* sub-community, also related to base-rich water, but nutrients concentrations were increased. Substrate type was a floating vegetation raft, leading to permanently wet conditions.

- The unproductive *C. rostrata - M. trifoliata* species-poor fen was also found on floating vegetation rafts with a base-rich water type. Nutrient concentrations were much reduced compared to the productive species-poor fen.

- The *Potentilla palustris - C. rostrata* transitional fen was associated with base-rich water types with slightly elevated nutrient concentrations. Both floating and semi-floating vegetation rafts were found within this vegetation type, with the semi-floating rafts leading to a dynamic hydrological regime with more frequent, deeper flooding.

- Finally, the *Sphagnum*-rich *Eriophorum vaginatum - S. magellanicum* mire, and the *C. rostrata - S. squarrosum* fen were distributed in relation to the highly base-poor, nutrient-poor water types, although with some increase in phosphate. Both vegetation types were found on firmer peats, either as continuous deposits or as thick stable peat rafts. This led to some water level draw down in summer, but no inundation.

7.5 Further Research

Although a brief assessment of the distribution and hydrotopographical type of fen sites across mainland Scotland was carried out, a full and detailed analysis of the Scottish fen habitat was not within the scope of the study. As such there is a gap in information about an important and apparently widespread habitat type. This gap has been previously highlighted (Wheeler & Shaw 1991, Lindsay 1995), but to date no published work adequately addresses this. A more comprehensive study on the general distribution, type and condition of fens across Scotland is therefore recommended.

The large degree of seasonal variation in catchment run off and nutrient inputs to fen areas has been highlighted by this relatively short term (18 month) study. Many studies assessing the nutrient status of a fen or its water inputs use shorter term studies, or may sample only once. This study shows that single sampling periods are generally unrepresentative of the overall fen nutrient status, and longer term repeat sampling is required. In addition, sampling inflows to gain information about fen nutrient status is not adequate, as conditioning factors on the fen (*e.g.* floating raft formation, physiochemical reactions) can alter nutrient cycling and lead to internal nutrient release and eutrophication (Koerselman *et al.* 1990a).

The potential for plant traits to act as predictors of vegetation types and environmental conditions has been highlighted in this study, although multicollinearity can make it difficult to the elucidate the most useful variables. Other studies show the potential importance of plant height in predicting competitive ability (Givnish 1982, Keddy & Shipley 1989) or environmental conditions (Willby *et al.* 1997). In this study plant height appeared to be related to flooding tolerance (stress tolerance *sensu* Grime 1973). Plant height does, of course, relate to individual species and any index of fertility based on height would need to assess minimum and maximum expected height ranges for each species. A plant close to it minimum then indicates low fertility, whilst a plant close to its maximum indicates high fertility. A similar approach has been taken for selected species and their water level range (Newbold & Mountford 1997), although this has been developed as a tool for predicting the potential impact of drainage on areas, it could be similarly used to assess basic hydrological conditions of any area.

The range of plant traits and environmental variables potentially useful as predictors of the ecological environment is large, and only a small selection were assessed in this study. One plant trait not measured in this study is the ratio of nitrogen (N) and phosphorus (P) in plant tissue, which has been shown to be effective in determining if an ecosystem is N or P limited, by indicating the relative amounts of N and P available to plants (Koerselman & Mueleman 1996). Greater research into the potential of plant traits and environmental variables in predicting general vegetation types and/or environmental conditions in both fens, and mires in general, is required.

Although the present study emphasises the relationships between vegetation types and hydrology and hydrochemistry, the processes underlying these relationships were not within the scope of this project. These processes are undoubtedly important in fen ecosystem functioning, and will contribute to an understanding of the high degree of spatial and temporal variation in hydrochemistry. They may also enable better prediction of how impacts such as nutrient input and drainage may perturb a fen system. In particular, mineralization processes have been shown to be important in nutrient cycling in fens (Verhoeven *et al.* 1988b, 1990, Koerselman *et al.* 1989, Updegraff *et al.* 1995), and affected by hydrochemistry, temperature, and water level (Koerselman *et al.* 1993). More detailed studies on the temporal and spatial variability of fen mineralization processes in relation to substrate type, temperature, pH, nutrient inputs and the effects of flooding and drying, and their role in determining nutrient availability too plants, are required.

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APPENDIX A1

Details of SSSI sites in Scotland with some fen habitat, as obtained from Scottish Natural Heritage.

Site Name	Grid Ref.	Local Authority Region
ABBEY ST BATHANS WOODLANDS	NT762622	Borders
COLDINGHAM COMMON, LONG MOSS	NT856685	Borders
COLDINGHAM LOCH	NT895685	Borders
DRONE MOSS	NT844669	Borders
GORDON MOSS	NT635425	Borders
GREENLAW MOOR	NT705500	Borders
HULE MOSS EAST	NT724491	Borders
LANGTON LEES CLEUGH	NT740523	Borders
PEASE BAY COAST	NT781718	Borders
THE HIRSEL	NT825413	Borders
ACREKNOWE RESERVOIR	NT495105	Borders
BERRY MOSS	NT491250	Borders
BITCHLAW MOSS	NT525121	Borders
BLACKCRAIG MOSS	NT502208	Borders
BOGHALL MOSS	NT491186	Borders
BORTHWICKSHIELS LOCH	NT425153	Borders
CLERKLANDS MOSS	NT494253	Borders
CURDYHAUGH MOSS	NT504282	Borders
DRY MOSS	NT483266	Borders
ESSENSIDE LOCH	NT449208	Borders
EWENS MOSS AND KAIMEND MOSS	NT514137	Borders
FLUTHER MOSS	NT548123	Borders
GREEN DIAMONDS	NT466250	Borders
GREENHEAD LOCH	NT497293	Borders
HAINING MOSS	NT467273	Borders
HALL MOSS	NT489197	Borders
HARDEN MOSS	NT449164	Borders
HARE MOSS	NT468247	Borders
HARTWOODBURN MOSS	NT466269	Borders
HEADSHAW LOCH	NT463238	Borders
HIGHCHESTERS MOSS	NT463145	Borders
HUNTLEY MOSS	NT413248	Borders
HUTLERBURN LOCH	NT420253	Borders
JUBILEE BRIDGE MOSS	NT534256	Borders
LILLIESLEAF MOSS	NT539251	Borders
LIONFIELD MOSS	NT485161	Borders
LITTLE MOSS	NT540144	Borders
LOCH SIKE	NT452238	Borders
MABONLAW MOSS	NT455167	Borders
NEWHOUSE MOSS	NT518234	Borders
NIG KNOWES MOSS	NT490122	Borders
PICKMAW MOSS	NT493281	Borders
RIDDELLSHIEL MOSS	NT501253	Borders
ROTTEN MOSS	NT460170	Borders
SEA CROFT MOSS	NT478104	Borders
SELKIRK HILL MOSS	NT486285	Borders
SELKIRK POT LOCH	NT478283	Borders
SHIELSWOOD LOCH	NT453191	Borders
STONEYFORD MOSS	NT486204	Borders
STOUSLIE POOL	NT490170	Borders
SYNTON LOCH	NT483206	Borders
TANDLAW MOSS	NT490177	Borders
TATHYHOLE MOSS	NT475218	Borders
THREEPHEAD MOSS	NT450175	Borders
TOCHER LODGE MOSS	NT438231	Borders
TODSHAWHILL MOSS	NT452122	Borders
WHITHOPE MOSS	NT433123	Borders
WHITMUIR MOSS	NT492269	Borders

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Site Name	Grid Ref.	Local Authority Region
WILLIESTRUTHER LOCH	NT489113	Borders
WOLLRIG MOSS	NT447232	Borders
WOOLAW MOSS	NT465172	Borders
AKERMOOR LOCH	NT407210	Borders
ASHKIRK LOCH	NT476192	Borders
AVENEL HILL AND GORGE	NT522374	Borders
BEMERSYDE MOSS	NT612330	Borders
BLIND MOSS	NT458184	Borders
BROWNMOOR HEIGHTS FEN COMPLEX	NT460254	Borders
CATSHAW HILL	NT536222	Borders
CLARILAW GRASSLANDS	NT540277	Borders
CRAIGDILLY	NT184208	Borders
DUNHOG MOSS	NT474247	Borders
FALDONSIDE LOCH	NT505328	Borders
GATTONSIDE MOSS	NT548368	Borders
HERMANLAW AND MUCKRA CLEUCHS	NT221165	Borders
KINGSIDE LOCH	NT342134	Borders
LINDEAN RESERVOIR	NT502291	Borders
OVER WHITLAW MOSS	NT508300	Borders
PRIESTON MIRES	NT528282	Borders
RISKINHOPE	NT234190	Borders
SELKIRK RACECOURSE MOSS	NT498278	Borders
ST MARYS LOCH	NT250228	Borders
THREEPWOOD MOSS	NT518424	Borders
TWEEDWOOD - GATEHEUGH	NT583342	Borders
WHITLAW MOSSES	NT506286	Borders
WHITLAW RIG	NT518293	Borders
WHITMUIRHALL LOCH	NT499273	Borders
BACK LOCH	NT358157	Borders
DEEP SLAID MOSS		Borders
GREENSIDE MOSS	NT518258	Borders
GROUNDISTONE MOSS		Borders
LADYWOODEDGE MIRE	XX488256	Borders
MALCOLM'S MOSS		Borders
MUIRFIELD MOSS		Borders
ST. LEONARD'S MOSS		Borders
UPPER LOCH LOCHMAEN LOCHS	NY071835	Borders
WHITHAUGHMOOR MOSS	NT477177	Borders
ADDERSTONELEE MOSS	NT534120	Borders
ALEMOOR WEST LOCH AND MEADOW	NT389148	Borders
BRANXHOLME WESTER LOCH	NT420109	Borders
BUCKSTRUTHER MOSS	NT540120	Borders
DIN MOSS AND HOSELAW LOCH	NT806315	Borders
HUMMELKNOWES MOSS	NT515127	Borders
KIPPILAW MOSS	NT492154	Borders
LONG MOSS - DRINKSTONE HILL	NT480185	Borders
LURGIE LOCH	NT677395	Borders
WOODHEAD MOSS	NT613262	Borders
YETHOLM LOCH	NT803280	Borders
DOLPHINTON - WEST LINTON FENS AND GRASSLAND	NT111476	Borders
MOUNT BOG	NT103419	Borders
WESTWATER RESERVOIR	NT117523	Borders
WHIM BOG AND WOOD	NT206535	Borders
ALLOA INCHES	NS865920	Central
BACK BURN WOOD & MEADOWS	NS995986	Central
CRAIG LEITH & MYRETON HILL	NS867979	Central
DAMHEAD WOOD	NS965968	Central
DEVON GORGE	NT000988	Central

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Site Name	Grid Ref.	Local Authority Region
DOLLAR GLEN	NN948000	Central
GARTMORN DAM	NS920943	Central
LINN MILL	NS932939	Central
CARRON DAMS	NS876826	Central
DARNRIG MOSS	NS863755	Central
DENNY MUIR	NS758829	Central
KINNEIL KERSE	NS970825	Central
SKINFLATS	NS932845	Central
BALLAGAN GLEN	NS572800	Central
BEN AN & BRENACHOILE WOODS	NN495079	Central
BLACKWATER MARSHES	NN535060	Central
BRIG O'TURK MIRES	NN540068	Central
CAMBUSURICH WOOD	NN627346	Central
CARBETH LOCH	NS535794	Central
COILLE COIRE CHUILC	NN330280	Central
COLLYMOON MOSS	NS588971	Central
CONIC HILL	NS421916	Central
CRAIGALLIAN MARSHES	NS536774	Central
CUILVONA AND CRAIGMORE WOODS	NN507016	Central
DALVEICH MEADOW	NN608245	Central
DOUBLE CRAIGS	NS636872	Central
DRUMORE WOOD	NS487990	Central
DUMBROCH LOCH MEADOWS	NS549783	Central
EDINCHIP WOOD	NN584227	Central
FLANDERS MOSS	NS630985	Central
GARTFARRAN WOODS	NS529959	Central
GLEN FALLOCH PINEWOOD	NN365228	Central
GLEN FALLOCH WOODS	NN323190	Central
GLEN LOCHAY WOODS	NN532353	Central
INNISHEWAN WOOD	NN470285	Central
KILLORN MOSS	NS622962	Central
LOCH LUBNAIG MARSHES	NN559157	Central
LOCH MACANRIE FENS	NS566992	Central
LOCH MAHAICK	NN707069	Central
LOCH TAY MARSHES	NN584334	Central
LOCH WATSTON	NN712004	Central
LOCHAIN LARIG CHIELE	NN558279	Central
MUGDOCK WOOD	NS549767	Central
OCHTERTYRE MOSS	NS735975	Central
OFFERANCE MOSS	NS538957	Central
PASS OF LENY FLUSHES	NN596086	Central
POLLOCHRO WOODS	NN336120	Central
RIVER DOCHART MEADOWS	NN437274	Central
ROWARDENNAN WOODLANDS	NN338043	Central
SHIRGARTON MOSS	NS646962	Central
STRATHFILLAN MARSHES	NN395252	Central
STRONVAR MARSHES	NN534206	Central
WESTER BALGAIR MEADOW	NS591896	Central
WESTER MOSS	NS837909	Central
WESTERTON WATER MEADOW	NN728026	Central
CASTLE LOCH	NY087815	Dumfries & Galloway
LOCHMABEN LOCHS	NY062838	Dumfries & Galloway
PERCHHALL LOCH	NY110879	Dumfries & Galloway
RAEBURN FLOW	NY295718	Dumfries & Galloway
UPPER SOLWAY FLATS AND MARSHES	NY160610	Dumfries & Galloway
BLACK LOCH	NX991875	Dumfries & Galloway
KIRKCONNELL FLOW	NX970700	Dumfries & Galloway
ABBEY BURN FOOT TO BALCARY POINT	NX790469	Dumfries & Galloway

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Details of SSSI sites in Scotland with some fen habitat, as obtained from Scottish Natural Heritage.

Site Name	Grid Ref.	Local Authority Region
ARDWALL HILL	NX575573	Dumfries & Galloway
AUCHENCAIRN & ORCHARDTON BAYS	NX809517	Dumfries & Galloway
BORGUE COAST	NX610457	Dumfries & Galloway
CARRICK PONDS	NX581506	Dumfries & Galloway
HEART MOSS	NX770480	Dumfries & Galloway
KENMURE HOLMS	NX638765	Dumfries & Galloway
MILTON LOCH	NX840715	Dumfries & Galloway
NEWLAW MOSS	NX733479	Dumfries & Galloway
RIVER DEE PARTON TO CROSSMICHAEL	NX710685	Dumfries & Galloway
THREAVE AND CARLINGWARK LOCH	NX743625	Dumfries & Galloway
TORRS TO MASON'S WALK	NX710437	Dumfries & Galloway
TORRS MOSS	NX781618	Dumfries & Galloway
AUCHROCHAR WETLANDS	NX094605	Dumfries & Galloway
BACK BAY TO CARGHIDOWN	NX400367	Dumfries & Galloway
BAILLIEWHIRR	NX427414	Dumfries & Galloway
BLOOD MOSS	NX272725	Dumfries & Galloway
CAIRNBABER	NX486762	Dumfries & Galloway
CARSEGOWAN MOSS	NX429588	Dumfries & Galloway
DOWALTON LOCH	NX400467	Dumfries & Galloway
ELLERGOWER MOSS	NX482796	Dumfries & Galloway
FLOW OF DERGOALS	NX245580	Dumfries & Galloway
GLENTROOL OAKWOODS	NX400788	Dumfries & Galloway
KILHERN MOSS	NX200628	Dumfries & Galloway
KIRKCOWAN FLOW	NX255705	Dumfries & Galloway
MOCHRUM LOCHS	NX295535	Dumfries & Galloway
MULL OF GALLOWAY	NX115315	Dumfries & Galloway
RAVENSHALL WOOD	NX510531	Dumfries & Galloway
RING MOSS	NX332672	Dumfries & Galloway
TORRS WARREN - LUCE SANDS	NX140545	Dumfries & Galloway
WOOD OF CREE	NX382712	Dumfries & Galloway
CULLALOE RESERVOIR	NT188877	Fife
DALBEATH MARSH	NT151907	Fife
LIELOWAN MEADOW	NT090926	Fife
LOCKSHAW MOSSES	NS989909	Fife
OTTERSTON LOCH	NT165851	Fife
PARK HILL AND TIPPERTON MOSSES	NT064957	Fife
ROSCOBIE HILLS	NT083927	Fife
STEELEND MOSS	NT046922	Fife
SWALLOW CRAIG DEN	NT046946	Fife
WETHER HILL	NT045964	Fife
CAMILLA LOCH	NT220915	Fife
CARRISTON RESERVOIR	NO327037	Fife
HOLL MEADOWS	NO223036	Fife
BALLO & HARPERLEAS RESERVOIRS	NO212054	Fife
BANKHEAD MOSS	NO447102	Fife
BLACK LOCH (ABDIE)	NO262149	Fife
CAMERON RESERVOIR	NO470112	Fife
CASSINDONALD MOSS	NO467128	Fife
CRAIGMEAD MEADOWS	NO233059	Fife
DUMBARNIE LINKS	NO451017	Fife
DUNBOG BOG	NO270167	Fife
EARLSHALL MUIR	NO485220	Fife
EAST WEMYSS - ANSTRUTHER COAST	NT465997	Fife
EDEN ESTUARY	NO475195	Fife
FIFE NESS COAST	NO625107	Fife
FLEECEFAULDS MEADOW	NO400085	Fife
ISLE OF MAY	NT655995	Fife
KILCONQUHAR LOCH	NO488017	Fife

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Details of SSSI sites in Scotland with some fen habitat, as obtained from Scottish Natural Heritage.

Site Name	Grid Ref.	Local Authority Region
LACESSTON MUIR & GLEN BURN GORGE	NO185064	Fife
LINDORES LOCH	NO266164	Fife
LOCHMILL LOCH	NO223163	Fife
MORTON LOCHS	NO463265	Fife
NORTH FIFE HEATHS	NO286195	Fife
PICKLETILLEM MARSH	NO443249	Fife
ST ANDREWS - CRAIG HARTLE	NO545152	Fife
ST MICHAELS WOOD MARSHES	NO449234	Fife
STAR MOSS	NO308041	Fife
SWINKY MUIR	NO559109	Fife
TAYPORT TENTSMUIR COAST	NO452294	Fife
WALTONHILL & CRADLE DEN	NO362093	Fife
CORBY,LILY AND BISHOPS LOCHS	NJ912143	Grampian
SCOTSTOWN MOOR	NJ935116	Grampian
BULLERS OF BUCHAN COAST	NK110380	Grampian
CULLEN TO STAKENESS COAST	NJ574669	Grampian
GAMRIE AND PENNAN COAST	NJ824673	Grampian
GIGHT WOODS	NJ796382	Grampian
LOCH OF STRATHBEG	NK075590	Grampian
MOSS OF CROMBIE	NJ573523	Grampian
REIDSIDE MOSS	NJ605570	Grampian
TORE OF TROUP	NJ840600	Grampian
FOVERAN LINKS	NK000225	Grampian
LOCH OF SKENE	NJ785075	Grampian
MEIKLE LOCH AND KIPPET HILLS	NK029311	Grampian
MORTLACH MOSS	NJ505449	Grampian
RED MOSS, OLDTOWN	NJ827318	Grampian
SANDS OF FORVIE AND YTHAN ESTUARY	NK020275	Grampian
WARTLE MOSS	NJ723324	Grampian
CRATHIE WOOD	NO270950	Grampian
ESLIE MOSS	NO645707	Grampian
FINDON MOOR	NO941974	Grampian
GLEN TANAR	NO460930	Grampian
LOCH OF ABOYNE	NO537999	Grampian
LOCH OF LUMGAIR	NO853826	Grampian
LOCH OF PARK	NO767988	Grampian
MORRONE BIRKWOOD	NO135902	Grampian
RED MOSS OF NETHERLEY	NO861940	Grampian
WEST BRADIESTON & CRAIG OF GARVOCK	NO729688	Grampian
GLEN EY GORGE	NO087873	Grampian
BUINACH & GLENLATTERACH	NJ194546	Grampian
CULBIN SANDS,FOREST AND FINDHORN BAY	NH990625	Grampian
DEN OF PITLURG	NJ440454	Grampian
GULL NEST	NJ225505	Grampian
LOCH OIRE	NJ289609	Grampian
LOCH SPYNIE	NJ234661	Grampian
SPEY BAY	NJ325660	Grampian
ALVIE	NH837093	Highland
KINVEACHY FOREST	NH856175	Highland
LOCH VAA	NH913175	Highland
NORTH ROTHIEMURCHUS PINEWOOD	NH930100	Highland
RIVER SPEY INSH MARSHES	NH780013	Highland
BEINN FREICEADAIN AND BEN DORRERY	ND061555	Highland
BLAR NAM FAOILEAG	ND144445	Highland
BRAWLBIN	ND062582	Highland
BROUBSTER LEANS	ND035611	Highland
COIRE NA BEINNE MIRES	ND142398	Highland
DUNBEATH WATER	ND139316	Highland

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Site Name	Grid Ref.	Local Authority Region
DUNNET LINKS	ND220690	Highland
HILL OF LEODEBEST	ND185345	Highland
HILL OF WAREHOUSE	ND314412	Highland
HOLBORN HEAD	ND073712	Highland
KNOCKFIN HEIGHTS	NC949334	Highland
KNOCKINNON HEATH	ND172315	Highland
LAMBSDALE LEANS	ND052548	Highland
LANGWELL WATER	ND080225	Highland
LOCH BRICKIEGO	ND302440	Highland
LOCH CALUIM FLOWS	ND012533	Highland
LOCH HEILEN	ND255684	Highland
LOCH LIEURARY	ND074642	Highland
LOCH MORE WETLANDS	ND065659	Highland
LOCH OF DURRAN	ND207653	Highland
LOCH OF WESTER	ND325592	Highland
LOCH OF WINLESS	ND294545	Highland
LOCH SCARMCLATE	ND189596	Highland
LOCH WATTEN	ND230560	Highland
LOCHS OF AUKENGILL	ND353652	Highland
LOWER WICK RIVER	ND347515	Highland
MOSS OF KILLIMSTER	ND304552	Highland
NEWLANDS OF GEISE MIRE	ND095674	Highland
OLICLETT	ND289446	Highland
OUSDALE BURN	ND073190	Highland
PHILLIPS MAINS MIRE	ND309709	Highland
REISGILL BURN	ND241353	Highland
RIVER THURSO	ND109656	Highland
RUMSDALE PEATLANDS	NC977388	Highland
SANDSIDE BAY	NC965655	Highland
SHIELTON PEATLANDS	ND220465	Highland
STRATHMORE PEATLANDS	ND080445	Highland
STROMA	ND350780	Highland
STROUPSTER PEATLANDS	ND335684	Highland
THRUMSTER MILL LOCH	ND327446	Highland
USHAT HEAD	ND035710	Highland
WESTFIELD BRIDGE	ND056638	Highland
WICK RIVER MARSHES	ND309525	Highland
AFFRIC-CANNIC HILLS	NH160300	Highland
BALNAGRANTACH	NH495327	Highland
BEAULY FIRTH	NH580480	Highland
DAVIOT FENS AND MEADOWS	XX390725	Highland
GLEN AFFRIC	NH240246	Highland
GLEN STRATHFARRAR	NH270370	Highland
KILDRUMMIE KAMES	NH834531	Highland
LEVISHIE WOOD	NH400180	Highland
LOCH BATTAN	XX539391	Highland
LOCH BRAN	NH508192	Highland
URQUHART BAY WOODS	NH518295	Highland
ARIUNDLE	NM843645	Highland
BEN HIANT & ARDNAMURCHAN COAST	NM600610	Highland
BEN NEVIS	NN205720	Highland
BLAR NA CAILLICH BUIDHE	NM685905	Highland
CANNA AND SANDAY	NG250060	Highland
CARNACH WOOD	NN098584	Highland
CLAISH MOSS	NM720675	Highland
COILLE PHUITEACHAIN	NN095845	Highland
DRIMNIN TO KILLUNDINE WOODS	NM575503	Highland
GLEN BEASDALE	NM720846	Highland

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Site Name	Grid Ref.	Local Authority Region
GLEN COE	NN144570	Highland
INNINMORE BAY	NM719423	Highland
KENTRA BAY AND MOSS	NM650685	Highland
LOCH DUBH	NM672848	Highland
LOCH MOIDART	NM672734	Highland
LOCHAN BIENN IADIN	NM694535	Highland
LON LEANACHAIN	NN198786	Highland
RAHOY WOODLANDS	NM630580	Highland
RUM	NM370980	Highland
SOUTH LAGGAN FEN	NN302982	Highland
ACHAHALT MARSHES	NH265613	Highland
ALLT NAN CAORACH	NH514676	Highland
BRAELANGWELL WOOD	NH688632	Highland
CALROSSIE	NH792784	Highland
COILLE DUBH	NG811727	Highland
CONON ISLANDS	NH552570	Highland
COULIN PINEWOOD	NH000560	Highland
CROMARTY FIRTH	NH650670	Highland
CULBOCKIE	XX610590	Highland
DAM WOOD	NH642570	Highland
DOIRE DAMH	NG870510	Highland
DORNOCH FIRTH	NH760860	Highland
DRUMMONDREACH WOOD	NH582575	Highland
DUNDONNELL WOODS	NH120848	Highland
EASTER FEARN	NH658868	Highland
INVERPOLLY	NC135125	Highland
KINRIVE-STRATHRORY	NH700760	Highland
LOCH ACHNACLOICH	NH665735	Highland
LOCH EYE	NH831798	Highland
LOCH USSIE	NH505570	Highland
MONADH MOR	NH582538	Highland
MORRICH MORE	NH830840	Highland
MUNLOCHY BAY	NH672528	Highland
PITMADUTHY MOSS	NH780776	Highland
RIDORROCH WOOD	NH170947	Highland
ROSEMARKIE TO SHANDWICK COAST	NH744586	Highland
ROSKILL	NH652553	Highland
SCOTSBURN	XX736788	Highland
SHIELDAIG WOODS	NG820530	Highland
TALLADALE GORGE	NG916690	Highland
COILLE MHIALAIRIDH	NG820122	Highland
COILLE THOGABHAIG	NG615128	Highland
COSAG SALLOW CARR	NG824196	Highland
CUILLINS	NG430190	Highland
GLEN BARISDALE	NG870025	Highland
LOCH NA DAL	NG703143	Highland
LOCHS AT SLIGACHAN	NG473305	Highland
ALTNAHARRA	NC560363	Highland
AMAT WOODS	NH466902	Highland
BAD NA GALLAIG	NC620405	Highland
BADANLOCH BOGS	NC775374	Highland
CNOC AN ALASKIE	NC490260	Highland
CROSS LOCHS	NC878466	Highland
DRUIM NAM BAD	NC485385	Highland
ERIBOLL	NC445570	Highland
FORSINARD BOGS	NC875455	Highland
GRUDIE PEATLANDS	NC500100	Highland
HANDA ISLAND	NC138480	Highland

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Details of SSSI sites in Scotland with some fen habitat, as obtained from Scottish Natural Heritage.

Site Name	Grid Ref.	Local Authority Region
KYLE OF SUTHERLAND	NH521992	Highland
LEDMORE WOOD	NH664891	Highland
LOCH A' MHUILINN	NC166394	Highland
LOCH DOLA	NC606080	Highland
LOCH FLEET	NH800960	Highland
LOCH MEADIE PEATLANDS	NC539417	Highland
LOCH STACK	NC290430	Highland
MOUND ALDERWOODS	NH765990	Highland
SHEIGRA - OLDSHORE MORE.	NC192589	Highland
SKELPICK PEATLANDS	NC759505	Highland
SKINSDALE PEATLANDS	NC735242	Highland
SLETHILL PEATLANDS	NC953457	Highland
SPINNINGDALE BOG	NH667906	Highland
STRATH DUCHALLY	NC430258	Highland
STRATH OKYLE AND GLEN CASSLEY	NH515990	Highland
STRATHFLEET	NC757010	Highland
STRATHY BOGS	NC790555	Highland
SYRE PEATLANDS	NC663451	Highland
TORBOLL WOODS	NH741984	Highland
TRUDERSCAIG	NC705323	Highland
WEST BORGIE	NC638545	Highland
WEST HALLADALE	NC845542	Highland
WEST STRATHNAVER	NC696526	Highland
ABERLADY BAY	NT465815	Lothian
BARNSNESS COAST	NT696781	Lothian
DANSKINE LOCH	NT568682	Lothian
TRAPRAIN LAW	NT582746	Lothian
WOODHALL DEAN	NT680728	Lothian
BALERNO COMMON	NT162635	Lothian
DUDDINGSTON LOCH	NT281724	Lothian
BLACKBURN	NT235583	Lothian
CRICHTON GLEN	NT382606	Lothian
DUNDREICH PLATEAU	NT285489	Lothian
FALA FLOW	NT432586	Lothian
GLADHOUSE RESERVOIR	NT299535	Lothian
NORTH ESK VALLEY	NT155579	Lothian
ROSLIN GLEN	NT280633	Lothian
BLACKNESS BAY	NT067795	Lothian
BLAWHORN MOSS	NS886684	Lothian
COBBINSHAW MOSS	NT035570	Lothian
COBBINSHAW RESERVOIR	NT016570	Lothian
CRAIGENGAR	NT078549	Lothian
HERMAND BIRCHWOOD	NT031618	Lothian
LINHOUSE VALLEY	NT072643	Lothian
LINLITHGOW LOCH	NT003775	Lothian
LOCHCOTE MARSH	NS979742	Lothian
PETERSHILL	NS985696	Lothian
TAILEND MOSS	NT013678	Lothian
DOOMY AND WHITEMAW HILL	HY547322	Orkney
GLIMS MOSS AND DURKADALE	HY310237	Orkney
LOCH OF ISBISTER AND THE LOONS	HY254240	Orkney
MILL LOCH, EDAY	HY565368	Orkney
NORTH HILL, PAPA WESTRAY	HY500550	Orkney
NORTHWALL	HY740445	Orkney
STROMNNESS HEATHS AND COAST	HY226135	Orkney
WARD HILL CLIFFS	ND466885	Orkney
WAULKMILL	HY377065	Orkney
WEST WESTRAY	HY425464	Orkney

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Details of SSSI sites in Scotland with some fen habitat, as obtained from Scottish Natural Heritage.

Site Name	Grid Ref.	Local Authority Region
ALT NA MUILINE	NB227288	Outer Hebrides
LOCH A' CHOIN	NB228291	Outer Hebrides
LOCH MHICLEOID	NB273308	Outer Hebrides
LOCH NAN CAOR	NB355185	Outer Hebrides
LAIRD'S LOCH	NO259357	Perth and Kinross
AITH MEADOWS	HU440293	Shetland
CRUSSA FIELD AND THE HEOGS	HP625105	Shetland
CULSWICK MARSH	HU273445	Shetland
FAIR ISLE	HZ213720	Shetland
FOULA	HT960390	Shetland
HASCOSAY	HU553923	Shetland
HILL OF COLVADALE & SOBUL	HP610052	Shetland
LOCH OF GIRLSTA	HU433522	Shetland
LOCHS OF SPIGGIE AND BROW	HU374160	Shetland
MOUSA	HU461242	Shetland
NORTH FETLAR	HU625930	Shetland
NORWICH MEADOWS	HU670915	Shetland
NOSS	HU545404	Shetland
PAPA STOUR	HU165610	Shetland
SANDWATER	HU415547	Shetland
TINGON	HU255840	Shetland
TRONA MIRES	HU670915	Shetland
WARD OF CULSWICK	HU268463	Shetland
AN FHAODHAIL & THE REEF	NM014454	Strathclyde
ARDMORE, KILDALTON & CALLUMKILL WOODLANDS	NR450495	Strathclyde
ARDPATRICK & DUNMORE WOODS	NR765610	Strathclyde
BEN LUI	NN265264	Strathclyde
CENTRAL LOCHS BUTE	NS075615	Strathclyde
CLAIS DHEARG	NM935314	Strathclyde
COILLE LEITIRE	NN085266	Strathclyde
COLADOIR BOG	NM549289	Strathclyde
CROSSAPOL AND GUNNA	NM124530	Strathclyde
DALAVICH OAKWOOD	NM965129	Strathclyde
DOIRE DARACH	NN289415	Strathclyde
DUN BAN	NR595141	Strathclyde
EILEAN NA MUICE DUIBHE	NR320550	Strathclyde
ELLARY WOODS	NR730750	Strathclyde
FEUR LOCHAIN	NR252695	Strathclyde
GLAC NA CRICHE	NR225708	Strathclyde
GLASDRUM	NN005460	Strathclyde
GLEN NANT	NN017278	Strathclyde
GLEN RALLOCH TO BARAVALLA WOODS	NR838677	Strathclyde
GRUINART FLATS	NR285665	Strathclyde
INVERNEIL BURN	NR831818	Strathclyde
KENNACRAIG & ESRAGAN BURN	NM997347	Strathclyde
KILBERRY COAST	NR716690	Strathclyde
KINUACHDRACH	NR707979	Strathclyde
LAGGAN PENINSULA & BAY	NR297555	Strathclyde
LAGGANULVA WOOD	NM450420	Strathclyde
LINNE MHUIRICH	NR726847	Strathclyde
LISMORE LOCHS	NM808376	Strathclyde
LOCH EDERLINE	NS864081	Strathclyde
LOCH FADA	NR383956	Strathclyde
LOCH TALLANT	NR335578	Strathclyde
MACHRIHANISH DUNES	NR653238	Strathclyde
MOINE MHOR	NR815925	Strathclyde
NORTH COLONSAY	NR415985	Strathclyde
NORTH EAST COLL LOCHS AND MOORS	NM243608	Strathclyde

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Details of SSSI sites in Scotland with some fen habitat, as obtained from Scottish Natural Heritage.

Site Name	Grid Ref.	Local Authority Region
NORTH END OF BUTE	NS009719	Strathclyde
RHUNAHAORINE POINT	NR695493	Strathclyde
RINNS OF ISLAY	NR235620	Strathclyde
RUEL ESTUARY	NS010800	Strathclyde
STAFFA	NM325355	Strathclyde
TANGY LOCH	NR695282	Strathclyde
TARBERT TO SKIPNESS COAST	NR901640	Strathclyde
TAYNISH WOODS	NR735850	Strathclyde
TAYVALLICH JUNIPER & FEN	NR725858	Strathclyde
TORRISDALE CLIFF	NR798348	Strathclyde
TRESHNISH ISLES	NM274412	Strathclyde
BRAEHEAD MOSS	NS958515	Strathclyde
CARNWATH MOSS	NS967482	Strathclyde
COALBURN MOSS	NS827365	Strathclyde
CRANLEY MOSS	NS925475	Strathclyde
MILLERS WOOD	NS820283	Strathclyde
BORLOSH MOSS	NS486185	Strathclyde
BARLOSH MOSS	NS486185	Strathclyde
BOGTON LOCH	NS470052	Strathclyde
DALMELLINGTON MOSS	NS465064	Strathclyde
LOCH DOON	NX497975	Strathclyde
MARTNAHAM LOCH AND WOOD	NS393173	Strathclyde
ASHGROVE LOCH	NS275443	Strathclyde
BOGSIDE FLATS	NS305394	Strathclyde
CLAUCHLANDS POINT - CORRYGILLS	NS048338	Strathclyde
COCKINHEAD MOSS	NS356490	Strathclyde
GLEANN DUBH	NR985335	Strathclyde
SOUTH COAST OF ARRAN	NR951208	Strathclyde
ABER BOG, GARTOCHARN BOG & BELL MOSS	NS435875	Strathclyde
ARDMORE POINT	NS314785	Strathclyde
AUCHENREOCH GLEN	NS419784	Strathclyde
BEN VORLICH	NN296123	Strathclyde
BLAIRBEICH BOG	NS435835	Strathclyde
CALDARVAN LOCH	NS423837	Strathclyde
DUMBARTON MUIR	NS445795	Strathclyde
ENDRICK MOUTH AND ISLANDS	NS430895	Strathclyde
GEAL AND DUBH LOCHS	NS320165	Strathclyde
INCHMOAN	NS376907	Strathclyde
ROSS PARK	NS357880	Strathclyde
WEST LOCH LOMONDSIDE WOODLANDS	NS339999	Strathclyde
BROTHER AND LITTLE LOCHS	NS505525	Strathclyde
BISHOP LOCH	NS688668	Strathclyde
CART AND KITTOCH VALLEYS	NS581575	Strathclyde
POSSIL MARSH	NS585699	Strathclyde
BLANTYRE MUIR	NS663525	Strathclyde
BOTHWELL CASTLE GROUNDS	NS686594	Strathclyde
CANDER MOSS	NS782460	Strathclyde
HAMILTON LOW PARKS	NS718575	Strathclyde
MILLBURN	NS785513	Strathclyde
AILSA CRAIG	NX020998	Strathclyde
FEOCH MEADOWS	NX270821	Strathclyde
KNOCKDAW HILL	NX155883	Strathclyde
LITTLETON & BALHAMIE HILLS	NX130867	Strathclyde
LADY BELLS MOSS	NS810651	Strathclyde
LONGRIGGEND MOSS	NS812696	Strathclyde
NORTH BELLSTANE PLANTATION	NS758716	Strathclyde
WOODEND LOCH	NS705667	Strathclyde
BARMUFFLOCK DAM	NS369649	Strathclyde

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Details of SSSI sites in Scotland with some fen habitat, as obtained from Scottish Natural Heritage.

Site Name	Grid Ref.	Local Authority Region
CASTLE SEMPLE AND BARR LOCHS	NS360585	Strathclyde
DARGAVEL BURN	NS371712	Strathclyde
GLEN MOSS	NS368699	Strathclyde
LOCH LIBO	NS435557	Strathclyde
SHOVELBOARD	NS387691	Strathclyde
SOUTH BRAES	NS617773	Strathclyde
ARDGARTH LOCH	NO281374	Tayside
BALLOCH MOSS	NO353576	Tayside
BARRY LINKS	NO532319	Tayside
CARROT HILL MEADOW	NO470404	Tayside
DEN OF OGIL	NO444620	Tayside
DILTY MOSS	NO515427	Tayside
DUN'S DISH	NO648610	Tayside
ELLIOT LINKS	NO620390	Tayside
LOCH OF KINNORDY	NO360542	Tayside
RESCOBIE AND BALGAVIES LOCHS	NO523516	Tayside
RESTENNETH MOSS	NO483517	Tayside
ROSSIE MOOR	NO650540	Tayside
BALSHANDO BOG	NO279361	Tayside
BLACKLAW HILL MIRE	NO282346	Tayside
CRAIGS OF LUNDIE AND ARDGARTH LOCH	NO279376	Tayside
GAGIE MARSH	NO449370	Tayside
LOCHINDORES	NO270357	Tayside
LONG LOCH OF LUNDIE	NO287386	Tayside
REDMYRE	NO280340	Tayside
ROUND LOCH OF LUNDIE	NO300383	Tayside
ARDBLAIR AND MYRESIDE FENS	NO168445	Tayside
BEINN A GHLO	NN960730	Tayside
BEN VRACKIE	NN950630	Tayside
BISHOP HILL	NO183036	Tayside
BLACK LOCH (CLEISH)	NT074963	Tayside
BLACK WOOD OF RANNOCH	NN550550	Tayside
BOG WOOD & MEADOW	NN921092	Tayside
CAIRNLEITH MOSS	NO079365	Tayside
CARDNEY WOOD	NO045452	Tayside
CARIE & CRAGGANESTER WOODS	NN649368	Tayside
CARNLEITH MOSS	NO079365	Tayside
CARSEBRECK AND RHYND LOCHS	NN865095	Tayside
COILLE CHRICHE	NN617227	Tayside
CONNACHAN MARSH	NN895268	Tayside
CROFTINTYGAN MEADOW	NN672391	Tayside
DALCROY PROMONTORY	NN778590	Tayside
DRUMMOND LOCHS	NN852185	Tayside
DRUMOCHTER HILLS	NN630765	Tayside
DUN MOSS	NO169559	Tayside
DUNALASTAIR RESERVOIR	NN695585	Tayside
DUPPLIN LAKES	NO030205	Tayside
FOREST OF ALYTH MIRES	NO175577	Tayside
GLEN FENDER MEADOWS	NN895671	Tayside
GLENARTNEY JUNIPER WOOD	NN761181	Tayside
GLENEAGLES MIRE	NN914107	Tayside
HARE MYRE MONK MYRE AND STORMONT LOCH	NO187423	Tayside
KINGS MYRE	NO113363	Tayside
LADY LOCH	NO196137	Tayside
LOCH CON	NN687679	Tayside
LOCH FREUCHIE MEADOWS	NN876368	Tayside
LOCH LEVEN	NO145015	Tayside
LOCH MARLEE	NO136446	Tayside

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Details of SSSI sites in Scotland with some fen habitat, as obtained from Scottish Natural Heritage.

Site Name	Grid Ref.	Local Authority Region
LOCH MORAIG	NN906666	Tayside
LOCH TUMMEL FLUSH	NN822599	Tayside
LOCHS CLUNIE AND MARLEE	NO128444	Tayside
LOCHS OF BUTTERSTONE, CRAIGLUSH, LOWES	NO046440	Tayside
LOGIERAIT MIRES	NN967534	Tayside
LURG AND DOW LOCHS	NT094966	Tayside
MEGGERNIE AND CROCH NA KEYS WOODS	NN530455	Tayside
MEIKLEOUR AREA	NO134395	Tayside
METHVEN MOSS	NO011236	Tayside
MILL DAM	NO055385	Tayside
MILTON WOOD	NO170509	Tayside
MORENISH MEADOW	NN608352	Tayside
PITARRIG MEADOW	NN961598	Tayside
PITKEATHLY MIRES	NO109143	Tayside
RANNOCH MOOR	NN350520	Tayside
SHINGLE ISLANDS	NN962553	Tayside
STORMONT LOCH	NO187422	Tayside
STRALOCH MORAINES	NO031639	Tayside
STRUAN WOOD	NN791659	Tayside
TORFLUNDIE MIRE	NO198146	Tayside
TULACH HILLS	NN896634	Tayside
WEST LOCH DOINE	NN455183	Tayside
BALESHARE & KIRKIBOST	NF785623	Western Isles
BALRANALD BOG AND LOCH NAM FEITHEAN	NF712705	Western Isles
HOWMORE ESTUARY	NF756356	Western Isles
LITTLE LOCH ROAG VALLEY BOG	NB140250	Western Isles
LOCH AN DUIN	NF935740	Western Isles
LOCH BEE	NF770430	Western Isles
LOCH BEE MACHAIR	NF755430	Western Isles
LOCH DALBEG	NB227457	Western Isles
LOCH DRUIDIBEG	NF782378	Western Isles
LOCH HALLAN	NF738224	Western Isles
LOCH NA CARTACH	NB534499	Western Isles
LOCH NAN EILEAN VALLEY BOG	NB237234	Western Isles
LOCH OBISARY	NF896620	Western Isles
LOCH STIAPAVAT	NB528643	Western Isles
LOCH TUAMISTER	NB264455	Western Isles
MONACH ISLANDS	NF626623	Western Isles
NORTHTON BAY	NF990920	Western Isles
ST KILDA	NF095995	Western Isles
STORNOWAY CASTLE WOODLANDS	NB416330	Western Isles
STORNOWAY VALLEY WETLAND		Western Isles
WEST BENBECULA LOCHS	NF771521	Western Isles
FELL HILL	NX168929	
KNOCKORMAL HILL	NX136884	
LOCH LOCHTON	NX174924	
BEN HOGH	NM180584	
CLIAD PASTURES AND LOCH	NM199594	
LOCH CLIAD	NM212583	
DULLATER MARSH	NS755779	
ABERNETHY FLUSH AND FOREST	NJ017145	
LOCH ARAIL	NR804794	
CAIPLACH	NG472327	
LOCH MEODAL	NG656114	
SLIGACHAN	NG477306	
NEIPAVAL	NB232290	
NORTH CNOC ARNISH	NB418311	
LOCH A' BHOGAIDH	NR225576	

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Details of SSSI sites in Scotland with some fen habitat, as obtained from Scottish Natural Heritage.

Site Name	Grid Ref.	Local Authority Region
LOCH A' GHEOIDH	NR259660	
LOCH AN RAOIN	NR274647	
LOCH CORR	NR222695	
LOCH GORM NORTHWEST AND ALTNA CRICHE	NR243656	
LOCH TREUNAIDH	NR256637	
RIVER LEOIG REEDBED	NR237692	
GOTT VALLEY MIRE	NM028462	
LOCH BHASAPOLL	NL974464	
LOCH NAN FAING	NL977424	
MILLTON	NM080480	
CARRON DAMS		
CNOC A SROINE	NC534402	
CNOCH AN DAIMH MOR	NC542428	
CNOCI AN MHOID	NC563402	
CORRIE FEE, CAENLOCHAN	NO250749	
CREAG AN ACHAIDH MOR	NC602407	
DOON VALLEY WETLAND	NS455065	
FERRY HILLS		
KELTNEYBURN		
LENDALFOOT - SOUTH BALLARD	NG477306	
LOCH AN TAUBH	NC570313	
LOCH AN TUIRC	NC551398	
LOCH EILEANACH	NC598406	
LOCH MALLACHIE	NH962172	
LOCH STAING	NC586409	
LOCHAINS SOUTH OF LOCH MALLACHIE		
MONTROSE BASIN		
RHIFAIL LOCH	NC717416	
SKAIL BURN	NC707487	
SOUTH AND NORTHWEST DIONACH	NC558398	
ST ABBS HEAD TO FAST CASTLE HEAD		

APPENDIX 2

General site descriptions for the 18 fen sites surveyed, including vegetation descriptions.

Site name - Aird's Meadow SSSI

National Grid Reference - NS 365 585

Castle Semple and Barr Lochs was previously one large loch known as Loch Winnoch. The River Calder deposited sediments into this loch. In the late 1600s the first records of drainage appear, although this was apparently unsuccessful (MacFarlane unpublished). In the mid 1700s the first road and bridge were built at the mouth of the River Calder. In 1814 the main drainage scheme was implemented to create the separate Castle Semple and Barr Lochs. After the First World War drainage maintenance declined and the area began to flood. The 1960s saw the loch's develop as they are seen today, and the area was designated an RSPB reserve in 1974. Aird's Meadow is situated to the south south-west of Castle Semple Loch.

The vegetation on the site was complex, but was not surveyed closely because of wet conditions. Canary reed grass (*Phalaris arundinaceae*) and the common reed (*Phragmites australis*) were seen frequently on the edge of the site. Water sedge (*Carex aquatilis*) has been noted on the site (Fojt unpublished). Main vegetation types also described for the area are bottle sedge (*Carex rostrata*) - marsh cinquefoil (*Potentilla palustris*) fen, bottle sedge - water horsetail (*Equisetum fluvialtile*) sub-association, and the water sedge sub-association (Shaw & Wheeler 1991).

Site name - Barmufflock Dam SSSI

National Grid Reference - NS 369 649

A reasonably small basin fen is found to the east of the Site of Special Scientific Interest (SSSI) extent, which appears to be a remnant of a larger fen area. The outflow of the site in the south-east was dammed during the 1790s to the 1800s to provide water for woollen mills in the Bridge of Weir (Shaw & Wheeler 1990). The dam is now in disrepair. The catchment land-use types include pasture, and a golf course adjacent to the fen area in the north.

The remnant basin fen showed a clear transition from bog vegetation to fen vegetation, and was surrounded by scrub and tree cover. Within the eastern section there was a central area of quaking poor fen (*Carex rostrata - Sphagnum squarrosum* fen). To the west semi-floating poor fen/bog vegetation had developed, with scattered birch (*Betula*). This grades to mixed deciduous woodland with an understorey of grasses and sedges (*Carex* spp.), before becoming dense woodland to the west. East of the central floating area was a fen community dominated by bottle sedge (*C. rostrata*) and bog moss (*Sphagnum recurvum*), with an open cover of birch and scattered willow (*Salix*). To the north the vegetation community was dominated by a sedge (*Carex*) - moss (*Polytrichum*) fen, and formed a soft springy surface, again with a fairly open canopy of birch and willow. To the eastern side the site was bounded by slope with heathland dominated by heather (*Calluna vulgaris*) and gorse (*Ulex europaeus*).

Site name - Barr Loch Meadow SSSI

National Grid Reference - NS 347 567

Castle Semple and Barr Lochs Site of Special Scientific Interest (SSSI) was previously one large loch known as Loch Winnoch. The River Calder deposited sediments into this loch. In the late 1600s the first records of drainage appear, although this was apparently unsuccessful (MacFarlane unpublished). In the mid 1700s the first road and bridge were built at the mouth of the river. In 1814 the main drainage scheme was implemented to create the separate Castle Semple and Barr Lochs. After the First World War drainage maintenance declined and the area began to flood. The 1960s saw the lochs develop as they are today, and the area was designated an RSPB reserve in 1974.

This small area of flooded fen, identified as 'Barr Loch Meadow' within this study, lies directly south of Barr Loch. Barr Loch is isolated from Millbank Burn, Dubbs Water and the River Calder (all of which enter Castle Semple Loch), and the loch appeared to be the main water source of the fen. The vegetation was a complex of different types, dominated by canary reed grass (*Phalaris arundinaceae*), but was not surveyed closely because of wet conditions.

Site name - Black Loch SSSI

National Grid Reference - NX 991 875

Black Loch was a relatively small fen, within a larger basin previously the site of a drained loch Around the fen thin peat had developed over gently sloping ground, and had a more typical rain-fed (ombrotrophic) vegetation type. The fen was fenced off from cattle along the north and east sides, although the surrounding area was cattle grazed. Adjacent land was used as rough pasture (south), and improved pasture (north and east). A road ran along the west side which divides the fen from a forestry plantation developed in 1980.

To the north of Black Loch, in Lakehead Moss, the vegetation was predominantly rain-fed mire. This was dominated by the heather (*Calluna vulgaris*) - cotton grass (*Eriophorum vaginatum*) vegetation type, with widespread and abundant bog myrtle (*Myrica gale*). Continuing south, towards the loch basin, the surface became wetter and the vegetation changed to quaking poor-fen with bottle sedge (*Carex rostrata*) - marsh cinquefoil (*Potentilla palustris*) community, water horsetail (*Equisetum fluviatile*) sub-community. Birch (*Betula*) and willow (*Salix*) has begun to encroach on the fen and became more dominant within the area marked as the former loch extent (1984 OS map, 1:25 000). The fairly closed canopy of trees had extended into the central area previously mapped as an open fen area, and noted as "scattered willow bushes", in 1985 (McKinnell unpublished). There appeared, therefore, to be encroachment of this area by trees, but the high water table (5cm above surface even after an unusually dry summer) may have reduced the rate of this encroachment. To the south-east the fen was acid grassland, while the south-west was richer in shrubs, such as bog myrtle (*M. gale*), and rushes (*Juncus* spp.).

Site name - Brownmoor Heights SSSI

National Grid Reference - NT 460 254

This Site of Special Scientific Interest (SSSI) consists of four small basin mires within unimproved sheep-grazed grassland. The larger basin fen, situated at the source of Brownmoor Burn, was surveyed. In general, this small site (1ha) showed obvious changes in vegetation. Quaking herb and moss fen around the edges (lag area), changed to a firmer central area dominated by bog species (ombrotrophic dome development). The quaking edge vegetation was dominated by bog mosses (*Sphagnum squarrosum* and

S. recurvum) along with cotton grass (*Eriophorum angustifolium*), sedges (*Carex* spp. including *C. rostrata* - the bottle sedge) and bog bean (*Menyanthes trifoliata*). This showed affinities with both the bottle sedge - bog moss (*S. recurvum*) mire, and the bottle sedge - bog moss (*S. squarrosum*) fen. The central vegetation was best described as cross-leaved heath (*Erica tetralix*) - bog moss (*Sphagnum papillosum*) mire. It was dominated by moss hummocks (both *Polytrichum* and *Sphagnum*), with occasional heather (*Calluna vulgaris*), sedges and cotton grass on the hummocks and in the hollows. The hollows also contained bog mosses and, less frequently, bog bean (*M. trifoliata*). The surface was soft and springy due to the moss cover. There was a patch of soft rush (*Juncus effusus*) to the south south-east of the fen, which may indicate a water seepage area. Towards the outflow there was a prominent quaking area of bog moss (*S. squarrosum*).

Site name - Glen Moss SSSI

National Grid Reference - NS 368 699

This large basin fen had developed over the original open water habitat. Originally a mill was built at the site of 'Glenmosston' house to the south-west (the outflow stream). After the first World War this same site was developed as a 'model farm', hence the outflow stream have probably been altered for many decades. The fen and loch were used as a curling pool at the turn of the century (Mrs. Dunn, Kilmacolm Civic Trust, pers. comm.). The area was still used for recreation with footpaths around the edges, although the main part of the moss was too treacherous for general public access. The site was within a pasture land catchment, with a golf course to the east. This survey concentrated on the area south of the remaining open water, the more northerly area being fairly inaccessible.

Generally the site was quaking moss- and herb-dominated fen with some scrub development. The main southern area was poor-fen vegetation (*Carex rostrata - Sphagnum recurvum* fen and *C. rostrata - Potentilla palustris* fen). Some areas were quaking while others were semi-floating. There were extensive quaking vegetation mats the edges of the remaining open water. Towards the south-west there was birch (*Betula*) and willow (*Salix*) encroachment. Dense birch and willow scrub, with an understorey of either rush (*Juncus*), wavy hair-grass (*Deschampsia flexuosa*) or (on a raised ridge) bilberry (*Vaccinium myrtillus*), was found to the south-west. To the east of the open water was a mineral ridge with heath vegetation dominated by heather (*Calluna vulgaris*) and gorse (*Ulex europaeus*). Along the base of the ridge a grassy area has developed over peat deposits, with grasses such as Yorkshire fog (*Holcus lanatus*) and wavy hair-grass. This joined the inflow stream. To the north of this stream the vegetation changed to extensive quaking fen with bottle sedge (*Carex rostrata*), and occasional marsh willow-herb (*Epilobium palustre*), bog bean (*Menyanthes trifoliata)*, and bog pondweed (*Potamogeton polygonifolius*). To the west (near the outflow stream) scrub had developed, dominated by gorse (*U. europaeus*) and brambles (*Rubus* spp.). Reed (*Phragmites australis*) was found around the sluice on the outflow stream.

Site name - Greenside Moss SSSI

National Grid Reference - NT 518 258

Greenside Moss Site of Special Scientific Interest (SSSI) was a relatively small fen developing over an area of open water. The site was surrounded by conifer plantation (north and west), and a thin band of mixed deciduous trees (south and west), with improved grazed pasture on the gentle slopes beyond. A large number of ducks were present, possibly reared for shooting as there was evidence to suggest they may be fed at the site. The main fen development occurs to the west of the open water.

In general the fen was quaking and showed obvious zonations between vegetation types. To the far west tall herb fen was dominated by meadowsweet (*Filipendula ulmaria*) and water horsetail (*Equisetum fluviatile*). Water mint (*Mentha aquatica*) increased towards the edge of the open water. Further along the fen the vegetation became dominated by rushes (*Juncus* spp.) and panicled sedge (*Carex paniculata*), then changed to soft rush (*Juncus effusus*) and bog moss (*Sphagnum squarrosum*) dominated fen. Eventually a complete moss carpet with both *S. recurvum* and *S. squarrosum* and very few herbs developed. In the far north-east the vegetation was quaking, and grass and rush species increased. Around the very edge of the open water the vegetation was a mixture of marsh cinquefoil (*Potentilla palustris*), cowbane (*Cicuta virosa*), water mint (*M. aquatica*), Yorkshire fog (*Holcus lanatus*), marsh bedstraw (*Galium palustre*) and panicled sedge (*C. paniculata*) forming a quaking fen vegetation.

Site name - Heart Moss SSSI

National Grid Reference - NX 770 480

Heart Moss was a large basin mire which showed many variations in vegetation types and hydrology. The site was adjacent to rough pasture/fen meadow to the west, and an established Norway spruce plantation to the east noted on the 1849 OS (2.5") map (Shaw & Wheeler 1991). Cattle grazed the pasture and had access the fen, but there was only evidence of grazing and poaching on the very outskirts, also noted in 1987 (Hawker unpublished).

The vegetation variation was complex and difficult to assess thoroughly from one site visit. There were some general changes from south to north following the perceived main water flow. Notably there were two areas in the south dominated by reed (*Phragmites australis*). These extended either side of an old drain that forms the central east-west boundary. Both reed areas had standing water, but the western area was slightly wetter (8cm water) compared to the east (5cm). Earlier survey records in 1975 (Jermy *et al.* unpublished) and 1985 (Hawker unpublished) indicated increased size and density of the reed areas. In addition, the reed - heather (*Calluna vulgaris*) community, as noted in 1982 (Anonymous unpublished), was not surveyed possibly indicating increased wetness.

To the north the vegetation abruptly changed to quaking poor-fen dominated by vegetation of the bottle sedge (*Carex rostrata*) - marsh cinquefoil (Potentilla palustris), water horsetail (*Equisetum fluviatile*) sub-community. This extended to the northern outflow stream. Alongside this vegetation, to the west, there was a patchy mosaic of fen, dominated by bilberry (*Vaccinium myrtillus*) and sedge (*Carex* spp.), with pools that contained bog bean (*Menyanthes trifoliata*). This quaking area had abrupt patches of firm ground which may have suggested past domestic peat-cutting (Fojt unpublished). This area followed the line of open water area connected by a stream, as marked on the 1986 OS map (1:25,000). A 1982 survey (Anon unpublished) indicates that the area of bottle sedge fen extended more westerly than at present. This may now be encroached by fen meadow and reed.

Site name - Loch Lieurary SSSI

National Grid Reference - ND 074 642

This large fen Site of Special Scientific Interest (SSSI) had developed over a loch that has been subject to increasing sedimentation, and more recently drainage and marl extraction. Subsequent flooding of the marl extraction pits had produced a mosaic of fen meadow, sedge-rich fen and swamp habitat types. The surrounding land was pasture and arable.

The vegetation communities on the site were complex, with zonations from dryer fen meadow to swamp and open water communities. Along the main drain (running west to east) dense meadowsweet (*Filipendula ulmaria*) and occasional yellow flag (*Iris pseudocorus*) had developed, typical species of water seepage areas (Grime *et al.* 1995). The main pool systems occurred north and south of this drain, both with some open water bordered by water horsetail (*Equisetum fluviatile*) swamp. Firmer ground between the two northern swamp areas had developed swamp vegetation dominated by bottle sedge (*Carex rostrata*) and water horsetail (*E. fluviatile*). Towards the south, closer to the drain, meadowsweet dominated. The southern pool system was bordered to the west by a bottle sedge - marsh cinquefoil (*Potentilla palustris*) poor fen, the water horsetail subcommunity. Bottle sedge became dominant over water horsetail as the substrate became dryer. To the east, and over the majority of the SSSI area, meadowsweet - wild angelica (*Angelica sylvestris*) mire has developed, dominated by vigorous meadow sweet. In the far south-east corner a more species-rich, tussocky, sedge-dominated fen had developed, with shorter meadowsweet, marsh cinquefoil, soft rush (*Juncus effusus*), and purple moor-grass (*Molinia caerulea*). This may indicate a fluctuating water level, or increased sub-surface water movement (Grime *et al.* 1995). In addition, there was a small area of firm peat dominated by bottle sedge swamp, bog bean (*Menyanthes trifoliata*) - water horsetail subcommunity.

Site name - Long Moss SSSI

National Grid Reference - NT 480 185

This elongate basin mire showed transitions from moss-dominated, rain-fed (ombrotrophic) to a groundwater-fed (minerotrophic) quaking mire. It was surrounded by semi-natural grassland grazed by sheep and cattle, but received no artificial fertiliser. There was some indication from surface patterning that the south-east and south-west fields may have drains. There may be some suggestion that the that the site was becoming wetter, as the 19 OS maps (1" 1st edition) showed the area as rough pasture (Shaw & Wheeler 1991). The current 1982 OS map (1:10 000) depicts marsh symbols.

Generally the site showed fairly simple vegetation patterning with clear zonations between vegetation types. The main vegetation changes were seen south-west to north-east along the direction of water flow. An area of quaking fen vegetation extended from the inflow and around the northern edge. This almost formed a 'lagg' zone around the northern slightly domed area dominated by bog moss (*Sphagnum*). The quaking fen that formed the lagg extends and expands down to the outflow. Almost in the centre of the basin area was an area dominated by jointed rush (*Juncus articulatus*). The substrate was firmer with some mineral soil and peat deposits, and adjoined a steep slope to the north side of the basin. This slope appeared to be eroding down onto the fen causing incursion of mineral soil. Further west and north there was quaking tall herb fen of the bottle sedge (*Carex rostrata*) - marsh cinquefoil (*Potentilla palustris*) type, the bottle sedge - water horsetail (*Equisetum fluviatile*) sub-community. Water level was high, and the area probably flooded during the winter months.

Site name - Nether Whitlaw Moss SSSI

National Grid Reference - NT 506 294

This elongate basin mire formed part of the Whitlaw Mosses National Nature Reserve, and was also a Grade 1 Nature Conservation Review (NCR) site. It was surrounded mainly by improved pasture (grazed by sheep) and arable land, along with some conifer plantation and moorland.

There have been indications of nutrient-enriched water entering the site from the surrounding arable land (Heathwaite unpublished). From 1988-1993 the area was subject to an Environmentally Sensitive Area (ESA) agreement. This gave a 20m buffer strip around the fen, which was not subject to fertiliser application, in an attempt to reduce inputs of nitrogen, phosphorus and potassium. Research suggested that this type of management maybe effective in reducing nutrient loading to fens (Gaffney & Ross 1995). In addition, the subsurface run-off from the tile drains in the arable areas was partly channelled away from the fen by installing a main drain to collect run-off and divert it out of the fen basin.

Generally the vegetation was complex over the site, ranging from short-herb fen in the south-west, to moss (*Sphagnum*) and tree areas, and also some rush (*Juncus*) and sedge (*Carex*) dominated vegetation in the north-east. There was some indication that the main vegetation changes occurred along the fen in a west-easterly direction. This appeared to follow the main line of water flow. There were some changes in the edge vegetation of the site, although there was no obvious lagg. The central mineral soil ridge added to the vegetation (and stratigraphical) variation. The fen had developed around this ridge creating an island of non-peat deposits and grassy vegetation. Birch trees (*Betula*) and bog mosses (*Sphagnum*) have developed to the north of this ridge, with a more open short-herb fen to the south.

The south-west (close to the input from the reservoir) sees quaking floating fen dominated by water horsetail (*Equisetum fluviatile*), while bog bean (*Menyanthes trifoliata*) and water sedge (*Carex aquatilis*) increase to the west. Within this area there were patches of open water, and areas almost completely dominated by bog bean (*M. trifoliata*). This vegetation was the bottle sedge (*Carex rostrata*) - marsh cinquefoil (*Potentilla palustris*) fen type. Towards the central area of the fen birch began to increase, and the surface became vegetated with bog moss (*Sphagnum squarrosum*) along with frequent short herbs. Here the groundwater level was above the surface (10cm), and the surface was springy due to the moss cover. To the south of this birch area was the mineral soil ridge. This supported grass-dominated vegetation with no peat development. Around the ridge were shallower peat deposits which supported quaking fen vegetation but with some grass species present.

The birch cover increased to the east, although still with a bog moss understorey. Then the vegetation changed abruptly to fen dominated by soft rush (*Juncus effusus*), possibly a modified bottle sedge - marsh cinquefoil fen type. Here the water level was once again more or less at the surface. Soft rush becomes dominant to the far north-east of the site, occurring over amorphous peat close to the outflow stream. Adjacent to this area was a quaking patch of creeping bent (*Agrostis stolonifera*) which may indicate some nutrient enrichment (Grime *et al.* 1995).

In 1986 the fen site an a whole was described as 'essentially open in character with some scattered and low *Salix* [birch] scrub half way down' (Fojt unpublished). This suggests the more dense tree cover has developed over the last ten years.

Site name - Newlands of Geise Mire SSSI

National Grid Reference - ND 095 674

A relatively small, elongate basin fen which had two main areas of fen partly separated by a mineral ridge. Much of the surrounding land was a golf-course, with the remaining third being rotational pasture or arable crop land. The vegetation on the site was complex and ranged from drier fen meadow (west), to herb-rich fen (with both floating vegetation/root mats and firmer areas), and to more nutrient-poor acidic (ombrotrophic) mire. There was a small patch of common reedmace (*Typha latifolia* - 'bulrush') to the east of the site which indicates eutrophic water (Grime *et al.* 1995). Much of the site is marked as 'rough pasture' on the 1977 OS map (1:25,000), but was actually quite wet open fen vegetation, dominated by marsh cinquefoil (*Potentilla palustris*) and sedges (*Carex* spp.). In 1983 (Mitchell unpublished) the site was noted to contain species-rich floating moss carpets and tall fen/swamp vegetation. In 1989 a survey showed this vegetation type appeared to have become much dryer (Cranna unpublished), so there may be an indication that the site is losing its moss flora. This would need to be established from a more thorough investigation, although this survey also found a herb-dominated flora rather than moss-dominated.

Site name - Perchall Loch SSSI

National Grid Reference - NY 110 879

A relatively small, slightly elongate basin fen which had developed over a loch basin that was partly drained in 1814, with more extensive drainage (probably the edges only) in 1909 (unpublished SNH filenote). The fen had suffered disturbance around the edge. Along the west side was the A74 and the more recent M74 road developments, while on the eastern side was the railway. Both these structures had altered the hydrology of the fen. The catchment was generally improved arable land, while there was a disused rubbish dump which may release some leachate into the fen. The eastern area of reed (*Phragmites australis*) may have been previously sprayed with herbicide, and was cut in 1990 (unpublished SNH filenote). A small pile of cut reeds on the eastern side suggested more recent cutting.

The site was surrounded by mixed deciduous woodland, willow (*Salix*) and alder (*Alnus*) to the north, and birch (*Betula*), willow and alder to the south. This graded to willow and birch carr towards the remaining central fen vegetation area. The site showed transitions between carr, reed beds (*P. australis*) and open, quaking poor fen of the bottle sedge ((*Carex rostrata)* - marsh cinquefoil (*Potentilla palustris)* community, water horsetail (*Equisetum fluviatile)* sub-community. The central open fen area (approximately 80x80m), was dominated by water horsetail (*E. fluviatile*), and flanked by reed beds (*P. australis*) to the east and west. To the north marsh bedstraw (*Galium palustre*) and water horsetail declined, and a scrub vegetation (willow and birch) developed over very soft amorphous peats. To the south scrub vegetation developed but with a ground cover of mosses (*Sphagnum recurvum* and *Polytrichum commune*) that formed an undulating, soft surface.

Site name - Restenneth Moss SSSI

National Grid Reference - NO 483 517

Restenneth Moss was a large basin mire (approximately 35.4ha) formerly a loch, then drained and extracted for marl around 200-300 years ago (Gubbins unpublished). The fen area appeared to have spread from the confines of the original loch basin, possibly as a result of flooding. This gave the impression that the site was a 'valley' fen rather than a basin fen, especially as the Lunan Water runs through it. The whole site was within an arable catchment. Reed, for thatch and animal feed, was cut until some 25 years ago (Mr. Law, Restenneth Farm, pers. comm.).

The vegetation variation was complex, with zonations from monoculture stands of reed (*Phragmites australis*), to areas of willow (*Salix*) and birch (*Betula*) scrub. There are also to tall- and short-herb fen, and some remnant areas with quaking bog moss (*Sphagnum*) carpets. The change between vegetation types were distinct, especially between reed- and sedge-dominated areas.

Site name - Rossie Moor SSSI

National Grid Reference - NO 650 540

Rossie Moor Site of Special Scientific Interest (SSSI) contained several fen areas within relatively undisturbed moorland. Two of these areas were surveyed, Loch Lemann (NO 655 544) to the north, and Nicholl's Loch (NO 649 537) to the south. Both fens had developed over small, shallow basins that were formerly open water lochs.

Both sites showed similar vegetation characteristics of poor fen and swamp communities. Loch Lemann was surrounded by birch (*Betula*) and willow (*Salix*), along with heather (*Calluna vulgaris*) moorland. Some of these trees have extended onto the fen and developed as willow carr with a bog moss (*Sphagnum*) understorey. There were no significant areas of open water, although the vegetation was quaking, especially toward the centre.

Nicholl's Loch's surface was dominated by bog moss, making it soft and springy with some wetter hollows. There were scattered open-water pools with bog bean (*Menyanthes trifoliata*), sedges (*Carex* spp.) and occasional bog pondweed (*Potamogeton polygonifolius*). To the east of the site there was some tree encroachment and herb species increase. Towards the south and south-west edges plant species, such as the round-leaved sundew (*Drosera rotundifolia*), bog rosemary (*Andromeda polifolia*), and cross-leaved heath (*Erica tetralix*), indicate a more acidic, nutrient-poor environment (Grime *et al.* 1995). This suggests potential development of a rain-fed (ombrotrophic) bog, rather than a groundwater-fed (minerotrophic) fen.

Site name - Torrs Moss SSSI

National Grid Reference - NX 780 620

A relatively small basin mire with extensive cover of fen carr and some mixed deciduous woodland. There was a remaining central fen area that was dominated by reed (*Phragmites australis*), and had some scrub removed in 1993 (Anonymous unpublished). There were several well-maintained footbridges over deep peripheral drains, and obvious tracks through the carr and wood. This all suggests the area was highly managed. The site was surrounded by improved pasture and arable land. The 1853 OS map (1st ed. 2.5") shows extensive drainage, with the site named 'Torrs Loch'. On the 1894 OS map (1st ed. 2.5") tree symbols appeared (Shaw & Wheeler 1991), which may indicate the site has dried out and become encroached by trees and scrub in 40 years or so. The current 1983 OS map (1:25 000) marked Torrs Moss with marsh and scrub symbols. This may indicate the effect of management, such as scrub removal, on the site.

The reed (*P. australis*) area to the north end of the site covers approximately 100x100m, with the reed height varying from about 1m (centre) to 2m (edges). The central area also had some water horsetail (*Equisetum fluviatile*) suggesting a higher water level (Grime *et al.* 1995). Sedges (*Carex* spp.) and meadowsweet (*Filipendula ulmaria*) increased towards the edge. Around this area carr dominated by willow (*Salix*) and birch (*Betula*) has developed. In addition, dense reeds (*P. australis*) occurred as an understorey, along with meadowsweet (*F. ulmaria*), common skullcap (*Scutularia galericulata*), soft rush (*Juncus effusus*) and willow herb (*Epilobium* sp.). At the south and north ends of the SSSI boundary canary reed grass (*Phalaris arundinaceae*) and nettle (*Urtica dioica*) occurred. Both these species indicate drier substrate with some increased nutrients (Grime *et al.* 1995), possibly from surrounding land. A small north-west section of the SSSI was disturbed land with some rubbish dumped. The bottle sedge (*Carex rostrata*) - bog moss (*Sphagnum squarrosum*) mire noted previously for this site (Shaw & Wheeler 1991) was not seen.

Site name - Hill of Warehouse Mire SSSI

National Grid Reference - ND 312 412

This Site of Special Scientific Interest (SSSI) contained three areas of basin fens, all developed over loch basins. They were Broughwhin's Loch to the north-west, Groat's Loch to the south-east, and a small area at the head of the inflow to Groat's Loch, called (for the purposes of this study) Groat's Lochan. Only Broughwhin's Loch and Groat's Lochan were surveyed in detail, as Groat's Loch seemed to contain more open water, and less peat development, perhaps because of its larger size. Past human activity was apparent across the site, with many ancient monuments. Despite this, the surrounding heathland and bog had not been improved, but there was evidence of former domestic peat cutting just south of Broughwhin's Loch (also noted by Shaw & Wheeler 1990).

Broughwhin's Loch

The vegetation was a poor-fen type, divided into three main areas which corresponded to the two inflows and the single outflow. To the south there was bottle sedge (*Carex rostrata*) swamp, bog bean (*Menyanthes trifoliata*) - water horsetail (*Equisetum fluviatile*) sub-community. This extended towards the centre where there was a change to a brighter green bottle sedge - marsh cinquefoil (*Potentilla palustris*) fen, bottle sedge - water horsetail sub-community. This was more species-rich, and extended to the north edge of the site where there was a second burn inflow. Towards the outflow to the east the species diversity again increased, with plants such as marsh pennywort (*Hydrocotoyle vulgaris*) and lesser spearwort (*Ranunculus flammula*) appearing. These were probably more indicative of the typical bottle sedge - marsh cinquefoil fen. A small northern, firmer peat area was dominated by the soft rush (*Juncus effusus*).

Groat's Lochan

The main vegetation of this site was dominated by bottle sedge and cotton grass (*Eriophorum angustifolium*), with less water horsetail. This may have affinities to the bottle sedge - marsh cinquefoil fen type, but the yellow loosestrife (*Lysimachia vulgaris*) sub-community. There was a central brighter green area (10m diameter) where water horsetail and marsh cinquefoil increased, giving the same basic fen type, but the bottle sedge - water horsetail sub-community.

Site name - Loch of Winless SSSI

National Grid Reference - ND 294 545

This Site of Special Scientific Interest (SSSI) was more typical of an open water transition fen than a basin fen. There was a good deal of open water, although much of what was mapped as open water on the 1978 OS map (1:25,000) was now revegetated with quaking fen or swamp vegetation. The southern half of the loch basin, and the fen area around the outflow stream to the south were surveyed. The surrounding land use was sheep-grazed dry and wet-heath, with some arable and pasture land to the east.

The vegetation that had developed on the loch included reed (*Phragmites australis*) swamp. Towards the firmer edges of the loch basin short-herb fen had developed, dominated by bottle sedge (*Carex rostrata*) swamp. To the south of the loch basin, near the outflow, quaking fen vegetation had developed, dominated by meadowsweet (*Filipendula ulmaria*) and marsh cinquefoil (*Potentilla palustris*). Along the western side of the outflow was wet meadow dominated by rush (*Juncus* spp.) This graded to an acidic nutrient-poor (ombrotrophic) blanket bog community with some affinity to the cross-leaved heath (*Erica tetralix*) - bog moss (*Sphagnum papillosum*) mire. Vegetation was more variable to the east. Fen meadow had developed adjacent to the outflow, and changed to an unusual mixture of short reed growing through a blanket bog type community on the slopes. This had some affinities to the purple moor-grass (*Molinia caerulea*) - marsh plume thistle (*Cirsium dissectum*) fen meadow. This altered to an area dominated by meadowsweet, possibly indicating groundwater seepage (Grime *et al.* 1995), then back again to a blanket bog vegetation without reed.

Appendix A3.1

Pairwise interactions between the fifteen fen site using the Tukey-Kramer multiple comparison test for hydrochemical parameters. NS = not significant; *** = significant pairwise interactions. EC = electrical conductivity. Loch of Winless, Barr Loch Meadow and Aird's Meadow were removed due to small sample sizes. Potassium showed no significant pairwise interactions, therefore, results not presented. Sample abbreviations as for site names Fig. 2.4

Sample	BarD	BL	BMH	GM	GrM	HM	LL	LM	NWM	NoG	PL	RM	RoM	TM
pH														
BL	NS													
BMH	NS	NS												
GM	NS	NS	NS											
GrM	NS	NS	***	***										
HM	***	***	***	***	NS									
LL	***	***	***	***	NS	NS								
LM	NS	NS	***	***	NS	NS	NS							
NWM	NS	NS	NS	NS	NS	***	***	NS						
NoG	***	***	***	***	NS	NS	NS	NS	***					
PL	NS	NS	***	***	NS	NS	NS	NS	NS	NS				
RM	***	***	***	***	NS	NS	NS	NS	***	NS	NS			
RoM	NS	NS	NS	NS	NS	***	***	NS	NS	***	NS	***		
TM	NS	NS	NS	***	NS	NS	NS	NS	NS	NS	NS	NS	NS	
HoW	NS	NS	NS	NS	NS	***	***	NS	NS	***	***	***	NS	***

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Pairwise interactions between the fifteen fen site using the Tukey-Kramer multiple comparison test for hydrochemical parameters. NS = not significant; *** = significant pairwise interactions. EC = electrical conductivity. Loch of Winless, Barr Loch Meadow and Aird's Meadow were removed due to small sample sizes. Potassium showed no significant pairwise interactions, therefore, results not presented. Sample abbreviations as for site names Fig. 2.4

Sample	BarD	BL	BMH	GM	GrM	HM	LL	LM	NWM	NoG	PL	RM	RoM	TM
EC														
BL	NS													
BMH	NS	NS												
GM	NS	NS	NS											
GrM	***	***	***	***										
HM	NS	NS	NS	NS	NS									
LL	***	***	***	***	***	***								
LM	NS	NS	NS	NS	NS	NS	***							
NWM	***	***	***	***	NS	NS	***	NS						
NoG	***	***	***	***	***	***	NS	***	***					
PL	NS	NS	NS	NS	***	NS	***	NS	***	***				
RM	***	***	***	***	NS	***	NS	***	***	NS	***			
RoM	NS	NS	NS	***	NS	NS	***	NS	NS	***	NS	***		
TM	NS	NS	NS	NS	NS	NS	***	NS	NS	***	NS	***	NS	
HoW	***	***	***	***	NS	NS	NS	NS	NS	***	***	NS	NS	***

Appendix A3.1

Pairwise interactions between the fifteen fen site using the Tukey-Kramer multiple comparison test for hydrochemical parameters. NS = not significant; *** = significant pairwise interactions. EC = electrical conductivity. Loch of Winless, Barr Loch Meadow and Aird's Meadow were removed due to small sample sizes. Potassium showed no significant pairwise interactions, therefore, results not presented. Sample abbreviations as for site names Fig. 2.4

Sample	BarD	BL	BMH	GM	GrM	HM	LL	LM	NWM	NoG	PL	RM	RoM	TM
Calcium														
BL	NS													
BMH	NS	NS												
GM	NS	NS	NS											
GrM	***	***	***	***										
HM	NS	NS	NS	NS	NS									
LL	***	***	***	***	***	***								
LM	NS	NS	NS	NS	NS	NS	***							
NWM	NS	***	***	***	NS	NS	***	NS						
NoG	NS	***	***	***	NS	NS	***	NS	NS					
PL	NS	NS	NS	NS	***	NS	***	NS	NS	NS				
RM	***	***	***	***	NS	***	NS	***	***	***	***			
RoM	NS	NS	NS	NS	NS	NS	***	NS	NS	NS	NS	***		
TM	NS	NS	NS	NS	NS	NS	***	NS	NS	NS	NS	***	NS	
HoW	NS	NS	NS	NS	NS	NS	***	NS	NS	NS	NS	***	NS	NS

Appendix A3.1

Pairwise interactions between the fifteen fen site using the Tukey-Kramer multiple comparison test for hydrochemical parameters. NS = not significant; *** = significant pairwise interactions. EC = electrical conductivity. Loch of Winless, Barr Loch Meadow and Aird's Meadow were removed due to small sample sizes. Potassium showed no significant pairwise interactions, therefore, results not presented. Sample abbreviations as for site names Fig. 2.4

Sample	BarD	BL	BMH	GM	GrM	HM	LL	LM	NWM	NoG	PL	RM	RoM	TM
Nitrate														
BL	NS													
BMH	NS	NS												
GM	NS	NS	NS											
GrM	NS	NS	NS	NS										
HM	NS	NS	NS	NS	NS									
LL	NS	NS	NS	NS	NS	NS								
LM	NS	NS	NS	NS	NS	NS	NS							
NWM	NS	NS	NS	NS	NS	NS	NS	NS						
NoG	NS	NS	NS	NS	NS	NS	NS	NS	NS					
PL	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS				
RM	NS	NS	NS	NS	NS	NS	NS	NS	***	***	***			
RoM	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS		
TM	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	
HoW	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	***	NS	NS

Appendix A3.1

Pairwise interactions between the fifteen fen site using the Tukey-Kramer multiple comparison test for hydrochemical parameters. NS = not significant; *** = significant pairwise interactions. EC = electrical conductivity. Loch of Winless, Barr Loch Meadow and Aird's Meadow were removed due to small sample sizes. Potassium showed no significant pairwise interactions, therefore, results not presented. Sample abbreviations as for site names Fig. 2.4

Sample	BarD	BL	BMH	GM	GrM	HM	LL	LM	NWM	NoG	PL	RM	RoM	TM
Phosphate														
BL	NS													
BMH	NS	NS												
GM	NS	NS	***											
GrM	NS	NS	***	NS										
HM	NS	NS	NS	NS	NS									
LL	NS	NS	NS	***	***	NS								
LM	NS	NS	NS	***	***	NS	NS							
NWM	NS	NS	NS	***	***	NS	NS	NS						
NoG	NS	NS	NS	***	***	NS	NS	NS	NS					
PL	NS	NS	NS	***	***	NS	NS	NS	NS	NS				
RM	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS			
RoM	NS	NS	NS	***	***	NS	NS	NS	NS	NS	NS	NS		
TM	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	
HoW	NS	NS	NS	***	***	NS	NS	NS	NS	NS	NS	NS	NS	NS

Appendix A3.2

Pairwise interactions between the fifteen fen site using the Tukey-Kramer multiple comparison test for peat soils. NS = not significant; *** = significant pairwise interactions. Loch of Winless, Barr Loch Meadow and Aird's Meadow were removed due to small sample sizes. LOI = loss on ignition, FSM = field soil moisture. Sample abbreviations as for site names Fig. 2.4

Sample	RM	RoM	HoW	LL	NoG	BL	PL	HM	TM	GM	BarD	LM	NWM	BMH
LOI														
RoM	NS													
HoW	NS	NS												
LL	NS	NS	NS											
NoG	NS	NS	NS	NS										
BL	NS	NS	NS	NS	NS									
PL	NS	NS	NS	NS	NS	NS								
HM	***	***	NS	***	NS	NS	NS							
TM	***	***	NS	***	NS	NS	NS	NS						
GM	***	***	NS	***	NS	NS	NS	NS	NS					
BarD	***	***	NS	***	NS	NS	NS	NS	NS	NS				
LM	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS			
NWM	***	***	NS	***	NS	NS	NS	NS	NS	NS	NS	NS		
BMH	***	***	NS	***	NS	NS	NS	NS	NS	NS	NS	NS	NS	
GrM	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Appendix A3.2

Pairwise interactions between the fifteen fen site using the Tukey-Kramer multiple comparison test for peat soils. NS = not significant; *** = significant pairwise interactions. Loch of Winless, Barr Loch Meadow and Aird's Meadow were removed due to small sample sizes. LOI = loss on ignition, FSM = field soil moisture. Sample abbreviations as for site names Fig. 2.4

Sample	RM	RoM	HoW	LL	NoG	BL	PL	HM	TM	GM	BarD	LM	NWM	BMH
FSM														
RoM	NS													
HoW	NS	NS												
LL	NS	NS	NS											
NoG	NS	NS	NS	NS										
BL	NS	***	NS	NS	***									
PL	NS	NS	NS	NS	NS	NS								
HM	NS	NS	NS	NS	NS	***	NS							
TM	NS	NS	NS	NS	NS	***	NS	NS						
GM	NS	NS	NS	NS	NS	***	NS	NS	NS					
BarD	NS	NS	NS	NS	NS	***	NS	NS	NS	NS				
LM	NS	NS	NS	NS	NS	***	NS	NS	NS	NS	NS			
NWM	NS	NS	NS	***	NS	***	NS	NS	NS	NS	NS	NS		
BMH	NS	NS	NS	NS	NS	***	NS	NS	NS	NS	NS	NS	NS	
GrM	NS	NS	NS	NS	NS	***	NS	NS	NS	NS	NS	NS	NS	NS

Appendix A3.3

Pairwise interactions between the inflow streams of seven fen site using the Tukey-Kramer multiple comparison test for hydrochemical parameters
NS = not significant; *** = significant pairwise interactions EC = electrical conductivity. All other sites with no inflow data. Potassium and phosphate significant differences between samples and is not presented Sample abbreviations as for site names Fig. 2.4

Sample	RM	BarD	BL	AM	HoW	LoW
Calcium						
BarD	***					
BL	***	NS				
AM	***	NS	NS			
HoW	***	***	***	***		
LoW	NS	***	***	***	NS	
NWM	NS	***	***	***	***	NS
Nitrate						
BarD	***					
BL	***	NS				
AM	***	NS	NS			
HoW	***	NS	NS	NS		
LoW	***	NS	NS	NS	NS	
NWM	***	NS	NS	NS	NS	NS

Appendix A4.1

Quadrat data for vegetation group 1; *Carex rostrata - Menyanthes trifoliata* poor fen, *Sphagnum squarrosum* subcommunity, showing the DOMIN score (1-10) for each species.

Quadrat No.	48	49	50	51	52	53	55	56	Constancy
Species name									
Carex rostrata	6	5	5	4	7	3		3	V
Menyanthes trifoliata	1	1		6	3	3	1	3	V
Aulacomnium palustre	3	3	7	4	3	6	5		V
Sphagnum squarrosum	9	5	3	8	8	8	6	7	V
Carex curta	3			4	5	4	4		IV
Betula pubescens seedling	4	4		1		1	1		IV
Eriophorum angustifolium		4				3	5	7	III
Sphagnum recurvum	5	9	7	5					III
Potentilla palustris				3		4		5	II
Epilobium palustre					3	3			II
Calliergon cordifolium					4	1			II
Hippuris vulgaris						3		1	II
Juncus effusus					1		6		II
Parmelia saxatilis	4		1		1				II
Carex ovalis	3		3						II
Equisetum fluviatile						3			I
Galium palustre						3			I
Carex diandra						4			I
Carex panicea	3								I
Ranunculus lingua						3			I
Potentilla erecta					5				I
Polytrichum commune	3								I
Pedicularis palustris						3			I
Angelica sylvestris						1			I
Calliergon stramineum						1			I
Polytrichum alpestre						5			I
No. species per sample	11	7	6	8	10	19	8	6	
mean no. species									9.38

Appendix A4.2

Quadrat data for vegetation group 2; *Potentilla palustris - Carex rostrata* fen, showing DOMIN score (1-10) for each species.

Quadrat No.	4	42	44	47	7	9	26	27	28	34	35	36	37	38	39	40	41	54	57	58	59	60	62	63	64	Constancy
Species name																										
Carex rostrata	7	2	4	6	6	4		1	4	2		4	5	1		2	2	4	3	7	6	4	9	6	6	V
Menyanthes trifoliata	6	7	7	6	6				8	6	6	6	5	4	4			4	8	5	6			9		IV
Equisetum fluviatile				4			9	8	8	6	5	6	4	9	9	9	7	3	6	7	6	6	4	6	4	IV
Galium palustre	4	3	2		7	3	7	5	5	6	4	4		4	5	5	5	4	4		4	4	2			IV
Potentilla palustris	1		3		4	5			2	5	1	3	3	2	4		4	4		4	3	3		2		IV
Lemna minor	1							3	3	1		1	1	3		3	3	6	9	9	9	9	5	5	3	IV
Carex diandra		2			4	6			4	5	8	8	8	4		5	3							3		III
Epilobium palustre	4			3	3		2	1			4	3		2				3					4		3	III
Cicuta virosa			1	1														4	1	1	1	4	3			II
Calliergon cordifolium			2			7				3	3		2		6	4									5	II
Ranunculus lingua							5	2		2								4			1		2	4	3	II
Plagiomnium elatum		3			7	5					3			2		4	4								4	II
Eriophorum angustifolium		4	4															3						2		I
Aulacomnium palustre	5																									I
Agrostis stolonifera	2						2		1	2							1									I
Sphagnum squarrosum																		5								I
Carex curta	6	4	4	6																						I
Lychnis flos-cuculi	4	2													3	3	3									I
Campylium stellatum		1	1																							I
Caltha palustris	1				4	4									1	1										I
Filipendula ulmaria							5	5							6	2	7									I
Hippuris vulgaris																		4	2							I
Holcus lanatus		3																								I
Juncus acutiflorus					3																					I
Juncus effusus																		7	7	6		7				I
Green algae (terrestrial)							3																			I
Cardamine pratensis						1																				I

Appendix A4.2

Quadrat data for vegetation group 2; *Potentilla palustris - Carex rostrata* fen, showing DOMIN score (1-10) for each species.

Quadrat No.	4	42	44	47	7	9	26	27	28	34	35	36	37	38	39	40	41	54	57	58	59	60	62	63	64	Constancy
Species name																										
Galium uliginosum						1																				I
Plagiomnium ellipticum	5	1	1																							I
Carex nigra						6																				I
Galium saxatile																									8	I
Myosotis laxa caespitosa																									3	I
Myosotis secunda	3					1																				I
Ranunculus flammula	1																									I
Scutellaria galericulata			2	2							4															I
Calliergon giganteum			4																							I
Carex aquatilis						3																				I
Poa trivialis					1																					I
Rhizomnium pseudopunctatum		4	1																							I
Pellia endiviifolia		4	1																							I
Chiloscyphus sp.		2	1																							I
Juncus articulatus								1																		I
Lemna trisulca																								2		I
Brachythecium albicans	5																									I
Brachythecium rutabulum				3																						I
Salix seedling			1																							I
No. species per sample	15	14	16	8	10	12	7	8	8	10	9	8	7	9	8	10	10	13	8	7	8	7	7	9	9	
mean no. species																										9.48

Appendix A4.3

Quadrat data for vegetation group 3; *Carex rostrata - Menyanthes trifoliata* poor fen, showing the DOMIN score (1-10) for each species.

Quadrat No.	1	2	3	6	43	45	46	61	Constancy
Species name									
Carex rostrata	8	8	6	7	4	7	6	5	V
Menyanthes trifoliata	4	6	8	9	9	7	8	9	V
Lemna minor	3	1	1	1	1		3	3	V
Eriophorum angustifolium					2	3	3	3	III
Galium palustre					1			1	II
Potentilla palustris		1	1				2		II
Potamogeton coloratus			5	5					II
Cicuta virosa					1			4	II
Hippuris vulgaris		2		1					II
Equisetum fluviatile								6	I
Carex diandra								1	I
No. species per sample	3	5	5	5	6	3	5	8	
mean no. species									5

Appendix A4.4

Quadrat data for vegetation group 4; *Carex rostrata - Menyanthes trifoliata* poor fen, *Equisetum fluviatile* subcommunity, showing the DOMIN score (1-10) for each species.

Quadrat No.	**5**	**8**	**29**	**30**	**31**	**32**	**33**	**65**	**66**	**67**	**Constancy**
Species name											
Carex rostrata	6		7	8	8	8	7	5	4	5	V
Menyanthes trifoliata	8	9	4	7	7		4	8	8	9	V
Equisetum fluviatile		1	4	4	3	4	4	4	6	5	V
Potamogeton coloratus	5	9		1	4	4		4	7	5	IV
Carex diandra	4	7	6				6				II
Green algae (terrestrial)				1	1	1	1				II
Potentilla palustris		4							3		I
Lemna minor			1	1							I
Cardamine pratensis		1									I
Calliergon giganteum			3								I
Carex aquatilis		4									I
Festuca rubra			1								I
Utricularia sp.		3									I
No. species per sample	5	9	5	6	5	4	5	4	5	4	
mean no. species											5.2

Appendix A4.5
Quadrat data for vegetation group 5; *Carex panicea - C. pulicaris* rich fen, showing the DOMIN score (1-10) for each species.

Quadrat No.	10	11	12	22	23	24	20	21	Constancy
Species name									
Carex panicea	6	7	6	6	7	7	6	6	V
Carex pulicaris	3	5	4	4	8	5	4	6	V
Galium palustre	7	4	3				2	2	IV
Potentilla erecta	1	1	3	3			4	2	IV
Equisetum palustre			4	3	3	3	2	3	IV
Campylium stellatum				2	1	4	5	5	IV
Holcus lanatus	3		4			1	1	4	IV
Juncus acutiflorus	5		6		3		4	5	IV
Molinia caerulea		4	6	4	4	5			IV
Carex lepidocarpa				7	7	7	6	6	IV
Calliergon cuspidatum	7	8	7	5	2				IV
Carex rostrata	6	6		5				2	III
Menyanthes trifoliata				5		6	5	5	III
Eriophorum angustifolium				1	4	4	4		III
Agrostis stolonifera		3		3	2				III
Galium uliginosum		2			2		1	1	III
Pedicularis palustris		3			3		1	1	III
Climacium dendroides	1	3	4				4		III
Drepanocladus revolvens				4	1	3	5		III
Fissidens adianthoides				4	1		4	5	III
Equisetum fluviatile	3	1							II
Potentilla palustris				4		2		2	II
Potamogeton coloratus				4		1		1	II
Lychnis flos-cuculi		3	3					3	II
Cardamine pratensis	2	1	3						II
Luzula multiflora				3			4	3	II
Plagiomnium ellipticum							4	4	II
Angelica sylvestris	2	3	2						II
Carex nigra	6						5	5	II
Galium saxatile			4	1				1	II
Myosotis laxa caespitosa							1	1	II
Ranunculus flammula	1					3			II
Succisa pratensis			3			2	4		II
Epilobium palustre		2							I
Plagiomnium elatum			1						I
Caltha palustris		4							I
Filipendula ulmaria	1								I
Myosotis secunda	2								I
Festuca rubra	1								I
Poa trivialis		3							I
Sphagnum cuspidatum						1			I
Briza media						2			I
Rumex acetosa		1							I
Danthonia decumbens								3	I
Plagiomnium rostratum	3								I
Philanotis fontana								4	I
Rhytidiadelphus squarrosus			1						I
Calypogeia fissa					1				I
No. species per sample	19	20	17	18	15	16	21	24	
mean no. species									18.75

Appendix A4.6

Quadrat data for vegetation group 6; E*riophorum angustifolium - Sphagnum magellanicum* mire, showing the DOMIN score (1-10) for each species.

Quadrat No.	13	14	25	15	16	17	18	19	Constancy
Species name									
Eriophorum angustifolium	4	5	4	4	5	4	5	4	V
Sphagnum magellanium	5	5	5	9	9	8	9	6	V
Sphagnum papillosum	5	6	4	4	4	4	4	6	V
Calluna vulgaris	3	3	6	4	4	5	4		V
Eriophorum vaginatum	3	4	7	5	6	6		3	V
Sphagnum capillifolium	8		8	4	4	6	4	4	V
Polytrichum commune	1			2	1	5	7	10	IV
Drosera rotundifolia	4	4	3	4		4	4		IV
Erica tetralix	1	3	3	4	4				IV
Aulacomnium palustre				3	2	3		1	III
Carex rostrata		1		1	4				II
Menyanthes trifoliata		1							II
Luzula multiflora						3		4	II
Cladonia arbuscula	1	4				3			II
Scirpus cespitosus	5	5							II
Sphagnum tenellum	1				1				II
Mylia taylorii			3	1					II
Agrostis stolonifera								2	I
Carex panicea								1	I
Sphagnum squarrosum			1						I
Potentilla erecta								3	I
Equistum palustre								1	I
Molinia caerulea								3	I
Green algae (terrestrial)	1								I
Caliergon giganteum			1						I
Calliergon stramineum						1			I
Sphagnum cuspidatum							1		I
Carex echinata								2	I
Narthecium ossifragum				6					I
Barbula nicholsonii			3						I
Hypnum cupresseforme						4			I
No. species per sample	13	11	12	12	11	14	8	14	
mean no. species									11.88

Appendix A5

Hydrochemical parameters for published mire types, and sites included in this study.

EC = electrical conductivity in uS cm^{-1}, all ions in mg l^{-1}.

Location	Site Type	EC	pH	Ca	K	NO_3	NH_4	PO_4	Source
Scotland, UK	*Phragmites* reedbed	354.96	7.74	46.19	0.86	3.240	0.070	0.610	Tratt 1997
Poland	floodplain fen		7.49	106.00	0.70			0.170	Wassen *et al.* 1992
Poland	floodplain fen	395.00	7.36	88.00	1.92			0.200	Wassen 1995
Poland	rich fen		7.33	63.00	0.40			0.020	Wassen *et al.* 1992
Scotland, UK	*Carex rostrata - potentilla palustris* fen	335.80	7.32	46.16	1.29	2.490	0.180	0.460	Tratt 1997
Netherlands	high productivity poor fen (ground water fed)		7.30	76.00	0.79	0.700	0.420	0.080	Wassen *et al.* 1990a
Poland	ground water fed rich fen		7.20	149.00	2.10			0.010	Wassen *et al.* 1990a
Netherlands	*R. repens* meadow		7.15	82.00	2.70	1.300	1.200	0.140	Wassen & Barendregt 1992
Scotland, UK	*Carex dioica - C. hostiana* fen	343.87	7.14	44.97	0.96	0.890	0.140	0.360	Tratt 1997
Netherlands	infiltrated surface water fen	57.00	7.10	75.00	2.60	0.150	5.500	0.380	Schot & Wassen 1993
Scotland, UK	*Juncus* pasture	196.40	7.09	25.43	1.33	0.690	0.050	0.240	Tratt 1997
Scotland, UK	mixed sedge rich fen	307.82	7.07	41.64	4.85	0.620	0.070	0.340	Tratt 1997
Scotland, UK	*Carex rostrata - Calliergon Plagiomnium* (b)	267.67	7.04	30.22	4.07	1.190	0.190	0.470	Tratt 1997
Poland	rich fen		7.03	45.00	1.00			0.050	Wassen *et al.* 1992
Scotland, UK	Long Moss lag stream	157.10	6.97	32.69	0.98	0.150	0.060	0.009	this study
Scotland, UK	Loch of Winless	526.00	6.90	63.74	0.15	0.140		0.035	this study
Netherlands	low productivity rich fen (ground water fed)		6.90	61.00	1.17	0.650	0.260	0.040	Wassen *et al.* 1990a
Netherlands	*E. fluviatile* reedbed		6.90	57.50	0.85	1.450	0.850	0.080	Wassen & Barendregt 1992
Netherlands	groundwater fen	342.00	6.90	49.80			0.400	0.100	Segal 1966
Scotland, UK	*Carex rostrata - Calliergon Plagiomnium* (a)	304.65	6.84	40.35	1.81	2.280	0.250	0.380	Tratt 1997
Poland	rich fen	312.50	6.81	50.00	0.49			0.070	Wassen 1995
Netherlands	groundwater recharge fen	25.00	6.80	34.00	2.00	0.260	1.000	0.340	Schot & Wassen 1993
Netherlands	artificial ground water	199.00	6.80	26.00	0.40	0.900	0.400	0.030	Koerselman & Verhoeven 1995
N. European	minerotrophic rich fen		6.80	18.00					DuRietz 1954; in Verhoeven 1986
Scotland, UK	*Molinia* wet grassland	235.00	6.76	31.41	1.02	1.020	0.050	0.320	Tratt 1997
Scotland, UK	Loch Lieurary	476.00	6.70	91.68	0.21	0.740		0.044	this study
Scotland, UK	Restenneth Moss	418.00	6.70	71.07	0.27	10.720		0.058	this study

Appendix A5

Hydrochemical parameters for published mire types, and sites included in this study.

EC = electrical conductivity in *u* S cm^{-1}, all ions in mg l^{-1}.

Location	Site Type	EC	pH	Ca	K	NO_3	NH_4	PO_4	Source
Netherlands	*C. lasiocarpa* fen		6.05	16.00	0.35	0.250	0.450	0.600	Wassen & Barendregt 1992
Scotland, UK	*Carex rostrata - Sphagnum recurvum* poor fen	68.28	6.03	4.74	2.62	0.640	0.070	0.330	Tratt 1997
Michigan, USA	fen		6.00	34.30	0.80	0.070	1.800		Richardson & Marshall 1986
Scotland, UK	Greenside Moss	296.00	5.90	46.90	0.14	0.120		0.306	this study
Scotland, UK	Long Moss (1996-97)	121.10	5.90	23.48	1.42	0.200	0.480	0.024	this study
Scotland, UK	Long Moss (1995)	211.00	5.90	20.48	0.33	0.150		0.024	this study
Scotland, UK	Hill of Warehouse Mire - Broughwhin's Loch	345.00	5.80	43.48	0.14	0.270		0.009	this study
Scotland, UK	Barmufflock Dam	93.00	5.80	7.91	0.10	0.740		0.041	this study
Scotland, UK	Hill of Warehouse Mire - Groat's Lochain	337.00	5.70	21.64	0.11	0.110		0.004	this study
Netherlands	transitional rich - poor fen	67.00	5.70	7.80			0.170	0.700	Segal 1966
Scotland, UK	Nether Whitlaw Moss (1995)	294.00	5.60	38.30	0.24	0.110		0.048	this study
Scotland, UK	Black Loch	92.00	5.60	9.13	0.15	0.110		0.093	this study
Scotland, UK	rainwater fed fen	66.72	5.58	20.31	0.70	0.240			Grieve *et al.* 1995
Scotland, UK	floodplain fen	56.00	5.52	2.49	0.73	1.210			Grieve *et al.* 1995
Canada	*Sphagnum* mire		5.50	1.60	0.10				Malmer *et. al* 1992
Netherlands	infiltration fen	305.00	5.40	36.00	0.17	1.900	2.200	0.800	Wassen *et al.* 1989
N. European	minerotrophic poor fen		5.40	9.50					DuRietz 1954; in Verhoeven 1986
Netherlands	*S. pratensis* fen		5.35	21.50	0.40	0.600	0.750	0.850	Wassen & Barendregt 1992
Netherlands	poor fen	110.00	5.30	6.40	6.50	0.100	0.500	0.200	Koerselman *et. al* 1989
Netherlands	river water fed base poor *C. acutiformis* fen	1100.00	5.30	6.40	6.50				Verhoeven & Aerts 1992
Scotland, UK	patterned fens		5.30						Charman 1993
Scotland, UK	*Eriophorum - Sphagnum* bog	109.50	5.29	1.25	2.06	0.990	0.010	0.030	Tratt 1997
Netherlands	*J. acutiformis* fen		5.25	41.00	1.40	0.450	1.400	0.120	Wassen & Barendregt 1992
Netherlands	isolated fen	15.95	5.20	20.85				0.150	Beltman & Rouwenhorst 1994
Virginia, USA	*Juncus* dominated poor fen	23.30	5.20	6.00	0.60	0.000	0.100		Walbridge 1994
Scotland, UK	Glen Moss	93.00	5.10	7.51	0.10	0.130		0.141	this study
Netherlands	poor fen (floating)	56.00	5.10	3.81		22.000	0.350	0.300	Beltman *et. al* 1995
Scotland, UK	Rossie Moor - Loch Lemann	312.00	5.00	38.65	0.17	0.180		0.013	this study

Appendix A5

Hydrochemical parameters for published mire types, and sites included in this study.

EC = electrical conductivity in u S cm^{-1}, all ions in mg l^{-1}.

Location	Site Type	EC	pH	Ca	K	NO_3	NH_4	PO_4	Source
Netherlands	infiltration fen	225.00	5.00	30.00	0.17	2.600	2.700	1.400	Wassen *et al.* 1989
Scotland, UK	Rossie Moor - Nichol's Loch	139.00	5.00	16.05	0.26	0.160		0.007	this study
Netherlands	infiltration fen	185.00	4.80	26.00	0.20	3.000	2.900	1.600	Wassen *et al.* 1989
Virginia, USA	*Carex stricta* dominated poor fen	23.20	4.80	3.20	0.60	0.100	0.200		Walbridge 1994
Virginia, USA	*Typha* poor fen	28.20	4.80	2.60	0.60	0.000	0.000		Walbridge 1994
Scotland, UK	Brown Moor Heights	93.00	4.70	7.76	0.15	0.310		0.028	this study
Netherlands	poor fen-bog	68.00	4.70	5.50			0.360	3.000	Segal 1966
Scotland, UK	surface water fed fen	77.25	4.58	5.93	0.81	0.500			Grieve *et al.* 1995
Netherlands	artificial rain water	51.00	4.40	1.00	0.20	0.800	1.500	0.000	Koerselman & Verhoeven 1995
Canada	*Sphagnum* mire		4.40	0.20	0.10				Malmer *et. al* 1992
Virginia, USA	*Polytrichum-Sphagnum* poor fen	37.10	4.00	1.60	0.50	0.000	0.200		Walbridge 1994
Virginia, USA	*Carex canescens* poor fen	46.20	3.80	1.40	0.30	0.000	0.300		Walbridge 1994
Virginia, USA	*Calamagrostis* poor fen	80.10	3.70	2.40	0.60	0.000	0.300		Walbridge 1994
Netherlands	discharge fen			a58.00	0.89	0.390	2.040	0.140	Beltman & Rouwenhorst 1991
Netherlands	discharge fen			a58.01	0.82	0.370	1.200	0.190	Beltman & Rouwenhorst 1991
Netherlands	recharge fen			b49.00	1.38	0.080	0.360	0.140	Beltman & Rouwenhorst 1991
Netherlands	recharge fen			b49.00	0.58	0.120	0.930	0.100	Beltman & Rouwenhorst 1991
Netherlands	recharge fen			b49.00	0.89	0.260	0.610	0.100	Beltman & Rouwenhorst 1991
Netherlands	*C. diandra* discharge fen	270.00		41.80	0.92	0.040	1.050	0.040	Koerselman & Verhoeven 1992
Netherlands	*C. acutiformis/ Sphagnum* recharge fen	247.00		26.50	2.49	0.040	0.540	0.090	Koerselman & Verhoeven 1992
Netherlands	transitional rich fen (discharge)				1.50	0.150	0.900	0.075	Koerselman *et. al* 1990a
Netherlands	poor fen (recharge)				4.50	0.075	0.600	0.150	Koerselman *et. al* 1990a
Michigan, USA	minerotrophic *Typha/Carex* fen				0.70	0.170	0.700		Richardson *et al.* 1978