Moorland vegetation history and climate change on the North York Moors during the last 2000 years

Richard Christopher Chiverrell

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The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

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A history of vegetation and climate change during the last two millennia is elucidated from ombrogenous blanket peat sequences from the central and eastern North York Moors. The evidence is derived from five mires Harwood Dale Bog, May Moss, Fen Bogs, Yarlsey Moss and Bluewath Beck. May Moss received particular attention because it is the only remaining unmodified blanket mire on the North York Moors. All the sites were cored, with May Moss yielding seven cores, four of which were extruded along a five metres transect. The cores were selectively analysed for plant macrofossil, testate amoebae, humification and pollen. Chronologies were constructed using ^{14}C dating and the judicious use of biostratigraphic marker horizons. Comparison of ^{14}C dates obtained on bulk peat samples and on pure *Sphagnum* remains encountered substantial differences, which raises anxieties about ^{14}C dating of a material as heterogeneous as peat.

The regional vegetation history elucidated from the pollen evidence reflects changes in the demography, culture, economy and climate of the North York Moors. Evidence of woodland decline and abundant agricultural taxa are attributed to phases of increased agricultural exploitation of the uplands in response to a commercial approach to farming during the Romano-British period, population expansion during the Anglo-Scandinavian period, and attempts to exploit the moorlands during the boom periods of the 12th-13th and 15th-16th centuries. Conversely, phases of woodland expansion and agricultural decline are associated with the Roman withdrawal from England, the 'harrying of the north' in AD 1069-70 and demographic collapse during the 14th century.

Testate amoebae, plant macrofossil and humification stratigraphies provide a record of mire palaeohydrology, which is used to infer a history of effective precipitation. There is a broad consistency within the palaeohydrological indications from a single core, which indicates that the techniques support each other. Furthermore, similar testate amoebae, plant macrofossil and humification stratigraphies were encountered in adjacent cores at May Moss. There is evidence of pronounced shifts to wetter/cooler conditions *circa* 500 BC, AD 450, 850, 1400, 1625 and 1825 separated by unambiguously drier/warmer phases *circa* AD 200-450, 700-800, 1100-1200, 1550-1600 and 1750-1800. The palaeoclimate time series displays a strong correlation with the record of solar variability; however, biosphere, atmosphere and oceanic interactions in the North Atlantic region and global volcanism also affect regional climate.

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1 Introduction

1.1 Introduction and objectives of this research

Since the early 1900s the North York Moors have been a popular region for palaeoenvironmental research. Much of this popularity stems from the abundance of organic sediment, peat, that blankets much of the upland moor. There is an abundance of palaeoenvironmental data available from the North York Moors, mainly in the form of pollen diagrams, which has produced a reasonably comprehensive regional vegetation history (Simmons *et al.*, 1993). Peat is an extremely useful sediment for palaeoenvironmental research because it contains a wealth of well-preserved fossil material, including leaves, seeds, flowers, stems and roots. These plant macrofossils are the main sedimentary components of peat; however, there is also a diverse range of micro-fossils within the sedimentary matrix, including pollen grains, fungal spores and various micro-organisms. Many of these remains are identifiable in a subfossil condition and are the subject for palaeoecological investigations of peat deposits.

The palaeoenvironmental information contained within this fossil archive is clearly controlled by the environmental parameters that affect the floral, faunal and mycological communities. This thesis concentrates upon two lines of palaeoenvironmental inquiry utilising the fossil record of pollen grains, plant macrofossils, testate amoebae and the degree of decomposition within several peat sequences. The first objective is to uncover a vegetation history for the central and eastern North York Moors using pollen analysis to provide regional and local information, and plant macrofossil analysis to provide purely local information. The second objective is to uncover a history of mire hydrology using moisture-related changes in local plant and testate amoebae communities, and moisture-driven fluctuations in the degree of peat humification. This environmental archive forms part of a project developing a climate and landscape history for the North York Moors.

A parallel component of this research involves the archive of documentary evidence for landscape and climate change collated by Noël Menuge during 1995-1996. The documentary evidence concentrates upon the last 1500 years (James Menuge, 1997); consequently a broadly equivalent time period was adopted for the palaeoecological analysis targeting the last two millennia.

1.2 Peat: an environmental archive

Peat is an organic sediment, with organic matter contributing at least 30% of the total dry weight. In the peat sequences utilised in this thesis organic matter typically forms 75-100 % of the total dry weight (Heathwaite *et al.*, 1993a). Peat accumulates because dead plant matter is rapidly incorporated within an oxygen-deficient sedimentary system which inhibits further decay. When mires exist for long periods of time deep peat sequences are produced, with the peat stratigraphy reflecting the development of a mire. The speed of accumulation is controlled by a balance between net productivity of plants on the mire and net losses through decomposition processes. However, accumulation of biomass is primarily the result of poor rates of decomposition, because mires are not noted for high rates of productivity. Decomposition processes are the critical control upon the nature of peat deposits (Clymo, 1991), with the rate of peat decomposition in turn controlled by surface saturation.

Peat sequences divide into two distinct layers. The uppermost surface layers are aerobic and the majority of decomposition occurs within this horizon. The deeper layers are anaerobic within which comparatively little decomposition occurs. Ingram (1978) termed these two layers the acrotelm and catotelm respectively. The boundary between these two horizons occurs at the mean minimum summer water table, which is the maximum depth beneath the mire surface experiencing aerobic decay. The depth of the acrotelm/catotelm boundary is a fundamental control upon the rate of peat accumulation, with surface saturation of the mire controlling the rate of decomposition.

Mires are very diverse and have been subject to a range of classification schemes (Heathwaite *et al.*, 1993a; Grosse-Brauckman, 1996). Sub-divisions using hydrochemical criteria or trophic conditions are particularly pertinent to this research. Minerotrophic mires or fens derive their water from both rainfall and surface flow from surrounding mineral soils or rocks, and are rich in nutrients and minerals. Ombrotrophic mires or bogs receive water solely through precipitation and are deficient in both minerals and nutrients. In ombrotrophic mires surface wetness is more or less directly coupled with rainfall, or more accurately "effective precipitation", which is the amount of water received as precipitation minus losses through evapotranspiration. Fluctuations in mire surface wetness, and by inference climate, have considerable impact upon both the degree of peat decomposition, and the flora and fauna inhabiting the mire. Evidence of these fluctuations can be incorporated with peat stratigraphy by the sedimentary process, providing a record of mire palaeohydrology. Careful analysis of the stratigraphy within a peat bog may uncover a history of moisture fluctuations, which in the case of ombrotrophic mires will reflect climate change. This precept is the foundation to peat-based palaeoclimate research.

Ombrotrophic mires include lowland raised bogs, which are domed shaped and raised above the mineral water table, and blanket bogs located in the water-shedding parts of the uplands. Both these environments reduce the water received as surface flow to negligible quantities and render the peat stratigraphy at these mires suitable for palaeoclimate research. Climate information is elucidated from ombrogenous peat stratigraphy using the history of surface moisture conditions reconstructed from the fossil record of mire plants, micro-organisms and the sedimentary characteristics of the peat matrix. In summary, peat bogs are an archive of environmental information, with the palynostratigraphy providing information about vegetation changes around the mire, and with the plant remains and other fossils providing information about environmental conditions on the mire (Barber, 1993).

1.3 Mire development and palaeoecology

Raised mires do not occur on the North York Moors. However, they warrant further comment because the vast majority of peat-based palaeoclimatic research has been centred on raised mires, for example in Cumbria (Barber, 1981: Barber *et al.*, 1994a) and the Netherlands (Aaby, 1976). Raised mires are domed lowland features likened to inverted “frying pans” (Heathwaite *et al.*, 1993a). The dome raises the peat above spring, soil or mineral water; consequently raised mires have an independent water table fed primarily by precipitation and can only form where precipitation exceeds evaporation and run-off. Rainfall is deficient in minerals and nutrients, and so the nutrient status of raised mires is poor. Acidic, oxygen-poor and nutrient-poor conditions inhibit the growth of many plant species, resulting in a distinctive low-diversity raised mire flora dominated by heather, sedges and bog-mosses.

Blanket mires cover large areas of north-western and upland Britain. They tend to form in areas of high precipitation, with accumulation initially centred where drainage is impeded. However as peat accumulates the mire spreads over the surrounding topography forming a “blanket” over large areas of land. Blanket mires consist of a mixture of ombrotrophic and locally rheotrophic facies. Ombrotrophic tracts of blanket mires are similar to raised mires in that they are characterised by acidic, nutrient-poor and oxygen-poor water conditions, and by a low-diversity flora dominated by heather, sedges and bog-mosses. Blanket mires do occur on the North York Moors and are utilised in this thesis.

Not all the changes within peat stratigraphy are a response to climate, with other sources of environmental change also important. This is clearly exemplified by the variety of reasons proposed as causes of the inception of peat accumulation. The initiation of peat accumulation is indicative of a change in the hydrological budget, with increased moisture availability (Moore, 1986). In the case of upland blanket mires on the North York Moors, peat inception occurs in response to a complex array of factors, with the formation of the wet mire habitat referred to as paludification. Inception of peat accumulation in upland Britain has been attributed to a combination of climate change, woodland clearance and pedological factors (Moore, 1986; Smith & Taylor, 1989). Particular climatic periods appear to favour the inception of peat accumulation, but climate is not the only factor. Forest clearance and subsequent pedological changes are believed to be important causes of peat inception and create favourable circumstances for the expansion of peat from accumulating centres (Smith & Taylor, 1989).

Hydrology is an important control upon peat stratigraphy after the blanket mire facies has become established. Hydrological changes on blanket mires arise owing to variations in either the net moisture gained or the net moisture shed by the mire. In the case of ombrotrophic mires, net moisture gained can only be affected by changes in effective precipitation, which could occur as the result of climate change or by increasing evapotranspiration around the mire. Moisture losses from ombrotrophic mires can only occur by means of natural or anthropogenic drainage of the mire. Elucidating the nature and origin of hydrological changes is a fundamental component of this thesis, which, given the use of ombrotrophic tracts of blanket mires, will contribute an understanding of climate history.

1.4 Organisation of the thesis

The thesis is divided into three sections. The first involves chapters two, three and four, which introduce and define the research strategy, objectives and methodologies. They also provide a review of previous research both within the region and research elsewhere using a similar methodological approach. The second involves the presentation of the results. Chapter five presents, interprets and discusses the results of the pollen analysis and formulates a regional vegetation history for the last two millennia. Chapter six presents the results of the peat stratigraphic research, and formulates a hydrological history for each of the mires. The final section, chapters seven and eight, presents a detailed discussion of the evidence for climate change on the North York Moors during the last 2000 years, which is discussed in relation to previous peat stratigraphic research, established histories of late Holocene climate and hypothesised forcing agents of global climate change. The implications of the research are also reviewed in terms of future moorland management and conservation, future peat stratigraphic research and predicted future climate changes.

2

Introduction to the North York Moors

2.1 The Physical Environment

The North York Moors is an isolated upland area located in the north-east of Yorkshire. The moors cover a large area stretching over 60 km from east to west and 35 km from north to south. The topography of the North York Moors is displayed in figure 2.1, which also identifies the locations referred to in this chapter. In the east the North York Moors are bounded by high cliffs overlooking the North Sea, which reach 210 m at Boulby - the highest cliff in England. In the north and west the moors are bordered by a steep 300m escarpment, which overlooks the Vale of York, the Vale of Mowbray and the lower Tees valley. The Hambleton, Tabular and Hackness Hills form the southern border of the North York Moors, sloping gently into the Vale of Pickering.

The moors can be divided into three broad upland areas. The Cleveland Hills to the north of Eskdale, rising to 328m on Guisborough Moor, have a Middle and Upper Jurassic bedrock. However, it is the central Middle Jurassic sandstone plateau covered by heather and peat that popularly characterises the North York Moors. The central belt is heavily dissected by broad, steep-sided dales, which drain to the north and south off this gently inclined plateau. Erosion of these dales has divided the central plateau into four upland masses aligned east to west across the moors.

In the east near the coast are Stainton Dale and Harwood Dale Moors, which rise to 266m. Six miles further inland is the Fylingdales Moor upland mass rising to 299m, bordered in the east by the headwaters of the river Derwent and in the west by the deeply incised Newtondale proglacial valley. Further west, the main upland massif of the North York Moors extends from Wheeldale Moor in the east to Urra Moor in the west. The majority of this plateau is over 300m rising to 454m at Urra Moor, the highest point on the North York Moors. The farthest-west upland area includes Bilsdale West Moor, Whorlton Moor and Snilesworth Moor, rising to 404m at Noan Hill, and is bordered by Bilsdale in the east and by the steep western escarpment.

The central plateau slopes gently southwards towards the Tabular Hills, Hackness Hills and part of the Hambleton Hills, which border the southern edge of the moors. These hills seldom exceed

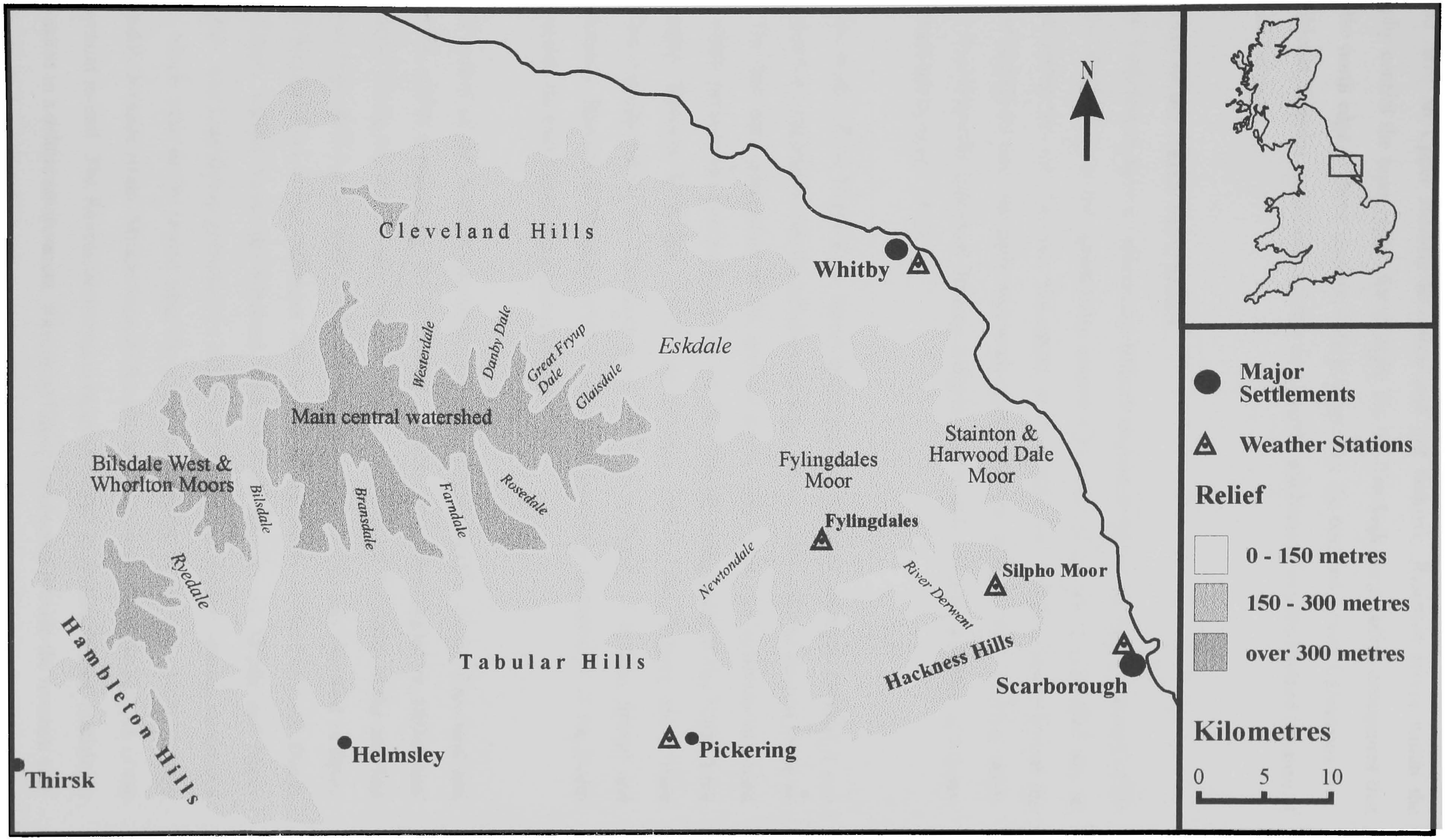


Figure 2.1. Topography and location map of the North York Moors

200m and have an Upper Jurassic limestone and grit bedrock. Resistant layers within the stratigraphy control the topography, for example the 60-70m high north-facing escarpment that delimits the north edge of these southern hills is capped by the resistant Lower Calcareous Grit. The Hambleton, Tabular and Hackness Hills slope gently southwards into the lowland expanse of the Vale of Pickering.

2.2 Geology of the North York Moors

The North York Moors have a sedimentary bedrock deposited during the Jurassic Period (195-135 million years ago) in the episodically marine Cleveland basin, which developed due to subsidence during the late Triassic. The strata of the North York Moors have attracted the attention of geologists since the early nineteenth century (Young & Bird, 1822; Phillips, 1829). The region is geologically important because it displays a virtually complete sequence of Jurassic strata (Hemmingway *et al.*, 1963).

Recently the strata of the North York Moors have attracted renewed attention, because it is a critical region for comparison with the off-shore geology, which is of particular interest to the oil industry. The following description of the geology draws heavily on two syntheses of recent research, which provide the current consensus on the Jurassic stratigraphy of the North York Moors, namely Rawson & Wright (1992) and Scrutton (1994). The Jurassic strata were deposited horizontally within the Cleveland basin and consist largely of marine, littoral and deltaic sediments. Rawson & Wright (1992) divide the sedimentary stratigraphy of the North York Moors into the four broad groups listed in table 2.1.

The central massif of the North York Moors forms the broad anticline of the Cleveland and Eskdale domes, which is responsible for the present drainage off the central plateau. Differential rates of erosion during the late Tertiary and Pleistocene have removed the centre of the anticline creating three geological regions with a different type of bedrock, which are identified in figure 2.2. Lower Jurassic Lias Group sediments are exposed in the centre of the Cleveland Dome, where the deeply incised broad flat-bottomed dales have cut through the Middle and Upper Jurassic strata. The Lias Group consists of a mixture of marine and shallow marine sandstones and shales, which were easily eroded after the rivers and streams of the dales broke through resistant Middle Jurassic strata. Middle Jurassic Ravenscar Group strata form the bedrock of the central moorland massif. The Ravenscar Group consists of fluvial to shallow marine sandstones mostly deposited in a deltaic environment. Ravenscar Group sandstones provide the resistant cap-rock for the central moorland plateau and the steep escarpment to the north and west of the

Table 2.1. Geological subdivision of the Jurassic strata of the North York Moors.

		GROUPS	AGE	FORMATIONS
Jurassic	Upper	Kimmeridge Clay Group	140 Ma	Kimmeridge Clay Formation
		Middle Oolite Group		Ampthill Clay Formation
				Upper Calcareous Grit Fm
				Coralline Oolite Formation
				Lower Calcareous Grit Fm
				Oxford Clay Formation
				Osgodby Formation
				Cayton Clay Formation
				Cornbrash Limestone Formation
	Middle	Ravenscar Group	160 Ma	Scalby Formation
				Scarborough Formation
				Cloughton Formation
				Eller Beck Formation
				Saltwick Formation
		Lias Group		Dogger Formation
	Lower		182 Ma	Blea Wyke Sandstone Formation
				Whitby Mudstone Formation
				Cleveland Ironstone Formation
				Staithes Sandstone Formation
			204 Ma	Redcar Mudstone Formation

Table 2.2. Meteorological information available for the North York Moors.

Weather Station	Grid Ref.			Rainfall (mm)	Relative Humidity (%)	Wind speed (knots)	Snow lying (days)	Sunshine (hours)
Fylingdales	SE 862 971	262 m	1984 to 1997	1984 to 1997	1984 to 1997	1984 to 1997	no data	no data
Pickering	SE 795 842	44 m	1962 to 1981	1962 to 1981	no data	no data	1971 to 1981	no data
Silpho Moor	SE 957 946	203 m	no data	no data	no data	1970 to 1986	no data	no data
Scarborough	TA 044 884	36 m	no data	no data	no data	no data	no data	1931 to 1986
Whitby	NZ 904 114	41 m	no data	no data	1983 to 1997	1983 to 1997	no data	1976 to 1997

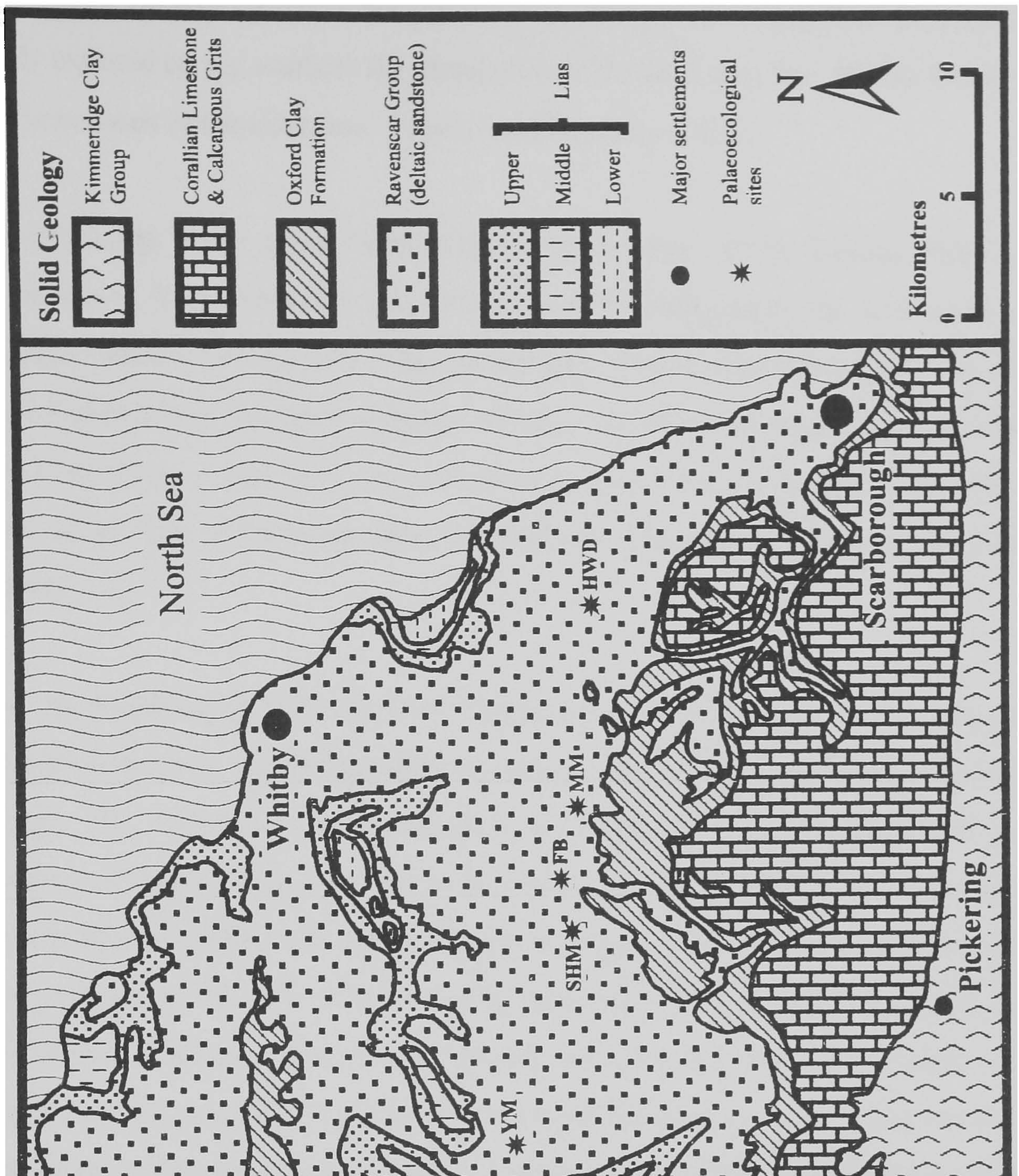


Figure 2.2. Geological map of the North York Moors, also identifying the location of the palaeoecological sites. MM= May Moss; FB= Fen Bogs; BWB= Bluewath Beck; HWD= Harwood Dale Bog; YM= Yarlsey Moss.

moors. Upper Jurassic Middle Oolite Group rocks have been eroded from the central plateau and are only exposed on the southern dip-slope of the Cleveland anticline. Middle Oolite Group strata form the bedrock of the Hackness, Tabular and Hambleton Hills.

The north-facing scarp slope forming the northern edge of the Tabular Hills is capped by resistant Lower Calcareous Grit. The formation of the escarpment was assisted by rapid erosion of the less resistant Oxford Clay exposed to north of the Lower Calcareous Grit outcrop. More recent sediments from the Kimmeridgian sub-stage and the Cretaceous Period are absent from the North York Moors. However, the soft Kimmeridge Clay Formation forms the sub-surface bedrock of the Vale of Pickering, albeit buried under Pleistocene alluvium, lacustrine and glacial sediments.

During the Pleistocene the North York Moors were affected by the vast climatic fluctuations, which almost certainly were responsible for substantial erosion of the uplands shaping the current landscape. The Pleistocene was characterised by severe climatic fluctuations that produced vast ice-sheets that blanketed much of the British Isles. The North York Moors were not covered by ice during the last glacial, with ice-sheets only impinging on the edges of the moors on the way to maximum limits in the Vale of York and on Holderness (Rose, 1985). Although Devensian ice only skirted around North York Moors, directly affecting the edges of the moors, the Cleveland Hills and Eskdale, proglacial drainage and out-wash associated with deglaciation had a profound impact on the landscape (Gregory, 1962; 1965). Proglacial and sub-glacial drainage produced numerous deeply incised valleys across the moors, including Newton Dale, Lady Bridge Slack, Moss Swang and Tranmire Slack, to name but a few (Gregory, 1962).

It is possible the North York Moors were covered with ice during previous glacial advances, possibly during the preceding Saalian glaciation ($\delta^{18}O$ stage 6-8) and almost certainly during the Elster glaciation ($\delta^{18}O$ stage 12). Catt (1987) attributes glacial deposits on the North York Moors to earlier pre-Devensian cold stages. However, considering the consensus is that the moors were not glaciated during many of the numerous cold stages of the Pleistocene, they did experience vigorous periglacial activity and proglacial fluvial erosion, which have assisted with formation of the current landscape.

2.3 Present day vegetation and landscape of the North York Moors

The mixture of vegetation and land-use covering the present day landscape of the North York Moors to some extent is controlled by the physical environment and bedrock geology, but mostly by the activity of people. Elgee (1908) thought the North York Moors were a natural landscape covered with a relict tundra flora. However, thirty years of palynological research reveals that people have interacted with and changed the vegetated landscape of the North York Moors throughout the last 9000 years (Simmons, 1995). A review of 15,000 years of vegetation history and palaeoecological research on the North York Moors is presented in chapter 2.5.

The high moorland with a Middle Jurassic sandstone bedrock is covered with the characteristic flora of the North York Moors, the heather, cotton-grasses, purple moor grass and mosses. The former Nature Conservancy Council survey the vegetation of the North York Moors in great detail in the Phase 1 Habitat Survey revealing substantial variation in the flora across the moors. The typical moorland plants prefer wet acidic conditions growing on deep peat deposits (3-5 metres) and in association with raw peat soils and stagnohumic gley soils that occur across the high moorland (Carroll & Bendelow, 1981). The peat and peat soils characterise the centre of the basins, with the stagnohumic gley soils around the margins.

This association of vegetation and soils is not the natural environment of the North York Moors, but is the product of human interference through woodland clearances during the last 8000 years and particularly due to land-use changes during the 19th century. Grouse rearing became the dominant land-use activity on the North York Moors and involved regular burning of the moorland to encourage a high density of heather. Land management practices have maintained the heather-covered moors since the late 19th century and encouraged the development of peat and stagnohumic gley soils that are little suited for utilisation other than as moorland or forestry.

The drier edges of the moorland and the steep valley sides are covered with a mixture of bracken, grassland and remnants of woodland. The soils of these areas vary from stagnohumic gley soils on the edge of the moors, which only sustain rough grazing, to loamy brown earths which sustain both pastoral and arable agriculture. Obviously in these valley side and moorland edge environments steepness of the slopes is an important factor controlling utilisation of the landscape. Much of the woodland that once covered the North York Moors has been cleared gradually during the last 8000 years, with the only remnants of the broad-leaved woodland remaining today limited to the steep valley sides and maintained woods located on the Tabular Hills (Atherden & Simmons, 1989). Woodland on the North York Moors has been supplemented with twentieth century conifer plantations, initially in the Dalby, Bickley and Hackness area, but later expanding into Wykeham, Cropton and Harwood Dale (Statham, 1989).

Farmland, including pastoral grassland and arable fields is restricted to specific areas within the North York Moors. The majority of arable activity on the moors is limited to the fertile soils, gentle slopes and lower rainfall of the Hambleton, Tabular and Hackness Hills. These areas sustain brown earth soils offering a soil-type better suited for arable and pastoral activity, which explains why the majority of arable cropping within the North York Moors takes place on the southern limestone hills. The coastal plain has also been improved for agriculture serving coastal fishing communities in Staithes, Runswick Bay and Robin Hood's Bay. The dominant land-use in the Dales and on areas of reclaimed moorland is livestock farming with fields developed for grazing and silage cropping, with the higher edges of the moors used as rough grazing.

The moors, particularly the higher moorland plateau and steep valley sides, have never been ideal for agricultural use. Statham (1989) suggests use of the moorland edge has fluctuated between exploitation during periods of agricultural boom and virtual abandonment during periods of agricultural depression. An important objective of this research is to investigate the palaeoecological evidence for landscape evolution on the North York Moors. Palaeoecological sites on or near the moorland edge may be ideally located for the identification of fluctuations in land-use pressure, between extensive use during favourable economic, social and climatic conditions, with perhaps virtual abandonment under inclement conditions.

2.4 Climate of the North York Moors

Located on the East Coast of England, the North York Moors are one of the driest uplands sustaining peat accumulation in the British Isles. Conditions favouring peat accumulation require a saturated environment caused either by impedance of drainage or by wet climatic conditions. The amount of rainfall received by the North York Moors indicates the region is currently marginal for the accumulation of peat.

Climatic information for the North York Moors is derived from recordings at five weather stations located at Fylingdales, Silpho Moor, Pickering, Whitby and Scarborough (information provided by the Meteorological Office). The locations of the weather stations are identified on figure 2.1. Unfortunately, a complete range of meteorological information was not available from all of the sites. The most complete set of data was obtained from the Fylingdales weather station located high on the Fylingdales upland massif (262m) and close to the palaeoecological sites. Relatively detailed records from Pickering provide a useful lowland comparison with the upland data. The type and duration of the information obtained from the weather stations are listed in table 2.2.

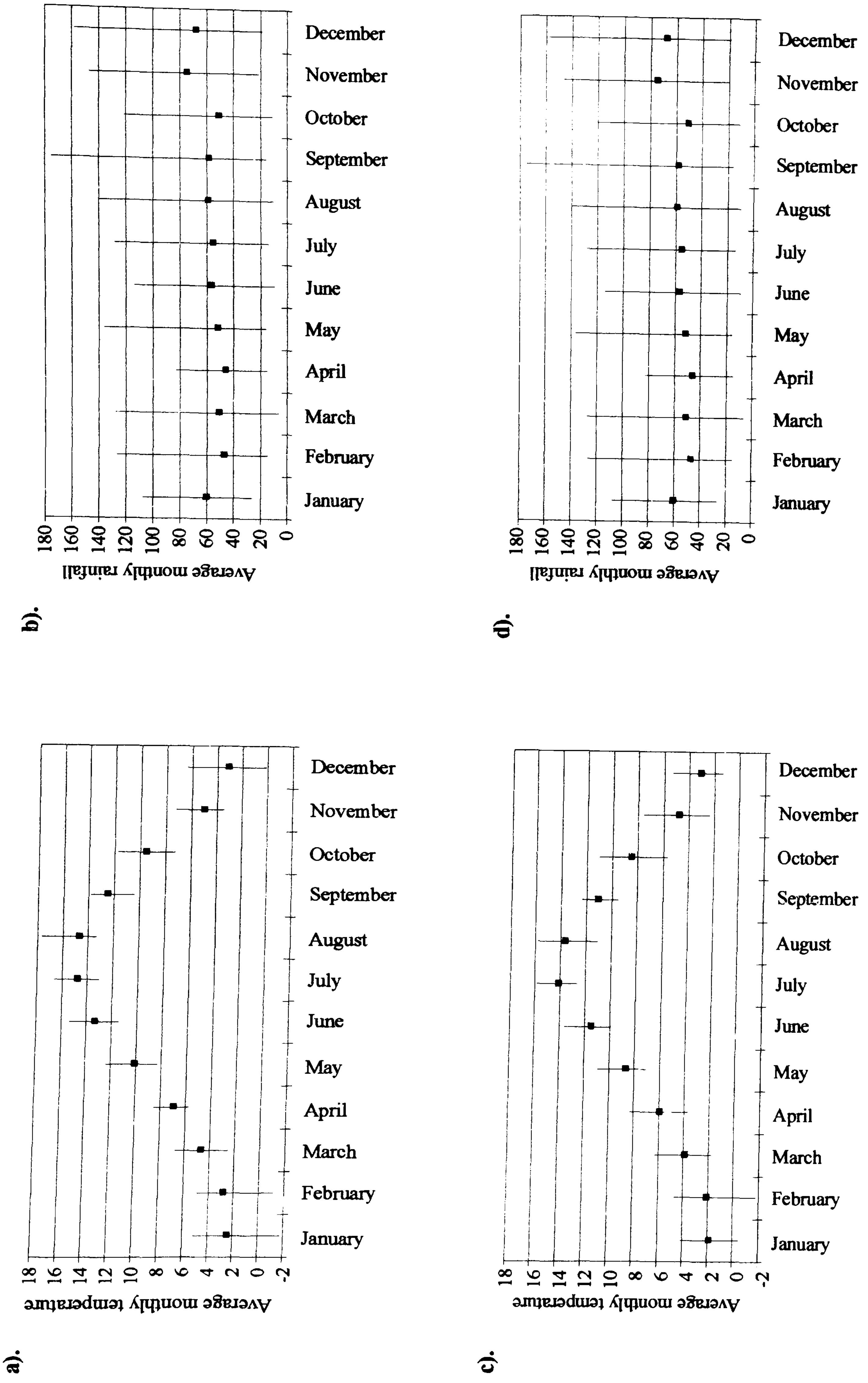


Figure 2.3. Meteorological data provided by the Met. Office. a) Average monthly temperature (degrees C) and b) average monthly rainfall (mm) recorded at Pickering between 1962 and 1981. c) Average monthly temperature (degrees C) and d) average monthly rainfall (mm) recorded at Fylingdales between 1984 and 1997.

The average and range of temperatures measured at Fylingdales and Pickering weather stations are displayed in figure 2.3. During the measurement period Fylingdales recorded an average annual temperature of 7.5°C, which is cooler than the 8.39°C recorded at Pickering. Fylingdales received an annual average rainfall of 908.8mm and a range of 1001.8-727.8mm. The average monthly distribution of rainfall, displayed in figure 2.3, highlights the marked dry summers experienced by the North York Moors. Pickering, in the lowlands to the south of the moors, receives an average annual rainfall of 686.6mm, with a range of 877-455.6mm. This evidence demonstrates that the high moors are on average 1°C cooler and receive 220mm more rainfall than the surrounding lowland areas. Furthermore the conclusion that the upland moors experience a wetter micro-climate is supported by the comparison of the annual average relative humidity of 87.5% at Fylingdales, with only 80.81% at Whitby.

Little information has been recorded about snowfall on the North York Moors. An average of 19 days per year with snow lying was recorded at Pickering between 1971-1981. The number of days with snow lying for upland sites is likely to be much higher. Wind-speed measurements are available for Silpho Moor, Fylingdales and Whitby. The highest annual average wind-speed (11.8 knots) was recorded on the coast at Whitby, with 11.3 knots recorded on the exposed Fylingdales Moor. Silpho Moor, which is at a lower altitude and less exposed than Fylingdales, recorded a much lower average wind-speed (6.29 knots).

The meteorological data provide useful information on the climatic parameters affecting the North York Moors and identify clear differences with other peatland sustaining environments in the British Isles. Areas of north-west Scotland, including the peatlands of Caithness and Sutherland; Wales; the Cumbrian lowlands; the Lake District and the west of the Pennines all sustain active peat accumulation and typically receive annual rainfall in excess of 1200mm and up to 2000mm. The average annual rainfall of 900mm on Fylingdales Moor suggests the North York Moors are not a prime region for the accumulation of blanket peat. Consequently peat stratigraphy on the North York Moors may be suited for the identification of significantly drier phases, because the impact of dry/hot climate on mire ecology will be magnified in a region marginal for peat accumulation. A principal aim of this research is to investigate the palaeoecological response of peatlands to drier climatic periods, perhaps providing an important analogue for environmental management in response to future climate change, which is particularly significant given the paucity of blanket mire on the North York Moors.

2.5 Published palaeoecological research from the North York Moors

2.5.1 Introduction

The North York Moors is one of the most intensively palaeoecologically investigated areas of the British Isles. Erdtman (1927) carried out the earliest palaeoecological research, and the North York Moors have attracted the attention of palaeoecologists throughout much of the last 70 years. This research has generated a large number of pollen diagrams produced with the aim of uncovering the post-glacial vegetation history of the North York Moors. Currently there are in excess of 30 published pollen profiles from the North York Moors, which are listed in table 2.3. The distribution of palaeoecological sites is displayed in figure 2.4, which reveals the coverage of sites across the moors is not uniform. The majority of sites are on the central moorland plateau, which has a Middle Jurassic sandstone bedrock and is typically covered with a blanket of peat. There is distinctly less peat in the lower dales and on the southern limestone hills, which explains the comparative lack of palynological analysis.

The initiation of peat formation is not synchronous across the moors, with peat deposits accumulating over differing periods of time. Consequently the peat stratigraphic record from the palaeoecological sites pertains to different sections of the Holocene. Figure 2.5 shows the duration of each peat profile and identifies extremely good coverage of the late Mesolithic, Neolithic, Bronze Age and Iron Age, and a comparative paucity of material pertaining to the Palaeolithic, early Mesolithic and post Iron Age. This is of particular significance for this project, with the current understanding of vegetation changes during the last 2000 years based on a small number of sites. Consequently there is considerable scope for further analysis, which will improve this database and address problems within the palynological record. Unfortunately the paucity of palaeoecological profiles covering the last 2000 years raises questions about the availability of peat stratigraphy of an appropriate age. A further limitation with current understanding of the vegetation history of the North York Moors is that the chronologies derived for the pollen diagrams are based on a relatively small number of radiocarbon dates. The extent of radiocarbon dated stratigraphy is also identified on figure 2.5.

The discussion above identifies previously published palaeoecological sites on the North York Moors, which provide the basis of current understanding of the region's vegetation history. However, nothing has been said about previous research on the North York Moors elucidating climatic changes from the peat stratigraphy, a palaeoecological approach widely applied to other peatlands in the British Isles, for example the Cumbrian lowlands (Barber, 1981; Barber *et al.*, 1993; 1994a; 1994b). Previous research of this type is remarkably limited on the North York

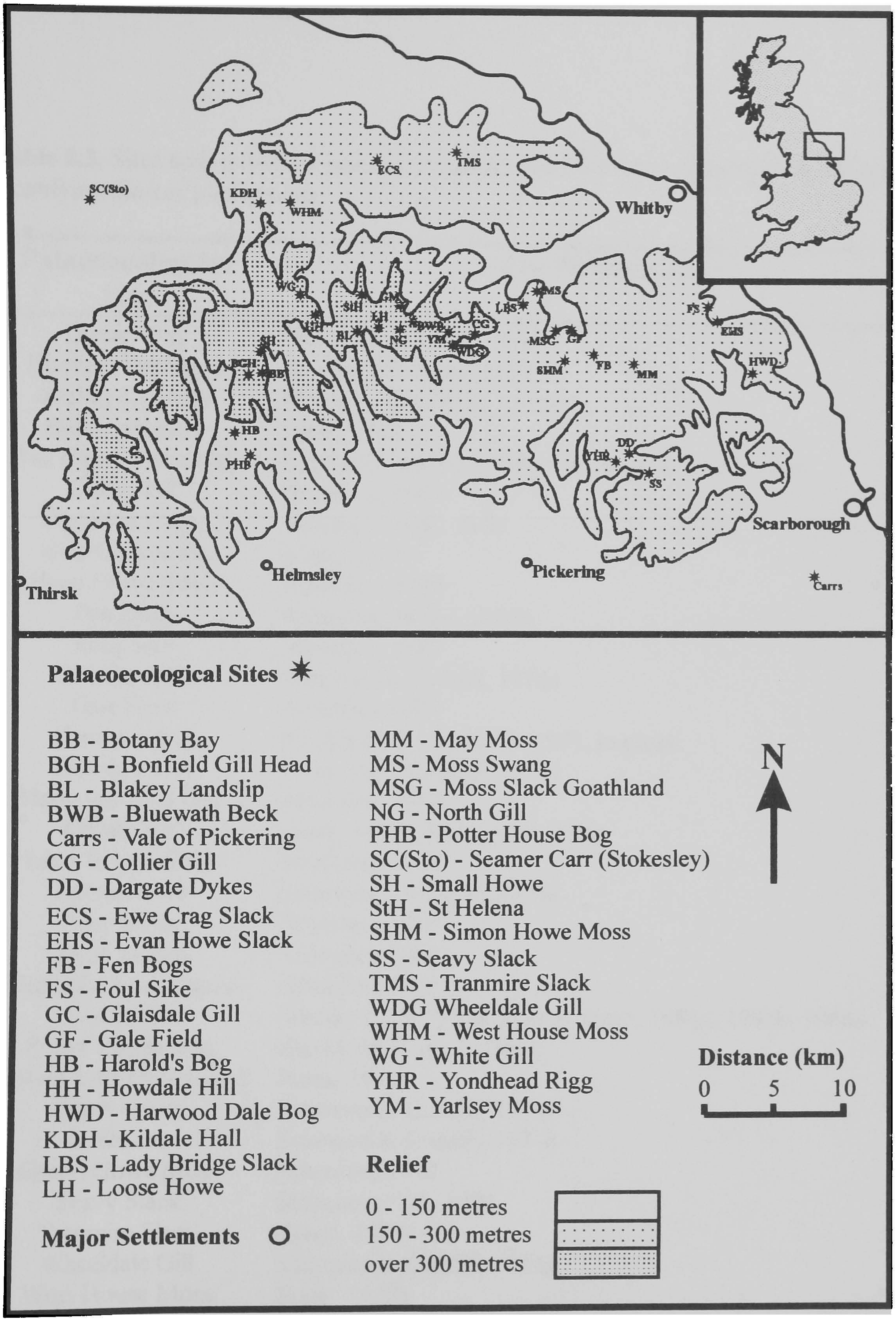


Figure 2.4. Distribution of palaeoecological sites investigated between 1960 and 1995. The chronological duration of each profile is identified in figure 2.5. The publications presenting the research at each site are listed in table 2.3.

Table 2.3. Sites with published palaeoecological research from the North York Moors identifying the key publications.

Palaeoecological Site	Key Publications
Botany Bay	Simmons & Innes, 1988c
Bonfield Gill Head	Simmons & Innes, 1988c
Blakey Landslip	Simmons & Cundill, 1974b
Bluewath Beck	Innes, 1981
The Carrs, Pickering.	Cloutman, 1988a; 1988b; Cloutman & Smith, 1988
Collier Gill	Simmons, 1969
Dargates Dykes	Simmons *et al.*, 1993
Ewe Crag Slack	Jones, 1978
Evan Howe Slack	Atherden, 1989
Fen Bogs	Atherden, 1976a; 1976b
Foul Sike	Atherden, 1989
Glaisdale Gill	Simmons & Cundill, 1974a
Gale Field	Atherden, 1979
Harold's Bog	Blackford & Chambers, 1991; in press
Howdale Hill	Simmons & Cundill, 1974a
Harwood Dale Bog	Atherden, 1989
Kildale Hall	Jones, 1977a; Keen *et al.*, 1984
Lady Bridge Slack	Simmons, 1969
Loose Howe	Simmons & Cundill, 1974a
May Moss	Atherden, 1979
Moss Swang	Simmons, 1969
Moss Slack Goathland	Atherden, 1979
North Gill	Simmons, 1969; Simmons & Innes, 1988a; 1988b; 1988d
Potter House Bog	Blackford *et al.*, in press
Seamer Carr (Stokesley)	Jones, 1976
Small Howe	Simmons & Cundill, 1974a
St Helena	Simmons & Cundill, 1974b
Simon Howe Moss	Atherden, 1979
Seavy Slack	Simmons *et al.*, 1993
Tranmire Slack	Jones, 1978
Wheeldale Gill	Simmons & Cundill, 1974a
West House Moss	Jones, 1977b
White Gill	Simmons & Cundill, 1974a
Yondhead Rigg	Simmons *et al.*, 1993
Yarlsey Moss	Simmons & Cundill, 1974a

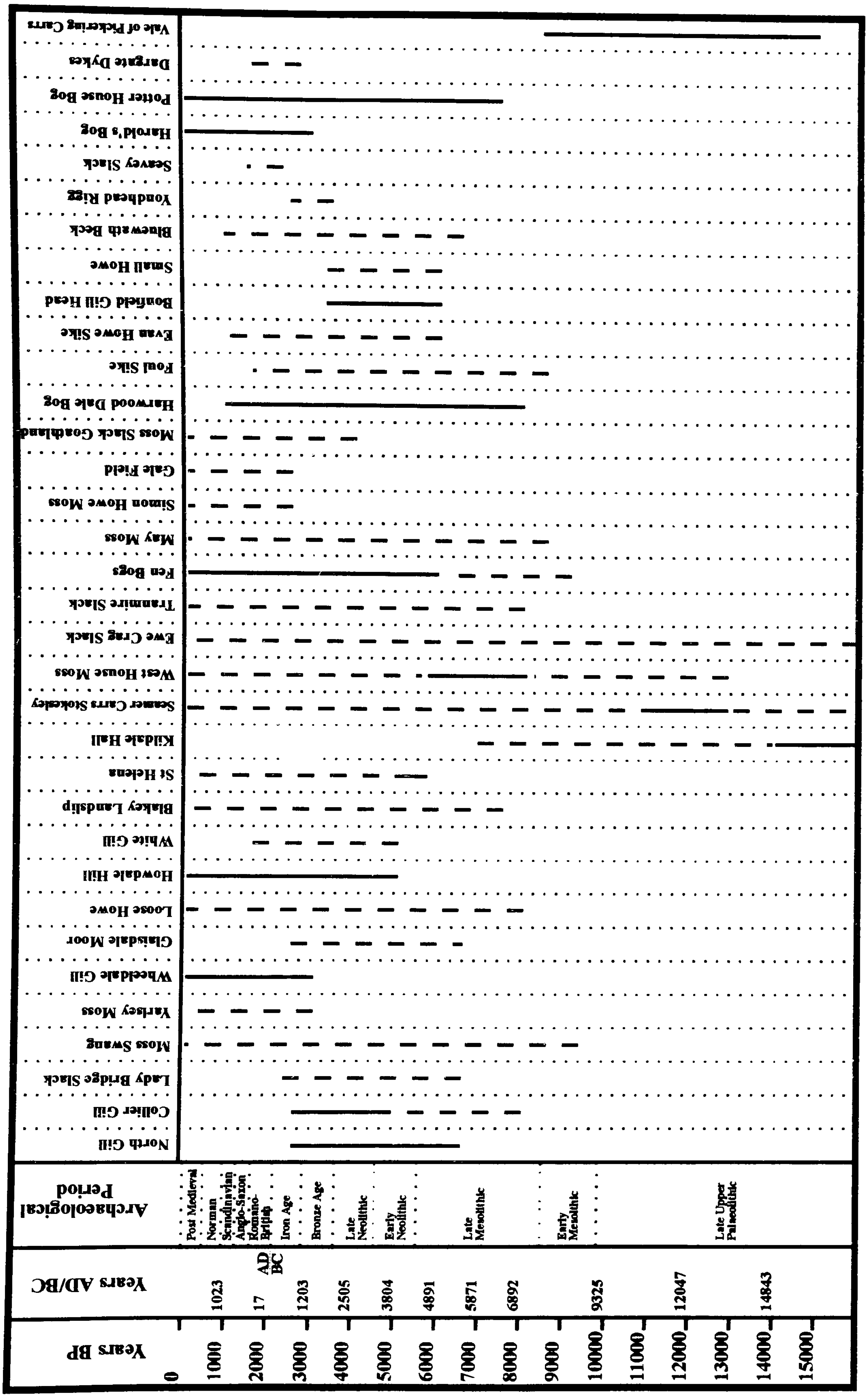


Figure 2.5. Duration of peat sequences investigated in previous research. Solid lines denote stratigraphy secured by radiocarbon chronology, whereas the dashed lines denote undated stratigraphy. The locations of these sites are identified in figure 2.4. The publications presenting the palaeoecological information are listed in table 2.3.

Moors, perhaps reflecting the absence of raised mires, the conventional environment for this type of research. In recent years increased attention has been paid to the palaeoclimate record contained in blanket peat sequences (Blackford, 1989; Tallis 1994), an environment the North York Moors has in abundance. Blackford & Chambers (1991; in press) analysed the peat stratigraphy from a blanket bog called Harold's Bog on Conisor Howl, East Bilsdale Moor. The degree of humification within a peat profile was utilised to identify fluctuations in mire surface wetness and this record was interpreted as a proxy-record of climatic fluctuations between 3170-300 years BP. This is the only example of research of this type previously carried out on the North York Moors.

2.5.2 Historiography of palaeoecological research on the North York Moors

The history of palaeoecological investigation of peat deposits on the North York Moors divides into three phases of research activity that may be termed the pioneer, proliferation and critical phases. Boundaries between the phases are diffuse reflecting the evolution in established knowledge, the scientific process, and gradual improvements within research techniques and methodologies.

Early palaeoecological investigations on the North York Moors demonstrate the importance of palynology as a tool for environmental reconstruction. Erdtman (1927) identified that trees were a component of the past vegetation, falsifying the traditional view that the heather moor and open grasslands were relict tundra ecosystems preserved by an upland climate since the last Ice Age (Elgee, 1912). Dimbleby (1961; 1962) and Simmons (1969) presented the earliest attempts to formulate a complete Holocene vegetation history of the North York Moors based upon pollen analysis of peat sediments, which included evidence of the post-glacial climatic amelioration and early Holocene forest development, predominantly controlled by climate change and differential speeds of tree immigration. Additionally a series of subsequent episodic forest clearances was identified throughout the Holocene, and have been attributed to the activity of prehistoric and historic populations.

Palaeoecological analysis on the North York Moors proliferated during the 1960s and 1970s, encouraged by the research of these early pioneers. This proliferation involved three doctoral research theses (Cundill, 1971; Jones, 1971; Atherden, 1972) supervised by Simmons at Durham University. This wealth of palaeoecological research based on a large number of sites from across the moors, generated a detailed vegetation history of the North York Moors from 16,000 BP to the present day. The improved spatial coverage of palaeoecological sites has enabled identification of regional variations in vegetation cover. The detailed regional vegetation history has been interpreted in the light of established archaeological (Jones *et al.*, 1979), historical (Atherden, 1976a) and palaeoclimatic knowledge (Godwin, 1975; Lamb, 1977).

Detailed scientific investigation often identifies as many problems and gaps in knowledge as it provides answers. The final and theoretically limitless phase of research involves detailed critical analysis targeting identified problem areas, thereby filling gaps in current understanding and providing further critical evaluation of the established knowledge. This phase has already included a number of research initiatives extending the temporal coverage, for example using palaeoecological and archaeological techniques to investigate the natural and cultural environment of upper Palaeolithic and Mesolithic sites in the Vale of Pickering, namely at Seamer, Star and Flixton Carrs (Cloutman, 1988a; 1988b; Cloutman & Smith, 1988).

Simmons & Innes (1988a; 1988b; 1988d) applied fine-resolution pollen analysis to North Gill and other sites on the central watershed, in an investigation of the nature of Mesolithic/Neolithic woodland disturbances on the upland moors. Further improvements in the spatial coverage of palaeoecological sites were made investigating peat sequences on the coastal fringe of the North York Moors (Atherden, 1989; Simmons *et al.*, 1993), and on East Bilsdale Moor (Simmons & Innes, 1988c). Turner *et al.* (1989) carried out a critical evaluation of the accuracy of palynological investigation by analysing replicate profiles from the same peat sequence, which assesses within-site variation in the pollen record. Blackford & Chambers (1991; in press) extended the range of palaeoecological procedures applied to peat sequences on the North York Moors by using analysis of the degree of peat humification to elucidate palaeoclimatic information from the peat stratigraphy.

The research in this thesis is a further addition to the "critical" phase, contributing to the understanding of the environmental history of the North York Moors. Pollen analysis is utilised to investigate a series of sites, concentrating solely on peat stratigraphy post-dating the Iron Age. Additionally all of the sites are located in the eastern half of the North York Moors. Furthermore a wider range of palaeoenvironmental techniques, namely testate amoebae, plant macrofossil and humification analysis, are applied to these peat sequences as an integrated strategy for the first time on the North York Moors. Each of these palaeoenvironmental procedures provides information about mire palaeohydrology, which in the case of ombrotrophic peat stratigraphy is a proxy record of climate change.

2.5.3 Vegetation history of the North York Moors

Uninterrupted peat stratigraphy covering the entire period from the termination of the Devensian Ice Age to the present day is not abundant on the North York Moors. Consequently the vegetation history of the North York Moors is derived from analysis at over thirty sites each covering differing parts of the Holocene. The pollen diagrams from these sites are interpreted to form a composite vegetation history formulated by correlating changes in the palynostratigraphy between peat sequences. However the reconstruction of Holocene vegetation history is assisted by the presence of three pollen profiles that extend from the base of the Holocene to the present day, namely Fen Bogs (Atherden, 1976a; 1976b), May Moss (Atherden, 1979) and West House Moss (Jones, 1978). Vegetation history research relies heavily on independently dated pollen diagrams and the ^{14}C dated peat sequences are identified on figure 2.5. Unfortunately Fen Bogs, Harwood Dale Bog, Wheeldale Gill, North Gill and Bonfield Gill are the only peat sequences secured with a reasonable number of ^{14}C dates.

Termination of the Devensian Ice Age

The earliest palaeoecological record on the North York Moors began ca. 16,700 BP at Kildale Hall (Jones, 1977a). In the Devensian, glacial ice reached the northern and eastern flanks of the North York Moors, filling the Leven-Esk valley, but it did not mount either the prominent western escarpment or the high massif of the moors during the advance to glacial maximum limits in the Vale of York (Gregory, 1965). Despite the absence of glacial activity there are relatively few sites with a complete record of the complex vegetational and climatic changes associated with this period. These sites are Kildale Hall (Jones, 1977a; 1977b; Keen *et al.*, 1984), Seamer Carr near Stokesley (Jones, 1976) and Seamer, Flixton and Star Carr in the Vale of Pickering (Cloutman, 1988a; 1988b). These organic and inorganic sediments yielded substantial quantities of palaeoecological evidence, specifically pollen, plant macro-fossils and molluscs, which have provided a relatively complete history of the climate and vegetation changes associated with the late Devensian climatic amelioration. A chronology for this period is available at Kildale Hall, Seamer Car near Stokesley and the Carrs in the Vale of Pickering. The late Devensian environmental history for the North York Moors is summarised in table 2.4. This late Devensian vegetation sequence conforms with the established view of climatic change found in areas adjacent to the North Atlantic (Lowe *et al.*, 1994).

Holocene vegetation history of the North York Moors

The Holocene vegetation history for the North York Moors is derived from over thirty pollen profiles generated across the region. A summary of the Holocene vegetation history is presented

Table 2.4. Summary of Late Devensian climatic and vegetation changes on the North York Moors. Location and citation for the ^{14}C ages [a] Kildale Hall (Jones, 1977a). [b] Seamer Carr near Stokesley (Jones, 1976). [c] Seamer Carr in the Vale of Pickering (Cloutman, 1988b).

Stratigraphy	Age (BP)	North York Moors Vegetation	Climate
Holocene		Characteristic Flandrian vegetation changes	Warm
"Younger Dryas Stadial"	10,350 ±200[a] 12,010 ±130[c]	Herbaceous and shrub heath communities, with limited tree growth in isolated sheltered localities.	Cold
Late Glacial Interstadial "Alleröd"		Open birch woodland, with diverse herbaceous and shrub heath communities.	Warm
"Older Dryas Stadial"	13,042 ±140[b]	Reduction in tree birch, with increased abundance of open habitat shrubs and herbs.	Cold or unstable environment
"Bölling Interstadial"		Species-rich shrub and herb communities, with stands of tree birch.	Warmer
Devensian Glaciation	16,713 ±340[a]	Sparse herbaceous and shrub heath communities. Ice Covered in some places.	Cold

in figure 2.6. During the early Holocene the climate continued to improve and the landscape of the North York Moors was altered by the immigration of tree species, eventually leading to the formation of a mixed deciduous forest during the Mesolithic. Kildale Hall, Seamer Carrs (Stokesley),Tranmire Slack, West House Moss (Jones, 1976; 1977a; 1977b, 1978), Fen Bogs, May Moss, Harwood Dale Bog, Foul Sike (Atherden, 1976a; 1976b; 1979; 1989) and Moss Swang (Simmons, 1969) all contain evidence of woodland colonisation during the early Holocene. Woodland immigration commenced with pioneer colonising species producing a birch forest. Colonisation of the upland areas lagged behind the lowlands, with the development of a species-rich heath scrub and scattered *Betula* woodland. However, as the climate ameliorated *Betula* woodland covered the upland areas.

Corylus avellana infiltrated the *Betula* forests *circa* 9500 BP during the early Holocene, and subsequently after 9000 BP this *Betula-Corylus avellana* association was succeeded by a *Pinus-Corylus avellana* forest. With the exception of the 6550 BP *Alnus* rise, the chronology of early Holocene woodland colonisation on the North York Moors is not secured by ^{14}C dating and is derived by correlation with a standard British chronological sequence derived by pollen analysis (West, 1970; Godwin, 1975). The thermophilous trees, *Ulmus*, *Quercus*, *Tilia* and *Alnus*, began to invade the lowlands surrounding the North York Moors around 8000 BP, shortly after the establishment of the *Pinus* / *Corylus avellana* forest at higher altitudes. Between 8000 and 6600 BP the flora of the North York Moors evolved from a *Pinus* / *Corylus avellana* forest to a mixed deciduous woodland dominated by *Ulmus*, *Quercus*, *Tilia* and *Alnus*, with an under-storey of *Corylus avellana*.

A large part of the palaeoecological research on the North York Moors has concentrated upon the late Mesolithic, primarily after the development of this mixed deciduous forest. This research has produced a vast archive of palynological data from North Gill (Simmons, 1969; Simmons & Innes, 1988a; 1988b; 1988d; Simmons *et al.*, 1989; 1993; Turner *et al.*, 1993), other sites on Glaisdale Moor (Simmons & Innes, 1988 d) and Bonfield Gill Head on East Bilsdale Moor (Simmons & Innes, 1988 c). These pollen profiles identify a number of episodic woodland clearances, which have been divided into stability and disturbance phases (Simmons *et al.*, 1993). These phases are related to the activity of Mesolithic people clearing and thinning woodland to encourage larger accessible populations of game. Woodland clearance appears to be partially responsible for the onset of peat accumulation at several sites, especially in poorly drained localities. In summary, the Mesolithic vegetated landscape of the North York Moors can be described as an ever-changing mosaic of open woodland, cleared ground and regenerating

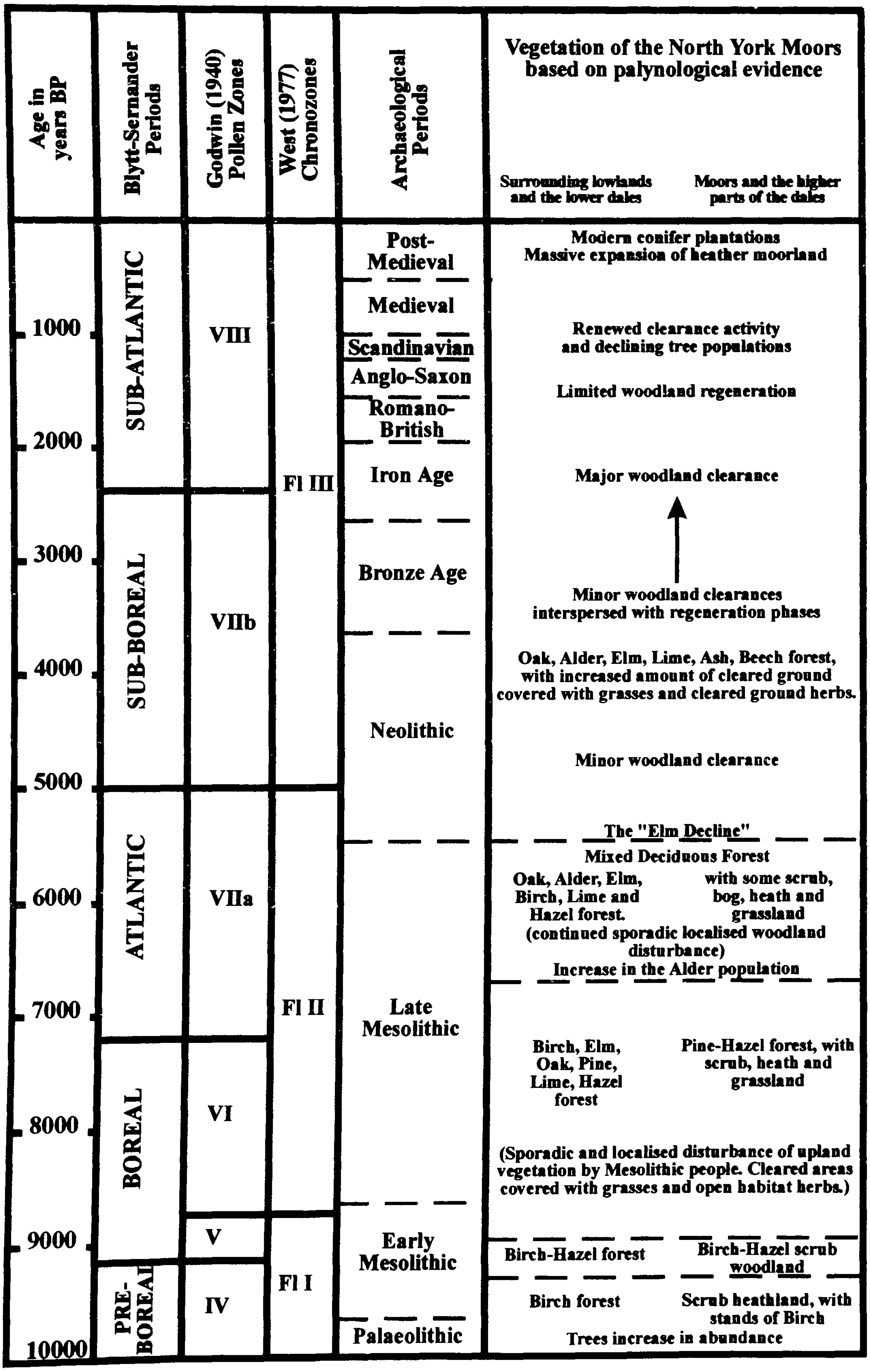


Figure 2.6. A summary of the Holocene vegetation history on the North York Moors modified from Simmons *et al.*, (1993), identifying the Blytt-Sernander periods, Godwin's (1940) pollen zones, West's (1977) pollen chronozones and the main archaeological periods (Spratt, 1993).

woodland communities, with semi-permanent areas of bog, heath and cleared ground (Simmons, 1995). This landscape has changed and evolved in response to a complex mixture of climatic change, migration of Mesolithic people, pedogenic factors and vegetational succession.

The cultural change to a farming economy associated with the Mesolithic-Neolithic transition had a significant impact on the vegetation of the North York Moors. The elm decline is a characteristic feature of north-west European pollen diagrams. On the North York Moors it is ^{14}C dated to 4767 ±60 BP at North Gill (Jones *et al.*, 1979) and 4720 ±90 BP at Fen Bogs (Atherden, 1976a). There are also declines in other arboreal species during the Neolithic, with significant woodland clearances identified at Fen Bogs, May Moss, Harwood Dale Bog (Atherden, 1976a; 1976b; 1979; 1989), Collier Gill, North Gill and Bonfield Gill Head (Simmons, 1969; Simmons & Innes, 1988a; 1988b; 1988c; 1988d). The Neolithic woodland clearances were by no means comprehensive, and woodland disturbance probably was only occurring on a limited and sporadic scale (Atherden, 1976b). Peat accumulation began at a number of sites during the Neolithic, including Bonfield Gill Head, Howdale Hill, White Gill and Moss Slack Goathland, which perhaps reflects a causal link between forest clearance and the inception of peat accumulation (Moore, 1986). The initiation of peat accumulation is the product of a number of factors, which include forest clearance, wetter climatic conditions and local impedance of drainage.

The first widespread destruction of woodland on the North York Moors occurred during the Bronze Age. Although woodland clearance had occurred during the Mesolithic and Neolithic, the decline in Bronze Age arboreal pollen and the abundance of Bronze Age archaeological remains on the moors denote woodland clearance and human activity on a much larger scale. Declines in arboreal pollen frequencies are evident at several sites including Fen Bogs, May Moss, Moss Slack Goathland, Harwood Dale Bog (Atherden, 1976a; 1976b; 1979; 1989) Wheeldale Gill and Loose Howe (Simmons & Cundill, 1974a). These clearances have been ^{14}C dated to 3210 ±90 BP at Wheeldale Gill (Simmons & Cundill, 1974a) and 3400 ±90 at Fen Bogs (Atherden, 1976a). These woodland clearances are the result of human pressure on the landscape, and although pastoralism probably was the dominant agricultural activity on the moors during this period, cereal pollen grains signify arable activity (Simmons *et al.*, 1993). Towards the end of the Bronze Age there is evidence of limited woodland regeneration, reflecting a reduction in agricultural pressure. This woodland regeneration may also reflect the impact of a climatic deterioration *circa* 3250-3000 BP during the late Bronze Age (Barber *et al.*, 1994a), which would have had a considerable impact on subsistence communities exploiting the upland moors.

A series of temporary woodland clearances characterises the early Iron Age. These clearances are evident in peat sequences from across the moors including the radiocarbon-dated profiles at Fen Bogs and Harwood Dale Bog (Atherden, 1976b; 1989). The most significant decline in the arboreal population of the North York Moors visible in pollen profiles occurs during the late Iron Age. This massive clearance has been ^{14}C dated to 2280 ±120 BP at Fen Bogs (Atherden, 1976b), 2190 ±90 BP at Harwood Dale Bog (Atherden, 1989) and approximately 2390-1570 BP at Wheeldale Gill (Simmons & Cundill, 1974a). During the Iron Age and the subsequent Romano-British period the population of the North York Moors increased, expanding the area of the landscape exploited for pastoral or mixed agricultural activity (Simmons *et al.*, 1993). Archaeological evidence suggests the population mainly occupied the southern hills and the bottoms of the dales. These settlement patterns probably represent the culmination of a trend begun in the Neolithic (Spratt, 1993). Low arboreal pollen frequencies occur at all palynological sites across the North York Moors throughout the Romano-British period, reflecting increased agricultural activity stimulated by economic prosperity during the period of Roman occupation.

The last 2000 years are of most interest in terms of the focus of this thesis, and the remainder of this section synthesises current understanding of vegetational and environmental changes during this period. The North York Moors at the end of the Iron Age was a largely treeless agriculturally exploited landscape, with remaining woodland limited to steep valley sides and the moorland edge. Figure 2.5 indicates palaeoecological evidence pertaining to the last 2000 years is available at several sites; however, only peat profiles from Fen Bogs, and to a lesser extent Wheeldale Gill and Harwood Dale Bog are secured by ^{14}C dates.

The Iron Age / Romano-British clearance phase terminates sharply at many sites, with an increase in the abundance of arboreal species recorded at Fen Bogs, May Moss and Harwood Dale Bog (Atherden, 1976b; 1979; 1989). The woodland regeneration is ^{14}C dated to 1530 ±130 BP at Fen Bogs, which is broadly synchronous with the Roman withdrawal from Britain. Although increases in the heliophytic trees, *Betula* and *Fraxinus*, are accompanied by a regeneration of *Quercus*, *Alnus* and *Corylus avellana*, pollen frequencies do not return to the levels in existence before the Iron Age/Romano-British clearance. Atherden (1976b) suggests that, although the Roman withdrawal had a significant impact on the land-use of the North York Moors, continued exploitation by native Britons, albeit at a reduced level, only allowed limited regrowth of woodland in marginal areas, for example the steep sides of the dales and the moorland edge.

After the initial woodland regeneration following the Roman withdrawal arboreal pollen frequencies begin to decline during the Anglo-Scandinavian period. This decline is evident at numerous sites on the North York Moors; however, only Fen Bogs has ^{14}C dates for this period. Atherden (1976b) found the woodland regeneration was particularly noticeable in heliophytic species, specifically *Betula*, *Fraxinus*, *Salix* and *Corylus avellana*, and that there was a subsequent decline in arboreal species extending up to 1060 ±160 BP at Fen Bogs. Atherden (1976a; 1976b) attributed the Anglo-Scandinavian woodland clearances to a period of more intensive agricultural activity, perhaps related to monastic settlement encouraging increased exploitation of upland marginal agricultural land and the peripheral lowland areas of the North York Moors.

Atherden (1976a) links historical records of tree felling within the Royal Forest of Pickering during the late Medieval period to further declines in arboreal frequencies. The Royal Forest is in the pollen catchment area for peat sequences at Fen Bogs, May Moss, Simon Howe Moss, Gale Field and Moss Slack Goathland. All of these sites display evidence of woodland clearance during the Medieval Period, which has been ^{14}C dated to 1060 ±160 BP at Fen Bogs (Atherden, 1976a; 1976b; 1979). There is a minor expansion of trees towards the end of the Medieval Period, evidenced at Fen Bogs, Gale Field and Moss Slack Goathland, which has been attributed to the impact of the Dissolution of the Monasteries in cal. AD 1536, which encouraged a reduced scale of agricultural activity in upland areas as the monastic estates were dispersed amongst lay farmers (Atherden, 1976a; 1979).

A decline in woodland species and an expansion of *Calluna vulgaris* can be identified towards the top of the pollen diagrams from Fen Bogs, May Moss, Simon Howe Moss (Atherden, 1976b; 1979), West House Moss (Jones, 1977) and Yarlsey Moss (Simmons & Cundill, 1974a). This arboreal decline is attributed to extensive woodland exploitation during the 17th and 18th centuries, and the *Calluna vulgaris* rise is the product of moorland expansion during the 19th and 20th centuries, produced by management of the upland moors to raise grouse. A further palynological change visible in peat sequences on the North York Moors entails an increase in pine frequencies and occasional spruce and fir towards the top of pollen diagrams. The increase in conifer populations is the product of modern commercial afforestation across the moors from the 1930s onwards.

Published palaeoclimate research on the North York Moors is not as comprehensive as investigations into the vegetation history. Previous analyses are limited to a single peat profile from Harold's Bog on Conisor Howl, East Bilsdale Moor (Blackford & Chambers, 1991; in press). This research analysed the degree of humification in a peat sequence and the humification stratigraphy was used to identify changes to a wetter mire surface. The palaeohydrological history is used to identify several shifts to wetter conditions *circa* 900-600 cal. BC, between 168 cal. BC and cal. AD 130, cal. AD 540-730, 890-1160, 1000-1260 and 1565, which are attributed to climatic change (Blackford & Chambers, in press).

2.6 Gaps in the palaeoecological history

The previous discussion identifies a considerable quantity of research carried out on the North York Moors; however, gaps can be identified in this established knowledge. At present, understanding of the vegetation history is hampered by a paucity of ^{14}C dates and an absence of fine-resolution pollen analysis pertaining to most of the Holocene, with the noticeable exception of the Mesolithic period where the North York Moors has both in abundance. There are few pollen sites away from the central sandstone moorland plateau and this lack of a complete regional coverage especially on the southern limestone hills is keenly felt (Simmons, 1995). A further gap involves the virtual absence of palaeoclimate research utilising the evidence contained within peat stratigraphy, with the exception of the research on East Bilsdale Moor (Blackford & Chambers, 1991; in press).

There is considerable scope for further research on the North York Moors using fine resolution pollen analysis and detailed ^{14}C dating to investigate Neolithic, Bronze Age, Iron Age and Historic peat sequences. Research of this type would redress an imbalance in palynological research on the North York Moors by concentrating on parts of the Holocene other than the Mesolithic. Simmons (1995) links the comparative lack of palynological investigation of the post-Iron Age to a relative absence of peat profiles pertaining to this period, and this problem may hamper future research. Research extending the spatial range of palynological sites would also be useful; however, this will be hampered by a paucity of peat away from the central sandstone plateau. Furthermore, peat stratigraphies on the North York Moors have been under-utilised as a source for palaeoclimate research and there are several ombrogenous peat sequences suitable for research of this type.

This thesis addresses two of these gaps, by carrying out a detailed palaeoclimatic reconstruction utilising the peat stratigraphy from five sites on the North York Moors. Previous palaeoclimate research is limited to stratigraphic analysis of a single site, which identifies changes to a wetter climate *circa* 168 cal. BC - cal. AD 230, cal. AD 540-730, 890-1160 and 1565. Additionally pollen analyses supplemented by ^{14}C dating will address the relative lack of radiocarbon dated palynological profiles pertaining to the last 2000 years. Current understanding of the vegetation history for the last 2000 years identifies woodland clearance phases *circa* 400 cal. BC - cal. AD 450, cal. AD 900-1450 and from cal. AD 1600 onwards, separated by limited woodland generation cal. AD 500-900 and AD1500-1600. These vegetation changes are correlated with periods of either enhanced or reduced agricultural exploitation of the uplands, which arise for a variety of reasons discussed in the previous sections. This thesis contributes a detailed regional climatic history elucidated from peat stratigraphy and improves current understanding of the regional vegetation history during the last two millennia on the North York Moors.

3

Peat stratigraphy: an archive of climate history

3.1 An introduction to peat-based palaeoclimate research

There is a vast amount of published research that uses the stratigraphy of ombrotrophic peat bogs to reconstruct past climate. Although palaeoclimate research utilising peat sequences began in the late 19th century, it is a resurgence of interest during the last 20 years that is responsible for many of the procedures currently applied in peat stratigraphic research. This resurgence of interest has seen a number of methodological advances within the field of mire palaeoecology. A semi-quantitative method of analysing the degree of peat humification popularised by Aaby (1976), has been rigorously assessed and improved by Blackford & Chambers (1993). Barber and a series of doctoral students have developed plant macrofossil analysis as a tool for identifying moisture shifts within peat stratigraphy (Barber, 1981; Haslam, 1987; Stoneman, 1993; Barber *et al.* 1994a; 1994b). Testate amoebae have long been utilised in investigations of peat stratigraphy (Tolonen, 1966; Aaby, 1976), but recent ecological research has enabled quantitative reconstruction of past environmental characteristics, for example the depth of the mire water table (Warner & Charman, 1994; Woodland *et al.*, 1998).

Van Geel (1978; 1986) attempted to identify and record all the micro-fossils encountered within a palynological preparation, which include numerous fungal and algal remains, an approach he complemented with plant macrofossil analysis of several Dutch peat sequences to produce detailed environmental histories. A different procedure for elucidating a climate history from peat deposits has recently been developed, which involves isotopic analysis. Brenninkmeijer *et al.* (1982) used ^{2}H/H and ^{18}O/^{16}O ratios determined from analysis of cellulose to reconstruct climatic variations. Subsequent research has tentatively linked fluctuations in isotope stratigraphies to changes in temperature and precipitation (Dupont & Brenninkmeijer, 1984; Dupont, 1986; van Geel & Middeldorp, 1988), thereby providing the most specific climatic information that has currently been obtained from peat sequences. This variety of palaeoenvironmental techniques allows detailed reconstruction of mire surface conditions and in some cases allows investigation of the precise nature of an environmental or climatic change, for example the depth of the water table or temperature. Peat stratigraphic research currently involves the utilisation of several palaeoecological techniques to investigate a sequence. This multi-proxy approach has the advantage that it increases confidence in the eventual environmental reconstruction, and it is now rare to find palaeoecological research investigating mire environments relying upon a single procedure.

During the past 120 years, like many sciences, peat stratigraphic research has experienced a number of paradigm shifts. The earliest palaeoclimate research using peat sequences divided the Holocene into the five broad climatic periods listed in table 3.1 (after Blytt, 1876; Sernander, 1908). This research held that layers of poorly decomposed *Sphagnum*-rich peat were indicative of a wetter, colder climate and well decomposed horizons of peat were attributed to drier, warmer periods, using evidence derived from the peat humification and plant macrofossil stratigraphy. The Blytt & Sernander scheme was not initially universally accepted and now is generally regarded as an oversimplification (Smith, 1981; Bell & Walker, 1993; Blackford, 1993; Ballantyne & Harris, 1994). However, the Pre-Boreal, Boreal, Atlantic, Sub-Boreal and Sub-Atlantic climatic periods are a cornerstone of Holocene research. Even though anxieties regarding regional correlation, stratigraphic resolution and geochronology reduce the value of the scheme (Smith & Pilcher, 1973; Birks, 1975; Smith, 1981; Blackford, 1993), it is still referred to in recent palaeoecological publications Simmons *et al.*, 1993 for example.

Table 3.1. The Blytt & Sernander post-glacial climatic periods (after Sernander, 1908).

Climatic Period	Climatic Conditions
Sub-Atlantic	Humid and at the beginning cool.
Sub-Boreal	Dry and warm.
Atlantic	Maritime and mild, probably with warm and long autumns.
Boreal	Dry and warm.
Pre-boreal	Undetermined climatic conditions.

Early research using peat stratigraphy to elucidate climate history concentrated upon features called recurrence surfaces (Weber, 1900). Recurrence surfaces are stratigraphic changes, in which well humified peat is succeeded by poorly humified *Sphagnum*-rich peat. Recurrence surfaces reflect an ecological and diagenetic response to increased availability of water on the mire surface (Blackford, 1993). Much of the peat-based palaeoclimatic research during the first half of the twentieth century concentrated upon identifying and correlating these recurrence surfaces between mires across north-west Europe, a strategy Barber (1982) describes as a "search for fixed points".

The other foundation to peat stratigraphic research during the first half of the twentieth century was the autogenic theory of bog evolution, which held that bogs were self-perpetuating systems with changes in peat stratigraphy reflecting replacement of a hollow environment with that of a hummock (Osvald, 1923; 1949). Tansley (1939) and Godwin & Conway (1948) have subsequently perpetuated the theory. The autogenic theory has also been referred to as the regeneration cycle theory or complex (Barber, 1981), and as the hummock-hollow cycle or complex. Figure 3.1 displays a diagrammatic representation of the autogenic theory, which demonstrates how a hollow through comparatively rapid peat accumulation can reach topographic parity with the surrounding hummocks and ridges, eventually transforming into a hummock. This process of mire evolution involves a change in local surface moisture conditions, which occurs independently of any external influences, for example mire drainage or climate. The autogenic hummock-hollow cycle is a neatly encapsulated closed system. Plant macrofossil and humification analyses were an integral part of research identifying these autogenic cycles (Osvald, 1923).

Clearly the existence of recurrence surfaces constitutes an interruption to the autogenic process of bog evolution, thereby denoting an allogenic impact on the mire environment. It became the established scientific orthodoxy that recurrence surfaces, the major changes in peat stratigraphy, were the only evidence of climate fluctuations contained within peat sequences, with the majority of the stratigraphic changes being the product of the hummock-hollow cycle (Barber, 1981; 1982). Recurrence surfaces were first identified by Weber (1900), who termed the major change in peat decomposition in north-western and central European mires the *Grenzhorizont*. Granlund (1932) developed this theme identifying five recurrence surfaces in Snoeroms Moss, a raised mire in Sweden. The recurrence surfaces were numbered RY I to V, and they occurred *circa.* 2300 BC, 1200 BC, 500 BC, AD 400 and AD 1200. This chronology was based upon correlation of palynological and archaeological evidence. Recurrence surfaces have been identified within the humification (Weber, 1900; Granlund, 1932), plant macrofossil (Granlund, 1932; Nilssen, 1935; 1961; Tolonen, 1966; Dickinson, 1975) and testate amoebae (Tolonen, 1966) stratigraphies of peat sequences across Europe.

The development of ^{14}C dating as a routine tool in palaeoecological research led to the questioning of regional correlation of recurrence surfaces. Features perceived to be an equivalent horizon yielded a variety of ^{14}C ages (Frenzel, 1983; Barber, 1981; 1982; Blackford, 1993). Haslam (1987) used a detailed program of ^{14}C dating to confirm a wide spread of ages for the Main Humification Change in mires across northern Europe. Despite the realisation that recurrence surfaces were not always regional phenomena and were an unsuitable basis for correlation of peat sequences, the detailed research involved in their identification had a number of benefits. Blackford (1993) ascribes a change in focus associated with this phase of research,

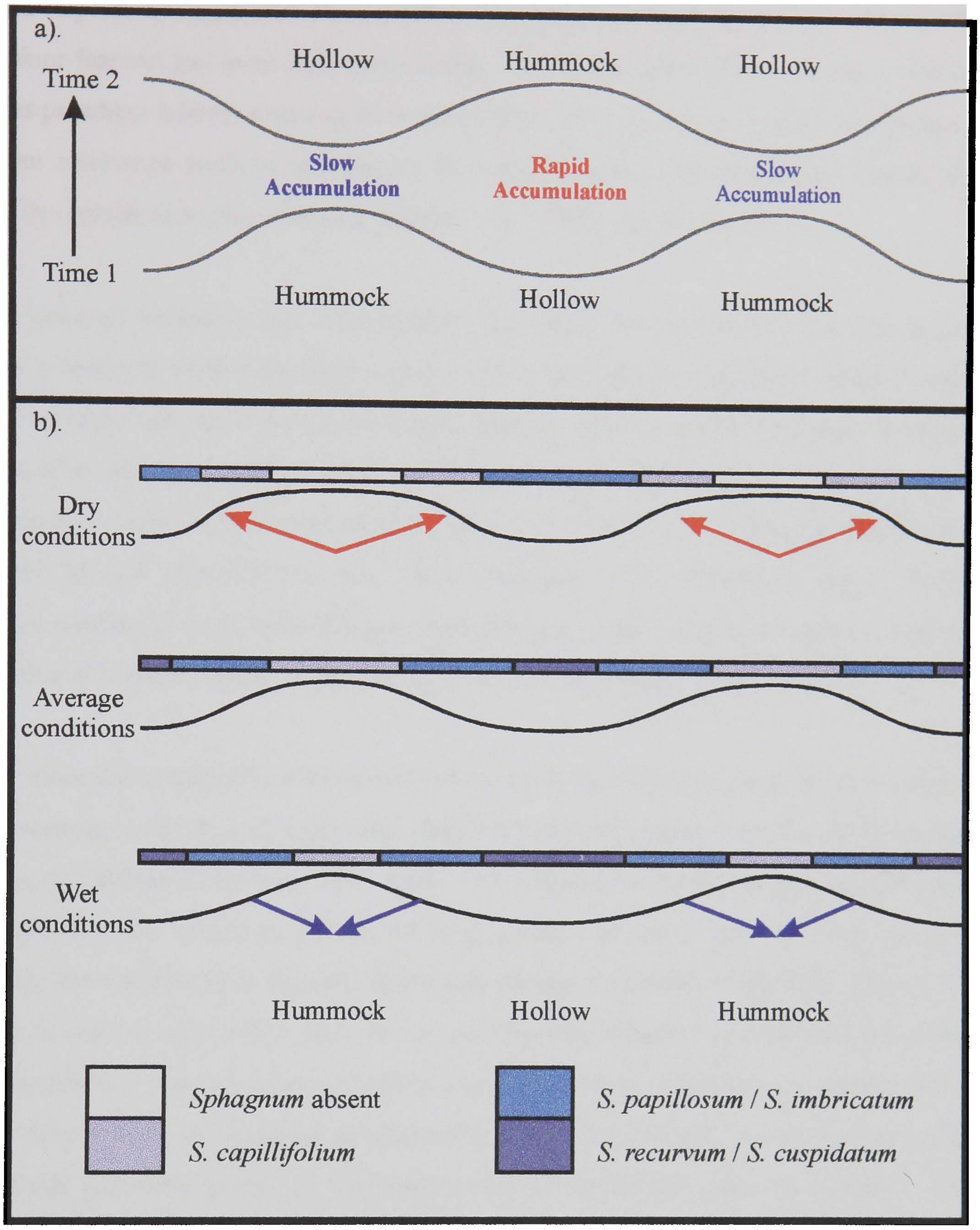


Figure 3.1.

a). A schematic stratigraphic cross-section across a hummock / hollow microtopography demonstrating the pattern of changes expected through time under the autogenic theory of mire evolution (after Osvald, 1923).

b). A schematic stratigraphic cross-section across a hummock / hollow microtopography, identifying the expansion (blue) and contraction (red) of habitats expected in a system controlled by climatically driven moisture changes (after Walker & Walker, 1961; Aaby, 1976; Barber, 1981). Also demonstrating the hypothetical distribution of *Sphagnum* communities expected on the North York Moors, under wet, average and dry conditions.

concentrating upon local fine-resolution variations in the recurrence surface record, which clearly contrasts with the regional low-resolution approach of the Blytt and Sernander scheme. This local emphasis is partially responsible for a greater understanding of mire hydrology, and for a focus upon minor features and local differences within peat stratigraphies. There are some drawbacks with this paradigm mainly involving the concentration on a narrow chronological period around the major recurrence surfaces, and arising from the imprecise and problematic climate history yielded by recurrence surface research (Barber, 1981; 1982; Blackford, 1993).

Despite research indicating that chronological correlation of peat sequences using recurrence surfaces is unsound, as discrete features they do represent shifts to wetter mire surface conditions and are an important focus for palaeoclimate research. Several studies have used humification analyses often integrated with other palaeoecological procedures to identify a number of periods favouring the formation of recurrence surfaces, *circa* 3850 BP, 3500 BP, between 2800-2200 BP, 2050 BP and 1400 BP (Tolonen, 1966; Dickinson, 1975; Blackford, 1993). The broad consensus unaffected by the chronological controversies is that recurrence surfaces form due to increased availability of water on the mire surface and they reflect a wetter climate.

Doubts about the validity of the hummock-hollow theory as a main cause of changes within peat sequences began to surface as researchers failed to find stratigraphic evidence of the hummock-hollow cycle (Walker & Walker, 1961; Aaby, 1976; Barber, 1981). It was becoming evident that hummocks had the ability to persist for long periods of time, with the hummock habitat expanding and contracting in response to climatic change or moisture availability. Barber (1981) formally tested the hummock-hollow theory investigating the plant macrofossil stratigraphy of Bolton Fell Moss, a raised mire in Cumbria and claimed to have falsified the hummock-hollow theory. Subsequently he proposed an alternative theory, the "Phasic" theory of bog evolution, which holds that mire growth is controlled above all by climate, with stratigraphic changes reflecting expansion and contraction of drier habitats in response to phases of dry or wet climate. The evolution of a mire conforming to the phasic theory is displayed schematically in figure 3.1.

Implicit in the phasic theory of bog evolution as proposed by Barber (1981), is that the plant macrofossil communities evidenced in the peat stratigraphy of an ombrotrophic mire will contain a continuous record of climate-driven moisture changes. This record will include climate fluctuations of the magnitude of recurrence surfaces and a series of less visual yet significant stratigraphic changes. Aaby & Tauber (1975) and Aaby (1976) suggest that climate was the major factor behind changes in the peat humification, plant macrofossil and testate amoebae stratigraphy of six Danish mires, supporting the view that climate is perhaps the most important factor controlling bog development. There has been a wealth of research on the mire environment since doubts were expressed about the chronology of recurrence surfaces and the validity of the hummock-hollow theory in the 1960s. This research includes attention to present day hydrological, chemical and ecological characteristics of the mire ecosystem, which have been synthesised in a number of excellent texts (Moore & Bellamy, 1974; Gore, 1983; Heathwaite & Göttlich, 1993).

The majority of peat-based palaeoclimate research has concentrated upon raised mires. However in recent years there has been an increase in research investigating the climate signal contained within ombrotrophic blanket peat. Tallis (1985; 1987; 1991; 1994; 1995) and Tallis & Livett (1994) present detailed analyses of the stratigraphy of blanket mires in the south Pennines, which include quantitative analysis of plant macrofossils. Tallis (1994) identified a series of shifts in mire surface wetness within the macrofossil stratigraphy at Alport Moor. There is a broad agreement between the climate curves generated from raised mire stratigraphies (Barber, 1981; Barber *et al.*, 1994a; 1994b) and the moisture signal identified in the peat stratigraphy at Alport Moor (Tallis, 1994). Blackford & Chambers (1991; 1993; 1995) and Chambers *et al.* (1997) used a humification procedure and uncovered evidence of changes in palaeohydrology within blanket mire peat sequences across the British Isles. These studies demonstrate the potential of upland ombrotrophic blanket peat, which currently is an under-exploited resource for palaeoclimate research.

The wealth of peat stratigraphic research has made substantial contributions to the understanding of climate history. This palaeoclimate history is more appropriately discussed alongside the research on the North York Moors in chapter 7. Recent methodological advances within the field of palaeoecology offer a range of opportunities for palaeoclimate research utilising blanket mire stratigraphy. Research of this type has not previously been applied to blanket mires of the North York Moors. The research presented in this thesis utilises three palaeoenvironmental procedures, assessing sub-fossil testate amoebae, plant macrofossils and the degree of peat humification to reconstruct mire palaeohydrology, and by inference past climate.

3.2 Analysing the degree of peat humification

Peat humification stratigraphy became a focus for palaeoenvironmental investigation because researchers became aware of a propensity for prolonged periods of dry climate to produce highly decomposed peat. Conversely, prolonged wet climate produces saturated mire surface conditions, which inhibit decay processes producing poorly decomposed peat. A logical progression of this state of affairs is that in fossil peat, well-humified layers will reflect a dry or hot climate and poorly humified layers will identify periods with a cold or wet climate. Two main processes of decomposition operate within peat bogs. Humification is the process by which organic matter is converted into humic substances, thereby losing cellular and tissue structure. Mineralisation involves microbial utilisation of organic matter, releasing carbon dioxide, water and other nutrients from the original plant material (Eggelsmann *et al.*, 1993). Both of these decomposition processes require the presence of active microorganisms to breakdown organic matter (Kuster, 1993). Peat comprises a mixture of primary or partially decomposed plant material and various humic substances, which accumulate because decomposition processes are negligible or occur extremely slowly under anaerobic conditions.

The abundance and composition of the microbial population varies with depth and the degree of aeration of the peat profile. Aerobic micro-organisms are responsible for humification, and so this only occurs in the aerobic surface layers of a mire. Anaerobic bacteria are not very abundant in peat, but they can occur throughout the peat sequence and are essential for the mineralisation processes to take place. Ingram (1978) termed this aerobic zone the "acrotelm" and the lower anaerobic zone the "catotelm". Many researchers indicate the rate of decomposition in the catotelm is either extremely slow or negligible, and the actual processes and rate of decomposition within the catotelm are poorly understood (Eggelsmann *et al.*, 1993). The transition from the acrotelm to the catotelm occurs within the surface layers of peat and the boundary is typically located at the depth of the average minimum summer water table (Ingram, 1978). The state of decomposition displayed by fossil peat reflects endurance of relatively rapid acrotelmic decay and slow/negligible catotelmic decay, both experienced during the sedimentary process.

The majority of decomposition experienced by peat appears to occur in the acrotelm above the water table prior to further burial, and so the degree of peat decomposition broadly corresponds to the amount of time spent in the acrotelm. The degree of humification displayed by deep peat reflects the depth of the acrotelm at the time of sedimentation. If peat is poorly humified the acrotelm was probably quite shallow and the water table was close to the surface, whereas well-humified peat is produced by a greater duration of acrotelmic decay indicating that the water table was deeper. In summary the degree of peat humification can be regarded as a semi-quantitative proxy record of average minimum summer water table depths, which if the mire is ombrogenous will reflect climatic conditions (Aaby & Tauber, 1975).

Early research assessed the degree of decomposition by means of visual examination of the peat sediment, which typically involved description of colour, identification of the main plant species and qualitative assessment of the degree of preservation displayed by the plant remains. Von Post (1924) developed a 10-point categorical scheme to describe the degree of peat humification qualitatively. Von Post's scheme is based on several descriptive characteristics, including colour, texture and the state of physical deterioration of plant remains, and has been widely used to describe sedimentary sequences normally in association with other palaeoecological techniques, for example pollen analysis.

In the wake of the falsification of the autogenic theory of bog evolution and chronological debate about recurrence surfaces, a new approach to peat-based palaeoclimate research has developed. The approach relies upon detailed systematic analysis of entire peat sequences, producing high-resolution palaeoenvironmental histories. In this context there are several methodological problems with the von Post peat humification classification, which arise because it is a classification producing qualitative results not recorded on a continuous measurement scale. Measurements on a continuous numeric scale are essential for the detection of short duration changes in peat humification. The von Post scheme is also subjective and dependent on the judgement of the individual researcher, an approach that is inadequate for identification of small-scale or cyclic changes in peat humification. Furthermore, the von Post scheme is reliant on *Sphagnum* remains for categories one to seven, which renders it of limited use in peat where *Sphagnum* species are either rare or absent. In some blanket mires the entire peat sequence will fall into categories 8-10, in which case the von Post scheme is of limited value for analysing small-scale changes in peat humification.

Various methods of quantifying the degree of peat humification have been developed, which assess the colour either of extracted peat water or a chemical extraction of humic acid. Troels-Smith (1955) devised a method for assessing humification, which involved squeezing the peat and dividing the extracted peat-water into five colour classes. Similarly Stoneman (1993) devised a "turbidity index" of peat humification, which assesses the quantity of disaggregated peat required to obscure a mark on the base of a water-filled measuring cylinder. Both these methods operate with the premise that the degree of humification is reflected in the abundance of dark humic substances contained within peat. The most significant methodological development in the analysis of peat humification, involved the creation of a technique that assesses humification on a continuous numeric scale. Aaby (1976) applied a chemical procedure, originally developed by Overbeck (1947) and Bahnson (1968), to assess the degree of humification in peat sequences from raised mires in Denmark. Aaby and Tauber (1975) used time series analysis of this humification signal to infer hydrological and climatic changes with a 260-year periodicity.

Humic acids are produced by decomposition of organic matter, with the quantity of humic acid increasing as plant remains decompose. The amount of humic acid in peat could provide a measure of the degree of humification. Humic acids are complex compounds and typically are dark brown in colour. The alkali extraction produces a brown solution and the darkness of this solution reflects the concentration of humic acid. The darkness of the solution can be measured on a spectrophotometer, which assesses the quantity of light either transmitted through, or absorbed by the alkali solution. The percentage of light transmission recorded on a spectrophotometer through an alkali extraction of humic acid is used as a semi-quantitative estimate of the degree of peat humification (Aaby, 1976; Blackford & Chambers, 1993). High percentages of light transmission identify a low humic acid content, and conversely low percentage light transmission indicates the extract is rich in humic acids. The percentage light transmission curve for a peat profile will identify changes in peat humification, which in turn will reflect changes in mire surface wetness. Blackford & Chambers (1993) rigorously tested the alkali-extract procedure and improved the methodological integrity of the technique, recommending several modifications.

Rowell & Turner, (1985), Blackford & Chambers (1991; 1993; 1995; in press), Chambers *et al.* (1997) and Caseldine *et al.*, (1998) have used the alkali extraction procedure in palaeohydrological investigations of mires across the British Isles. Humification stratigraphies have been used to reconstruct a Holocene climatic history for the British Isles, and have identified several phases of wetter climatic conditions during the last two millennia, *circa* 1450 BP, 550 BP and 300 BP (Blackford & Chambers, 1991; 1995). Wet climatic periods signified in peat stratigraphies appear to be concurrent with phases of reduced sunspot activity, and solar forcing has been proposed as a possible cause of climate change during the late Holocene (Blackford & Chambers, 1995). Linking the palaeoclimate history derived from peat stratigraphy with factors hypothesised as potential agents affecting or forcing global climate change is not without problems. A discussion of these issues at this stage is premature and the debate is presented in the context of the palaeoclimate history for the North York Moors in chapter seven.

3.3 Plant macrofossil analysis

The principal aim of plant macrofossil analysis is to reconstruct a history of the local mire vegetation from a palaeoecological sequence. The vegetation of an ombrotrophic mire is a complex community, which prefers environmental conditions that are inhospitable to a large number of species. These saturated acidic nutrient-poor conditions encourage the development of a low diversity flora dominated by ericaceous shrubs, sedges and bryophytes. The Sphagnaceae, a group of mosses particularly abundant on ombrotrophic mires, dominate the bryophyte community. Less abundant members of this blanket mire community, include *Drosera* spp., *Narthecium ossifragum*, *Molinia caerulea* and *Myrica gale*, amongst others (Heathwaite *et al.*, 1993a). The flora of blanket mires is not uniformly distributed across a complex micro-topography consisting of hummocks and hollows. Furthermore, each mire has individual environmental characteristics that affect the composition of plant communities.

Surface moisture conditions are identified as a critical factor controlling the distribution of plants, with certain species preferring specific environmental habitats - for example the tops of hummocks, sides of hummocks, hollows and pools. Individual species often prefer an environmental habitat a specific distance from the water table, and the abundance of plant species with specific moisture requirements can allow mire surface wetness to be monitored through changes in the composition of the mire flora. Changes in the mire flora have been used as a tool for monitoring a variety of environmental changes, including the assessment of hydroseral changes (Tallis, 1983) and the success of mire restoration schemes (Heathwaite *et al.*, 1993b; Buttler *et al.*, 1996).

The mire vegetation is transformed into peat through sedimentary and decompositional processes. The nature of the eventual peat sediment is controlled by the composition of the bioceonosis combined with the vigour of diagenetic processes. Dead plant matter loses cellular structure and mass as it is incorporated into the acrotelm, until after further sedimentation the plant remains reach the relative safety of the catotelm. The majority of decay experienced by dead plant material must occur before reaching this anaerobic zone, because rates of decomposition in catotelmic peat are very slow (Eggelsmann *et al.*, 1993). Despite the decomposition involved in transforming plant material into peat sediment, a large proportion of plant remains is preserved as fossils within the peat stratigraphy, and many of these sub-fossils are identifiable to species or sub-genus level (Barber, 1993).

Changes in the mire flora elucidated from the sub-fossils contained within peat sequences reflect the response of species or communities to various environmental parameters. Reconstructing climate change through analysis of plant macrofossils contained within peat stratigraphy is based upon two underlying precepts. Firstly, the mire under investigation must be ombrogenous, which provides a more or less direct link between surface wetness conditions and effective precipitation. Secondly, changes in mire surface wetness must be identifiable through ecological interpretation of the plant macrofossil history. In the absence of human interference, changes in mire surface wetness most likely reflect fluctuations in effective precipitation, thereby providing a proxy climatic record.

The change in emphasis associated with the establishment of the phasic theory (Barber, 1981), has necessitated a number of methodological advances in plant macrofossil analysis. Analysis of small-scale fluctuations in peat stratigraphy requires sequential sampling at a fine-resolution, and furthermore the abundance of plant macrofossils has to be assessed quantitatively. Traditionally, the abundance of plant macrofossils has been recorded either qualitatively as presence/absence data, or semi-quantitatively using a "rare, occasional, frequent, common and abundant" categorical procedure (Walker & Walker 1961; Tolonen, 1966; van Geel, 1978; Barber 1981). In fact much of the research questioning the synchrony of recurrence surfaces and the validity of the autogenic regeneration model relied on this semi-quantitative categorical scale (Walker & Walker, 1961; Aaby, 1976; Barber, 1981). In comparison with other palaeoecological techniques, for example pollen analysis, plant macrofossils have proved relatively difficult to quantify (Birks & Birks, 1980).

There are a number of problems with the rare, occasional, frequent, common, abundant scheme, which arise because the classification is dependent on the researcher's judgement of the abundance of plant remains. Additionally the scheme produces categorical data, which hinders the identification of small-scale fluctuations in the composition of *Sphagnum* communities and furthermore it is difficult to carry out quantitative analysis on categorical data. There are further problems arising from the unsystematic manner in which this categorical procedure has been used, with one or two samples extracted within pre-determined stratigraphic units (Barber, 1981). In order to extract fine-resolution climatic data, the peat stratigraphy must be sampled systematically using a close sampling interval.

Recent research at Southampton University has put plant macrofossil analysis of mire sediments firmly on a quantitative footing (Haslam, 1987; Stoneman, 1993). Haslam (1987) developed a "Quadrat and Leaf Count" method, in which the main peat components; Unidentified Organic Matter (UOM), Monocotyledonous remains, Ericaceae remains and Identifiable *Sphagnum* are identified and quantified. The *Sphagnum* leaf counts and estimated abundance of the main peat components are expressed as percentages. Stoneman (1993) modified the quadrat and leaf count method by expressing the *Sphagnum* leaf counts as percentages of the total identifiable *Sphagnum*, which gives the *Sphagnum* leaf counts equal weighting with the percentages of the main peat components. Barber *et al.* (1994b) used a weighted average ordination technique on this quantitative data to generate palaeohydrological curves, by giving each species a value reflecting respective moisture tolerance.

Barber *et al.* (1994a) used a different ordination technique, unconstrained detrended correspondence analysis (DCA), as a tool to interpret the macrofossil data objectively. Axis 1 of the DCA summarised the majority of the variation within the data set and appeared to identify a moisture gradient, with species preferring wetter environmental conditions (e.g. *Sphagnum* section *Cuspidata*) located at one end of the axis and species preferring drier environmental conditions (e.g. Ericaceae and *Sphagnum* section *Acutifolia*) grading to the other end. If DCA axis 1 does represent a moisture gradient the scores for each fossil sample on this axis provide a record of changes in mire surface wetness and by inference palaeoclimate. The sample scores on DCA axis 1 of a core from Bolton Fell Moss have been proposed as a more accurate model of Holocene climate change than produced by previous methods of interpreting peat sequences, namely recurrence surface stratigraphy and the Blytt-Sernander scheme (Barber *et al.*, 1994a).

Methodological developments improving the plant macrofossil analysis procedure have provided a means of quantitatively assessing the relative abundance of components within peat sequences. Perhaps more importantly, it has also become possible to analyse changes in plant macrofossil communities statistically and present semi-quantitative moisture gradients using various ordination techniques. This approach has the advantage of providing a long and continuous history of mire evolution, which in the case of an ombrotrophic mire can be viewed as a proxy-history of climate change.

3.4 Analysis of sub-fossil testate amoebae

3.4.1 Introduction

Protozoa in the subphylum Sarcodina and the superclass Rhizopodea are a group of freshwater organisms that produce tests or shells. These tests are readily incorporated and preserved within aquatic and semi-aquatic sedimentary sequences. They are the subject of a palaeoecological technique colloquially referred to as "testate amoebae analysis" (Warner & Charman, 1994) or "rhizopod analysis" (Tolonen, 1986). Research on testate amoebae is limited to mire, lacustrine and soil environments. However, this thesis relies entirely on analysis of peat sequences, and so the remainder of this section concentrates upon testate amoebae analysis as a palaeoecological tool for analysing peat sequences. Peat stratigraphic research using testate amoebae was first applied by Steinecke (1927) and subsequently testate amoebae analysis has been utilised by various researchers to investigate mire palaeoecology (Harnisch, 1927; Grospietsch, 1958; Tolonen, 1966; Aaby, 1976; Beyens, 1985; Warner & Charman, 1994; Woodland *et al.*, 1998).

Testate amoebae are a very abundant component of the microfauna of *Sphagnum* mires, with a biocoenosis of *circa* 1.6×10^7 live organisms m^{-2} and a necrocoenosis of *circa* 2.0×10^7 individuals

m^{-2} (Heal, 1962). This level of abundance combined with the fact that many species are readily preserved within peat, allows quantitative investigation of sub-fossil communities. Testate amoebae have a number of advantageous characteristics that render them an extremely useful tool for palaeohydrological research; for example a wealth of research into ecology of modern testate amoebae suggests that mire surface wetness is the most important control on the occurrence of species and the composition of communities (Heal, 1961; 1962; 1964; Meisterfeld, 1977; Harnisch, 1927; Schönborn, 1962; Tolonen *et al.*, 1992; 1994; Warner & Charman, 1994; Woodland *et al.*, 1998). Systematic accumulation of peat converts the necrocoenosis into a representative fossil assemblage, with no significant loss of species during the fossilisation process (Woodland *et al.*, 1998). The diversity of sub-fossil communities is typically high with *circa* 15 species per sample, with most testate amoebae taxonomically identifiable to species level in a sub-fossil condition. Additionally, many testate amoebae species display a reasonable turnover along a number of environmental parameters. These factors render testate amoebae analysis an extremely valuable tool for the interpretation of peat sequences.

Testate amoebae are unicellular organisms, which consist of a cytoplasm surrounded and protected by a single chamber test or shell. In the case of smaller testate amoebae the cytoplasm fills the test chamber. However, species with larger tests only partially fill the test chamber, attaching themselves to the wall with cytoplasmic strands extended from the cytoplasm (Ogden & Hedley, 1980). Typically the tests have either one or two openings which are utilised for both movement and feeding. Testate amoebae achieve mobility using flowing extensions to the cytoplasm, which are projected through an aperture. These cytoplasmic strands are called pseudopodia and are also used to adhere the test to the substrate. Taxonomic classification of testate amoebae is based on the form of the pseudopodia; however, this is of little use when analysing sub-fossil assemblages because the soft body parts are not preserved. The formation of the test is tied in with the reproductive cycle, with identical tests constructed on daughter cells prior to mytosis. In sub-fossil testate amoebae the manner of test construction, the sculpture, shape and size of the test and test aperture are used as taxonomically diagnostic features (Grospietsch, 1958; Ogden & Hedley, 1980; Heathwaite *et al.*, 1993).

Detailed ecological research on modern testate amoebae populations in Britain identifies that most species are active between May and October, followed by death or encystment during the winter (Heal, 1961; 1962; 1964). Testate amoebae appear to feed on bacteria, algae and fungi, with larger species preying upon other testate amoebae, diatoms and rotifers (Heal, 1964; Corbet, 1973; Ogden & Hedley, 1980). In addition some species, including members of the genus *Amphitrema*, digest symbiotic zoochloroellae, which live within tests, and derive food and energy directly from sunlight. Heal (1962) and Meisterfeld (1977) found that no living testate amoebae occur beneath the brown undecomposed section of Sphagnum moss, which can vary from a depth of 10-15 cm in very wet Sphagnum carpets to just beneath the mire surface in dry dense hummocks. The lack of living testate amoebae at depths in mires is due to the lack of interstitial gaps and the anoxic conditions prevalent in deep peat (Tolonen, 1986). There is vertical variation in the occurrence of species in the surface layers of *Sphagnum* moss, with species sustained by symbiotic zoochloroellae displaying a maximum abundance in the top 6 cm, because they require light to survive. Species without symbiotic zoochloroellae have their maxima at depths between 6-12 cm, perhaps reflecting a need for peat and mineral particles for test construction (Meisterfeld, 1977). Beneath *circa* 15 cm very few living testate amoebae occur and the necrocoenoses are gradually converted into fossil assemblages.

3.4.2 Ecology of modern testate amoebae

Palaeoecological research requires a full understanding of the ecological and environmental requirements of modern populations. Tolonen (1986) and Warner & Charman (1994) recommend caution in the use of sub-fossil testate amoebae until more is known about the distribution and ecology of modern communities. This caution is surprising given that testate amoebae have been a subject for research since the early 20th century (Steincke, 1927). There is a substantial body of published literature on the ecology of modern testate amoebae (Harnisch, 1927; 1951; Schönborn, 1962; 1964; 1967; Grospietsch, 1953; 1958; Meisterfeld, 1977; 1979). A problem arises because few ecological measurements of the habitats preferred by modern testate amoebae have been obtained by direct field analysis (Heal, 1964; Meisterfeld, 1977). This imbalance has been recently re-addressed to some extent (Tolonen *et al.*, 1992; 1994; Charman & Warner, 1992), and continues to be addressed in research (Woodland, 1996; Woodland *et al.*, 1998). Despite these problems there is a broad agreement that habitat moisture conditions are the most important of the environmental parameters affecting the distribution of species. Many species are sufficiently stenotopic to be placed within substrate moisture categories and early research on their ecology concentrates on analysing the species assemblages associated with specific moisture conditions (Harnisch, 1927; Grospietsch, 1958; Schönborn, 1963). Other environmental factors affecting the distribution of testate amoebae include acidity of the mire water, the trophic conditions and, in the case of testate amoebae that construct their tests from detritus, the availability of material.

Early research on the ecology of testate amoebae communities assigned species to categories using a long-established moisture-conditions classification scheme, with each category possessing a distinctive assemblage of testate amoebae (Harnisch, 1927; Grospietsch, 1958). The testate amoebae communities associated with the four categories are displayed in table 3.2, alongside a description of the moisture conditions. Harnisch (1927) and Grospietsch (1958) also proposed a series of diagnostic communities for a variety of mire habitats including forested mires, fen mires, bog pools and bog hummocks. Schönborn (1962) and Meisterfeld (1977) improved the classification of testate amoebae communities by linking the occurrence of species to moisture conditions, using the eight-point categorical scheme displayed in table 3.3. Direct linkage of the occurrence of testate amoebae species with specific ecological conditions is a preferable interpretative tool to the broad groups devised by Harnisch (Heathwaite *et al.*, 1993a; Tolonen, 1986). The moisture classes and representative testate amoebae assemblages form the ecological basis for much of the published palaeoecological analyses of subfossil testate amoebae (Tolonen, 1966; Beyens, 1985).

The resurgence of interest in peat-based palaeoclimate research during the last decade has had a particular focus upon methodological advances (Blackford, 1993). In the case of testate amoebae analysis this has necessitated comprehensive quantitative assessment of the environmental preferences of modern testate amoebae. Surveys carried out in Finland (Tolonen *et al.*, 1992; 1994), Canada (Charman & Warner, 1992) and Great Britain (Woodland, 1996; Woodland *et al.*, 1998) have quantified the average ecological preferences and the range of environmental conditions tolerated by most testate amoebae species.

Tolonen *et al.* (1992; 1994) assessed the impact of water table depth, percentage moisture content of the substrate, trophic conditions, acidity of the mire water, electric conductivity of the mire water, peat bulk density, calcium content, nitrogen content, the carbon:nitrogen ratio and quantity of dissolved organic carbon upon the distribution of testate amoebae at ninety micro-sites from six mires in Finland. Two of the mires were ombrotrophic raised mires and the other four displayed a wide range of trophic conditions. Tolonen *et al.* (1992) suggest this selection of sites is representative of the range of unmodified mires in this area of Finland. Detrended correspondence analysis of the data attributes 70% of the variation in the distribution of testate amoebae species to these environmental parameters (Tolonen *et al.*, 1994). The most important factors in decreasing order of importance were identified as the depth of the water table, soil moisture content and trophic conditions. Charman & Warner (1992) carried out a similar survey on 107 microsites representative of a wide range of managed and unmanaged habitats on a forested peatland in north-eastern Ontario, Canada. The distribution of testate amoebae species was most strongly affected by depth of the water table, moisture content of the substrate and acidity of the mire water (Charman & Warner, 1992). Both these studies converted the raw data summarising the environmental conditions tolerated by individual testate amoebae species into

Table 3.2 Moisture categories and typical testate amoebae species assemblages (after Harnisch, 1927; Grospietsch, 1958).

Moisture Category	Moisture Conditions	Characteristic species
Tyrphoxene	Dry or drained peat or moorland	*Hyalosphenia subflava, Bullinularia indica, Trigonopyxis arcula*
Xerophilous	Moderately dry mire habitat	*Bullinularia indica, Assulina muscorum*
Hygrophilous	Damp to wet mire habitat	*Nebela collaris, Assulina seminulum*
Hydrophilous	Very wet mire habitat	*Amphitrema flavum, Amphitrema wrightianum*

Table 3.3. Testate amoebae communities associated with the average water content of the substrate categories of Jung (1936), according to Schönborn (1963) and Meisterfeld (1977).

Moisture Category	Average water content of the substrate	Characteristic species.
I	Open water or submerged vegetation. >95%	*Arcella discoides*
II	Floating vegetation, partly submerge and partly at the surface. >95%	*Amphitrema stenostoma* *Amphitrema wrightianum*
III	Emerged vegetation, very wet, water drops out without pressure. >95%	*Hyalosphenia papilio* *Amphitrema flavum*
IV	Wet, water drops out with weak pressure. ~95%	*Hyalosphenia elegens* *Hyalosphenia papilio* *Arcella artocrea*
V	Half wet, water drops out with moderate pressure. 95-85%	*Arcella artocrea*
VI	Moist, water drops out with strong pressure. 90-85%	*Corythion dubium*-type *Assulina muscorum* *Assulina seminulum*
VII	Half dry, a few drops with strong pressure. <80%	*Assulina muscorum*
VIII	Dry, no water drops out with strong pressure. <50%	*Bullinularia indica* *Trigonopyxis arcula* *Hyalosphenia subflava*

weighted averages and weighted standard deviations. These values are quantitative estimates of the optimum environmental preferences and the range of environmental conditions tolerated by testate amoebae species.

The ecological research of Woodland (1996) is particularly pertinent for this research project, because it involves quantitative assessment of the environmental preferences and the range of environmental conditions tolerated by testate amoebae in the British Isles. The survey utilised 163 micro-sites from nine peatlands distributed across England, Scotland and Wales. The survey assessed the impact of the mean annual water table depth, percentage moisture content of the substrate, bulk density, vegetation cover, acidity, electric conductivity and temperature of the mire water, and the Cl^{1-}, SO_4^{2-}, Ca^{2+} and Mg^{2+} ionic content of a mire water sample on the occurrence of testate amoebae. Canonical correspondence analysis of the data indicated that mean annual water table depth and percentage moisture content of the substrate were the most important environmental parameters controlling the distribution of species (Woodland *et al.*, 1998).

This research in Finland, Canada and Britain has moved understanding of testate amoebae ecology from the qualitative base of the 1960s and 1970s (Harnisch, 1927; Grospietsch, 1958; Schönborn, 1962; Meisterfeld, 1977). Currently testate amoebae analysis is based on a rigorous quantitative ecological approach, which potentially renders it an invaluable tool for environmental monitoring of peatlands (Buttler *et al.*, 1996). Numerical estimation of the environmental conditions preferred by testate amoebae species has allowed quantitative reconstruction of palaeohydrology using ecological transfer functions (Warner & Charman, 1994; Woodland *et al.*, 1998). Quantitative coupling of the ecological tolerance and sub-fossil abundance of testate amoebae has greatly advanced testate amoebae analysis as both an ecological and palaeoecological tool.

3.4.3 Testate amoebae analysis as a palaeoecological tool

Testate amoebae were first utilised in palaeoecological research by Steinecke (1927), and by Harnisch (1927) and Grospietsch (1958). Early palaeoenvironmental research using testate amoebae concentrated on clarifying the changes in mire surface wetness integral to the Blytt/Sernander scheme. Testate amoebae analysis has proven useful in peat-based research investigating recurrence surface stratigraphy (Frey, 1964; Tolonen, 1966). Tolonen (1966) used testate amoebae stratigraphy to identify the regeneration or 'hummock/hollow' complex in a Finnish peat sequence. It should be noted that Barber (1981) suggests this site is different from most raised mires, and regional correlation of recurrence surfaces and the status of the 'cyclic regeneration theory' are difficult to sustain in the light of subsequent research (Walker & Walker, 1961; Aaby, 1976; Barber, 1981; 1985; Haslam, 1987).

Aaby & Tauber (1975) and Aaby (1976) made use of testate amoebae, alongside pollen analysis, humification analysis and quantification of the abundance of *Sphagnum* remains to reconstruct a 5,500 year surface moisture history for raised mires in Denmark. Aaby identified units where *Assulina* spp. and *Amphitrema flavum* were abundant, which were interpreted as indicative of a wetter mire surface. Aaby attributed fluctuations in mire surface wetness to cyclic climate changes, not to the autonomic wet/dry fluctuations of the hummock/hollow regeneration cycle. Unfortunately, Aaby (1976) eliminated a number of species by using a pollen preparation procedure, which selectively removes species by sieving and chemically destroying certain tests (Hendon & Charman, 1997). However, only two genera were counted and both do not appear to be affected by this procedure; consequently these results are of interest identifying a broad agreement between surface moisture information derived from testate amoebae and other palaeoenvironmental procedures. Beyens (1985) reconstructed climatic conditions from a Sub-Boreal peat sequence in Belgium, by assigning moisture content classes developed by Meisterfeld (1977) to the peat stratigraphy based on the sub-fossil testate amoebae communities. The moisture classes were assigned to the sub-fossil testate amoebae assemblages allowing the generation of a relative surface wetness curve, which summarised mire surface moisture conditions between *circa* 4680 and 3200 BP.

Palaeoecological research prior to the 1990s was based on qualitative or semi-quantitative assessment of the present-day ecology of testate amoebae. Warner & Charman (1994) used transfer functions to link the optimum environmental tolerances of modern testate amoebae with sub-fossil assemblages to reconstruct the moisture content of the substrate and depth to the water table for a mire in north-west Ontario during the last 6500 years. This procedure aided the interpretation of the palaeoecological sequence by examining the evolution of a mire from a limnic environment to a relatively wet *Sphagnum*-dominated peatland. Using the optimum ecological tolerances of modern testate amoebae to reconstruct past environments from sub-fossil assemblages in this manner is at an embryonic stage as a quantitative palaeoecological tool. Warner & Charman (1994) demonstrate the considerable potential of this approach, but they suggest that much more research is required on the ecology of testate amoebae, and at this developmental stage they recommend that these surface wetness curves are only used as a semi-quantitative aid to palaeoenvironmental reconstruction.

Woodland *et al.* (1998) used a British ecological data-set to reconstruct water table depth fluctuations during the last 1,500 years from sub-fossil testate amoebae communities based upon analysis of a peat core from Bolton Fell Moss, Cumbria. Quantitative reconstruction of environment parameters of this type is a significant development in peat-based palaeoclimate research, because the magnitude of moisture changes can now be assessed rather than relying upon the semi-quantitative assessments produced by plant macrofossil, humification and until recently testate amoebae analysis. The reconstructions of water table depth derived from testate amoebae allow the comparative performance of other palaeoecological procedures to be assessed against a quantitative palaeoenvironmental parameter. Research of this type is currently at an embryonic stage and is further advanced in the context of ombrotrophic blanket mires in this thesis.

3.4.4 Problems and limitations with testate amoebae analysis

The previous two sections discuss a series of recent developments in testate amoebae analysis, which suggest that the future of palaeoecological research reconstructing mire water table depths lies in quantitative environmental estimations derived using modern ecological data (Charman & Warner, 1992; Warner & Charman, 1994; Woodland *et al.*, 1998). In spite of a resurgence of interest in testate amoebae and these methodological developments a number of problems remain. Firstly, there are only three data-sets describing the environmental conditions preferred by modern testate amoebae, measured in Finland (Tolonen *et al.*, 1992), northern Ontario, Canada (Charman & Warner, 1992) and Britain (Woodland *et al.*, 1998). This record of modern testate amoebae communities is by no means comprehensive and data from a wider set of geographical locations and environmental conditions is required before testate amoebae analysis can offer a reliable quantitative model for reconstructing past environments. Quantitative reconstruction of environmental parameters should only be attempted if there is modern ecological data for that particular region.

The multivariate statistics, employed by Charman & Warner (1992), Tolonen *et al.* (1994) and Woodland *et al.*, (1998), reveal that not all the variation in the distribution of species can be attributed to the environmental parameters assessed. It is possible this may be due to the incomplete geographical and environmental coverage within the ecological data, but there are also problems with the individual ecological data-sets. Charman & Warner (1992) obtained more samples from micro-sites with a 75-95% moisture content, because testate amoebae were more likely to occur than at drier sites. Although this selection procedure introduces an inherent bias in the weighted averages, it should be overcome as research progresses increasing the range of habitats or environmental conditions sampled.

The response or distribution of testate amoebae along an ecological or environmental gradient can be modelled by a Gaussian curve, with a species most abundant at the ecological optimum and decreasing away from the optimum (Birks, 1995). The weighted standard deviations express the range of environmental conditions tolerated by testate amoebae, which indicates that some species are extremely stenotopic, whereas others are eurytopic, with an optimum occurrence over a wide range of environmental conditions. The ecological transfer functions use the entire fossil assemblage to generate a weighted average reconstruction of an environmental parameter. Therefore this reconstruction is based on a range of stenotopic and eurytopic species, and consequently it will be an approximation. Eventually, after substantial improvements in the knowledge of testate amoebae ecology, it may be possible to base an environmental reconstruction solely on stenotopic species, but at present this is an inadvisable approach (Woodland *et al.*, 1998).

The mire surface wetness data are presented as estimates of both water table depth and percentage moisture content (Charman & Warner, 1992; Tolonen *et al.*, 1992). This is a problem, because the assessments of the ecological parameters were derived on single field visits, producing 'snap-shot' ecological data. The degree of surface wetness will be affected by the season in which the measurement was made and by antecedent weather conditions. Surface wetness should be measured continuously over several years, but in many cases this would be prohibitively expensive and time consuming.

Woodland *et al.* (1998) address this problem in the context of the British data-set, by basing the ecological research at sites recording mean annual water table information. For the first time the occurrence of testate amoebae species are linked with a meaningful environmental parameter - the mean annual depth of the water table. It is possible to calculate numerical estimates of environmental parameters from sub-fossil testate amoebae, which are broadly equivalent to the reconstructions of salinity possible using sub-fossil diatom assemblages and palaeotemperature histories derived using sub-fossil Coleopteran communities. One reservation with these numerical estimates arises because testate amoebae are active between May and October, which implies that perhaps mean summer water tables operate a greater control over testate amoebae communities than the mean annual water table. Consequently at sites with pronounced seasonal water table variations the value of the reconstructed mean annual water table depths can be questioned. At present it is difficult to envisage or realise a solution to some of the problems introduced above, but fortuitously for this research the geographical range of ecological data does cover the British Isles (Woodland *et al.*, 1998). Despite the remaining problems testate amoebae analysis offers a great deal to the mire palaeoecologist, because this type of 'quantitative' reconstruction outperforms many other palaeoenvironmental techniques.

3.5 Problems with peat-based palaeoclimate research

The resolution and precision of the palaeoclimate signal available from peat causes problems. The taxonomic and ecological resolution of palaeoecological analysis affects the sensitivity of the climate signal yielded by ombrotrophic peat stratigraphy. This problem is best exemplified by species within *Sphagnum* section *Acutifolia*, which contains a number of species capable of inhabiting a wide range of moisture conditions. Unfortunately it is not possible to identify subfossil *Sphagnum* section *Acutifolia* leaves to species level, and so *Sphagnum* section *Acutifolia* are of limited value for palaeohydrological research. The ideal palaeoecological site will have a stratigraphy containing several identifiable species which clearly fluctuate in response to changes in bog surface wetness (Barber, 1993).

Accumulation and decay rates in peat bogs are so slow that potentially not all the climatic shifts will be represented in the peat stratigraphy. The degree of peat decomposition depends on the depth of the water table or acrotelm over a long period of time, and so peat humification effectively summarises average surface wetness conditions over a decade or more, thereby reducing the resolution of the climate signal. Precision in this type of research is inherently constrained, because a definitive climatic variable cannot be elucidated from peat stratigraphy. Humification, plant macrofossil and testate amoebae analyses effectively only identify qualitative oscillations between a dry mire surface and a wet mire surface, and it is impossible to identify whether these conditions arise from changes in precipitation or temperature (Aaby, 1976). A palaeoecological technique reconstructing mire surface wetness only provides a history of precipitation received by the mire surface after losses through evapotranspiration, surface flow and mire seepage.

Problems arise from anxieties about the link between surface wetness and the evidence recorded in peat stratigraphy. Environmental factors other than mire surface wetness can affect peat stratigraphy. The plant remains forming the peat will affect the rate of decomposition, because some species decay more rapidly than others. Coulson & Butterfield (1978) measured the rates of decay of different plant species, revealing that *Calluna vulgaris* and *Eriophorum vaginatum* decay more rapidly than *Sphagnum*, which has implications for plant macrofossil and humification analysis. Blackford & Chambers (1993) suggest the impact of plant species may actually enhance the palaeohydrological signal contained in the humification record. Peat stratigraphy dominated by *Sphagnum* is likely to have accumulated under relatively wet conditions, which is an environment likely to produce relatively poorly humified peat. The tendency of *Sphagnum* remains to decompose slowly will contribute to the formation of poorly humified peat, thereby enhancing the indication of a wet environment. The reverse is trúe of Ericaceae remains, which decay rapidly and are typical of a drier mire environment. This is a combination of environmental conditions and plant species likely to encourage the production of well-humified peat.

There is also considerable variation in the rate of decay between sections of the same plant. Aerial parts of vascular plants decay rapidly, for example the cotton-grasses (e.g. *Eriophorum*) and Ericaceae (including *Calluna vulgaris*, *Erica tetralix*, *Vaccinium oxycoccus*, *Andromeda polifolia*), whereas *Sphagnum* remains decay relatively slowly (Coulson & Butterfield, 1978). Consequently the proportions of leaves, twigs and stem fragments of vascular plants preserved in peat may not be an accurate reflection of their past abundance. Despite these problems assessment of the varying proportions of plant remains, the quantity of Unidentifiable Organic Matter and the degree of peat humification allow the generation of a detailed local vegetation history (Barber, 1993).

The importance of mire surface wetness as a factor controlling the nature of peat stratigraphy should not rule out the possibility of other factors affecting changes. Stoneman *et al.* (1993) discuss the problematic decline of *Sphagnum imbricatum*, a species that is very abundant in Holocene peat. A variety of reasons has been proposed to explain the decline of *Sphagnum imbricatum*, for example it is possible that in hollow or lawn environments *Sphagnum imbricatum* has been out-competed by other species, e.g. *Sphagnum magellanicum*. The environmental niche occupied by *Sphagnum imbricatum* may have contracted during the late Holocene, becoming limited to hummock tops. Anthropogenic industrial pollution during the last 200 years contributing additional nutrients into the system is another possible cause of the decline in *Sphagnum imbricatum*. It is difficult to prove any of these theories conclusively, but perhaps more importantly this issue indicates that changes in the ecological preferences of species and a wide range of environmental changes must be considered when interpreting palaeoecological profiles.

Mires are characterised by an uneven surface covered with hummocks, ridges, hollows and pools. This microtopographic variation controls local surface moisture conditions, which has an impact on the distribution of plant and testate amoebae species. Peat stratigraphy may vary across a mire because of differences in the depth of the acrotelm beneath an undulating surface topography. The possibility of local variations in acrotelm depth affecting the humification signal suggests reconstruction of mire palaeohydrology should not be based on a single humification profile. This problem can be overcome by description of the detailed field stratigraphy if a cut-section is available; however, in actively accumulating mires cut-sections are seldom available. Detailed analysis of several closely spaced cores extruded along a levelled transect describing the current micro-topography would assess whether the humification stratigraphy is representative of the mire as a whole, improving confidence in eventual palaeoenvironmental interpretations.

The various microenvironments have differing degrees of sensitivity to climate change. An outcome of the falsification of the autogenic regeneration theory, was that hummocks are viewed as more stable long-lived features (Aaby & Tauber, 1975; Aaby, 1976; Barber, 1981), with the hummock habitat expanding and contracting from a stable centre in response to climatic change. Barber (1981) suggests that hollows or *Sphagnum* lawns will be more sensitive to moisture changes than the relatively stable hummock centres. The palaeohydrological record beneath a hollow or *Sphagnum* lawn will display a greater range of fluctuations than peat stratigraphy beneath a hummock, where the hydrological record may be more subdued due to the stability of hummock centres. The topographic high of a hummock perhaps acts as a natural buffer to the extremes of surface saturation caused by climatic fluctuations. Tallis (1994) contests this view holding that wet shifts recorded in hummock stratigraphy are undeniably a response to an allogenic change in the mire hydrological budget and the record of major hydrological changes is recorded with greater clarity because of the stability of hummock centres.

Changes in the composition of the mire vegetation and surface moisture conditions do not always occur in response to climate change. Under stable climatic conditions due to the accumulation of sediment, growth of the mire surface could out-pace upward migration of the mire water table (Aaby, 1976), which would produce a drying trend in the peat stratigraphy identical to that produced by a drier climate. Aaby (1976) suggested that only changes to a wetter mire surface could be attributed to climate with any degree of confidence. This point emphasises that whilst many researchers have rejected “cyclic regeneration” as a mechanism for mire evolution, autogenic processes remain an important component affecting mire evolution. Heathwaite *et al.* (1993a) assert that it is impossible in analysis of peat stratigraphy to tell whether a change to a wetter or drier mire surface was caused by autogenic or allogenic factors. However, if a substantially drier mire surface can be identified in peat stratigraphy across a mire, it probably reflects a large-scale change in the mire moisture budget, which implies an external cause.

Palaeoecological analysis of mires across Northern Europe indicates that some regions are more sensitive to climate change than others. Haslam (1987) found that bogs in Poland and Germany endure a continental climate experiencing less frequent and lower magnitude changes in surface wetness than bogs formed under the oceanic climate of western Europe and Britain. The geographical location of a mire must be considered when interpreting the climatic signal. This is particularly pertinent with regard to this project investigating upland blanket mires on the drier east coast of Britain, which will provide a valuable contrast with much of the published peat-based palaeoclimate research in the British Isles, which typically utilises raised mire peat stratigraphies in the wetter west.

The problems introduced in this section are not insurmountable and peat stratigraphies have been used with considerable success in Holocene palaeoclimate research. To generate an accurate hydrological and climatic history it is important to assess whether the stratigraphic changes occur across the mire, either by recording a detailed field stratigraphy or by analysing several cores. The consistency of stratigraphy can be assessed if cut sections are available by recording the field stratigraphy or by analysing a series of closely spaced cores extruded along a levelled transect describing the current microtopography. Either approach will assess whether stratigraphic changes occur independently of microtopography. If the peat stratigraphy across a mire contains evidence of fluctuations in surface wetness, this indicates that significant changes have occurred within the hydrological budget of the mire. An allogenic change of some magnitude is required to alter the hydrology of a mire, by altering either the amount of water received or the ability of the mire to retain water. Drainage of a mire, by either unnatural alteration (human induced) or natural processes (bog-bursts), and climatic fluctuations are the only likely causes of changes in the hydrological budget of a mire.

The research strategy employed in this thesis ensures that environmental and ecological factors are not overlooked in the quest for a palaeoclimate history. This is achieved by using a series of cores along a levelled transect, which will assess the permanency of hummocks and hollows, and identify whether autogenic changes in mire microhabitat are responsible for changes in moisture conditions. External forcing of changes in the mire moisture budget is more likely when surface wetness changes occur across the mire within adjacent microhabitats. Regional climate change and drainage arising from land-use changes are the most likely allogenic factors affecting mire hydrology. Additionally, several palaeoecological techniques are integrated to corroborate the surface wetness signal, which involves analysing sub-fossil plant and testate amoebae communities, and analysis of the degree of peat humification. This integrated and rigorous approach should ensure that analysis of peat stratigraphy will provide a valuable record of past environmental conditions and specifically a history of surface saturation.

3.6 Objectives and context for palaeoclimatic research of the North York Moors

Peat stratigraphic research has had an important role in unravelling a history of Holocene climate change in the British Isles. Methodological advances during recent years have allowed detailed fine-resolution climatic histories to be reconstructed from peat stratigraphy in various locations across the British Isles, including Cumbria (Barber, 1981; Haslam, 1987; Stoneman, 1993; Wimble, 1986), the Scottish Borders (Chambers *et al.*, 1997), the Humberhead Levels (Smith, 1985), the Pennines (Tallis, 1994) and Ireland (Blackford & Chambers, 1995; Caseldine *et al.*, 1998). The quality of this palaeoenvironmental research has improved in many ways over the years, with now virtually all the palaeoenvironmental techniques recording information on a continuous numeric scale. This approach has the advantage that it is possible to discern relatively minor fluctuations in palaeoenvironmental histories, which is a clear improvement upon concentrating on the major stratigraphic events, such as recurrence surfaces and the Blytt/Sernander zones. This numeric approach has encouraged fine-resolution sampling within a peat sequence, because if relatively minor stratigraphic changes can be identified, detailed analysis is worthwhile. In the past the constraints inherent in qualitative and categorical data have rendered systematic high-resolution analysis of limited value.

Despite the advances of recent years it is not possible to elucidate a direct unproblematic climatic variable from peat stratigraphy. The foundation of palaeoclimatic interpretation of peat sequences remains unchanged, which is that mire surface wetness reflects the amount of effective precipitation received by a site, but there have been considerable improvements in the power of each palaeoenvironmental technique. The nature of the palaeoenvironmental signal derived from each technique is the basis for the division of the techniques into three distinct categories. The first category of technique allows the direct numerical reconstruction of a climate variable, such as temperature for example. At present, isotopic analysis of cellulose remains from within peat sequences is the only technique that allows direct reconstruction of specific climatic parameters - in this case, temperature and precipitation. It was not possible to use isotopic analysis within this research, because of a lack of time and the appropriate equipment. The second category includes techniques that allow the numerical reconstruction of environmental parameters, such as salinity or acidity, for example. Testate amoebae analysis is the only technique that falls within this category, because it currently allows mean annual water table depth and percentage moisture content of the substrate to be reconstructed using ecological transfer functions. The third category of technique allows inferences to be made about specific environmental parameters, without producing a quantitative estimate of that environmental parameter. The degree of peat humification is controlled by the mean summer water table and, by inference, effective summer rainfall (Blackford, 1993). The distribution and occurrence of *Sphagnum* species, *Calluna* *vulgaris*, Cyperaceae and other mire plants is controlled by the mean height of the water table. The data produced by these techniques will reflect responses to climate change, and methodological advances within each technique have allowed production of data on a continuous measurement scale. However, data of this type do not provide a direct reconstruction of an environmental parameter, but allow a series of changes to be inferred from a proxy palaeoenvironmental curve.

Despite a wealth of research, the range of techniques currently available and a reasonable geographical distribution of peat sequences, the potential of the palaeoclimate history contained within peat has yet to be fully realised. This thesis addresses several gaps within peat stratigraphic research, for example by redressing an understandable spatial imbalance within peat-based palaeoclimate research. The eastern half of Britain is not a prime site for the accumulation of peat deposits, and it displays a paucity of raised and blanket mires in comparison with the wetter west. Previous peat-based palaeoclimate research in eastern England is limited to the investigation of single peat sequence on East Bilsdale Moor on the North York Moors (Blackford & Chambers, 1995; in press) and extensive analysis of the Humberhead Levels (Smith, 1985).

The contribution made by this thesis is to produce a palaeoclimate history for the North York Moors, expanding a growing database of peat stratigraphic research within the British Isles. The results from the North York Moors must be viewed in the context of the range of climatic conditions that occurs across the British Isles. Annual rainfall on the North York Moors is currently around 1000ml, which is substantially less than that received by mires in western Britain. This research examines the response of an endangered habitat to climatic changes within a comparatively dry region. Peat stratigraphies of mires in eastern Britain may contain clearer evidence of the impact of drier climatic periods than sites in the wetter west.

The majority of peat-based palaeoclimate research has utilised raised mire peat sequences. This tendency has been redressed to some extent in recent years (Blackford & Chambers, 1991; 1993; 1995; in press; Tallis, 1994; Chambers *et al.*, 1997) and this thesis contributes to this process by targeting upland ombrotrophic blanket mires on the North York Moors. Using a combination of testate amoebae, plant macrofossil and humification analysis to elucidate climate history from blanket peat is a development upon previous research, and should provide a rigorous test of the performance of blanket peat stratigraphy and the palaeoecological procedures used to uncover climate histories from peat.

The multiple technique approach utilising testate amoebae, plant macrofossil and humification analysis assesses the comparative performance of the palaeoenvironmental approaches. This will address some important questions including:

- Do the environmental signals respond at the same time or is there a time-lag between different techniques?
- Do the techniques identify the same environmental changes or do they have different thresholds before a change is recorded in the fossil record?

Combined with the integrated palaeoecological strategy is a multiple-profile approach, in which several cores are analysed from the same site. Analysis of several profiles will identify whether there are significant variations across a mire and will assess whether the information derived from a single core is a representative sample of the stratigraphy as a whole. The strategy designed to analyse peat sequences on the North York Moors attempts to assess the consistency of the stratigraphies at each site and provide a comprehensive test of the comparative performance of each palaeoenvironmental technique when investigating ombrotrophic blanket peat stratigraphy.

4

Research methodology

4.1 Introduction

The research objectives of this thesis divide neatly into two broad areas. Firstly, peat stratigraphies on the North York Moors are analysed in order to reconstruct regional vegetation history. Secondly, several palaeoenvironmental procedures are utilised to elucidate a history of surface moisture conditions at several ombrogenous blanket mires, thereby providing a record of climatic fluctuations. This thesis concentrates upon the last 2000 years of vegetation and climate history, because this time period proved logistically possible in terms of the available peat sequences. Additional research paralleling the palaeoecological analysis, investigates the historical evidence for landscape and climate change on the North York Moors and only identifies sufficient coverage of documentary material during the last 1500 years (James Menuge, 1997; unpublished). The vegetation history of the North York Moors is reconstructed from the results of palynological investigations, supplemented with macrofossil analyses of the local mire flora. The pollen analysis has two main objectives: firstly to provide a chronological framework for correlation of peat sequences, and secondly to redress an imbalance in previous palynological research on the North York Moors, which apart from a few notable exceptions (Jones, 1977b; Atherden, 1976a; 1979), concentrates extensively on the earlier periods of the Holocene. The palaeoclimate research utilises testate amoebae, plant macrofossil and humification analysis to investigate the surface wetness history of a mire.

This chapter presents research methodology, defining the rationale for site selection and the field sampling methodology. The five palaeoecological sites are introduced, presenting information about location, topography, sedimentary evolution and present vegetation cover of each mire. The pollen, plant macrofossil, humification and testate amoebae analysis laboratory methodologies are introduced, with reference to previous research and recent methodological developments. Dating the peat sequences relies on ^{14}C age determinations and palynological marker horizons. The geochronological strategy utilised for each peat sequence is defined in the following sections. Finally the format used to present the palaeoenvironmental results is introduced, which defines the analytical process and statistical procedures utilised to assist with interpretation.

4.2 The criteria and methodology of site selection

Mires intended to produce palaeoclimatic information should all be ombrotrophic, because there is link between mire surface saturation and effective precipitation. Effective precipitation exerts considerable control upon mire surface wetness, which in turn affects the peat stratigraphy. The principal aim of this research is to uncover detailed vegetation and climate histories for the last two millennia, and so the peat sequences must have been accumulating throughout the period. Rapidly accumulated peat offers the best stratigraphic resolution for uncovering palaeoecological histories. The requirements outlined above present problems for palaeoecological research on mires in Britain today. The blanket mire habitat is under threat at a regional, national and international level (Heathwaite *et al.*, 1993a). In Britain 90% of the area formerly covered by blanket mire has been lost, with currently only around 125,000 hectares remaining (Royal Society for Nature Conservation, 1990). Blanket mires on the North York Moors are under attack on several fronts. Peat extraction or cutting is a major threat to the mire habitat at a national level, but is only a minor player in the conflict on the North York Moors.

There is currently low key hand-cut extraction taking place at Harwood Dale Bog and evidence of unmechanised peat extraction elsewhere on the central watershed of the North York Moors. It is possible that peat extraction may have occurred on a larger scale in the past, but several factors argue against widespread peat extraction on the North York Moors. Firstly, peat does not accumulate evenly or to great depths across the topography of the moors, with areas of deep peat either localised or limited to the flat plateau of the central watershed. Secondly, peat is not a particularly good fuel in comparison to wood or coal; consequently it is regarded as an emergency fuel for use when other sources are either in short supply or prohibitively expensive, and apart from during the last few centuries there has been plenty of wood available on the North York Moors (James Menuge, 1997).

The major assault on the peatlands of the North York Moors involves changes in land-use activity. Between 1853 and 1986 the area of moorland vegetation boundaries of North York Moors National Park has declined from 49% to 35% (Statham, 1989). The moorland landscape has been gradually converted into improved farmland and forestry. Since 1853 the area of improved farmland within the boundaries of the current National Park has fluctuated around 40% of the total area, which may reflect recent attempts to conserve the moorlands and perhaps more significantly that farming on the improved farmland proved far from lucrative. Between 1904 and 1986 the area of land covered with forestry in the National Park has increased by 15%, which identifies commercial forestry as most significant threat to peatlands on the North York Moors

(Statham, 1989). In the 1920's the Forestry Commission purchased land and commissioned vast conifer plantations on the moors at Dalby, Bickley and Hackness. Further plantations followed at Wykeham and Cropton, with smaller plantations across the Tabular, Cleveland and Hambleton Hills. In some areas these plantations threaten and have damaged areas with deep peat, for example on Harwood Dale Moor and at May Moss. In recent years there has been a growing awareness of the value and rarity of unmodified mires; consequently various methods have been used to try and protect these endangered habitats, for example conferring SSSI status on Fen Bogs and May Moss. Additionally bodies like Forest Enterprise have become involved in the conservation of the remaining mires and are even contemplating clearing planted trees around May Moss, expanding the area of blanket moor.

Large areas of the remaining moorland are managed for grouse-rearing. Management of moorland involves regularly burning the heather to maintain a vegetated environment blanketed with young heather, mainly *Calluna vulgaris*. Regularly burning the surface of mires will reduce the amount of organic matter deposited inhibiting peat accumulation and may actually damage the mire surface. This process also reduces the floristic diversity on the moors producing an artificial *Calluna vulgaris* monoculture. Management for grouse-rearing has also involved drainage of boggy areas and the construction of grouse-butts across deep peat sites, as for example on Yarlsey Moss in October of 1996. Severe fires have also damaged large areas of the moor, as for example the fires on Wheeldale Moor, in the dry summer of 1976, which damaged deep peat sites at White Moor and Blue Man-i'th'-Moss.

In summary, the picture for actively accumulating ombrotrophic peat on the North York Moors is very bleak. This project entails palaeoecological investigation of recently accumulated ombrotrophic peat and unfortunately the land-use history of the North York Moors suggests this type of environment is very rare. Consequently several strategies were used to identify potential sites rapidly. The large quantity of published palaeoecological research on the North York Moors was reviewed, identifying sites with a sedimentary history for the last 2000 years. The vegetation history of the North York Moors is discussed in chapter two, and age range of the peat sequences examined in previous research confirms the anxiety that palaeoecological profiles pertaining to the last 2000 years are not abundant.

The NCC Phase 1 Habitat Survey contains information about the distribution of blanket mire on the North York Moors (Nature Conservancy Council, unpublished). This survey examined the entire National Park, assessing the current vegetation and grouping areas into a series of habitat categories. The category of interest (E1) identifies unmodified bog, blanket bog and raised bog, which typically have a *Sphagnum*-rich vegetation over peat deposits more than 0.5 metres deep (Nature Conservancy Council, 1990). This category is subdivided into four units. Raised bogs are ombrotrophic mires and have been the basis for the majority of palaeoclimate research using peat stratigraphy (Barber, 1981; Aaby 1976). However, these are typically lowland features and do not occur within the North York Moors National Park. The category blanket bog will identify actively accumulating ombrotrophic peat sequences on the North York Moors, especially if they occur in water-shedding locations. The final two categories are wet and dry modified bog, referring to former blanket mire affected by peat cutting, heavy grazing, burning or drainage. Modified mires will have peat deposits of over 0.5 m, but unfortunately the potential of the stratigraphy may be reduced by truncation of the peat sequence.

The NCC Phase 1 habitat maps identified that the majority of the actively accumulating deep peat sites are located in the eastern half of the North York Moors and most have been investigated before. Much of the published palaeoecological research on the North York Moors used pollen analysis to reconstruct vegetation history; whereas the intention of this research is to reconstruct mire palaeohydrology from peat stratigraphy. This thesis uses a series of sites in the east of the North York Moors, all of which have been previously investigated using the technique of pollen analysis. May Moss SSSI, Fen Bogs SSSI, Yarlsey Moss, Harwood Dale Bog and Bluewath Beck are the sites that form the basis of the research and these sites are identified on figure 4.1. Several other sites, also identified on figure 4.1, received a preliminary investigation to assess their viability for further research.

4.3 Palaeoecological sites

4.3.1 May Moss SSSI

May Moss SSSI covers almost 1 km^2 centred on the grid reference SE 876 960 and is identified on figure 4.2. The site is the largest remaining area of actively accumulating blanket mire on the North York Moors and probably in eastern England. The site is an ombrotrophic watershed mire at an altitude of 244 metres, accumulating on the headwaters of the southward-flowing Long Grain and Grain Beck, and the northward-flowing Eller Beck. The topography and drainage patterns suggest that the site is both water-shedding and largely ombrotrophic. The peat has accumulated directly over a bedrock of weathered Middle Jurassic sandstone of the Osgodby Formation. Atherden (1972; 1979) used pollen analysis to construct an 8000-year vegetation history for May Moss.

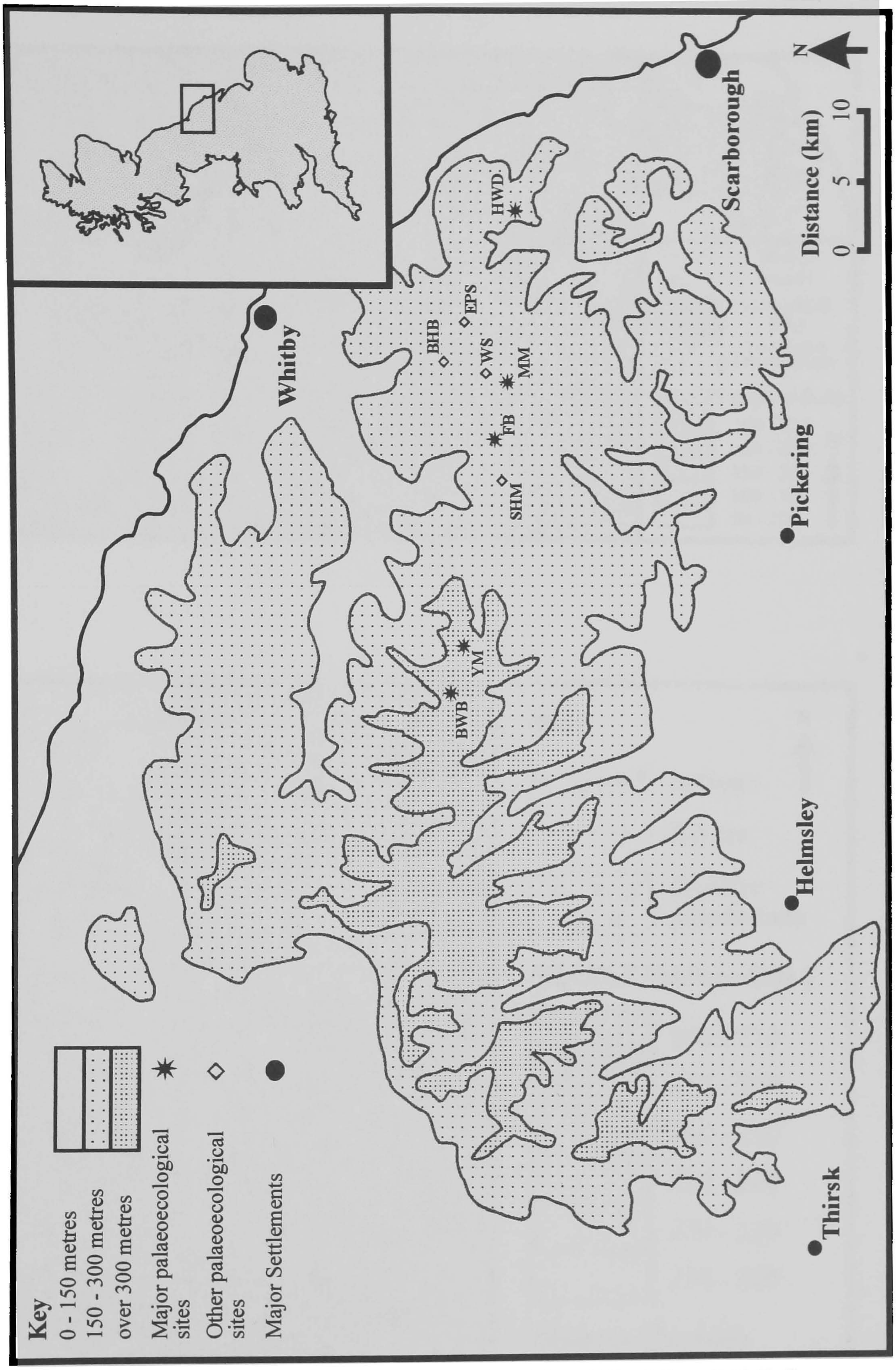
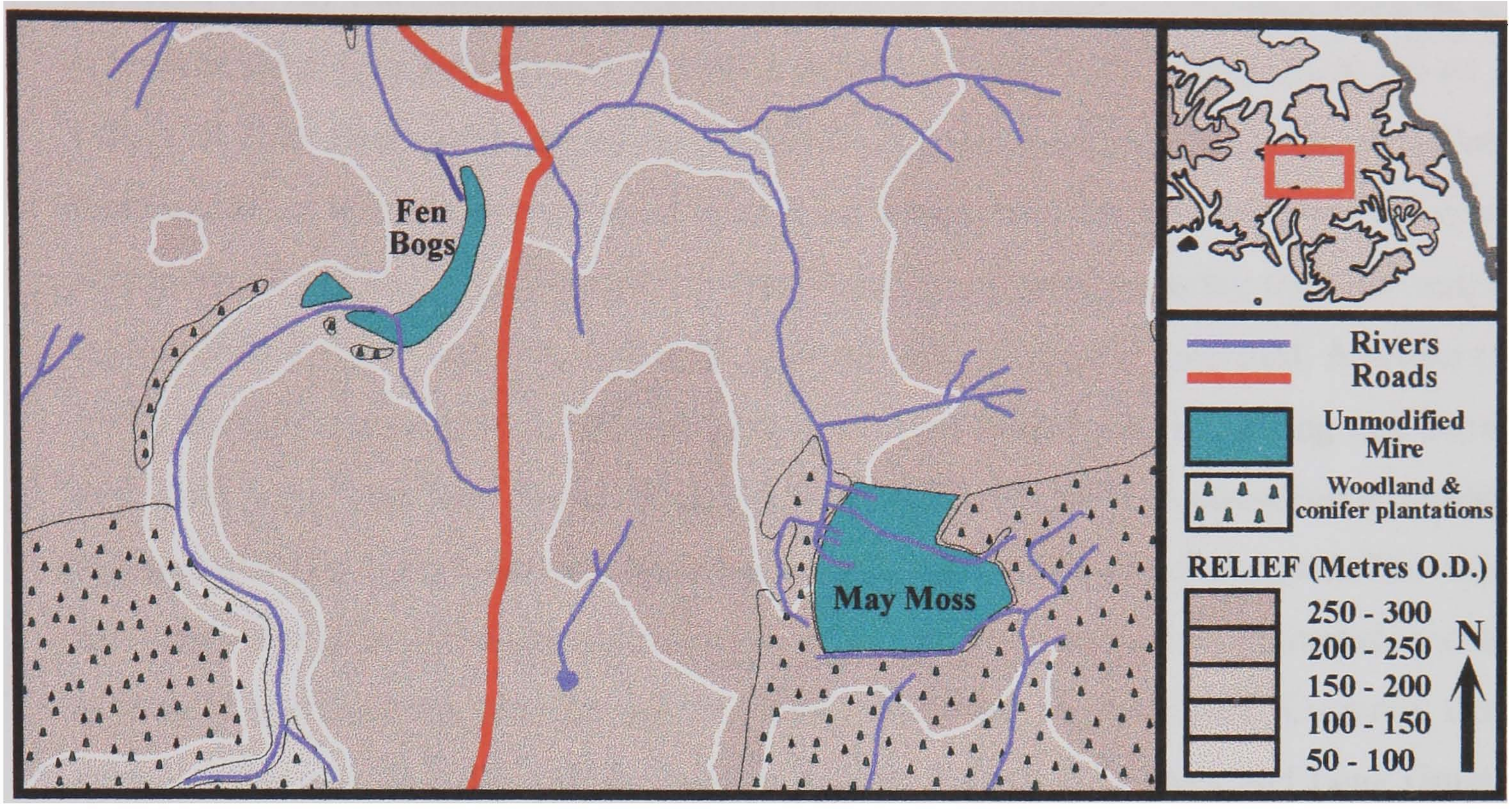


Figure 4.1. Location of the main palaeoecological sites; May Moss (MM), Fen Bogs (FB), Yarlsey Moss (YM), Bluewath Beck (BWB) and Harwood Dale Bog (HWD), and additional sites receiving a preliminary investigation; Simon Howe Moss (SHM), Worm Sike (WS), Blea Hill Beck (BHB) and Ewe Pond Slack (EPS).

a).



b).

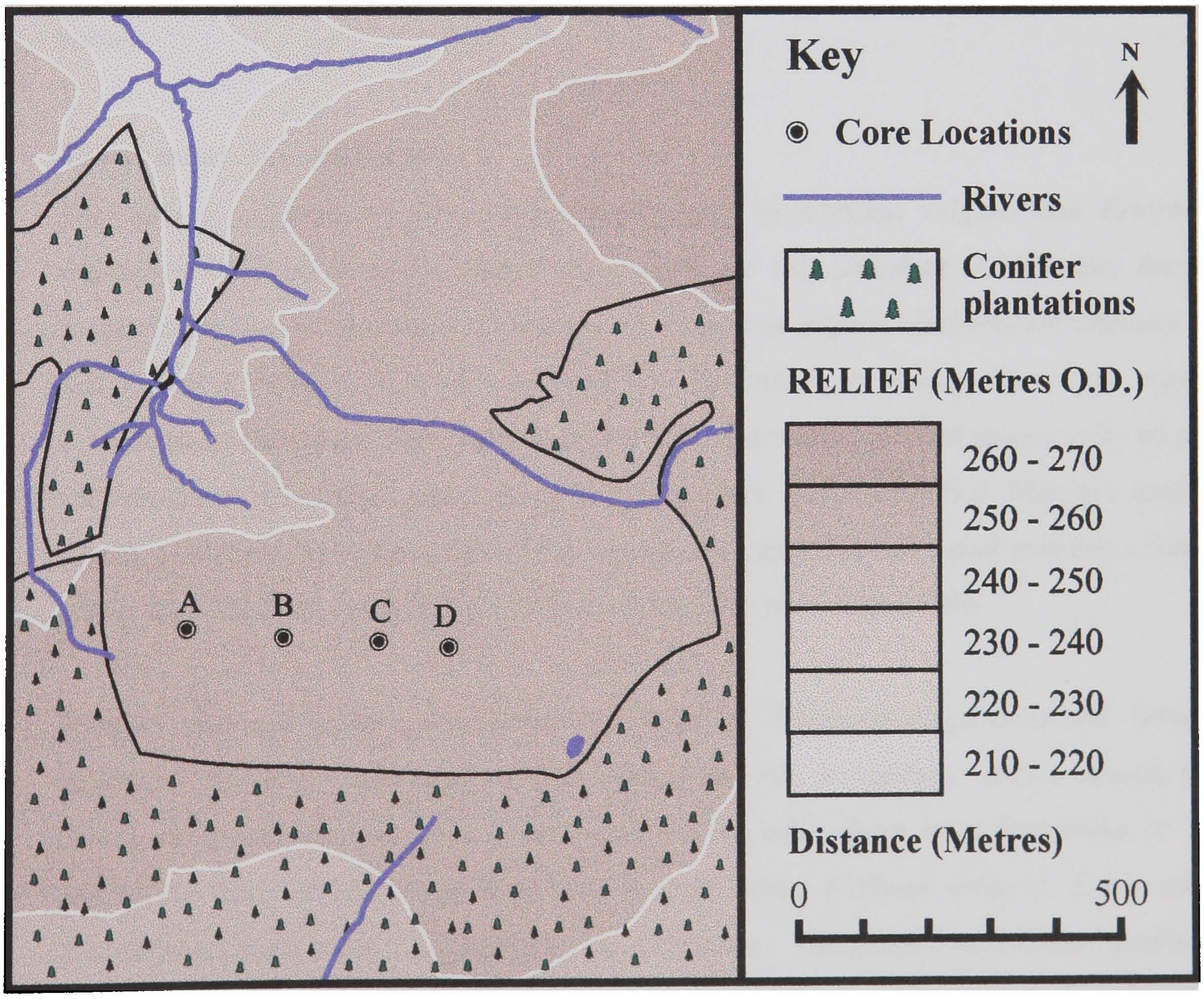


Figure 4.2.
a). Location of May Moss and Fen Bogs, North York Moors, northeast England.
b). Location of the core sites, and the landscape around May Moss SSSI.

Sedimentary Evolution of May Moss

Atherden (1972) extruded thirty test cores to investigate the peat stratigraphy and peat depths across the site. These investigations identified peat depths of over five metres (max. 6.4 m) in the valleys of Eller Beck and Long Grain, which indicates peat accumulation probably initiated in these wet areas, with Monocotyledonous peat accumulating over bedrock, and a basal detrital soil rich in wood and charcoal fragments. In time peat accumulated covering the mire watershed: consequently the peat depths are shallower with only 3 metres on the watershed. Atherden (1972; 1979) analysed a core from the deepest part of the Eller Beck basin, identifying that during the last 2000 years over two metres of peat had accumulated. Further investigation during this research indicates that on the mire watershed similar accumulation rates operated. This supports the interpretation of the sedimentary history, in which peat accumulation initiated in channels eventually spreading up over the shallow incline blanketing the watershed. Currently the mire surface is broadly flat, although the mire does slope towards Eller Beck and Long Grain. The stratigraphic borings made by Atherden (1972) and borings made during this research reveal the peat stratigraphy consists of alternating layers of *Sphagnum*-rich and monocotyledonous peat, confirming that the mire was covered with a typical blanket bog flora throughout the sedimentary history.

The present-day vegetation

The surface vegetation of May Moss is dominated by *Calluna vulgaris* and *Eriophorum vaginatum*. *Sphagnum* species and *Erica tetralix* are also abundant. Additionally there are occasional to locally abundant occurrences of *Empetrum nigrum*, *Eriophorum angustifolium*, *Narthecium ossifragum*, *Drosera rotundifolia*, *Vaccinium oxycoccus*, *Vaccinium myrtillus*, *Andromeda polifolia* and *Rubus chamaemorus*. The distribution of plant species is by no means uniform across May Moss and a series of habitat types can be identified. Moisture conditions appear to control the composition of the vegetation in each habitat. Local moisture conditions across May Moss are controlled by the hummock-hollow micro-topography.

Pools or saturated hollows are typically colonised by *Sphagnum cuspidatum* and *Sphagnum recurvum*. *Drosera rotundifolia* is not widespread, but it typically occurs around pools. *Sphagnum papillosum* and *Sphagnum magellanicum* either form large hummocks or occur around the base of hummocks close to the water table. *Calluna vulgaris*, *Erica tetralix*, *Eriophorum vaginatum*, *Eriophorum angustifolium*, *Vaccinium oxycoccus*, *Andromeda polifolia*, *Rubus chamaemorus* and *Narthecium ossifragum* tolerate a range of moisture conditions, but they tend to avoid the wetter hollows or pools. *Sphagnum capillifolium* is common on hummocks in the drier parts of May Moss. The driest parts of May Moss are covered by *Hypnum jutlandicum*, lichen and liverworts under a canopy of *Calluna vulgaris*. These species only occur in the driest of habitats, which are becoming increasingly abundant as May Moss is affected by drainage and increased evapotranspiration associated with the conifer plantations. Monitoring of the vegetation at May Moss over the last twenty years and observation of the current flora identifies significant drying of the mire surface (Atherden, pers. com.).

Field Sampling

The criteria for site selection requires that peat profiles analysed in this research should be from the ombrotrophic water-shedding areas of blanket mires. Consequently peat cores from May Moss were extracted from the mire watershed, which is the highest point at the centre of the mire. These core sites receive water solely through precipitation. Eight cores were extracted from four sites on an east-west transect across May Moss. The locations of the core sites are identified on figure 4.2. The core numbers, core site location, the date sampled, the type of peat borer, the micro-environment of each core site and depth of peat sampled within each core are listed in table 4.1. Core site C is a five metre transect, which was surveyed to record the current micro-topography. Four cores were extracted along this transect sampling peat beneath present-day hummocks and hollows. The cores were extracted with either a 5×50 cm or a 10×30 cm Russian peat borer. Each core section was extruded in the field, wrapped in cling-film, stored in plastic guttering to protect the peat and then sealed in polythene bags. The samples were stored under refrigeration until required for analysis.

Table 4.1. Peat borings extruded from May Moss.

Core Site	Core Number	Date Sampled	Type of Corer	Micro-environment	Depth of peat sampled
A	1	19/11/95	50×5 cm	Hollow	2.30 m
B	1	19/11/95	30×10 cm	Hollow	2.75 m
C	1	15/04/96	50×5 cm	Hummock	2.10 m
C	2	15/04/96	30×10 cm	Hollow	2.10 m
C	3	15/04/96	30×10 cm	Hollow	2.10 m
C	4	15/04/96	50×5 cm	Hummock	2.10 m
D	1	29/05/95	50×5 cm	Hollow	2.75 m
D	2	09/10/96	30×10 cm	Hollow	2.10 m

May Moss is the best example of an ombrotrophic mire remaining on the North York Moors and it is the main site used in this research. The purpose of the detailed multi-profile sampling strategy was to address a series of problems perceived in peat-based palaeoclimate research on unmodified mires discussed in chapter 3. It is difficult to record the stratigraphy in unmodified mires because of a lack of cut-sections. Extracting series of cores increases the size of the sample upon which palaeoecological analysis is based, thereby improving the confidence in eventual palaeohydrological histories. Analysing a series of cores extracted across the watershed of May Moss assesses whether the moisture shifts are cross-mire phenomena; if so, whilst this is not proof of allogenic forcing of moisture fluctuations it is the logical explanation.

The transect sequence at site C is designed to throw further light on the allogenic/autogenic debate. This approach potentially investigates the permanency of mire micro-habitat, by assessing whether the peat beneath a present-day hollow was produced by a consistently wetter environment than peat extracted from beneath a hummock. Additionally the plant macro-fossil evidence may identify whether hummock species, for example *Sphagnum* section *Acutifolia*, persist throughout or dominate the fossil record beneath present-day hummocks. This approach is by no means ideal, but in the absence of open sections in the field it is the only alternative. Assessing either the present-day hydrology or the palaeohydrology along a transect it may be possible to identify whether moisture changes occur independently of micro-habitat. If moisture changes occur in all the cores along the transect, this perhaps indicates that an allogenic impact on the mire moisture budget is a more likely cause of the change in surface saturation. In summary, both the multiple profile and the transect sampling procedures attempt to define whether the moisture changes identified across a range of hummock-hollow micro-environments represent changes in the overall mire moisture budget. In the absence of evidence of human interference on the mire and considering the ombrotrophic nature of May Moss, any oscillations in the mire water budget are more likely to be the product of changes in effective precipitation, thereby providing evidence of climate change.

4.3.2 Fen Bogs SSSI

Fen Bogs is 1.5 km in length and 0.2 km in width covering about 300 m^2 centred on the grid reference SE 853 976, and the location is identified on figure 4.3. The site is a valley mire designated with SSSI status, and part of the mire is owned and managed as a nature reserve by the Yorkshire Wildlife Trust. The former Nature Conservancy Council regarded the site to be the best British example of an upland valley mire, with both ombrogenous and soligenous facies (Atherden, 1976b). The mire developed on the watershed in the deeply incised fluvioglacial channel of Newton Dale, which currently contains Pickering Beck. The surface of Fen Bogs is flat at an altitude of 164 metres and bordered by steep slopes rapidly rising 90 metres on both the east and west sides of the mire. Atherden (1976a; 1976b) investigated the pollen record contained within the peat stratigraphy. Fen Bogs contains the deepest peat deposits on the North York

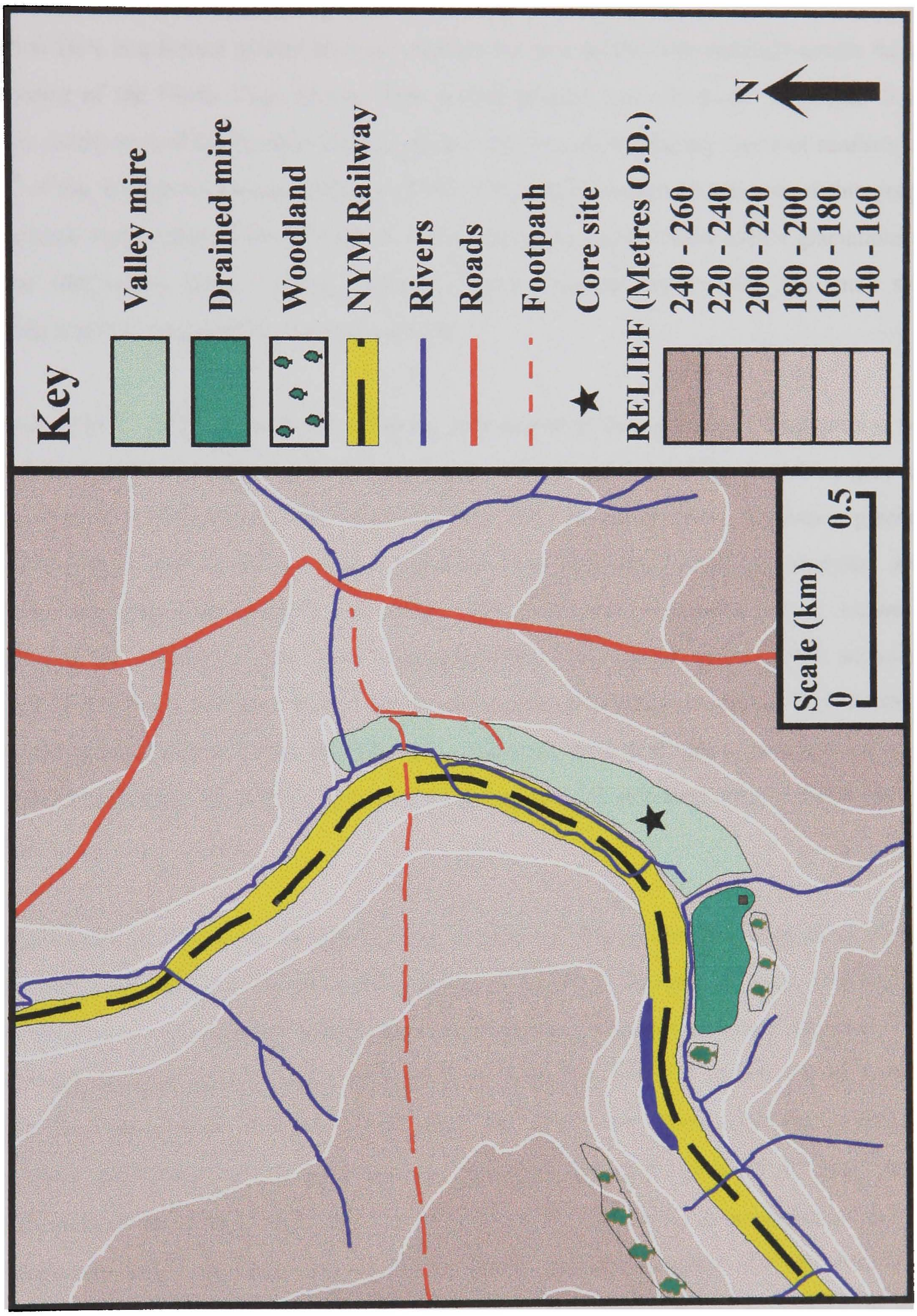


Figure 4.3. Location of Fen Bogs SSSI, North York Moors, northeast England. Identifying the location of the core site and the topography surrounding Fen Bogs SSSI.

Moors with over nine metres of peat, which have accumulated from the beginning of the Holocene to the present-day.

Sedimentary evolution of Fen Bogs

Newton Dale is a former glacial drainage channel cut in a north-south direction across the main watershed of the North York Moors. This central plateau has a bedrock of Middle Jurassic deltaic sandstone and the Newton Dale gorge has cut through alternating layers of sandstone and shale of the Ravenscar Group. Gregory (1962; 1965) attributed the formation of this gorge to sub-glacial and proglacial fluvial activity in the Devensian and probably earlier glaciations. The current steep-sided gorge certainly appears to be a temporal misfit, when the small stream flowing from the watershed today is considered.

Atherden (1972; 1976b) extensively cored the mire assessing the post-glacial stratigraphy, which revealed a maximum peat depth of 11.6 metres. The basal sediments were blue-grey clays believed to be solifluction deposits associated with the termination of the Devensian glaciation. Subsequently a carr or fen woodland deposited peat sediments containing abundant *Betula* remains, and fragments of *Salix* and *Alnus*. The wood peat was succeeded by brown peat dominated by *Phragmites* and other monocotyledons. Throughout much of the sedimentary history of Fen Bogs, the mire was a *Phragmites*-monocotyledonous swamp or bog. At the east and west edges of the mire near the steep slopes there are in-wash stripes of pale grey clay within the peat stratigraphy, which have been attributed to periods of increased erosion (Simmons *et al.*, 1975).

At approximately one metre beneath the mire surface there is an abrupt change in stratigraphy, with *Sphagnum* and *Eriophorum vaginatum* peat replacing the *Phragmites* peat. This represents a change from a predominantly soligenous to ombrogenous environment, which Atherden (1976b) linked with drainage schemes associated with the construction of the Whitby-Pickering railway in 1836. The radiocarbon chronology indicates that *Sphagnum* species became a significant component of the mire stratigraphy between 1060 ±60 BP and 390 ±100 BP, and although construction of the railway did affect mire hydrology, the change to an acidophilous mire with ombrogenous facies occurred during the Medieval period. Atherden (1976b) obtained six radiocarbon dates to secure a chronology for the most complete Holocene vegetation history uncovered on the North York Moors. The chronology indicates that the top 2 metres of peat accumulated during the last 2000 years, with an average accumulation rate during the Holocene of 1 metre per millennium.

The present-day vegetation

The mosaic of ombrogenous and soligenous tracts across Fen Bogs has encouraged the development of a diverse community of acidic fen and bog plants unrivalled on the North York Moors. The location of ombrogenous communities that cover the majority of the mire are identified on figure 4.3 (Atherden, 1976b) and can be further divided into two sub-communities typically inhabiting wetter and drier environments. *Sphagnum recurvum*, *Sphagnum cuspidatum* and *Eriophorum angustifolium* dominate the wetter locations; whereas the hummocks and drier environments sustain a mixed community containing *Sphagnum capillifolium*, *Molinia caerulea*, *Calluna vulgaris* and *Myrica gale*. Additionally along the eastern edge of the mire there are soaks and pools of standing water inhabited by true aquatic species- *Potamogeton poligonifolia* and *Menyanthes trifoliata*. There are numerous other less abundant species within this ombrogenous community, including *Erica tetralix*, *Vaccinium oxycoccus*, *Drosera rotundifolia*, *Potentilla erecta*, *Polygala serpyllifolia*, *Narthecium ossifragum*, *Eriophorum vaginatum*, *Rhynchospora alba* and numerous *Carex* species.

The southern section of Fen Bogs is an eutrophic mire dominated by *Phragmites communis* with occasional *Schoenus nigricans* and *Potentilla erecta*. This eutrophic community is associated with increased surface flow and input of mineral material near the headwaters of Pickering Beck and is perhaps an example of what the peat stratigraphy indicates the entire mire was like in the past. Towards the southern edge of the mire the eutrophic communities grade into a birch, willow and alder carr woodland with a *Phragmites australis* herb flora. Fen Bogs has a long history of human interference, which includes the development of the railway during the nineteenth century. Part of the mire south of Pickering Beck, indicated on figure 4.3, has been drained and improved for agricultural use. The drainage channels are currently inhabited by *Juncus* spp., as are the natural channels of Eller and Pickering Beck and drainage channels alongside the railway. The steep slopes bordering the mire support remnants of a Quercus and *Alnus* woodland, especially towards the southern end of Fen Bogs. There are also small recently planted tree plots along the eastern slopes of the mire. However the slopes are for the most part covered with *Pteridium aquilinum*, *Vaccinium myrtillus*, *Calluna vulgaris* and *Erica cinerea*.

Field sampling

Three replicate cores were extracted from the ombrogenous section of Fen Bogs on 27th April 1995. The three cores were extracted from the centre of the valley to reduce the impact of surface flow from the steep slopes bordering the mire. The location of the core site is indicated on figure

4.3. The individual cores were located within two metres of each other. The cores were extracted with a Russian peat borer (5×50 cm), sampling to a depth of three metres beneath the mire surface. This length of core was judged sufficient to obtain peat stratigraphy pertaining to the last 2000 years, according to the radiocarbon chronology developed by Atherden (1976b). The cores were extruded in the field, wrapped in cling-film, sealed in polythene and stored under refrigeration until required for analysis.

4.3.3 Harwood Dale Bog

Harwood Dale Bog was originally an extensive area of peat approximately 1 km north-south and up to 0.5 km east-west, centred on grid reference NZ 967 988. Currently the bog is covered by the Harwood Dale Forest conifer plantation, with only a clearing of 300 × 150 m of peat currently still visible. The bog was first described by Elgee (1912), as a 'saucer-shaped' lens of peat. The mire accumulated at an altitude of 200 metres on a flat plateau with a bedrock of Jurassic deltaic sand and silt-stone of the Ravenscar Group. The plateau is largely water-shedding, with drainage to the south-east in Thorny Beck and to the west in Black Sike. Peat extraction for domestic fuel has taken place for many centuries, which when combined with the impact of the conifer plantations has severely truncated the palaeoecological record and probably irrevocably damaged the mire habitat. A pollen profile produced from the remaining sediment reveals peat accumulation initiated in the early Holocene and the record terminates between *circa* AD 800-1200 (Atherden, 1989). The pollen record from Harwood Dale Bog is secured with five radiocarbon dates, providing a chronology for the vegetation history of the eastern North York Moors (Atherden, 1989; Simmons *et al.*, 1993).

Sedimentary evolution of Harwood Dale Bog

There are extensive peat cuttings currently visible at Harwood Dale Bog, which allow detailed examination of the peat stratigraphy. Atherden (1989) presented a four metre pollen profile extracted from a peat cutting of 2.35 metres, with the remainder sampled with a Russian peat corer. The stratigraphy reveals that during the early Holocene peat accumulated over bedrock and mineral charcoal-rich soil. The earliest peat was dominated by monocotyledonous remains; although abundant wood remains suggests the mire was wooded during its early history. Around 5310 ±80BP woodland appears to die out and the site was colonised by *Eriophorum*, although the bog probably remained partially wooded. The top 0.70 metres of peat contains evidence of a further stratigraphic change between *circa* 2190-1500BP, with *Sphagnum* remains becoming increasingly abundant. Subsequently the bog was colonised by a characteristic ombrogenous mire flora dominated by the Ericaceae, *Eriophorum*, *Sphagnum* section *Acutifolia* and *Sphagnum papillosum*.

The present-day vegetation

Currently the surface of Harwood Dale Bog is substantially damaged, the result of centuries of peat extraction and extensive recent plantation of conifer forests. The present-day flora is affected by that damage, with large areas of the cut-over peat surface lacking in vegetation and the remainder covered with *Calluna vulgaris*, *Erica tetralix*, *Erica cinerea*, *Eriophorum vaginatum*, *Polytrichum* spp. and *Sphagnum* spp. Little of the original bog surface remains, and these areas are dry and covered with *Calluna vulgaris*.

Field sampling

Previous palynological research at Harwood Dale Bog indicates the peat stratigraphy is truncated. The vegetation history includes evidence of the Iron Age/Romano-British woodland clearances at a depth of 0.75 metres. Consequently only the top 1.06 metres of peat were sampled to provide the stratigraphy required for this research. In October 1994 four monoliths of peat (25×15×10cm) were taken from a cleaned surface of a north-south peat cutting, approximately 15 metres from the eastern edge of the plantation at the northern end of the clearing. The location of the core site is identified on figure 4.4. The peat samples were wrapped in cling film, sealed in polythene and stored under refrigeration until required for analysis.

4.3.4 Yarlsey Moss

Yarlsey Moss is an extensive area of deep peat covering *circa* 1km^2 on the high central watershed of the North York Moors at an altitude of 312 metres centred on the grid reference NZ 760 005. The location of Yarlsey Moss is identified on figure 4.5. The NCC Phase 1 Habitat Survey (Nature Conservancy Council, unpublished) describes sections of Yarlsey Moss as wet modified bog. However the majority of Yarlsey Moss is blanket bog, in spite of current management practices maintaining the moor for grouse. Drainage channels and grouse butts were cut in October 1996 and this interference must be affecting moisture conditions on the moss. The centre of Yarlsey Moss is ombrotrophic, which is largely the result of its location on the watershed between Wheeldale Gill and Winter Gill. Peat accumulated over a Middle Jurassic Ravenscar Group sand and silt-stone bedrock. Cundill (1971) extracted a peat profile from grid reference NZ 762 005, recovering 2.13 metres of peat from the western part of the moss. An undated pollen diagram indicates peat accumulation began slightly before the Iron Age-Romano/British woodland clearances and the presence of a *Pinus* rise near the top of the profile reflects twentieth

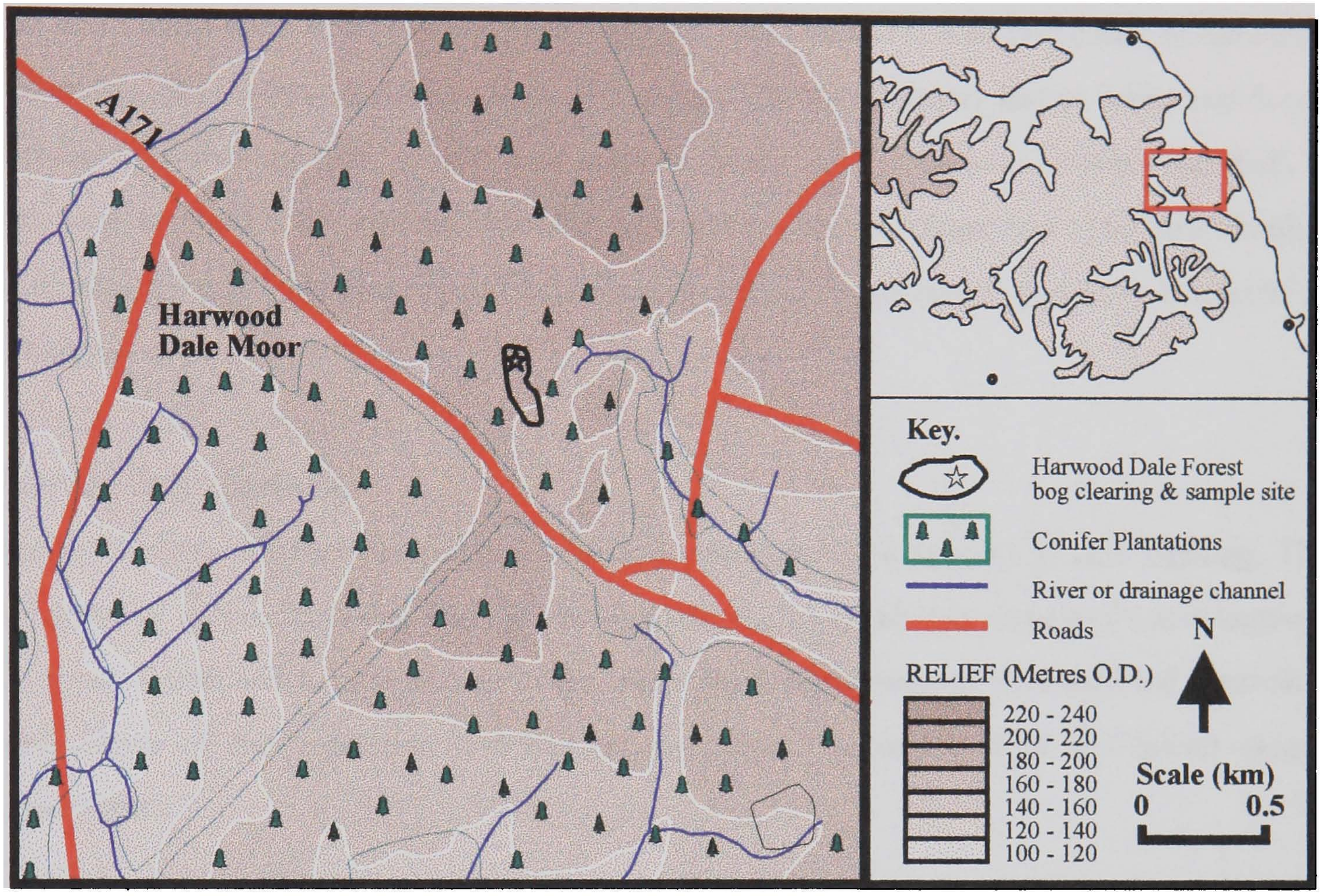


Figure 4.4. Location of the palaeoecological site and the topography surrounding Harwood Dale Bog.

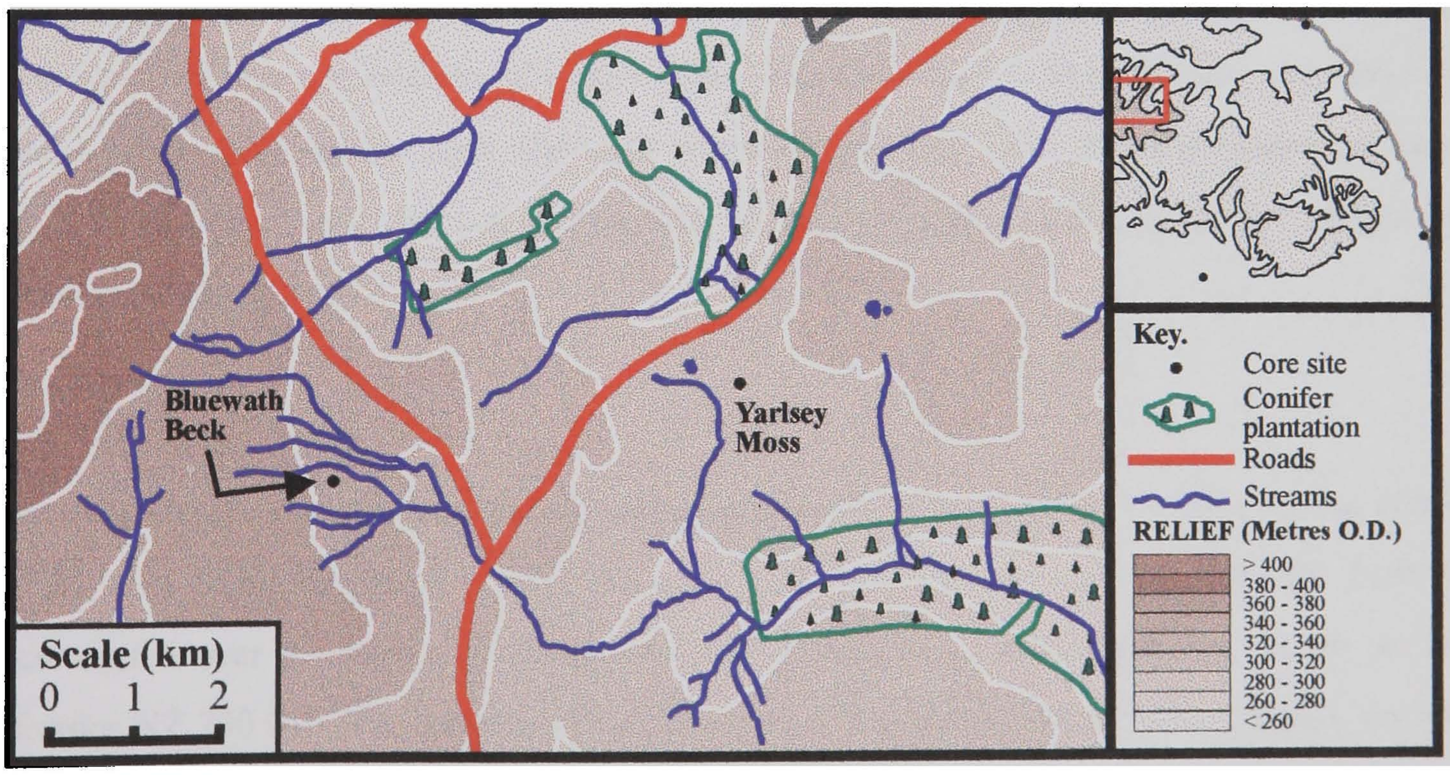


Figure 4.5. Location and the topography surrounding Yarlsey Moss and Bluewath Beck palaeoecological sites.

century commercial conifer afforestation and indicates peat accumulation continues to the present-day (Simmons & Cundill, 1974a).

Sedimentary evolution of Yarlsey Moss

The peat stratigraphy is dominated by monocotyledonous remains, with two bands of *Sphagnum*. The surface layers of peat contain fresh rootlets and *Calluna vulgaris* leaves, seeds and flowers. Peat accumulation appears to have been initiated on the wet spring-head of Wheeldale Gill, and expanded to blanket the plateau, forming an extensive area of deep peat. The stratigraphy is dominated by plant remains typical of a blanket mire: *Eriophorum vaginatum*, Ericaceae and *Sphagnum* spp.

Present-day vegetation

Yarlsey Moss is currently a managed moorland maintained primarily for grouse shooting. There is a series of grouse butts dug into the peat and drainage channels cut to prevent water-logging of the grouse-butts and to ease access to the moor. Cyclical burning of the moorland controls the composition of the vegetation and has encouraged the development of a *Calluna vulgaris* monoculture.

Field sampling

A peat profile 2.4 metres in length was taken from Yarlsey Moss on 23rd October 1996 (NZ 755 077). The location of the core site is identified on figure 4.5. The core was taken from the centre of the flat watershed away from any evidence of peat cutting, drainage channels and disturbance associated with the construction of grouse butts. The core-site is water-shedding and fulfils the criteria of an ombrotrophic mire. The core was extracted with a 10×30 cm Russian peat corer. The core sequences were wrapped in cling-film, sealed in polythene and stored under refrigeration until required for analysis

4.3.5 Glaisdale Moor

An extensive area of deep peat has accumulated at an altitude of 340 metres over the flat plateau of Glaisdale Moor, which forms the headwaters of Bluewath Beck and North Gill. Peat has accumulated over a bedrock of Middle Jurassic Ravenscar Group sandstone centred on grid reference NZ 730 010. The location of the moorland is identified on figure 4.5. Although the mire is a mixture of ombrogenous and soligenous facies, large sections of the moor are water-shedding with drainage to the south in North Gill, to the south-east down Bluewath Beck and to the north through Glaisdale Beck. The Bluewath Beck catchment has been exploited for fuel over many years leaving an extensive 1.5 metre peat cutting. This area of the moors has attracted considerable attention from palynologists. North Gill is a key site for studying the impact of Mesolithic communities on upland environments in the British Isles. The site has yielded numerous pollen profiles and is the most intensively analysed area of peatland on the North York Moors (Simmons, 1969; Simmons & Innes, 1988a; 1988d; Simmons *et al.*, 1989; Turner *et al.*, 1989). Simmons & Cundill (1974a) analysed a peat profile from Glaisdale Moor, and Innes (1981) produced a pollen profile from the headwaters of Bluewath Beck. These pollen profiles indicate the earliest peat accumulation within the catchment began around 6500 BP and has continued to the present-day where undisturbed.

Sedimentary evolution of Glaisdale Moor

Previous research on Glaisdale Moor indicates peat depths vary between 1-4 metres, and this variation is probably controlled by sub-surface topography and sedimentary evolution (Simmons & Innes, 1988a; 1988d). The earliest peat accumulated over a charcoal-rich mineral soil. The basal charcoal-rich peat has been attributed to the clearance of woodland by Mesolithic people. Fire-assisted woodland clearances are widely interpreted as an important factor causing the inception of peat accumulation (Moore, 1986; Simmons *et al.*, 1993). During the late Mesolithic and Neolithic Glaisdale Moor was probably covered with a mixture of oak and carr woodland, with ruderals and hazel scrub in the clearings. Peat accumulation was initiated in the wetter cleared basins. These spring-head basins once cleared of woodland, are ideal sites for peat initiation, because of the waterlogged nature of the environment. Additionally after the initiation of peat accumulation it requires a long period without human interference for woodland to re-established itself to the dominance achieved during the early Mesolithic, because the waterlogged, acidic and nutrient poor conditions in these peat basins inhibit the re-growth of woodland. Gradually the depth of the peat deposits increased and the area covered by blanket bog expanded covering the landscape. The expansion of the peat basins continued blanketing Glaisdale Moor and connecting the original centres of peat accumulation in the North Gill, Bluewath Beck and Glaisdale Beck catchments. Simmons & Innes (1988a) suggest unconfined blanket peat covered most of the plateau after *circa* 5000 BP and the peat stratigraphy indicates *Eriophorum vaginatum*, Ericaceae and *Sphagnum* dominated the mire vegetation.

Present-day vegetation

The head of Bluewath Beck has been exploited for peat over a number of years. Approximately 500 metres from the road which parallels Bluewath Beck there is a long north-west/south-east peat cutting. The peat surface lying between the cut-face and the road is a substantially damaged cut-over bog covered by *Calluna vulgaris*, *Eriophorum vaginatum*, *Juncus*, *Sphagnum* and *Polytrichum*. Although beyond the peat cutting the moor is largely undamaged, it is very dry owing to a lowering of the water-table caused by peat extraction. This largely undamaged moorland extends over into the North Gill catchment, and is covered by the *Calluna vulgaris* monoculture typical of the moors today. Glaisdale Moor is managed for grouse and is regularly burned to maintain a cover of young *Calluna vulgaris*. Beneath the *Calluna vulgaris* canopy, *Hypnum jutlandicum*, *Polytrichum* and various species of Liverwort dominate the ground-flora.

Field sampling

A peat profile was sampled from the headwaters of Bluewath Beck in October 1994. A series of monoliths (25×15×10cm) was extracted from the peat cutting approximately 500 metres from the road. The core site is located at grid reference NZ 742 007 at an altitude of *circa* 350 metres and the location is identified on figure 4.5. The monoliths were wrapped in cling film, sealed in polythene and stored under refrigeration until required for analysis.

4.3.6 Palaeoecological sites receiving a preliminary investigation

The palaeoecological sites introduced in the previous section are aligned in an east-west direction across the eastern North York Moors. These peat profiles offer the opportunity to reconstruct palaeoenvironmental conditions on the main upland masses of the North York Moors. They include two peat sequences on the main central watershed, on Glaisdale Moor and Egton High Moor; a peat sequence at May Moss on the Fylingdales Moor watershed; and a peat sequence from Harwood Dale Moor on the eastern most upland plateau of the North York Moors. This sampling strategy includes all of the upland masses between the coast and Glaisdale Moor, with the exception of Simon Howe Rigg.

Preliminary investigations were made at a number of locations to identify further palaeoecological sites. These investigations assess the potential of peat deposits on Simon Howe Rigg and investigate further catchment-head sites on Fylingdales Moor. Four sites were investigated:

- Simon Howe Moss on Simon Howe Rigg (SE 833 974).
- Worm Sike on Fylingdales Moor (SE 880 972).
- Ewe Pond Slack on Fylingdales Moor (SE 905 002).
- Blea Hill Beck on Fylingdales Moor (SE 887 998).

These sites were targeted to assess the peat deposits on Simon Howe Rigg, the only upland mass not yielding a peat profile on the east-west transect and to identify further profiles from Fylingdales Moor supplementing the main site utilised in this research, May Moss.

Preliminary coring across the Blea Hill Beck and Worm Sike catchments yielded disappointingly thin deposits of peat and clearly were unsuitable for further analysis. This is particularly disappointing in the case of Worm Sike, because the site is within the perimeter fences of RAF Fylingdales Early Warning Station, and has been unaffected by moorland management practices and grazing since the fences were erected in 1962. The site is of tremendous ecological interest, because it is one of the few unmanaged and ungrazed areas of moorland on the North York Moors. Comparatively deep peat deposits, reaching depths of 1.9 metres near Worm Sike, are not ombrotrophic, but potentially could be used to uncover a recent palaeoecological history for an unmanaged moorland. Coring and preliminary pollen analyses at Simon Howe Moss and Ewe Pond Slack were also disappointing. Simon Howe Moss is in a substantially drier state than when encountered in previous research (Atherden, 1979), with evidence of erosion and gullying in the headwaters of Blawath Beck. The palynostratigraphy of Ewe Pond Slack indicates the peat deposits are very recent, pertaining at most to the last 500 years. In summary none of these sites is ombrotrophic, and so all were unsuitable for further analysis.

4.4 Laboratory Methods

4.4.1 Humification analysis

The sampling interval used for the humification analysis was controlled by a number of factors. The degree of humification is controlled by the amount of time that fossil peat spent within the acrotelm, with dead organic matter subjected to rapid decomposition during its passage to the catotelm. Humification changes within peat stratigraphy reflect fluctuations in average moisture conditions over a couple of decades. Ombrogenous peat typically accumulates at a rate of 1 mm per year, and so 2 cm of peat would represent *circa* 20 years of peat accumulation. The degree of peat humification to some extent is subject to a natural smoothing process, because it can take newly deposited plant material up to 20 to 30 years to reach the relative safety of the catotelm. The resolution of the humification record is reduced, because movement of the acrotelm/catotelm boundary will affect more than just the surface layers of peat. Consequently, humification changes may reflect fluctuations in the depth of the water table over several decades. This natural buffering means the degree of peat humification provides a proxy record of variations in the depth of the average minimum summer water table. Fine resolution sampling for humification analysis therefore was not necessary, and the cores were divided into either a series of 1 or 2 cm contiguous samples, producing either 100 or 200 samples from a 2 metre core. Sampling at a finer resolution would be an unnecessary luxury and of limited value within the constraints of the technique. The location, length and sampling interval utilised for the humification analysis of each core are listed in table 4.2.

Table 4.2. The cores, depth of sediment and sampling interval used in the humification analysis.

Location	Core Number	Depth of Sediment	Sampling Interval
May Moss	B	2.3 metres	2 cm
May Moss	C2	2.1 metres	2 cm
May Moss	C3	2.1 metres	2 cm
May Moss	D1	2.7 metres	2 cm
May Moss	D2	2.1 metres	2 cm
Yarlsey Moss		2.4 metres	3 cm
Harwood Dale Moor		1.1 metres	1 cm
Bluewath Beck		1.3 metres	2 cm

The laboratory procedure follows methodological recommendations made by Blackford & Chambers (1993) and the procedure is listed below.

1. Contiguous samples of peat were dried in an oven at 50 °C. Matty sedge peat was cut with scissors to disaggregate the samples. The dried samples were ground with a pestle and mortar. If necessary the samples were dried until no further weight loss occurred. 0.2 g of powdered peat was mixed with 100 ml of freshly mixed 8% NaOH in a 200 ml volumetric flask, recording the time of mixing.
2. The samples were heated on a hot-plate. On boiling the temperature of the hot-plate was lowered and the samples simmered for one hour. After one hour the samples were removed and allowed to cool. The samples were topped up with distilled water to a 200 ml mark and well shaken. The solutions were filtered through Whatman Qualitative No. 40 filter papers. A 50 ml sample of the filtrate was diluted with one part distilled water and one part solution.
3. Percentage Light Transmission through the alkali extract was measured on an Elmer Perkin Visual/Ultra-Violet Light Spectrophotometer at a light wavelength of 540 *n*m. The consistency of the procedure was secured by regularly zeroing the spectrophotometer with distilled water and by running several replicate analyses of some of the samples. All of the analyses from a core were completed within an uniform time limit, typically two hours and up to a maximum of four hours, thereby avoiding fading of the extract after prolonged exposure to sunlight.

The maximum variation in percentage light transmission in samples from the North York Moors was detected between wavelengths of 520 and 590 *n*m. A high degree of variation is required for the identification of sequential changes in humification, and a wavelength within this range is recommended (Blackford & Chambers, 1993). Brown humic acid is a relatively complicated colour, produced by a mixture of the primary colours: red, yellow and blue. There is no light wavelength particularly well absorbed by a brown medium. However, above 500 *n*m there is an inflection in the absorption curve which identifies a rapid increase in the percentage of light transmitted by samples displaying a range of strengths of humic acid. These results support the findings of Blackford & Chambers (1993), who identified that wavelengths above 500 *n*m close to the inflection point on the absorption curve will identify most variability in strength of the humic extract.

Following the recommendations of Blackford & Chambers (1993) the results of the humification analyses are expressed as percentage light transmission and not converted to a percentage humification value *sensu* Aaby (1986). The raw data curves were spiky, reflecting minor variations in humic acid content. Consequently the data were smoothed using a three point moving average to dampen the background noise and produce a clear humification signal. The humification data are presented as "humification diagrams". The diagrams include three curves presenting: (a) the raw percentage light transmission data, (b) the raw data smoothed using an unweighted three point moving average reducing the amount of background noise, and (c) the smoothed data passed through a high pass filter emphasising low frequency events. Low percentages of light transmission denote well humified peat and high percentages poorly humified peat. Additionally, part (d) of the humification diagrams, if present, displays the results of the spectral analysis, with a graph identifying the peaks on the spectral density function, and a table listing the periodicity's signified by the main spectral peaks.

4.4.2 Plant Macrofossil Analysis

Methodology

Plant macrofossil analysis was applied to the peat sequences with the intention of reconstructing a local vegetation history for each mire. The methodology utilised quantifies the abundance of the various components within each macrofossil assemblage. The methodology is adapted from a "Quadrat and Leaf Count" procedure developed by Stoneman (1993) and will produce a numerical evaluation of the composition and nature of fossil vegetation communities. The plant macrofossils within each peat sequence were analysed using a variety of sampling intervals. The highest resolution sampling was at 4 cm intervals and the coarsest at 10 cm intervals. These intervals were selected because a finer resolution would be an unnecessary luxury and of limited value within the constraints of the technique. The location, length and sampling interval of each core utilised for the plant macrofossil analysis are listed in table 4.3. A minimalist preparation procedure was adopted for the plant macrofossil samples, following the recommendations of Stoneman (1993). The samples were not subjected to any of the conventional macrofossil preparation procedures typically involving maceration in NaOH or HNO_3, with the samples simply disaggregated in distilled water and then sieved to remove fine particulate matter. This procedure reduces the likelihood of damage to the macrofossil remains. The analytical procedure divides into two stages and is listed in table 4.4.

The first stage quantified the abundance of the main components in each peat sample and these components were identifiable Ericaceae, identifiable Monocotyledonous, identifiable *Sphagnum*, any other Bryophytes and Unidentifiable Organic Matter. The second stage quantified the relative abundance of *Sphagnum* species, and these values were expressed as percentages of the total identifiable *Sphagnum* derived in the first stage of the macrofossil procedure. Carrying out three replicate analyses on a series of fossil samples assessed the consistency of the method. Analysis of the variance within replicated analyses revealed no significant difference ($p>0.01$) in the composition of the samples, which suggests the methodology produces a replicable assessment of the plant macrofossil stratigraphy. Diagrams presenting the results of the plant macrofossil analyses were constructed using the TILIA and TILIAGRAPH computer packages (Grimm, 1993). The first stage of the macrofossil analysis quantifies the abundance of unidentified organic matter, identifiable monocotyledons, identifiable Ericaceae, identifiable *Sphagnum* and other Bryophytes, and the results are expressed as percentages of the total volume of peat. The second stage quantifies the abundance of *Sphagnum* branch leaves, with the raw counts converted into percentages and then moderated by expressing them as percentages of total identifiable *Sphagnum* estimated in the first stage of the analysis. In light of the problems with the taphonomy of leaves, seeds and flowers of the various vascular plant species encountered in this research the results of this analysis are presented as raw counts.

Taxonomy and ecological rationale for the macrofossil analysis

Plant species that contribute substantially to the formation of peat will produce the most abundant macrofossil remains. Ombrotrophic mires are characterised by a low diversity plant community, with certain species well adapted to the ecological conditions prevalent on blanket mires. This section reviews the taxonomy and criteria used to identify the plant macrofossils found within peat sediments on the North York Moors. In addition, the ecology and typical

Table 4.3. The cores, depth of sediment and sampling interval used in the plant macrofossil analysis.

Location	Core Number	Depth of Sediment	Sampling Interval
May Moss	B	2.3 metres	8 cm
May Moss	C1	2.1 metres	10 cm
May Moss	C2	2.1 metres	8 cm
May Moss	C3	2.1 metres	4 cm
May Moss	C4	2.1 metres	10 cm
May Moss	D1	2.7 metres	4 cm
May Moss	D2	2.1 metres	6 cm
Fen Bogs		2.7 metres	4 cm
Yarlsey Moss		2.4 metres	8 cm
Harwood Dale Moor		1.1 metres	8 cm
Bluewath Beck		1.3 metres	8 cm

Table 4.4. Laboratory and analytical procedure for the plant macrofossil analysis.

Laboratory preparation.

A 3 cm^3 sub-sample of peat was extracted from the core and placed in a centrifuge tube with 10-20 ml of distilled water. The samples were boiled in a hot water bath until the peat disaggregated. The disaggregated samples were washed through a 200 µm sieve mesh with distilled water. The sieve residues were transferred to large vials and stored under refrigeration until required for analysis.

First Stage.

Each sample was diluted in a petri dish with distilled water, producing a single layer of macrofossils. The petri dish was marked out with a grid of centimetre squares and fifteen of these squares are annotated. The samples were examined under low power microscope and the percentage cover of the different components was estimated for each of the annotated squares. At least three petri dishes were examined for each sample, which in most cases required all of the macrofossil residue. The abundance of each macrofossil component was expressed as a percentage, thereby providing a replicable semi-quantitative estimate of the abundance of each peat component.

Second Stage

A sub-sample of loose *Sphagnum* branch leaves was extracted from the annotated grid squares. The leaves were mounted on a microscope slide using glycerol as the mounting medium. The slides were traversed systematically and the leaves identified at ×50 magnification, with critical determinations on leaf cell structure made at ×400 magnification. A minimum of 100 *Sphagnum* leaves were counted for each sample.

environmental tolerance of the mire plant species are discussed, thereby presenting a rationale for palaeoenvironmental interpretation of the plant macrofossil stratigraphy.

The Bryophyte flora of a blanket mire

Bryophytes, specifically the genus *Sphagnum*, are a very important component of the ombrotrophic mire flora. The *Sphagnum* species commonly found on acidic ombrotrophic mires in the British Isles are listed in table 4.5. Species of *Sphagnum* prefer quite different ecological conditions and significantly for this research wetness of the mire habitat is a particularly important control on the distribution of species. Individual species prefer a particular topographic position on the undulating sequence of hummocks and hollows that typify blanket mires. Consequently the moss flora is distributed accordingly across the complex micro-topography of ombrotrophic mires. Figure 4.6 displays a theoretical distribution of *Sphagnum* species in relation to the water table across a hummock-hollow sequence. Forty species of *Sphagnum* occur in Europe and are spread across ten different taxonomic sections: *Sphagnum, Acutifolia, Cuspidata, Subsecunda, Rigida, Mollusca, Squarrosa, Insulosa, Polyclada and Hemitheca* (Daniels & Eddy, 1990). Furthermore Smith (1978) identifies 30 species of *Sphagnum* that can be found in the British Isles. This is an extensive number of species, but fortunately not all of these species occur on ombrotrophic mires, and several species can be removed from consideration in the macrofossil analysis on the grounds of rarity, present-day geographical distribution and ecological tolerance (Barber, 1981). Some species of *Sphagnum* are extremely unlikely to be encountered in peat stratigraphies on the North York Moors, because they will not inhabit acidic nutrient-poor ombrotrophic peat bogs.

Only species in *Sphagnum* sections *Sphagnum, Acutifolia, Subsecunda, Cuspidata* and *Rigida* are likely to occur on the North York Moors, and unfortunately some are difficult to identify in a sub-fossil condition to species level. Fortunately some species within these sections can also be discounted in the light of their ecological requirements, current geographical distribution and rarity (Barber, 1981; Stoneman, 1993; Daniels & Eddy, 1990). There are four species, *Sphagnum imbricatum, Sphagnum papillosum, Sphagnum magellanicum* and *Sphagnum palustre*, within *Sphagnum* section *Sphagnum* and these are the dominant peat-forming Sphagna. Fortuitously these species are relatively easy to identify in a sub-fossil state, with cymbifolian or "boat-shaped" leaves, and additionally they have taxonomically diagnostic ornamentation on the walls of photosynthetic cells. Furthermore *Sphagnum palustre* is unlikely to occur on blanket bogs, because it is limited to mesotrophic fen peatlands (Smith, 1978; Daniels & Eddy, 1990), whereas *Sphagnum imbricatum, Sphagnum papillosum* and *Sphagnum magellanicum* are all

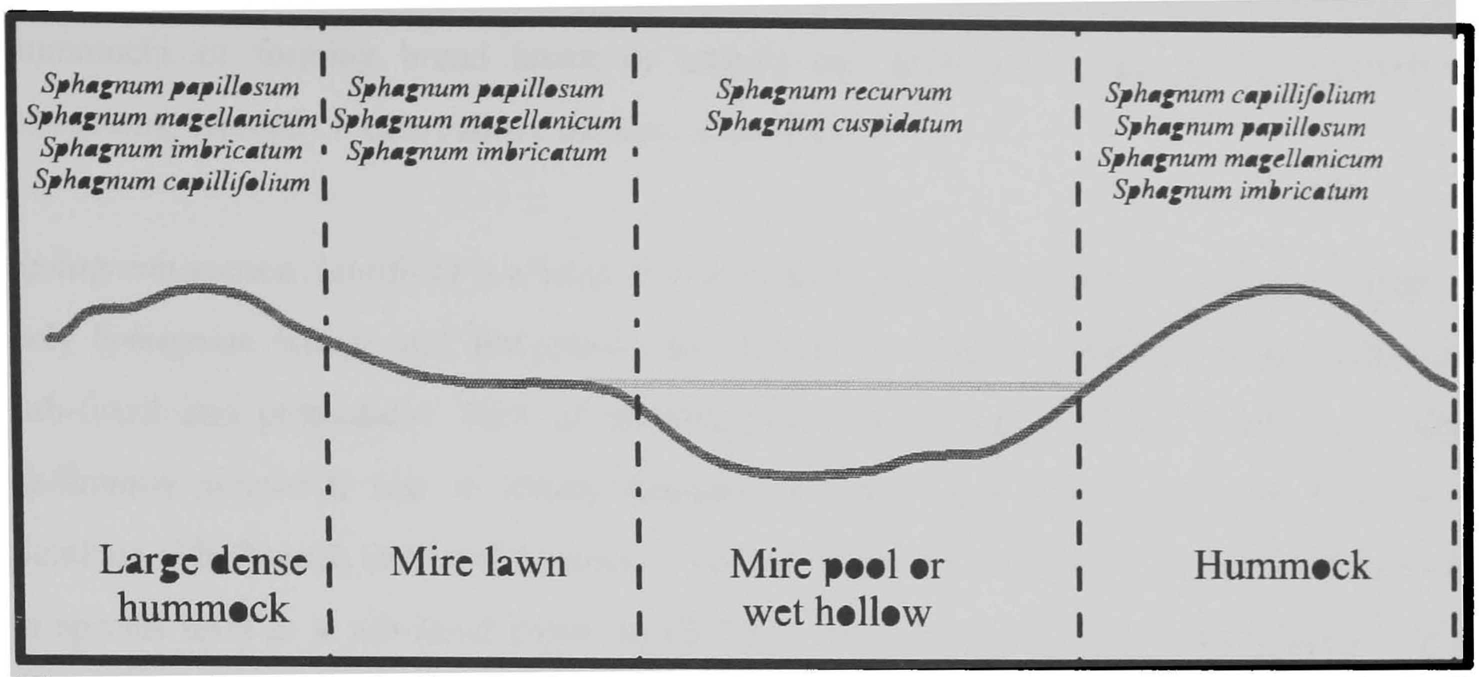


Figure 4.6. Typical distribution of *Sphagnum* species across a hummock hollow topography on the North York Moors.

Table 4.5. *Sphagnum* branch leaves identifiable as sub-fossils in peat on the North York Moors, listing the taxonomically diagnostic features (after Daniels & Eddy, 1990).

Species or Section	Diagnostic characteristics of branch leaves
Sphagnum imbricatum	Large (1.4-2.0 mm) cucullate or "boat-shaped" hooded leaves. Photosynthetic cells are exposed on both leaves surface, but broadly exposed on the concave surface. Photosynthetic cells are bordered with comb-like fibrils, which appear to project into the hyaline cells.
Sphagnum papillosum	Large (1.4-2.0 mm) cucullate or "boat-shaped" hooded leaves. The walls of the photosynthetic cells are coarsely papillose.
Sphagnum magellanicum	Large (1.4-2.0 mm) cucullate or "boat-shaped" hooded and often crimson leaves. Photosynthetic cells not or rarely exposed on the concave surface, often totally enclosed by hyaline cells.
Sphagnum section *Cuspidata*	Branch leaves are lanceolata, often more than twice as long as wide. The photosynthetic cells are more widely exposed on the convex surface, often not reaching the concave surface.
Sphagnum section *Acutifolia*	Branch leaves often small, under 1.4 mm. Photosynthetic cells are trapezoid, with the widest exposure on the concave leaf surface.
Sphagnum section *Rigida*	Branch leaves are very large, often exceeding 3 mm.

species commonly found on blanket mires. These species occur either forming large dense hummocks or forming broad lawns or carpets and ecologically they prefer relatively wet conditions, typically located above the mire water table.

Sphagnum section *Acutifolia* is a large section with eleven species currently extant in Europe, but only *Sphagnum fuscum* and *Sphagnum capillifolium* are likely to contribute substantially to the sub-fossil and present-day flora of ombrotrophic blanket mires on the North York Moors. *Sphagnum fuscum* is rare to locally frequent on mid-altitude bogs in northern England and Scotland. The branch leaves of *Sphagnum* section *Acutifolia* are notoriously difficult to identify to species level in a sub-fossil condition (Barber, 1981; Stoneman, 1993); consequently in this research the species are aggregated on macro-fossil diagrams as *Sphagnum* section *Acutifolia*. In the context of the North York Moors this group could consist of *Sphagnum capillifolium* and *Sphagnum fuscum*, although *Sphagnum capillifolium* is a more likely candidate. *Sphagnum capillifolium* is a very important member of the present-day *Sphagnum* flora on the North York Moors. Ecologically, sub-fossil *Sphagnum* section *Acutifolia* remains are interpreted as indicating a dry environment, with species typically forming dry hummocks and preferring a relatively dry mire surface.

Sphagnum cuspidatum and *Sphagnum recurvum* are the only species within *Sphagnum* section *Cuspidata* likely to occur within blanket mire peat stratigraphies on the North York Moors. They are both currently a component of the flora at May Moss and Fen Bogs. In the macrofossil analysis it is difficult to differentiate these two species, and the fossil remains are aggregated as *Sphagnum* section *Cuspidata*. Both species inhabit wet sites colonising inundated hollows and occurring as floating vegetation in pools, with *Sphagnum cuspidatum* preferring slightly wetter conditions (Daniels & Eddy, 1990). In this research the presence of *Sphagnum* section *Cuspidata* in peat stratigraphies indicates that the mire was relatively wet. The remains of *Sphagnum* section *Subsecunda* are only identified to section level. However, *Sphagnum auriculatum* is the only species in *Sphagnum* section *Subsecunda* likely to contribute to the ombrotrophic mire flora of the North York Moors. *Sphagnum* section *Subsecunda* are interpreted as indicating the presence of a relatively wet environment, because the only likely species, *Sphagnum auriculatum*, typically inhabits wet inundated hollows on oligotrophic mires. *Sphagnum strictum* and *Sphagnum compactum* are the only species within *Sphagnum* section *Rigida* that occur in Europe. Both species could inhabit ombrotrophic blanket mires on the North York Moors, but *Sphagnum strictum* is intolerant of subzero temperatures and is currently limited to the western extremities of the British Isles. Fossil remains of this section are not identified to species level, but grouped as *Sphagnum* section *Rigida*. Ecologically the section is tolerant of a wide range of moisture conditions, located mainly above the water table.

The *Sphagnum* leaves encountered in the macrofossil analysis are identified and grouped into eight species or sections: *Sphagnum imbricatum*, *Sphagnum papillosum*, *Sphagnum magellanicum*, *Sphagnum* section *Acutifolia*, *Sphagnum* section *Cuspidata*, *Sphagnum* section *Rigida*, *Sphagnum* section *Subsecunda* and *Sphagnum* undetermined. The identification of sub-fossil *Sphagnum* leaves was undertaken with reference to taxonomic keys in Smith (1978) and Daniels & Eddy (1990), and to a modern reference collection held in the PLACE Research Centre (University College of Ripon and York St John). The descriptions and diagnostic taxonomic characteristics of the *Sphagnum* species or sections identified in the course of this research are listed in table 4.5 (after Smith, 1978; Daniels & Eddy, 1990). The bryology was undertaken after tuition from Philip Bowes, an experienced Bryologist who has worked on the contemporary moss flora of the North York Moors. During the early stages of this analysis effort was expended in identifying anomalous forms; however, this proved unproductive.

Other bryophytes were encountered during the macro-fossil analyses, but these occurrences were infrequent and associated with periods when the mire surface was believed to be particularly dry. Identification and confirmation of the bryophyte types was carried out by Philip Bowes, with further identifications made with reference to the keys of Smith (1978) and type material held in the PLACE reference collection. Only three non-*Sphagnum* species were encountered during this research- *Hypnum jutlandicum*, *Pleurozium schreberi* and *Polytrichum commune*. *Hypnum jutlandicum* and *Pleurozium schreberi* are typically moorland species, which often occur together under a canopy of *Calluna vulgaris* in the drier parts of blanket mires (Hill *et al.*, 1996). Macro-fossil assemblages containing or dominated by these three species are interpreted as indicating a relatively dry environment. The abundance of these bryophytes was quantified in the first stage of the macro-fossil analysis, in which the relative abundance of the main peat-forming components was assessed. The branch leaves of these other bryophytes were not counted alongside the *Sphagnum* leaves, because of difficulties in integrating the data.

The vascular plant flora of a blanket mire

Vascular plants are an important component of the floral community on ombrotrophic mires, although there is considerable variation in the degree to which they are preserved within peat sequences. The vascular plant species that are most abundant as sub-fossils within blanket peat are the members of the Ericaceae, Cyperaceae and Poaceae. The species that are routinely easily preserved in peat are *Calluna vulgaris* and *Eriophorum vaginatum*. A number of less frequent plant remains are also preserved, including the leaves, stems and flowers of *Erica tetralix* and *Vaccinium oxycoccus*. The remains of *Drosera intermedia*, *Andromeda polifolia*, *Vaccinium myrtillus*, *Narthecium ossifragum* and *Rubus chamaemorus*, which are all components of the current ombrotrophic mire flora on the North York Moors, typically are not preserved within peat sequences. Consequently an absence of evidence within a fossil record cannot be used to identify that a plant species did not occur on a mire, because differential preservation of organic matter in the diagenetic process could be selectively removing certain species.

The taphonomy of plant remains is an important factor, which may control the composition of macrofossil assemblages. Different species will not be preserved to the same degree within peat, and so the eventual macrofossil assemblage may not be representative of the original bioceonosis. It is difficult to summarise the taphonomic controls on plant preservation, with considerable variation occurring across a mire and between different mires, because preservation is controlled by a combination of internal (plant) and external (environment) factors (Eggelsmann *et al.*, 1993). The resilience of *Sphagnum* may be due to the presence of lignin-like substances that are resistant to the processes of decay (Eggelsmann *et al.*, 1993). Furthermore the growth habit of *Sphagnum* encourages the preservation of sub-fossils, with the base of *Sphagnum* stems dying as the tops continue to grow. Consequently peat forms immediately beneath the living carpet of moss due to the sequential growth of living moss, which enhances the chances of preservation, thereby producing well preserved plant remains (Eggelsmann *et al.*, 1993).

Both aerial and subterranean parts of vascular plants are preserved in peat deposits and obviously they are subject to quite different taphonomic controls. The aerial parts of vascular plants fall onto the mire surface and experience a period of rapid aerobic decay. Variation in the potential for preservation will also be produced by the environment of deposition, for example pools, dry hollows and hummocks. If plant remains fall on rapidly growing *Sphagnum* or in a water-filled hollow or pool the period of exposure to oxygen and the amount of aerobic decay will be reduced, thereby improving the chances of preservation. Subterranean remains of vascular plants must also be interpreted with caution, because these remains are not contemporaneous with the surrounding fossils. Rootlets can penetrate into older plant communities, although the subterranean remains of all vascular plants must be viewed as non-contemporaneous with the remainder of the macro-fossil assemblage.

In the light of the taphonomic problems quantifying the remains of vascular plants, it appears impossible to reconstruct past bioceonoses accurately. Consequently the macrofossil stratigraphies are interpreted with due caution. Quantification of vascular plant fragments is limited to estimation of the relative contribution that Monocotyledons and Ericaceae remains make to the overall peat sediment. In addition leaves, flowers and seeds of *Calluna vulgaris*, *Erica tetralix* and *Vaccinium oxycoccus* were counted. Despite uncertainty in how representative these fossil remains are of the original bioceonoses these counts have proved useful, because they supplement quantitative estimations of the abundance of identifiable Ericaceae. Identification of vascular plant remains was undertaken with reference to Stace (1991) and to type material derived from vegetation currently growing on the North York Moors. The taxonomy and nomenclature of the vascular plant remains follows Stace (1991). Ecologically the abundance of various vascular plants has proved particularly useful. *Calluna vulgaris*, *Erica tetralix* and *Vaccinium oxycoccus* typically occur on hummocks, and so they are utilised as indicators of a relatively dry environment. The ecology of *Eriophorum vaginatum* is more complicated, because although able to tolerate relatively wet conditions, it will avoid areas with deep standing water. *Eriophorum vaginatum* typically forms large dense tussocks, which can persist for a long period of time producing a fossil record dominated by fibrous *Eriophorum vaginatum* remains.

4.4.3 Testate amoebae analysis

The testate amoebae stratigraphies were investigated at May Moss and Yarlsey Moss. The analysis at May Moss assessed the testate amoebae stratigraphy in five cores distributed across the mire. The analysis at Yarlsey Moss utilised a single core. Previous research has not attempted to assess the consistency of the testate amoebae sub-fossil record across a peat bog, which is surprising considering the potential for micro-topographically driven variations in surface wetness across an ombrotrophic mire. The mire environment contains a variety of habitats with quite different moisture conditions.

Table 4.6. The cores, depth of sediment and sampling interval used in the testate amoebae analysis.

Location	Core Number	Depth of Sediment	Sampling Interval
May Moss	B	2.3 metres	8 cm
May Moss	C1	2.1 metres	10 cm
May Moss	C3	2.1 metres	4 cm
May Moss	C4	2.1 metres	10 cm
May Moss	D2	2.1 metres	6 cm
Yarlsey Moss		2.4 metres	8 cm

Previous ecological research has identified that testate amoebae species are not uniformly distributed across a mire (Grospietsch, 1958; Tolonen, 1986), and this multiple profile approach is a valuable assessment of the internal integrity of sub-fossil testate amoebae analysis. The sampling interval adopted in this research differs between the cores, with the highest resolution sampling at 4 cm intervals and the lowest resolution sampling at 10 cm intervals. The location, core number, total depth of sediment and the sampling interval adopted for each core are listed in table 4.6.

Methodology

The laboratory procedure is very simple, processing 3 cm^3 sub-samples of peat. Two *Lycopodium clavum* spore tablets were added to each sample and disaggregated in 20 ml of distilled water (Stockmarr, 1971). The samples were boiled for between 15-20 minutes to thoroughly mix the exotics with the peat. The samples were stirred regularly to ensure that the peat and exotics spores were well mixed. The solution was then washed through a 500 μm sieve-mesh with distilled water, retaining the finer residue in small beakers. This residue was centrifuged to concentrate the material, stained with safranine and stored in glycerol. Solely boiling the samples in water avoids the problem of chemical damage to the sub-fossils. Additionally certain testate amoebae species are small, typically between 10-450 μm in long axis, and so sieving at 500 μm renders it highly unlikely that any testate amoebae species will be retained in the sieve-mesh; consequently the prepared samples will be representative of the fossil assemblage.

Well-mixed sub-samples of the residue were mounted on microscope slides and examined systematically with an Olympus CH Microscope at ×400 magnification. Identification of sub-fossil testate amoebae was carried out with reference to a series of texts, taxonomic keys and atlases of modern testate amoebae (Grospietsch, 1958; Corbet 1973; Ogden & Hedley, 1980). Reference was made to comments on testate amoebae taxonomy within a number of recent ecological publications (Warner, 1987; Charman & Warner, 1992; Tolonen *et al.*, 1992), because the ecological statistics presented in these publications form the basis for reconstructing past environmental conditions and a comparable taxonomy is essential. The testate amoebae samples were counted until 200 exotic spores had been encountered, which typically produced a sample size of between 100-150 tests. Woodland (1996) indicates a sample size of this magnitude will produce a representative assessment of the entire fossil assemblage. Diagrams of the sub-fossil testate amoebae stratigraphies were constructed using TILIA and TILIAGRAPH computer packages (Grimm, 1993). The abundance of individual testate amoebae species were expressed as percentages of the total number of tests encountered within each sample. The species were arranged along the diagram according to their respective tolerance of water table depths (after Woodland *et al.*, 1998), with species preferring very wet conditions at the left end of the diagram grading to species preferring dry conditions on the right. The species not included in the ecological database generated by Woodland *et al.* (1998) have an uncertain relationship to water table depth, and they were grouped together on the right of the diagrams.

4.4.4 Palynology

Methodology

The pollen diagrams were produced by sampling a peat profile at systematic intervals. The sampling intervals can vary considerably according to the purpose of the research. A coarse sampling interval reduces the chronological resolution of the analysis and may fail to identify short duration events. These problems can be overcome by contiguous sampling of the entire peat profile or by fine resolution pollen analysis (FRPA) which uses sample intervals of 1 mm or 3 mm, which decreases the duration of time contained within each sample (Simmons *et al.*, 1989). However FRPA is very time consuming, and the law of diminishing returns must come into play, and chronological resolution may be relinquished in favour of achievability and common sense (Barber, 1981). The pollen samples were extracted from freshly exposed surfaces of the cores. The samples were extracted with a volumetric sampler designed to a give consistent replicable quantity of peat, with a volume of 1 cm^3. The sampling intervals and depth of peat analysed varied between cores, and this information is recorded in table 4.7. The samples were extracted and prepared in the PLACE pollen laboratory minimising contamination by modern airborne pollen. A standard preparation procedure was utilised for all of the samples, but omitting treatments with hydrochloric and hydrofluoric acid because the peat contained no carbonate or mineral material (Moore *et al.*, 1991). The residues were stained with Safranine and stored in glycerol. Silicone oil was not used as a mounting medium, because the samples were not intended for long-term storage, thereby avoiding the lengthy dehydration procedure required for storage in silicone oil.

The pollen samples were counted under an Olympus CH Microscope at ×400 magnification with critical determinations made at ×1000 magnification under oil immersion. The identifications were made with reference to a number of specialist keys, photographic monographs and the PLACE research centre pollen reference collection. The main keys used were Moore *et al.* (1991) and Faegri & Iversen (1989). The photomicrograph volumes published by the *Laboratoire de Botanique, Historique & Palynologie*, in Marseilles were also an invaluable resource (Reille, 1992; 1995). A standardised format was used to present the various pollen diagrams. The raw counts of tree, shrub and non-mire herb pollen are all converted into percentages of the pollen sum. The raw counts of the aquatics, sedges and spores are converted to percentages of the pollen sum plus aquatics, sedges and spores. The taxa are arranged along the pollen diagrams in a conventional order. The pollen diagrams were constructed using the TILIA and TILIAGRAPH computer packages (Grimm, 1993).

Taxonomy and the pollen sum

The taxonomy of plant species follows the recommendations of Bennett *et al.* (1994). The classification of vascular plants follows Stace (1991) and bryophytes follows Smith (1978). The pollen classification includes several family names, which differ from those traditionally used by palynologists and these alterations are listed in table 4.8. Identification to species level is not always possible with pollen, and so certain types are only identified to genus or family. The classification of certain pollen grains is complicated; therefore the procedure used is clarified below. The Poaceae consists of both wild grasses and cereals. Faegri & Iversen (1989), Andersen (1979) and Moore *et al.* (1991) present keys which enable the identification of various cereal pollen grains. In this research grass pollen grains are divided into wild grasses and cereal-type on the basis of size and the diameter of the annulus. Grains less than 40 µm in length with a small annulus are likely to be wild grasses, and termed "Poaceae <40 µm". Grains larger than 40 µm in length and with an annulus larger than 10 µm are almost certainly cereal-type and referred to as "Poaceae >40 µm" (Moore *et al.*, 1991).

The nature of the pollen sum has attracted considerable comment in the literature (Birks & Birks, 1980; Barber, 1981; Faegri & Iversen, 1989; Moore *et al.*, 1991). Basically in this research the pollen sum is intended to provide realistic assessment of the regional vegetation. In previous research various taxa have been excluded from the pollen sum to achieve this objective. For example, mire taxa could be excluded from the pollen sum, because they will reflect the local vegetation and the aim may be to reconstruct changes in the regional landscape. Therefore a pollen sum containing trees, shrubs, grasses and all non-mire herbs would achieve this objective.

Throughout the last 2000 years, the North York Moors have been a deforested landscape, increasingly covered by Ericaceae moorland. Consequently some of the species- specifically *Calluna vulgaris*- are a significant component of the regional vegetation contributing pollen rain on to the palaeoecological sites. On an open upland moor like the North York Moors it is difficult to justify excluding wind-pollinating species like *Calluna vulgaris*, *Erica tetralix* and the

Table 4.7. The cores, depth of sediment and sampling interval used in the pollen analysis.

Location	Core Number	Depth of Sediment	Sampling Interval
May Moss	B	2.3 metres	8 cm
May Moss	D1	2.7 metres	4 cm
Fen Bogs		2.7 metres	4 cm
Yarlsey Moss		2.4 metres	8 cm
Harwood Dale Moor		1.1 metres	8 cm
Bluewath Beck		1.3 metres	4 cm

Table 4.8. Nomenclature changes in plant/pollen taxonomy (after Bennett *et al.*, 1994).

Families (after Clapham *et al.*, 1987)	Conventional Palynological Usage (after Moore *et al.*, 1991)	Recommended Usage (after Stace, 1991; Bennett *et al.*, 1994)
Gramineae	Gramineae	Poaceae
Cruciferae	Cruciferae	Brassicaceae
Umbelliferae	Umbelliferae	Apiaceae
Leguminosae	Leguminosae	Fabaceae
Compositae	Compositae Liguliflorae	Asteraceae (Lactucae)
Compositae	Compositae Tubuliflorae (including Carduus, Cirsium and Centaurea)	Asteraceae tribe Cardueae
Compositae	Compositae Tubuliflorae (including *Aster*–type and *Anthemis*-type	Asteraceae subf. Asteroideae
Not listed	Filicales (Monolete)	Pteropsida (monolete) indet.
Not listed	Filicales (Trilete)	Pteropsida (trilete) indet.

moorland grasses on the grounds that they are solely local in origin. Additionally, certain species that are components of the regional vegetation, including birch, rowan and pine, are capable of inhabiting a mire environment. The pollen sum utilised in this research excludes only the true aquatics, sedges and spores, because other pollen types conceivably could be regional in origin. This approach accepts that the pollen sum will include locally derived pollen grains, as a mechanism to get around this problem is difficult to envisage and it appeared sensible to derive percentages from a relatively complete fossil assemblage rather than arbitrarily excluding species. Pollen counting continued until a minimum of 150 arboreal pollen grains had been encountered and a pollen sum of at least 400 grains had been achieved. Both these limits were achieved in virtually all the samples and in many cases surpassed.

4.4.5 Geochronological analyses

Obtaining an independent chronology for sedimentary sequences is a critical component of Holocene palaeoenvironmental and palaeoclimate research. In comparison with many sedimentary deposits peat is particularly well suited for analysis by a number of geochronological procedures. A chronology for peat sequences that have accumulated during the last 2000 years can be derived using two radiometric decay techniques, radiocarbon and ^{210}Pb dating. Furthermore two stratigraphic procedures can assist with the production of a chronology for a peat sequence. Tephrochronology involves identification of volcanic ash layers within sedimentary sequences, which can then be related to a specific source eruption providing an age for the horizon. Significant changes in the vegetation can also operate as marker horizons if they are readily identifiable within the palynostratigraphy of peat sequences across a region. The chronologies derived for peat sequences on the North York Moors rely entirely upon radiocarbon dating and the use of palynostratigraphic marker horizons.

Tephrochronology is a relatively inexpensive geochronological technique that has been applied with some success to peat sequences in Ireland (Pilcher & Hall, 1992; Caseldine *et al.*, 1998) and north-west Britain (Dugmore, 1989; Blackford *et al.*, 1992; Pilcher & Hall, 1996; Dugmore *et al.*, 1995). The presence of tephra layers within peat sequences on the North York Moors was assessed in two cores from May Moss, namely D1 and B. The samples were prepared using a rapid combustion technique introduced by Pilcher & Hall (1992), and examined under a light microscope. Unfortunately no significant concentrations of tephra were identified within the peat sequences and tephrochronology was abandoned as a geochronological technique. The North York Moors are not a prime site for receiving volcanic ash falls from Iceland, because of the substantial deposition of ash that occurs within rainfall as the dust cloud crosses the British Isles and the comparatively low quantity of rainfall received by the North York Moors. Even if weather conditions and structure of North Atlantic pressure systems were appropriate for ash deposition on the North York Moors, the quantities would be quite small in comparison with western Britain.

Twenty-four radiocarbon dates were obtained in the course of this research. The samples selected for radiocarbon assay are listed in table 4.8, which identifies the core, the sample level, the sample material, the method used to obtain the date, the laboratory number, the $\delta^{13}C$ ratio and the radiocarbon age determination. Seventeen of these dates are conventional radiometric decay determinations carried out on bulk peat samples, but seven others are AMS dates on hand-picked *Sphagnum* leaves. There is considerable debate about the accuracy of radiocarbon dates obtained on peat samples. Peat is a heterogeneous deposit consisting of a mixture of short-lived components (*Sphagnum* and other bryophytes), the remains of older components such as *Calluna vulgaris* and the roots of younger plants penetrating the sediment from above (Pilcher, 1991). A growing consensus in recent research is that AMS dating of plant components selected on the grounds of contemporaniety with the horizon of accumulation is the best approach to dating peat sequences (Kilian *et al.*, 1995; Shore *et al.*, 1995; Oldfield *et al.*, 1997). *Sphagnum* remains meet this criterion, because as *Sphagnum* grows it systematically buries older material and is gradually converted into peat.

Sphagnum grows sequentially, with living moss immediately above dead leaves and stems. Consequently *Sphagnum* remains are always contemporaneous with the horizon of accumulation, which is not the case with rootlets of vascular plants and long-lived stems of *Calluna vulgaris* often encountered in fossil peat. This has obvious implications for this research, and so conventional radiometric decay dates were only carried out on samples dominated by *Sphagnum* remains. Furthermore seven AMS dates were obtained upon samples that had been dated using the conventional radiometric technique and these AMS dates analysed pure hand-picked *Sphagnum* remains, thereby providing the most accurate age estimates available from peat. Comparison of the results of the radiometric and AMS technique for these seven samples provides a preliminary assessment of the accuracy of conventional radiocarbon dating of peat deposits.

The samples utilised to obtain the radiometric ^{14}C dates, SRR 5920 to SRR 5930, are all of 3 cm vertical thickness from core sections taken with a 10 cm diameter Russian peat corer. These samples were pre-treated and dated at the NERC Radiocarbon Laboratory, East Kilbride. The samples were all *Sphagnum*-rich peat, extracted from the centre of the cores avoiding potential contamination at the edges of peat sampled with a Russian corer. The samples were digested in 2M HCl (at 80 °C for 24 hours), washed free of acid, filtered and dried to a constant weight in a drying oven.

The samples used to obtain the radiometric ^{14}C dates, BETA 106589 to BETA 106594, are of either 3 or 4 cm thickness, taken either from monolith tins (25×15×10 cm) or cores extruded with a 10 cm diameter Russian peat corer. The samples were all *Sphagnum*-rich peat, extracted from the centre of the peat sections avoiding potential contamination at the edges. These samples received a full acid/alkali/acid pre-treatment at the BETA ANALYTIC Radiocarbon Laboratory, which involved washing in hot HCl to remove carbonates, a further wash in hot NaOH to remove secondary soluble organic acids and a final HCl wash to neutralise the samples. During the washing obvious rootlets were removed from the samples. The acid/alkali/acid washing removes soluble organic acids, which are believed to produce age estimates younger than the true ^{14}C age of the horizon of accumulation (Dresser, 1970; Pilcher *et al.*, 1995; Shore *et al.*, 1995).

The samples used to obtain the AMS ^{14}C dates, AA-24208 to AA-24214, were all *Sphagnum* remains extracted from 1 cm vertical thickness slices of peat. The samples were prepared to graphite at the NERC Radiocarbon Laboratory. The samples were almost entirely composed of *Sphagnum* leaves and stems (estimated 99-100%). Samples producing the dates AA-24208 to AA-24214 consisted of *Sphagnum* section *Acutifolia* and were extracted by boiling the peat samples in distilled water to disaggregate the samples, followed by sieving at 200 and 500 µm mesh apertures to concentrate the *Sphagnum* remains. Further concentration of the samples was carried out by hand-picking the *Sphagnum* remains and by removing non-*Sphagnum* organic material. The sample producing the date AA-24208 consisted of *Sphagnum imbricatum* and *Sphagnum* section *Acutifolia* remains, which were hand-picked from the disaggregated peat samples. At the NERC Radiocarbon Laboratory, the samples were digested in 0.5M HCl (80°C for 10 hours) and then rinsed free of mineral acid with distilled water. The samples were homogenised, combusted to CO_2 in sealed quartz tubes and converted to graphite by Fe/Zn reduction. The samples were analysed by the AMS ^{14}C procedure at the University of Arizona NSF facility.

The radiocarbon dates both obtained for this research and referred to in discussion of previous research are presented following the recommendations of the 12th International Radiocarbon Conference (Mook, 1986). The laboratory numbers of the radiocarbon dates are listed in table

4.8. The original ^{14}C measurements are presented as years BP, with their 1 sigma errors. An important facet of both the palaeoclimate and vegetation history research involves comparison with historical events necessitating calibration of the radiocarbon dates to calendar years. The radiocarbon dates both obtained for this research and referred to in discussion of previous research are calibrated against a decadal tree-ring data-set utilised to generate the Pretoria calibration curve (Vogels *et al.*, 1993). Calibrated dates are quoted in years cal. AD and cal. BC, and always list the intercept with the calibration curve and the 2 sigma range for the calibrated date, e.g. [cal. AD 1640(1650)1665].

The radiocarbon dates were not obtained solely to age specific events, but to generate time series for the peat sequences. These time series allowed investigation of any cyclic structure within the palaeohydrological histories and provide a chronological basis for discussion of the climate and vegetation histories in comparison with previous research and other sources of evidence. To this end the radiocarbon dates were supplemented with various palynostratigraphic marker horizons, and an age/depth model was produced for each peat core. A simple linear regression model was used to generate the time-series and the calculations were performed using the calibrated dates and marker horizons in the TILIA computer package (Grimm, 1993). In certain cores there are insufficient chronological horizons, and so there are problems with the age/depth model. However, they have been calculated and are utilised on the palaeoecological diagrams, because the value of these interpolated time series outweighs problems caused by inherent inaccuracies.

4.5 Interpretative procedures

The large number of cores and range of techniques utilised in this research has produced a wealth of data. A consequence of this wealth is that the interpretation and discussion of the results could become very cumbersome, and so the interpretative procedure is clearly defined. This section presents the rationale for presentation and discussion of the results, and introduces the quantitative methods utilised to assist with interpretation of the data.

4.5.1 Zonation of the peat profiles

A current convention within palaeoecology is to subdivide fossil sequences, including pollen, diatoms, plant macrofossils and testate amoebae into assemblage zones, primarily to facilitate description and interpretation. Typically these zones group samples containing a similar assemblage of fossils, so that the zone boundaries identify the major changes in the fossil record for each core. Several techniques have been utilised to investigate peat sequences from the North York Moors, and so a zonation scheme could be created for each palaeoecological record.

Table 4.9. (part one). Radiocarbon dates obtained for peat sequences on the North York Moors.

Laboratory Number	**Peat Bog**	**Sample Depth**	**Sample Material**	**^{14}C analysis procedure**	**$\delta^{13}C_{PDB}$**	**Conventional ^{14}C age (Years BP ± 1σ)**
Beta 106589	Yarlsey Moss	76-80 cm	*Sphagnum* section *Acutifolia*/ Monocotyledonous peat	standard radiometric	-28.0	590 ±80 BP
Beta 106590	Yarlsey Moss	126-130 cm	*Sphagnum* section *Acutifolia*/ Monocotyledonous peat	standard radiometric	-26.6	740 ± 80 BP
Beta 106591	Yarlsey Moss	175-179 cm	*Sphagnum papillosum* / Monocotyledonous peat	standard radiometric	-27.6	1280 ±60 BP
Beta 106592	Bluewath Beck	60-63 cm	Monocotyledonous peat	standard radiometric	-26.6	1290 ±60 BP
Beta 106593	Harwood Dale Bog	30-34 cm	Monocotyledonous / *Sphagnum papillosum* peat	standard radiometric	-27.3	1460 ±60 BP
Beta 106594	Harwood Dale Bog	56-60 cm	Monocotyledonous / *Sphagnum papillosum* peat	standard radiometric	-27.6	1790 ±70 BP
SRR 5920	May Moss Core C3	49-52 cm	*Sphagnum imbricatum* peat	standard radiometric	-28.7	410 ±45 BP
SRR 5921	May Moss Core C3	64-67 cm	*Sphagnum* section *Acutifolia* peat	standard radiometric	-27.7	470 ±45 BP
SRR 5922	May Moss Core C3	75-78 cm	*Sphagnum* section *Acutifolia* peat	standard radiometric	-26.8	840 ±50 BP
SRR 5923	May Moss Core C3	95-98 cm	*Sphagnum* section *Acutifolia* peat	standard radiometric	-26.0	760 ±50 BP
SRR 5924	May Moss Core C3	110-113 cm	*Sphagnum* section *Acutifolia* peat	standard radiometric	-26.8	875 ±50 BP
SRR 5925	May Moss Core C3	125-128 cm	*Sphagnum* section *Acutifolia* peat	standard radiometric	-25.6	745 ±50 BP

Table 4.9. (part two).

Laboratory Number	Peat Bog	Sample Depth	Sample Material	^{14}C analysis procedure	$\delta^{13}C_{PDB}$	Conventional ^{14}C age (Years BP ± 1σ)
SRR 5926	May Moss Core C3	138-141 cm	*Sphagnum* section *Acutifolia* peat	standard radiometric	-27.6	1055 ±45 BP
SRR 5927	May Moss Core D2	80-83 cm	*Sphagnum imbricatum/* Monocotyledonous peat	standard radiometric	-26.5	685 ±50 BP
SRR 5928	May Moss Core D2	120-123 cm	*Sphagnum imbricatum/* Monocotyledonous peat	standard radiometric	-26.3	1195 ±50 BP
SRR 5929	May Moss Core D2	131-134 cm	*Sphagnum imbricatum/* Monocotyledonous peat	standard radiometric	-27.0	1305 ±50 BP
SRR 5930	May Moss Core D2	171-174 cm	*Sphagnum* section *Acutifolia/* Monocotyledonous peat	standard radiometric	-25.0	1640 ±55 BP
AA 24208	May Moss Core C3	52-53 cm	*Sphagnum imbricatum* leaves and stems	Accelerator Mass Spectrometry	-27.8	265 ±40 BP
AA 24209	May Moss Core C3	63-64 cm	*Sphagnum* section *Acutifolia* leaves and stems	Accelerator Mass Spectrometry	-25.87	310 ±40 BP
AA 24210	May Moss Core C3	74-75 cm	*Sphagnum* section *Acutifolia* leaves and stems	Accelerator Mass Spectrometry	-26.22	450 ±55 BP
AA 24211	May Moss Core C3	94-95 cm	*Sphagnum* section *Acutifolia* leaves and stems	Accelerator Mass Spectrometry	-25.92	620 ±40 BP
AA 24212	May Moss Core C3	113-114 cm	*Sphagnum* section *Acutifolia* leaves and stems	Accelerator Mass Spectrometry	-25.57	765 ±40 BP
AA 24213	May Moss Core C3	124-125 cm	*Sphagnum* section *Acutifolia* leaves and stems	Accelerator Mass Spectrometry	-26.18	680 ±40 BP
AA 24214	May Moss Core C3	141-142 cm	*Sphagnum* section *Acutifolia* leaves and stems	Accelerator Mass Spectrometry	-28.66	825 ±40 BP

Zonation of the palaeoecology based on the composition of fossil assemblages was not used in this research, because creating three of four sets of assemblage zones for a single profile would be an unwieldy and confusing procedure, hindering interpretation of the peat stratigraphy

However, dividing a palaeoecological profile into zones is a useful process, because it provides a structure for the discursive and interpretative process. The palaeoenvironmental data presented in chapters five and six were graphed against y-axes, which identify the depth and the chronology generated for each peat profile. These chronologies are not without problems, but they do provide a simple method for zoning the diagrams. Each peat profile is divided into zones with a duration of 500 years using the respective time-series. The zone boundaries are cal. AD 2000, cal. AD 1500, cal. AD 1000, cal. AD 500, cal. AD 0 and 500 cal. BC, and are the same for all of the cores and palaeoecological techniques. A zonation based on chronology avoids potential confusion inherent in schemes based on palaeoecology and has the advantage that the zones assist with comparison between the various palaeoenvironmental techniques and with correlation between peat sequences.

There are flaws with this approach arising mainly from anxieties about the accuracy of the time series derived from the ^{14}C dates and the chronological marker horizons. However these boundaries are not cast in stone and they are not proposed as exact ages, but as estimates with all the inherent errors of a time series interpolated from calibrated radiocarbon dates. The major advantage of this approach is the clarity offered by adopting a uniform structure. Diagrams presenting the results of the pollen, testate amoebae, plant macrofossil and humification analysis are annotated with these chronological periods, which provide a structure for interpretation, discussion and the eventual environmental reconstruction.

4.5.2 Statistical analysis

The quantity of numerical palaeoecological data generated in the course of this research renders quantitative analysis, an essential part of the interpretative procedure. Furthermore the palaeoenvironmental techniques were only selected if capable of producing numerical data susceptible to quantitative analysis. This quantitative approach has been assisted by a series of improvements to various palaeoecological techniques, which allow the production of quantitative data (Barber *et al.*, 1994a; Warner & Charman, 1994; Blackford & Chambers, 1993). Pollen, testate amoebae and plant macrofossil analyses all produce multivariate data, whereas the humification analysis produces univariate data. Interpretation of multivariate palaeoecological data can be hindered by the fact that it is inherently difficult to visually appreciate internal patterns and structure in multivariate data (Maddy & Brew, 1995).

Two broad methods of multivariate data analysis are utilised to assist with the interpretation of the palaeoecology, namely cluster analysis and ordination analysis. Cluster analysis encompasses a number of numerical techniques, which when applied to palaeoecological data will attempt to divide either or both the fossil samples and fossil species into discrete groups. These groups will contain members that are numerically similar; consequently the boundaries between these groups may represent significant differences within the data. Ordination analysis is a statistical procedure that summarises the most significant relationships within the data, which when applied in palaeoecology may identify the response of fossil communities to various environmental characteristics. Essentially ordination analysis in summarising the main trends, reduces the number of dimensions required to express the variation within a multidimensional data-set to three or four key axes. Each of these new axes produced by the ordination analysis expresses a calculable percentage of the overall variation within the data-set. Ordination analysis is a group of multivariate procedures, which identify and model the major changes within a palaeoecological sequence.

A further quantitative tool used to discern environmental information from palaeoecological data involves the use of ecological transfer functions. Transfer functions are used to couple the environmental tolerance displayed by extant species with the abundance of the organism in a fossil profile. Diatoms are unicellular aquatic algae, which have a fossil record that has been numerically linked using transfer functions to the optimum and range of salinity conditions tolerated by extant species to produce quantitative estimates of salinity conditions in the past. This type of approach would be invaluable in the investigation of mire palaeohydrology, if a group of organisms can be numerically associated with a specific moisture parameter. This is the case with testate amoebae, which can be linked numerically to the depth of the mean annual water table (Woodland *et al.*, 1998).

The three procedures introduced above assist with the interpretation of palaeoecological data and aid the reconstruction of environmental histories. A further area of quantitative analysis attempts to examine these environmental histories in the context of time. Chronologies were derived for each peat profile converting the palaeoenvironmental data into a time series. Analysis of these time series can identify and model the changes within palaeoenvironmental histories, perhaps throwing light on any periodicity, forcing and causes of environmental change (Green, 1995).

The quantitative procedures introduced above are utilised to varying degrees to assist with interpretation of the palaeoenvironmental techniques applied at each site. The following sections provide a more detailed introduction to each quantitative procedure, and outline how and if the quantitative procedures are applied to the pollen, testate amoebae, plant macrofossil and humification results. Furthermore the section explains how the results of the quantitative analysis are presented in later chapters, and sets out a rationale for interpretation and utilisation of these results.

Cluster Analysis

Cluster analysis is used to investigate structure within the pollen, testate amoebae and plant macrofossil data. The purpose of cluster analysis is to statistically identify either species that often occur together or groups of samples with a similar fossil assemblage (Kovach, 1995; Manly, 1994). In palaeoecological research the cluster analyses are often constrained by applying a predefined order to the samples. Stratigraphically constrained cluster analysis retains the stratigraphic order of the samples and the results of the cluster analysis will reflect the similarity of adjacent samples, which is particularly useful enabling the identification of significant changes within a stratigraphic profile. The results of cluster analyses are often presented as dendrograms, with the various branches of the dendrogram grouping similar members and the gaps between the larger branches often reflecting major stratigraphic changes.

There are various methods of carrying out cluster analysis, which are expertly reviewed in Birks & Gordon (1985) and Maddy & Brew (1995). The procedures utilised in this research are stratigraphically constrained sum of the squares cluster analyses implemented through the CONISS computer package (Grimm, 1987). Several other methods of cluster analysis were tested using the MVSP computer package (Kovach, 1993), and although there were occasional minor differences between the techniques, the major stratigraphic changes were almost always identified. In order that consistency is maintained within the statistical analysis, the procedures available in the CONISS computer package were utilised to analyse all the data, which has the further advantage that the results can be displayed as a dendrogram on palaeoecological diagrams produced using TILIAGRAPH (Grimm, 1993).

Most multivariate statistical procedures require certain characteristics within the object under investigation, which includes the requirement that the data should be normally distributed. However most multivariate procedures can be successfully applied to data that depart from normality (Kovach, 1995). There are numerous methods of data transformation available, which can be used to modify a dataset: for example, square root and logarithmic transformations are typically used to counter severe departures from normality. The pollen, testate amoebae and plant macrofossil data are all expressed as percentages and there are various methods of data transformation appropriate for percentage data. Aitchison's log-ratio transformation counters the effects of closure inherent in percentage data-sets, which arise because an increase in abundance of one species will cause a decrease in all others when expressed as percentages (Aitchison, 1986; Kovach, 1995). Standardised euclidean distance transformation gives all species equal weighting regardless of their actual abundance, which is particularly useful if changes in species with a low abundance are important for a particular inquiry.

Several methods of data transformation were tested using the CONISS and MVSP computer packages. However, they produce broadly similar results from the eventual cluster analysis. In the interests of consistency the standardised euclidean distance transformation was adopted, primarily because species with low abundance are an important component of the pollen, plant macrofossil and testate amoebae analysis, and furthermore the transformation procedure is easily performed within CONISS and the results displayed using TILIAGRAPH (Grimm, 1987; 1993). The effects of closure within percentage data were checked by carrying out minimum variance cluster analysis on log-ratio transformed data implemented using MVSP (Kovach, 1995), but the results were very similar.

Species with low or limited occurrence can have a detrimental effect on the results of a cluster analysis. A large number of taxa were encountered in the pollen analysis and some pollen taxa only occurred in a single sample. Consequently only pollen taxa achieving a minimum abundance of 1 % within a profile are included in the data receiving a cluster analysis. Fewer species were encountered in the testate amoebae and plant macrofossil profiles, and there are virtually no species with a low or limited occurrence. Consequently, in the case of the testate amoebae and plant macrofossil results all the species present are included for the cluster analysis.

Ordination Analysis

Ordination analysis is a multivariate statistical procedure used to summarise the most significant relationships within the plant macrofossil and testate amoebae stratigraphies, and these relationships may reflect the response of fossil communities to various environmental parameters. Detrended Correspondence Analysis (DCA) is a standard multivariate tool ideal for summarising the main trends within data collated in the form of contingency tables, which includes the results of testate amoebae and macrofossil analyses (Hill & Gauch, 1980; Kovach, 1995). The technique assumes that structure within the data-set occurs in response to a number of unknown environmental parameters and that the various species display a simple Gaussian response along these parameters, with maximum abundance at the environmental optima of each individual species. Basically DCA reduces the numbers of dimensions within a multidimensional data-set, expressing the most significant structure on a series of ordination axes (Kovach, 1995).

Each axis is described by an eigenvalue, which identifies the amount of variation within the data-set expressed on each individual axis. DCA generates a series of eigenvectors, which are scores on the new DCA axes for each object in the original data-set. DCA produces two series of eigenvectors, a set of scores for the fossil samples and a set for the species. DCA has a particular advantage over other ordination procedures, namely Principal Components Analysis and Principal Coordinates Analysis, because both sets of eigenvectors are ordinated together. Consequently the eigenvectors for the fossil samples and species have equivalent scaling and can be graphed together. This approach has been used in previous research, with DCA used to summarise the variations within macrofossil profiles from Bolton Fell Moss (Barber *et al.*, 1994a; 1994b). Axis 1 of the DCA identified the most significant changes within the data-set and the axis appears to identify a water-level gradient, with dry environment species at the opposite end of the axis to species preferring wet environmental conditions. Consequently the scores on axis 1 generated for each fossil sample may also summarise the moisture conditions, and a graph of the fossil samples scores on DCA axis 1 against depth has been proposed as a palaeohydrological history for Bolton Fell Moss (Barber *et al.*, 1994a; 1994b).

DCA was performed on percentage data of all the plant macrofossil and testate amoebae data using the MVSP computer package (Kovach, 1993). DCA was performed on percentages of the main macrofossil components: Identifiable Monocotyledons, Ericaceae and non-*Sphagnum* bryophytes; Unidentifiable Organic Matter; and the percentages of the various *Sphagnum* species. In the case of testate amoebae the DCA was performed on the percentages of all species present within the fossil profile. The results of the DCA include eigenvalues for each axis, the percentage of total variation explained by each axis signifying the most important ordination axes, and a series of eigenvectors for both samples and species on the DCA axes.

The species eigenvectors on DCA axes 1 and 2 are displayed as X/Y scatter-plots, enabling the identification the relationships between the main species. The location of species along detrended correspondence analysis axes 1 and 2 may reflect the distribution of individual species along specific environmental gradients. Careful ecological interpretation of these trends present on DCA axes may enable an axis to be identified as modelling a specific environmental parameter. Correlation coefficients were produced to assess the association between the percentages of fossil species and the axes generated by the DCA, which identifies the species that contribute the most significant structure within the data set. If the correlation coefficients and visual examination of the position of species on the DCA axes indicate that an axis clearly identifies an environmental gradient, then eigenvectors for the fossil samples on the same axis will also be on this environmental gradient. The eigenvectors generated for the fossil samples, if graphed against depth or a time series, model the most significant structure within the sub-fossil dataset, which may or may not reflect a response to one or more environmental gradients.

Ecological Transfer Functions

Transfer functions have been used to provide quantitative estimates of environmental variables from the composition of sub-fossil communities across a range of palaeoecological techniques, including foraminifera, diatoms and coleoptera (Birks, 1995). Ecological transfer functions using the sub-fossil testate amoebae data were carried out following a simple weighted averaging procedure. Weighted averages are used to generate a history of mean annual water table depths for the sub-fossil profiles on the North York Moors. The ecological data used for the transfer functions were kindly provided by Wendy Woodland, and are the subject of on-going research at Plymouth University and the University of the West of England. The environmental optima and tolerance ranges of the testate amoebae species are displayed graphically in figure 4.7.

The formula used to carry out the weighted average calculations is given below:

$$x_j = \frac{(\sum Wa_i \ Y_{ij})}{n_j}$$

x_j is the inferred depth to water table in sample j

Wa_i is the weighted average water table for species i

Y_{ij} is the percentage abundance of species i in sample j

n is the total percentage of tests in the fossil sample included in the analysis for sample j.

The optimum, maximum and minimum water table depth values for each species were input into the equation providing an estimation of the average water table depths and displaying the potential range or error of the water table depth reconstruction for each sub-fossil sample. The

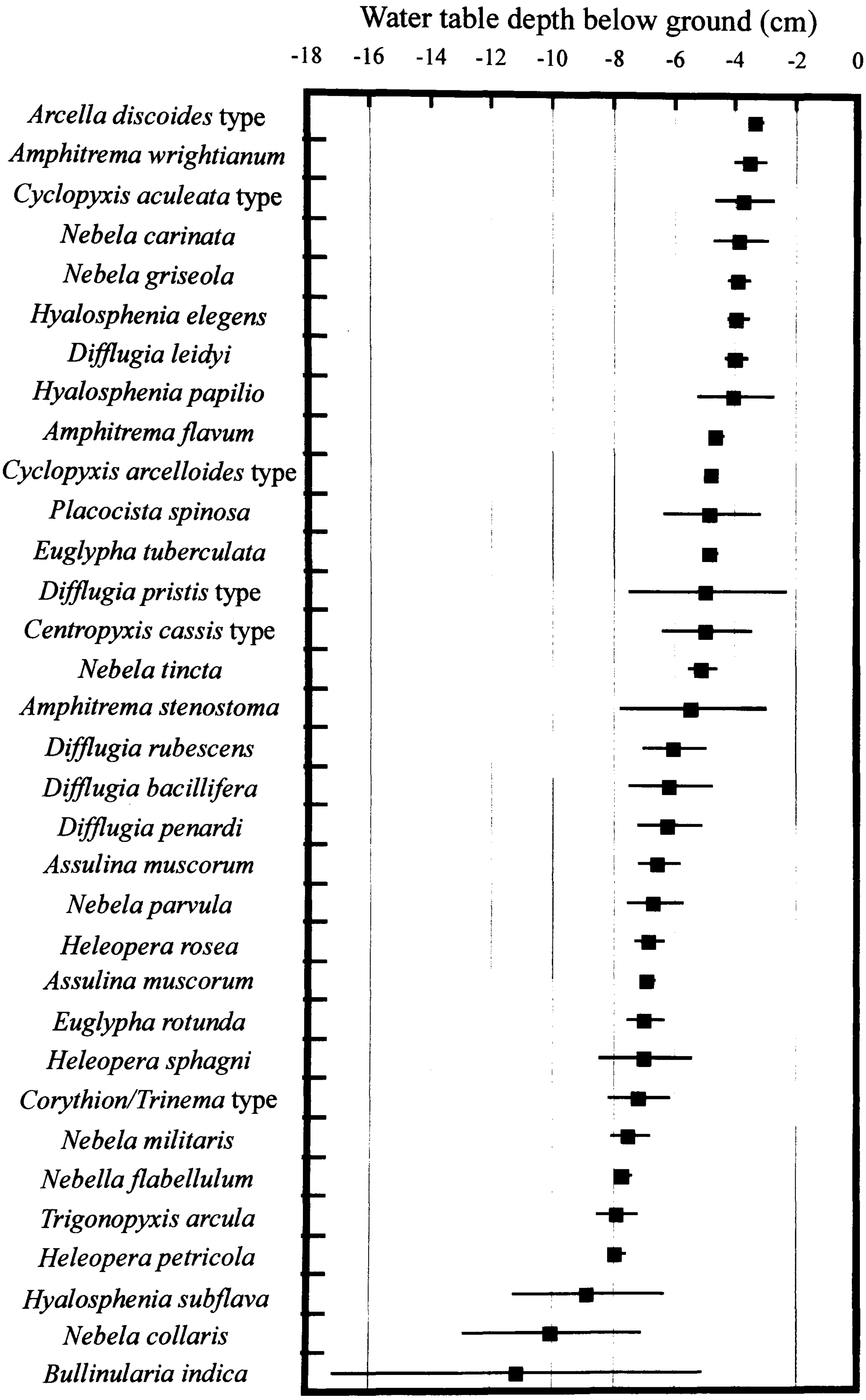


Figure 4.7. Individual species optima and tolerance range for mean annual water table, derived by assessment of extent testate amoebae communities in the British Isles (after Woodland *et al.* 1998).

three curves are appended to the testate amoebae diagrams in chapter six, and clearly identify fluctuations in moisture conditions at each site. The curves are not proposed as precise reconstructions of water table depth, but they do summarise changes in mire surface wetness.

Time Series Analysis

Investigations of peat deposits on the North York Moors and quantitative analysis of the results thereof, have enabled the production of three summary palaeoenvironmental curves, which can be viewed as hydrological histories. Humification curves broadly respond to fluctuations in mean summer water table. The water table depth curves generated using fossil testate amoebae model changes in the mean annual water table. Axis one of a DCA of both the plant macrofossil and testate amoebae fossil records may also model fluctuations in mire surface moisture conditions. A program of ^{14}C dating and the judicious use of chronological marker horizons has allowed the peat sequences to be converted into time series. Time series analysis can be used to examine trends and cyclic structure within the three types of palaeohydrological curve (Green, 1995).

There are often three components to any time series: a long term trend within the data, a series of cyclic fluctuations and background noise. These features are obviously combined, which renders time series often difficult to comprehend. There are numerous methods of filtering or smoothing time series to enhance or emphasise either the trends, cycles or noise (or short period cycles), without introducing new trends or noise. Noise is a particular problem in time series with numerous closely spaced samples; for example, the humification analyses utilise 1 to 3 cm contiguous samples. In essence, a large number of samples will increase the amount of noise, producing spiky curves. The moisture curves derived from the testate amoebae and plant macrofossil analyses will also contain noise, although the samples are spaced at 4 to 10 cm vertical intervals and this wider interval may reduce the impression of noise.

Palaeoecological data can be filtered prior to further time series analysis. Low pass filters are used to smooth high frequency cycles, thereby reducing the amount of noise within the time series; for example, a three point moving average will remove the extremes within time series (Green, 1995). A high pass or difference filter is used, when applied to the smoothed data, to emphasise remaining high frequency events and de-emphasise long term trend (Green, 1995). Time series analysis of a series filtered by this process should enable the identification of cyclic structure. Spectral analysis is the tool used to identify the periodicity of any cyclic structure within a dataset. To carry out spectral analysis the time series must have sample intervals representing similar time periods, and in the case of palaeoecological data any variations in the rate of sediment accumulation will preclude direct time series analysis.

Time series analysis is used to investigate cyclic structure within suitable palaeohydrological curves generated during palaeoenvironmental analysis. The time series analysis procedure is only applied if there is a statistically significant linear relationship between the interpolated chronology and depth, and if there is reasonable confidence in the geochronology. A further limitation to the application of time series analysis arises from a combination of the resolution of the palaeoenvironmental data and the purpose in applying the time series analysis. The rationale for time series analysis is to identify cyclic structure within palaeoenvironmental data pertaining to a 2000-year period. Clearly structure occurring at 500-year or above periodicities will only be represented on *circa* three occasions within the sequence, and this provides an upper limit to the periodicities identifiable by time series analysis.

In addition, the sampling interval provides a lower limit affecting the structure identifiable with shorter periodicities. The testate amoebae and plant macrofossil data were collected at 4 to 8 cm intervals, which at May Moss site D corresponds to 35 to 65 year intervals respectively. The age/depth model for May Moss site D signifies the stratigraphy is susceptible to direct time series analysis. However time series analysis of the testate amoebae and plant macrofossil palaeohydrological curves cannot be used to identify structure close to the sampling interval, because structure at 35-120 year periodicities will only reflect differences between a few fossil samples. The solution to this problem is fine resolution sampling at 0.5-1 cm intervals, but this was not possible within the time constraints of this thesis. These limitations reduce the value of time series analysis of the testate amoebae and plant macrofossil data, and this not been carried out in this research.

The humification data, sampled at 1-2 cm intervals equivalent to 8-16 years, is not susceptible to the problems discussed above, and spectral analysis was carried out on humification data for the North York Moors. There is a clear set of protocols followed in application of the time series analysis.

- **Constant Linear Sediment Accumulation Rate.** A least squares regression equation is generated for the relationship between depth and the interpolated chronology. If the coefficient of variation (r^2) approaches 100%, then the relationship between depth and the interpolated chronology is broadly linear and further time series analysis can proceed.

- **Filtering the Time Series.** A two stage filtering procedure is applied to the various time series. Firstly, a low pass filter is used to smooth the data reducing the amount of noise. The low pass filter calculates an unweighted three-point moving average for the time series. Secondly, a high-pass filter is used to remove long-term trends and emphasise the remaining high frequency structure. A difference filter is used to perform this transformation, applying the following formula.

  $$x = y^{(t)} - y^{(t-1)}$$

  where x = the filtered value; $y^{(t)}$ = the unfiltered value at time t ; $y^{(t-1)}$ = the unfiltered value at time (t-1).

- **Spectral Analysis.** Spectral analysis proceeded following the Fourier transformation method and the spectra were smoothed using a Daniell smoothing window (Green, 1995). The main spectral peaks are identified and the number of cycles per sampling interval of the peaks is converted using the regression equation between depth and the interpolated chronology to calculate the number of years within an individual cycle. The number of years within each cycle signifies the periodicities of the cyclic structure with the data.

5

A-2000 year regional vegetation history

5.1 Introduction

This chapter is a detailed account of the vegetation history of the central and eastern North York Moors during the last two millennia. Reconstruction of regional vegetation history is based on palynological analyses at May Moss, Fen Bogs, Yarlsey Moss, Harwood Dale Bog and Bluewath Beck. The palaeovegetation information contained within the six palaeoecological profiles is integrated to produce a picture of vegetation changes across the region. This chapter is divided into two sections: the first presents the results of the pollen analyses and defines the chronology of the vegetation changes; the second section synthesises the palynological results, formulating a regional vegetation history for the North York Moors. The regional vegetation history is discussed in relation to anthropogenic activity, and environmental and climatic changes.

Human impact on the vegetated environment is controlled by changes in regional politics, population levels, and variations in settlement patterns, the amount of industrial activity and the intensity of agricultural activity. These factors impact on the vegetated landscape, and are pertinent to the interpretation and discussion of the vegetation changes identified in the pollen diagrams. Climatic change is an important factor affecting the type of agrarian activity, and the occupation and settlement of areas marginal for agriculture (Higham, 1985; Parry, 1976; 1978). The parallel histories of human activity and anthropogenic vegetation change derived from pollen stratigraphies and documentary sources are discussed in the light of the climate history uncovered from peat deposits on the North York Moors.

The pollen rain received by a sedimentary system is derived from a wide source or catchment area, thereby incorporating pollen grains produced by the local mire vegetation, vegetation surrounding the mire and a wind-blown regional component. Consequently each pollen profile, to some extent, presents a picture of regional vegetation change; however, it is important to base an investigation of regional vegetation history on several pollen profiles spaced across the region. Additionally, analysing more than one profile at May Moss assesses the consistency of the palynostratigraphy within a single site. If there are differences in the palynostratigraphy within an individual mire this is more likely to reflect variations in local pollen production than variations in the regional pollen rain, which should be broadly similar on a broad open moor like May Moss. If the palynostratigraphy is similar, this lends support to the view that the palynological history reflects changes in the regional vegetation.

5.2 Results of the palynological analyses

5.2.1 May Moss

The vegetation history uncovered from the May Moss peat stratigraphy is based on pollen analysis of two sequences, core B and core D1. The core B pollen profile is displayed in figure 5.1 and the core D1 profile in figure 5.2. Cumulative curves on the far right of the pollen diagrams summarise fluctuations in the relative abundance of trees, shrubs, dwarf shrubs and herbs, thereby assisting with identification of major changes in the regional vegetation.

Neither profile has been directly ^{14}C dated, but core D1 is immediately adjacent to a further core, D2, which has been ^{14}C dated. The stratigraphies of both cores are virtually identical. Consequently the four dated horizons are confidently correlated to 10 cm vertical units of peat on the undated profile, and these four horizons are the basis of the chronology developed for the D1 peat sequence. Furthermore the palynostratigraphy contains evidence of two significant events in the regional vegetation history, which can be used as chronological marker horizons. Near the base of D1, the beginning of the Iron Age and Romano-British woodland clearances is clearly evident and this event has been ^{14}C dated at Harwood Dale Bog to 2190 ±90BP [400(200)5 cal. BC] (Atherden, 1989). There is a sharp increase in *Pinus* frequencies near the top of the pollen profile, which is attributed to modern conifer afforestation from the 1930s onwards (Statham, 1989).

The chronology derived for the site B peat profile is based entirely on correlation with palynostratigraphic events, which are used as tentative chronological marker horizons. These palynostratigraphic events are the beginning of the Iron Age/Romano-British woodland clearances ^{14}C dated at Harwood Dale Bog to 2190 ±100BP [400(200)5 cal. BC] (Atherden, 1989), the beginning of the post-Roman woodland regeneration dated at May Moss site D to 1640 ±50BP [cal. AD 260(420)555], a medieval woodland decline ^{14}C dated at May Moss site D to 685 ±50BP [cal. AD 1260(1293)1405] and the *Pinus* rise attributed to the onset of modern conifer afforestation after 1930 (Statham, 1989). The mire surface at May Moss provides another convenient chronological horizon, because the mire is actively accumulating. Consequently the surface of both profiles has a present-day age, AD 1995. The ^{14}C dated horizons and the

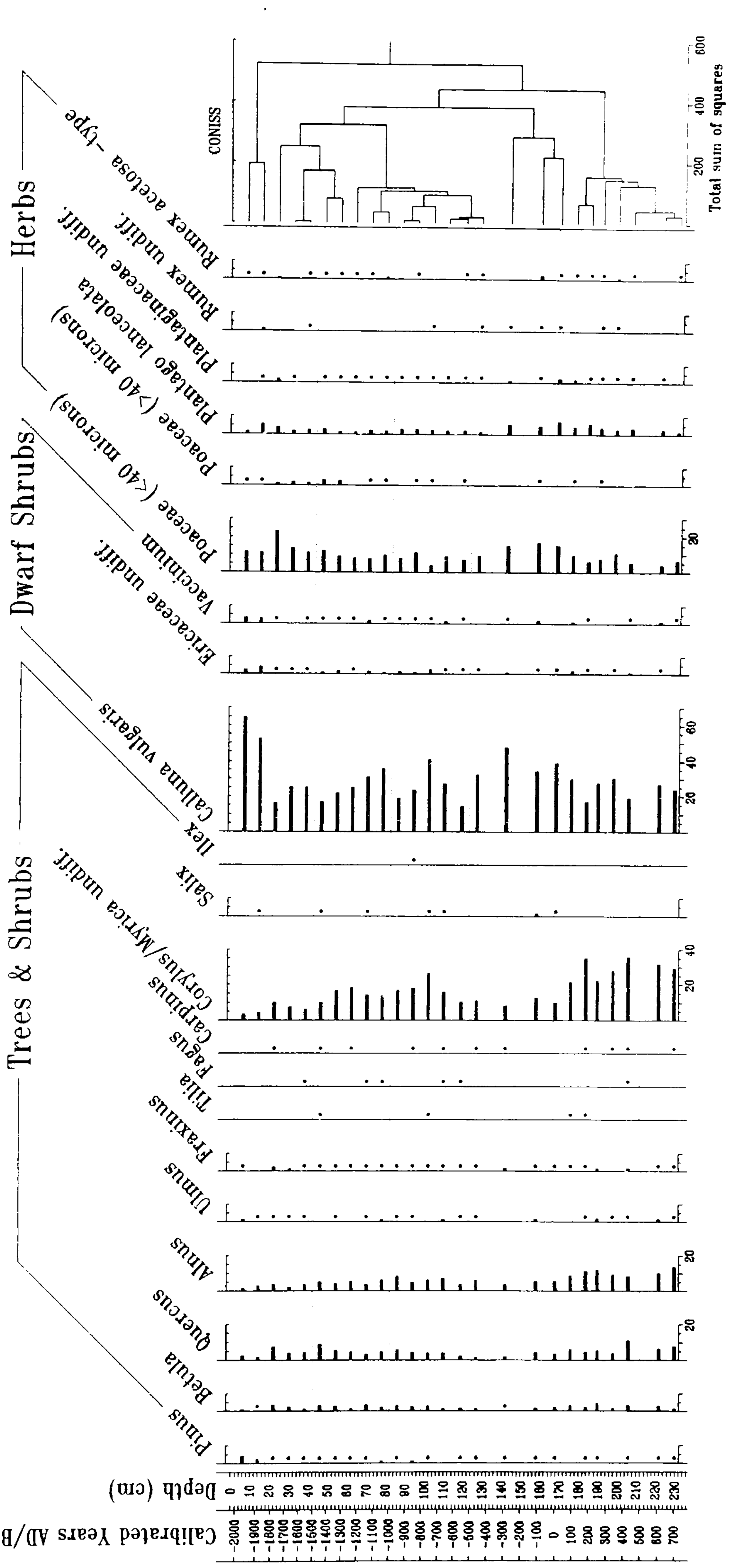


Figure 5.1. (part i). Pollen diagram from May Moss core B. Taxa are expressed as percentages of the pollen sum. Aquatics and spores are expressed as percentages of the pollen sum plus aquatics and spores. Circles signify frequencies amounting to less than 1% of the sum. The dendrogram presents the results of a sum of the squares cluster analysis.

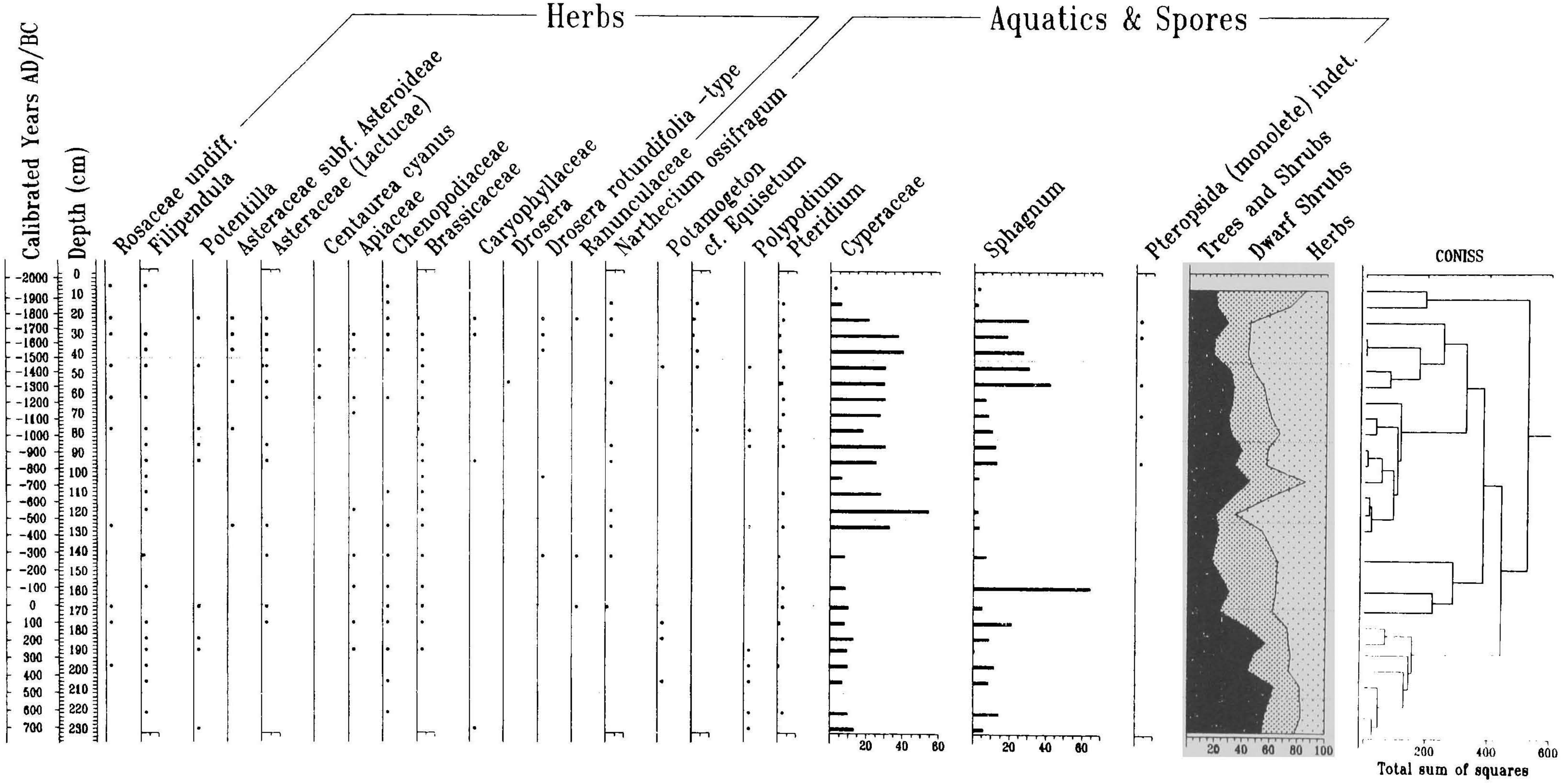


Figure 5.1. (part ii).

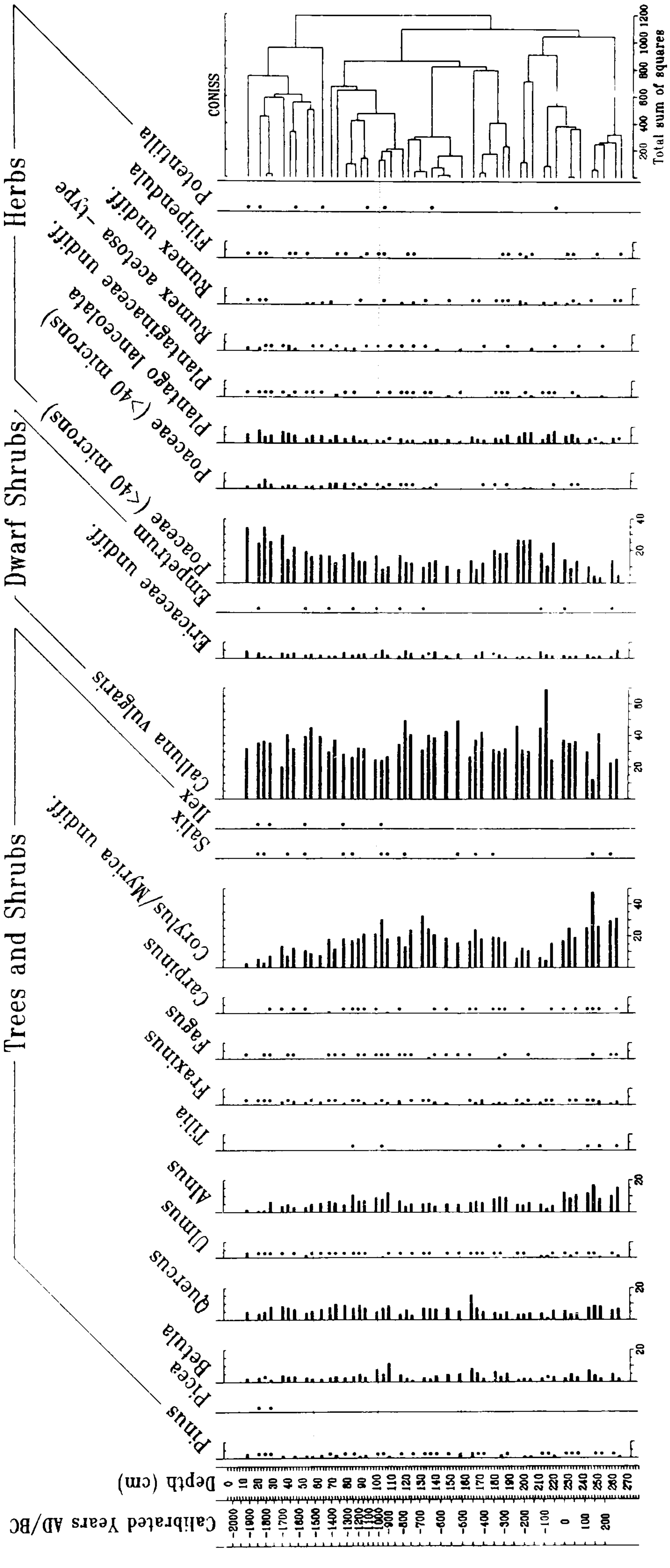


Figure 5.2. (part i). Pollen diagram from May Moss core D1. Taxa are expressed as percentages of the pollen sum. Aquatics and spores are expressed as percentages of the pollen sum plus aquatics and spores. Circles signify frequencies amounting to less than 1% of the sum. Charcoal frequencies are expressed as the number of shards per 50 exotics. The dendrogram presents the results of a sum of the squares cluster analysis.

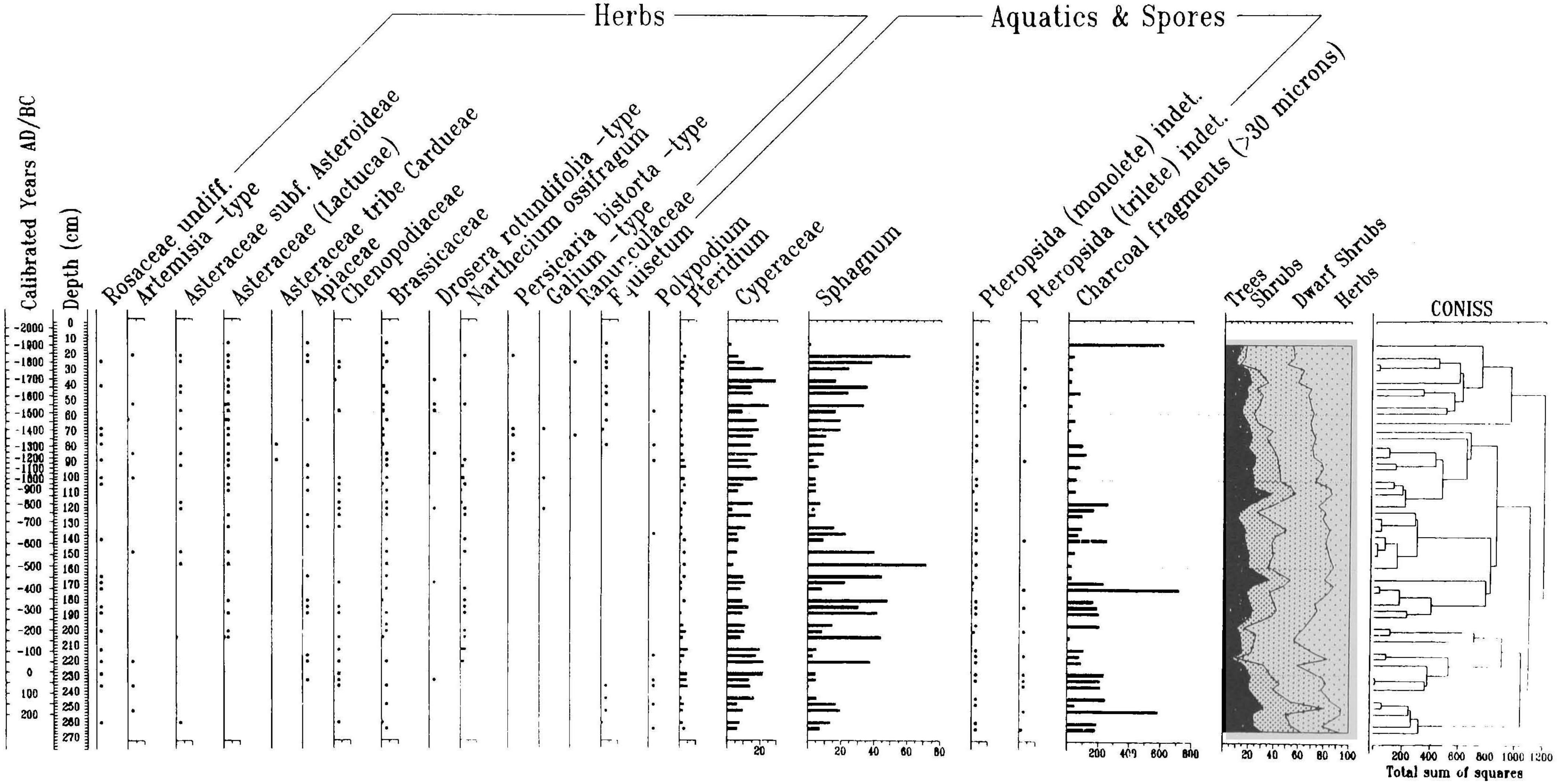


Figure 5.2. (part ii).

palynostratigraphic marker horizons on cores B and D1 are listed in table 5.1. Linear interpolation between these chronological horizons is used to generate time series for both peat sequences.

Both peat sequences cover the last two millennia, with the base of the core B sequence equivalent to 700 cal. BC and the base of the core D1 sequence equivalent to 250 cal. BC. The palynostratigraphy contains a series of fluctuations in the abundance of arboreal pollen, with the phases of woodland decline mirrored by expansions of non-arboreal pollen, mainly cleared ground indicators, agricultural weeds and moorland taxa. The cluster analyses of both pollen profiles signifies that the most significant changes within core D1 occurred *circa* 100 cal. BC, cal. AD 300-400, cal. AD 900, cal. AD 1450, cal. AD 1700 and cal. AD 1950, and the most significant changes within core B occurred *circa* 100 cal. BC, cal. AD 400, cal. AD 300 and cal. AD 1950. The most abundant tree species were *Quercus*, *Betula, Alnus* and *Fraxinus*. High frequencies of *Corylus/Myrica* type pollen imply there were substantial stands of hazel, although *Myrica gale* is currently locally abundant at Fen Bogs and may contribute quantities of pollen to this *Corylus/Myrica* group. *Calluna vulgaris*, Cyperaceae and *Sphagnum*, the dominant mire and moorland taxa, are abundant throughout the pollen profile. *Sphagnum* spores vary in abundance, and are particularly frequent between cal. AD 100 and 750, and from cal. AD 1300 to the present-day.

Between 800 cal. BC and 200 cal. BC, arboreal species and *Corylus/Myrica* are particularly abundant, with corresponding low frequencies of herbs and dwarf shrubs. After *circa* 200 cal. BC woodland trees and shrubs decline sharply. Herbs species are particularly abundant between 200 cal. BC and cal. AD 400, dominated by the Poaceae, *Plantago lanceolata* and Brassicaceae. A further important palynostratigraphic change identified by the cluster analysis, involves arboreal pollen frequencies increasingly sharply, an event which is ^{14}C dated to *circa* cal. AD 420 at site D. During this phase the most abundant woodland taxa are *Betula, Alnus, Quercus* and *Corylus/Myrica*-type. Paralleling the increase in trees and shrubs is a decline in herb species.

Trees and shrubs species remain abundant until *circa* cal. AD 750, when there is a gradual decline. Subsequently tree and shrub species increase in abundance between cal. AD 900 and 1400, which is followed by a gradual decline after cal. AD 1100. From cal. AD 1400 onwards, moorland and herbaceous taxa dominate the palynostratigraphy, with Poaceae, cereal pollen, *Plantago lanceolata* and *Rumex* the most abundant of the herb taxa. The final change in the

Table 5.1. Chronological horizons on the May Moss peat profiles. [1] age of the current mire surface. [2] onset of commercial conifer afforestation (Statham, 1989). [3] ^{14}C dates obtained from May Moss core D2 during this research. [4] ^{14}C date obtained at Harwood Dale Bog (Atherden, 1989).

Lab. No.	Depth on D2	Equivalent depth on D1	Equivalent depth on B	Conventional C^{14} age	Calibrated range BP (2σ) (with the intercepts)	Calibrated range AD/BC (2σ) (with the intercepts)
n/a	0	0	0	n/a	n/a	1997[1]
n/a	10-15	10-15	10-15	n/a	n/a	1940[2]
SRR 5927[3]	80-83	75-85	52-62	685 ±50	690(657)545	cal. AD 1260(1293)1405
SRR 5928[3]	120-123	105-115	n/a	1195 ±50	1260(1167,1163,1079)984	cal. AD 700 (870) 975
SRR 5929[3]	131-134	125-135	n/a	1305 ±50	1306(1260,1196,1192)1080	cal. AD 650 (690) 860
SRR 5930[3]	171-174	165-175	125-135	1640 ± 50	1690(1530)1407	cal. AD 260 (420) 555
HAR 5916[4]	n/a	250-260	180-190	2190 ±90	n/a	400 (200) 5 cal. BC

palynostratigraphy occurs towards the very top of the pollen profiles, with increases in the frequencies of *Pinus* and *Picea* during a phase when the majority of tree taxa decline.

5.2.2 Fen Bogs

The vegetation history uncovered from Fen Bogs is based on pollen analysis of a single peat core. The pollen diagram is displayed in figure 5.3. The Fen Bogs profile has not been ^{14}C dated, but a series of ^{14}C dates was obtained for a pollen profile sampled in close proximity to the current profile (Atherden, 1976a; 1976b). Depths equivalent to four of the horizons dated in the earlier research can be identified in this current pollen profile. These horizons occur at similar depths to those in the previous research and they are utilised to provide a chronology for the current pollen profile. A cautious approach is used, correlating these dates with a 10 cm vertical interval of peat across the stratigraphic event. The ^{14}C chronology is calibrated to an absolute chronology using a decadal tree-ring data-set (Vogels *et al.*, 1993). Additionally there is a sharp increase in *Pinus* frequencies near the top of the pollen profile reflecting modern conifer afforestation from the 1930s onwards. Fen Bogs is an actively accumulating mire, therefore the mire surface has a present-day age, AD 1995. All these chronological horizons are listed in table 5.2, and linear interpolation between the horizons is used to generate a time series for the peat sequence.

The Fen Bogs pollen diagram pertains to the last two millennia, with the base of the core equivalent to 100 cal. BC. The palynostratigraphy contains a series of clear fluctuations in the abundance of woodland trees and shrubs. Cluster analysis identifies six main clusters with similar pollen assemblages, and signifies that the most significant changes within the palynostratigraphy occurred *circa* cal. AD 500, 850, 1300, 1700 and 1950. The most abundant woodland taxa are *Betula, Quercus, Alnus* and *Corylus avellana.* However it must be noted that the taxonomic status of *Corylus/Myrica* type pollen presents problems at Fen Bogs, because *Myrica gale* is currently an important component of the flora, and may have also contributed quantities of pollen in the past. It is impossible to be certain whether the substantial quantities of *Corylus/Myrica* undiff. represent a local *Myrica gale* population or the presence of substantial stands of *Corylus avellana* within the pollen catchment area of Fen Bogs.

Between 150 cal. BC and cal. AD 500, near the base of the pollen profile tree populations were very low and herbaceous pollen dominates the assemblages, specifically the Poaceae, cereal pollen, *Plantago lanceolata* and the Brassicaceae. There were also substantial quantities of *Pteridium*. Cluster analysis identifies a significant change in the palynostratigraphy around cal. AD 500, which involves an expansion in the tree population and a decline in herb communities.

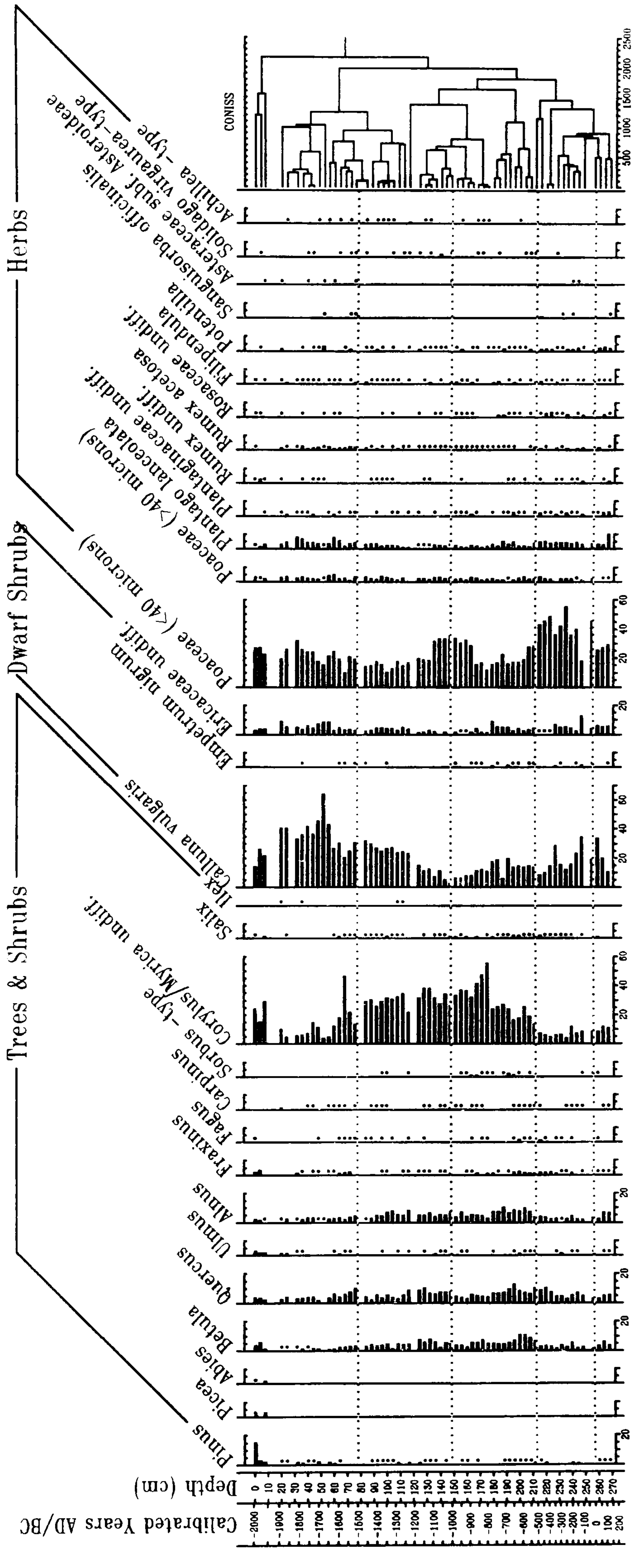


Figure 5.3. (part i). Pollen diagram from Fen Bogs. Taxa are expressed as percentages of the pollen sum. Aquatics and spores are expressed as percentages of the pollen sum plus aquatics and spores. Circles signify frequencies amounting to less than 1% of the sum. Charcoal frequencies are expressed as the number of shards per 50 exotics. The dendrogram presents the results of a sum of the squares cluster analysis.

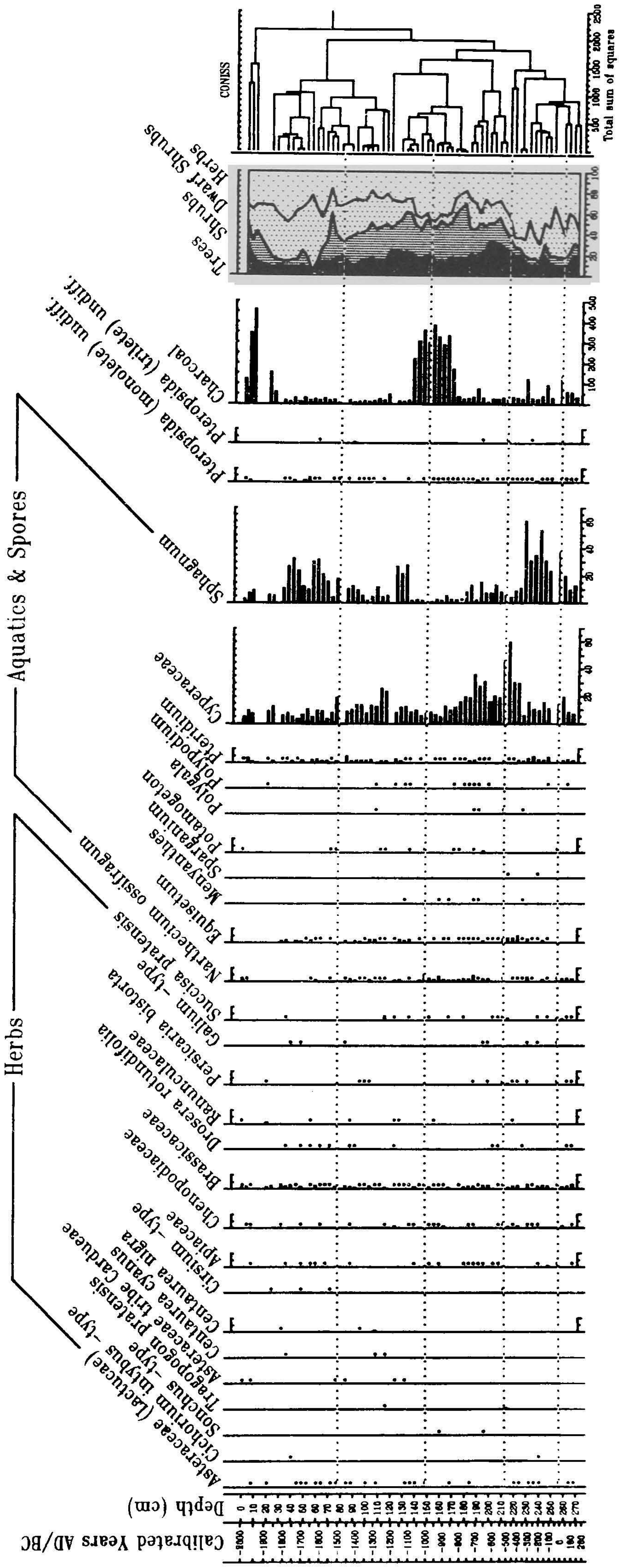


Figure 5.3. (part ii).

Table 5.2. Chronological horizons on the Fen Bogs peat profile. [1] age of the current mire surface. [2] onset of commercial conifer afforestation (Statham, 1989). [3] ^{14}C dates obtained at Fen Bogs by Atherden (1976).

Lab No.	Depth range (cm)	Central depth (cm)	Conventional C^{14} age	Calibrated range BP (2σ) (with the intercepts)	Calibrated range AD/BC (2σ) (with the intercepts)
n/a	0	0	n/a	n/a	1995[1]
n/a	5-15	10	n/a	n/a	1940[2]
T1151[3]	75 - 85	80	390 ±100	619 (464) 0	cal. AD 1331 (1486) 1954
T1087[3]	150 - 160	155	1060 ±160	1295 (995) 667	cal. AD 655 (955) 1283
T1086[3]	205 - 215	210	1530 ±130	1707 (1408) 1177	cal. AD 243 (542) 773
T1085[3]	280 - 290	285	2280 ±120	2714 (2325, 2319, 2313, 2214) 1951	764 (376, 370, 364, 265) 1 cal. BC

Tree pollen frequencies remain high until *circa* cal. AD 800, when a gradual decline is initiated, which continues until *circa* 1000. After *circa* cal. AD 1000 there is a clear increase in the abundance of tree species and a rapid expansion of moorland communities, namelv *Calluna vulgaris* and other Ericaceae. These changes are preceded by a sharp charcoal spike around cal. AD 1000.

Trees, specifically *Betula, Quercus* and *Alnus* are particularly abundant between cal. AD 1100 and 1400, after which there is a clear reduction in woodland communities and a concurrent expansion of herb and moorland taxa. Cereal pollen, *Plantago lanceolata* and Brassicaceae display their highest frequencies between cal. AD 1400 and the present-day. The cluster analysis dendrogram identifies this change as a highly significant event in the palynostratigraphy. Tree taxa remain in decline throughout the remainder of the profile, with the exception of a minor peak around cal. AD 1500-1600 and a substantial increase in *Pinus* and *Picea* within the surface layers.

5.2.3 Yarlsey Moss

The palynostratigraphy at Yarlsey Moss was uncovered through the analysis of a single peat profile. The pollen diagram is displayed in figure 5.4. Three horizons from the Yarlsey Moss peat profile were sampled for conventional radiometric ^{14}C analysis. The ^{14}C dates were calibrated to an absolute chronology using a decadal tree-ring data-set (Vogels *et al.*, 1993). In addition to the ^{14}C dated horizons, the palynostratigraphy contains evidence of two significant events in the regional vegetation history, which can be used as chronological marker horizons. Near the base of the peat profile there is a massive reduction in arboreal pollen frequencies, which represents the Iron Age and Romano-British woodland clearances, and this event has been ^{14}C dated at Harwood Dale Bog to 2190 ±80BP [400(200)5 cal. BC] (Atherden, 1989). The subsequent woodland regeneration is ^{14}C dated, although the dated horizon is 10 cm above the base of the increase in arboreal pollen. The increase in arboreal pollen is broadly linked to the Roman withdrawal from Britain, and has been ^{14}C dated in this project at May Moss site D to 1640 ±50BP [cal. AD 260(420)555]. These two palynostratigraphic horizons are used to supplement the ^{14}C chronology. Furthermore, Yarlsey Moss is an actively accumulating mire, consequently the mire surface has a present-day age, AD 1996.

The palynostratigraphic horizons and the ^{14}C dates are listed in table 5.3. Linear interpolation between these chronological marker horizons produced a time series for the peat sequence. The time series is displayed on the pollen diagram, which shows that the accumulation of peat at

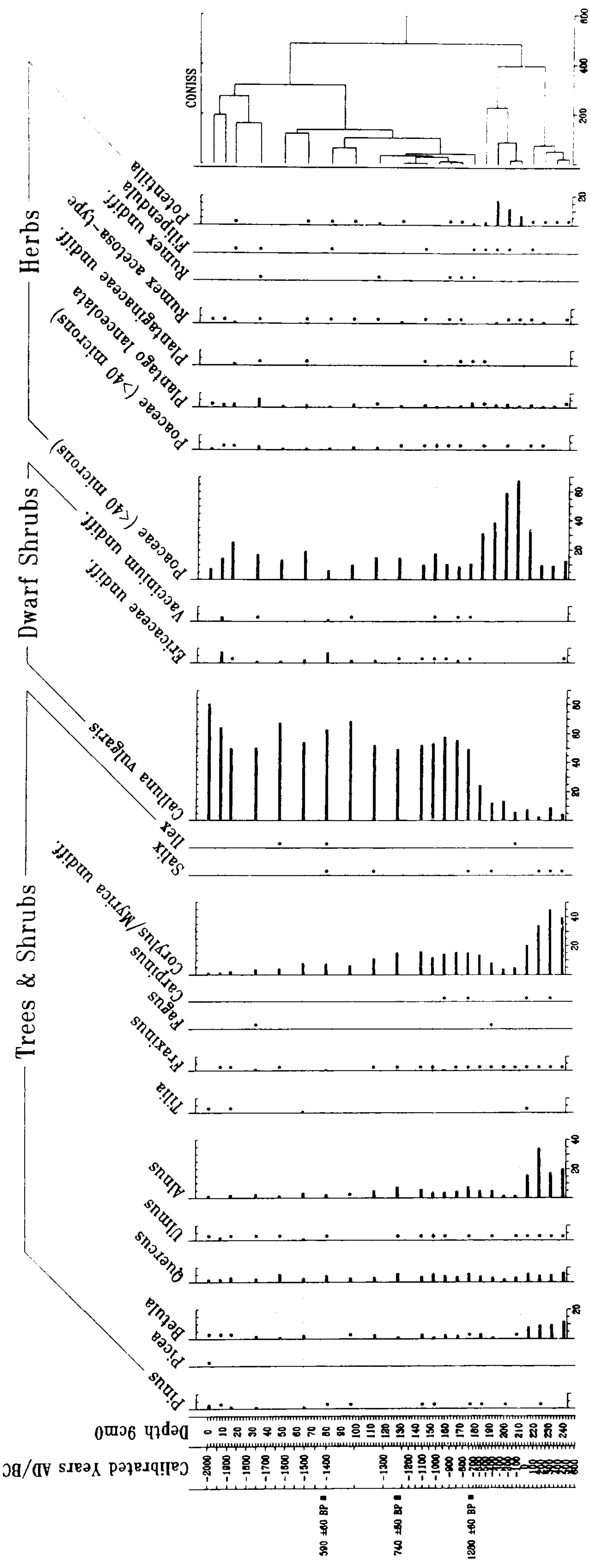


Figure 5.4. (part i). Pollen diagram from Yarlsey Moss. Taxa are expressed as percentages of the pollen sum. Aquatics and spores are expressed as percentages of the pollen sum plus aquatics and spores. Circles signify frequencies amounting to less than 1% of the sum. ^{14}C dates are expressed in years BP. The dendrogram presents the results of a sum of the squares cluster analysis.

Figure 5.4. (part ii).

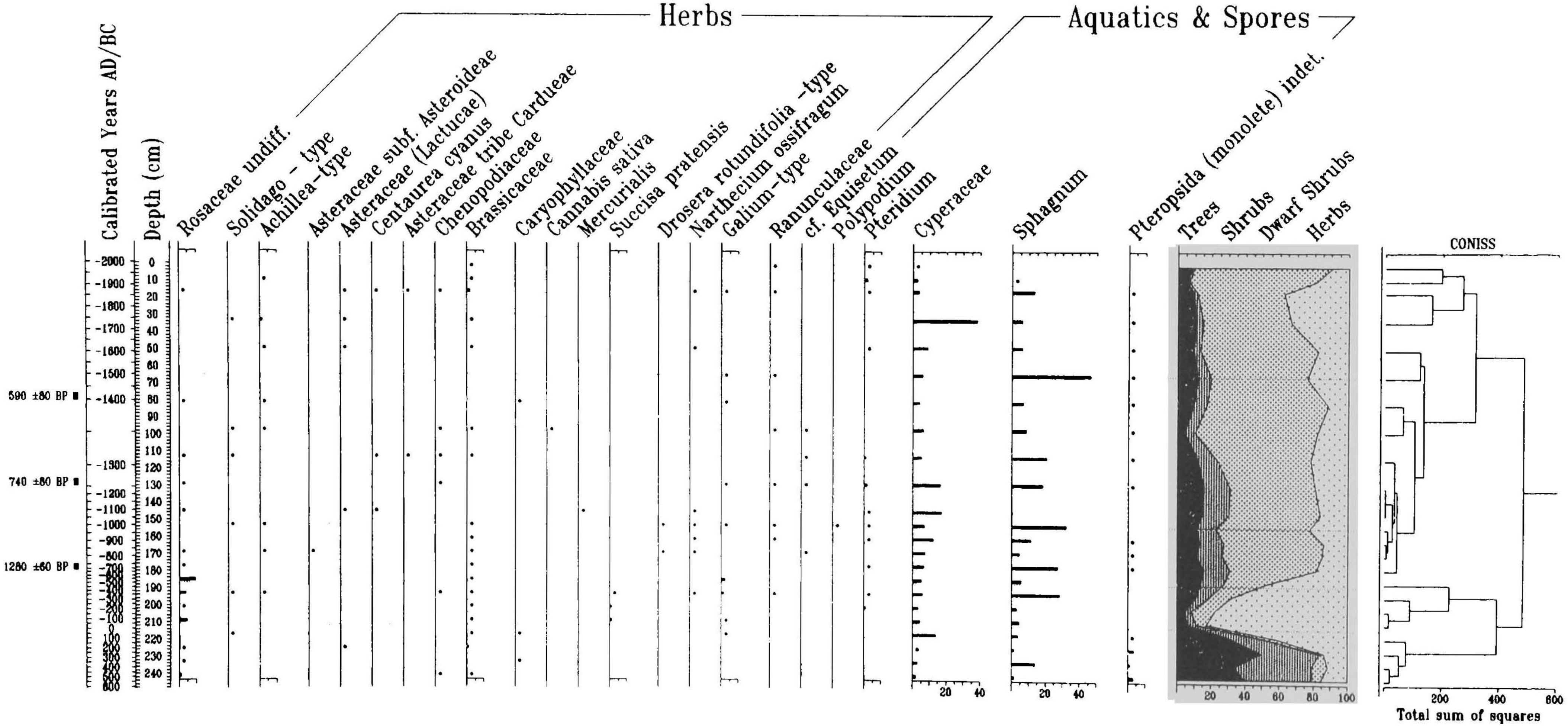


Table 5.3. Chronological horizons on the Yarlsey Moss peat sequence. [1] age of the current mire surface. [2] ^{14}C dates obtained at Yarlsey Moss during this research. [3] ^{14}C date obtained at May Moss. [4] ^{14}C date obtained at Harwood Dale Bog (Atherden, 1989).

Lab. No.	Depth (cm)	Conventional C^{14} age	Calibrated range BP (2σ) (with the intercepts)	Calibrated range AD/BC (2σ) (with the intercepts)
n/a	0	0 BP	n/a	AD 1996
BETA 106589	76-80	590 ±80 BP	671 (618,608,555) 504	cal. AD 1275 (1400) 1450
BETA 106590	126-130	740 ±80 BP	793 (668) 545	cal. AD 1170 (1280) 1400
BETA 106591	176-179	1280 ±60 BP	1304 (1235, 1204, 1181) 1009	cal. AD 650 (720, 735, 760) 885
SRR 5930[3]	185-195	1640 ±50 BP	1690(1530)1407	cal. AD 260 (420) 543
HAR 5916[4]	220-230	2190 ±80 BP	n/a	5 (200) 400 cal. BC

Yarlsey Moss has been far from consistent. A slower rate of accumulation clearly occurs at the base of the profile, if the palynostratigraphic horizons are to be believed. However this view is also supported by the plant macrofossil stratigraphy. The basal peat is highly humified with few recognizable plant remains, which are typical characteristics of peat that has accumulated slowly. After cal. AD 650 there is a stratigraphic change to poorly humified *Sphagnum*-rich peat, which typically accumulates relatively rapidly. These stratigraphic changes account for the variations identified in the peat accumulation rates and provide an explanation for the variations in the time series.

Peat accumulation at Yarlsey Moss was probably initiated around 400 cal. BC, and the stratigraphy covers the period from 400 cal. BC to the present-day. The cluster analysis identifies four main clusters with similar pollen assemblages, and signifies that the most significant changes within the palynostratigraphy occurred *circa* cal. AD 0, 500 and 1650. Trees are only abundant at the base of the profile and after a sharp decline around 50 cal. BC the percentages of tree pollen are very low, not exceeding 20%. The decline in woodland species is mirrored by a rise to dominance by mire and moorland taxa. *Calluna vulgaris,* Cyperaceae and *Sphagnum* are very abundant throughout the remainder of the profile, perhaps reflecting an absence of woodland on the central moorland plateau, which almost certainly was blanketed by heather moorland.

The sequence of vegetation changes is more complicated than indicated in the broad synthesis above, with tree taxa declining around 50 cal. BC and replaced by herb taxa, specifically the Poaceae, *Plantago lanceolata* and *Potentilla.* Around cal. AD 500 these herb taxa decline and there is a massive expansion of *Calluna vulgaris.* Additionally there are minor increases in the abundance of several tree taxa around cal. AD 500 *Betula, Quercus* and *Alnus.* The cluster analysis identifies the oscillations in tree frequencies between 100 cal. BC and cal. AD 700 as the most significant changes in the palynostratigraphy. Moorland taxa dominate the remainder of the pollen profile. However further fluctuations in the abundance of non-moorland taxa can be detected in the palynostratigraphy. Frequencies of tree pollen remain relatively constant between cal. AD 500 and 1200, even increasing slightly around 1000. However between cal. AD 1200-1300 there is a further decline in tree pollen, followed by subsequent expansion in tree pollen frequencies ^{14}C dated to 590±80 BP [cal. AD 1275(1400)1450]. This expansion was short-lived and followed by a gradual decline in tree species, which is mirrored by increases in the Poaceae, cereal pollen, *Plantago lanceolata* and Brassicaceae. These herb taxa are abundant from *circa* cal. AD 1400 to the present-day. The final event visible within the palynostratigraphy is the increase in *Pinus* frequencies towards the top of the pollen diagram.

5.2.4 Harwood Dale Bog

The vegetation history uncovered from Harwood Dale Bog is based upon pollen analysis of a single peat profile and the pollen diagram is displayed in figure 5.5. Two horizons from the Harwood Dale Bog peat profile were sampled for conventional radiometric ^{14}C analysis. The ^{14}C dates are calibrated to an absolute chronology using a decadal tree-ring data-set (Vogels *et al.*, 1993). In addition to the ^{14}C dated horizons, in previous research the entire Harwood Dale Bog peat sequence was analysed, a process that included ^{14}C dating of the palynostratigraphy (Atherden, 1989). These five ^{14}C dates are older than the 2000 year time frame that is the subject of this thesis, spanning the period from 5310 ±80 BP to 2190 ±80 BP. However the youngest ^{14}C date provides an age estimate for the base of the massive Iron Age and Romano-British woodland clearances, and these woodland clearances are visible in the current profile. Consequently the ^{14}C date obtained for this event by Atherden (1989) is applied to the current peat profile.

The palynostratigraphic marker horizon and the ^{14}C dates are listed on table 5.4. The three chronological horizons are evenly spaced down the profile, identifying a relatively uniform accumulation rate of 1 cm per 13.84 years. Linear interpolation between the chronological horizons generated a time series for the peat sequence, which is displayed on the pollen diagram. This time series indicates the peat stratigraphy is truncated, reflecting the impact of centuries of peat extraction at the site. The base of the pollen sequence is equivalent to *circa* 500 cal. BC and the truncated top of the sequence is equivalent to *circa* cal. AD 1100, with the palynostratigraphy containing approximately 1500 years of information.

Moorland taxa dominate the entire peat sequence, with *Calluna vulgaris* exceeding 20% throughout the profile; furthermore Cyperaceae and *Sphagnum* are also abundant. However, there are also significant fluctuations in the abundance of woodland species. The cluster analysis identifies four main clusters with broadly similar pollen assemblages, and signifies that the most significant changes within the palynostratigraphy occurred *circa* 150 cal. BC, cal. AD 400 and cal. AD 950. Tree species were abundant prior to 50 cal. BC, especially *Betula, Quercus* and *Alnus*. *Corylus*/*Myrica*-type was also abundant probably reflecting the presence of hazel within the region's woodland. Between 50 cal. BC and cal. AD 400 tree species decline sharply in abundance and herbs increase in abundance, with the Poaceae and *Plantago lanceolata* the dominant taxa. After cal. AD 400 tree species increase and remain abundant until *circa* cal. AD 950, when there is a further decline in arboreal pollen that extends to the top of the diagram.

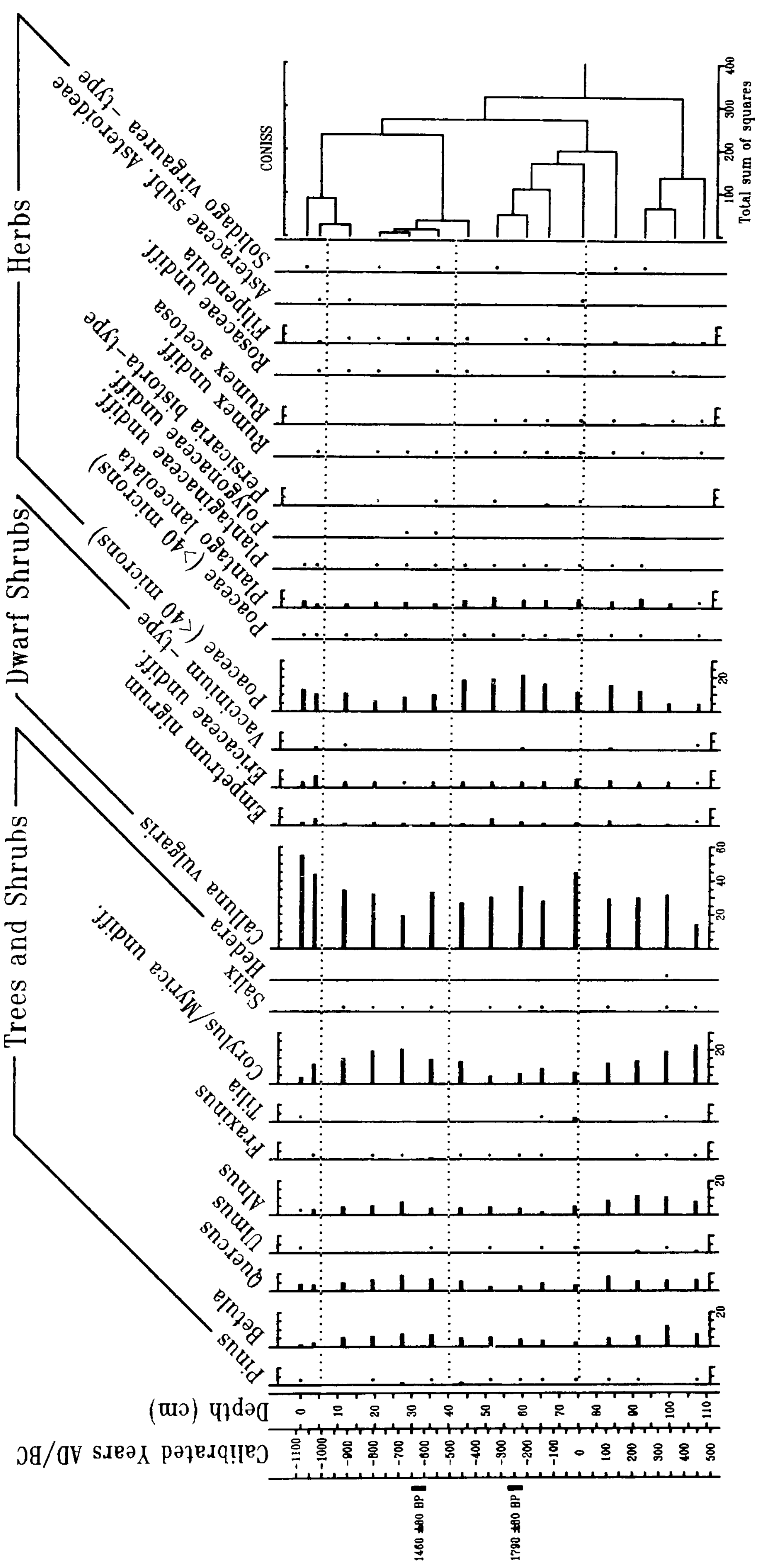


Figure 5.5. (part i). Pollen diagram from Harwood Dale Bog. Taxa are expressed as percentages of the pollen sum. Aquatics and spores are expressed as percentages of the pollen sum plus aquatics and spores. Circles signify frequencies amounting to less than 1% of the sum. Charcoal frequencies are expressed as the number of shards per 50 exotics. ^{14}C dates are expressed in years BP. The dendrogram presents the results of a sum of the squares cluster analysis.

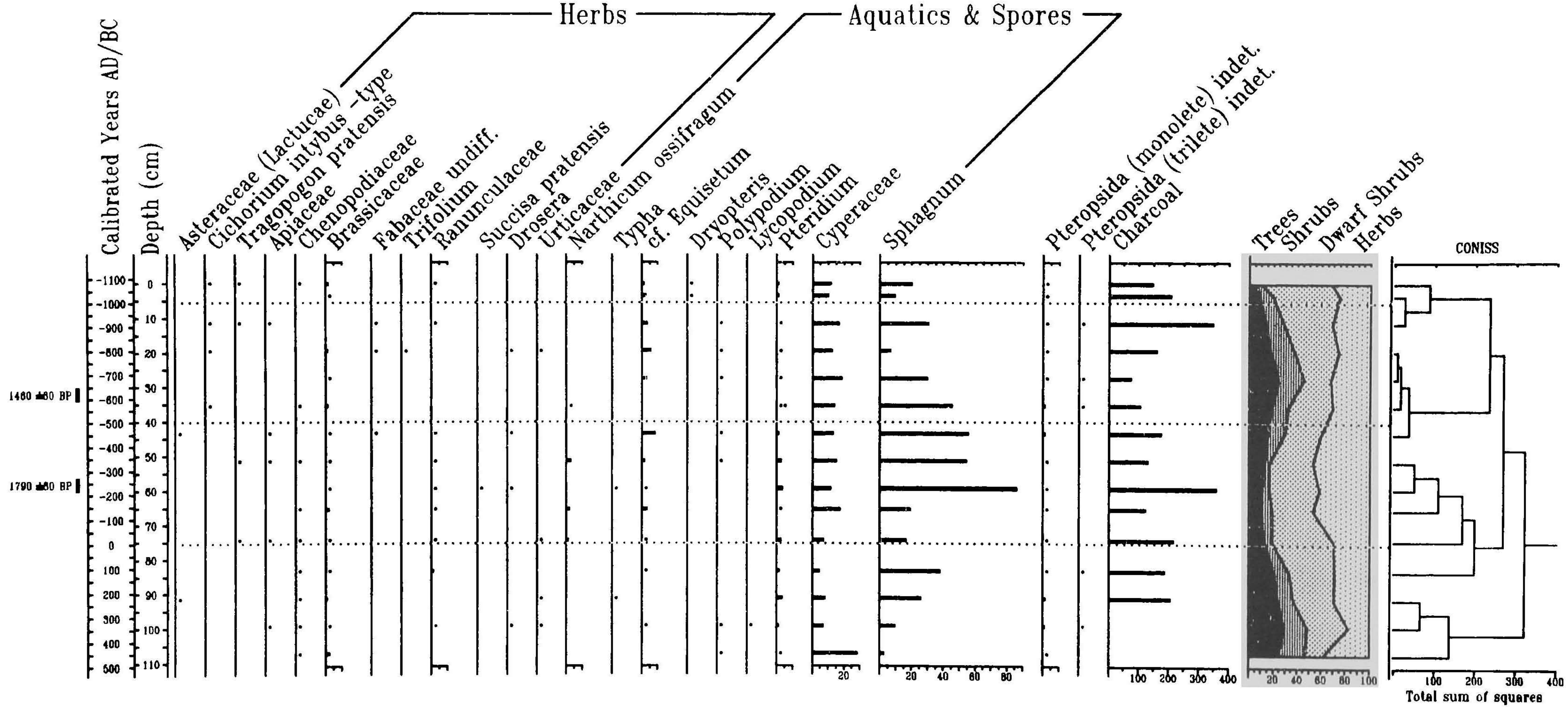


Figure 5.5. (part ii).

Table 5.4. Chronological horizons on the Harwood Dale Bog peat profile. [1] ^{14}C dates obtained at Harwood Dale Bog during this research. [2] ^{14}C date obtained at Harwood Dale Bog (Atherden, 1989).

Lab. No.	Depth (cm)	Conventional C^{14} Age	Calibrated range BP (2σ)	Calibrated range AD/BC (2σ)
BETA 106593[1]	30-34	1460 ±80	1408 (1338, 1322, 1314) 1294	cal. AD 430 (620) 695
BETA 106594[1]	56-60	1790 ±80	1878 (1706, 1645, 1635) 1531	cal. AD 85 (245) 415
HAR 5916[2]	90-100	2190 ±80	n/a	400 (200) 5 cal. BC

Table 5.5. Chronological horizons on the Bluewath Beck peat profile. [1] ^{14}C dates obtained at May Moss. [2] ^{14}C dates obtained at Bluewath Beck during this research. [3] ^{14}C date obtained at Harwood Dale Bog (Atherden, 1989).

Lab. No.	Depth (cm)	Conventional C^{14} Age	Calibrated range BP (2σ)	Calibrated range AD/BC (2σ)
SRR 5927[1]	5-15	685 ±50	690 (657) 545	cal. AD 1260 (1293) 1405
BETA 106592[2]	60-63	1290 ±60	1341 (1262) 1077	cal. AD 650 (705) 885
SRR 5930[1]	70-80	1640 ±50	1690 (1530)1407	cal. AD 260 (420) 555
HAR 5916[3]	95-105	2190 ±80	n/a	400 (200) 5 cal. BC

5.2.5 Bluewath Beck

The vegetation history uncovered from Bluewath Beck is based on pollen analysis of a single peat profile and the pollen diagram is displayed in figure 5.6. A single horizon from the Bluewath Beck peat profile was sampled for conventional radiometric ^{14}C analysis. The ^{14}C date was calibrated to an absolute chronology using a decadal tree-ring data-set (Vogels *et al.*, 1993). Furthermore the palynostratigraphy contains evidence of three significant events in the regional vegetation history, which can be used as chronological marker horizons. Near the base of the peat profile there is a decline in arboreal pollen frequencies, which represents the Iron Age and Romano-British woodland clearances ^{14}C dated at Harwood Dale Bog to 2190 ±80BP [400(200)5 cal. BC] and at Fen Bogs to 2280 ±120BP [407(377)189 cal. BC] (Atherden, 1976a; 1989). The subsequent woodland regeneration was ^{14}C dated, but the dated horizon is 10 cm above the base of the increase in arboreal pollen. This woodland regeneration has been ^{14}C dated in the course of this research at May Moss site D to 1640 ±50BP [cal. AD 260(420)555]. There is a further reduction in arboreal pollen in the top 10 cm of peat, which is correlated with a woodland clearance during the Medieval Period, also ^{14}C dated at May Moss site D yielding an age estimate of 685 ±50 BP [cal. AD 1260(1293)1405].

The ^{14}C date and the three palynostratigraphic marker horizons utilised to provide a tentative chronology for the peat sequence are listed in table 5.5. Linear interpolation between these chronological horizons generated a time series for the peat profile, which is displayed on the pollen diagram. This chronology indicates that peat accumulation extends up to *circa* cal. AD 1350, with the stratigraphy truncated a hypothesis that is supported by evidence of extensive peat cutting across the Bluewath Beck basin. The base of the pollen sequence is broadly equivalent to 400 cal. BC and the top of the profile is truncated with an age of approximately cal. AD 1400. Moorland taxa dominate the pollen sequence, with *Calluna vulgaris* fluctuating around 40% of the pollen sum. The cluster analysis identifies four main clusters with broadly similar pollen assemblages, and signifies that the most significant changes within the palynostratigraphy occurred *circa* cal. AD 0, 500 and 1100.

The base of the profile between *circa* 400 cal. BC and cal. AD 0 contains high frequencies of tree pollen, although they decline gradually after cal. AD 0. Tree pollen frequencies are low between cal. AD 0 and 500, with a concurrent increase in herb species, especially the Poaceae, cereal pollen, and *Plantago lanceolata*. This phase with reduced tree pollen frequencies is also mirrored by a substantial charcoal peak. After cal. AD 500 tree pollen frequencies increase and remain around 20% almost to the top of the profile, with the exception of a minor decline cal. AD 950-

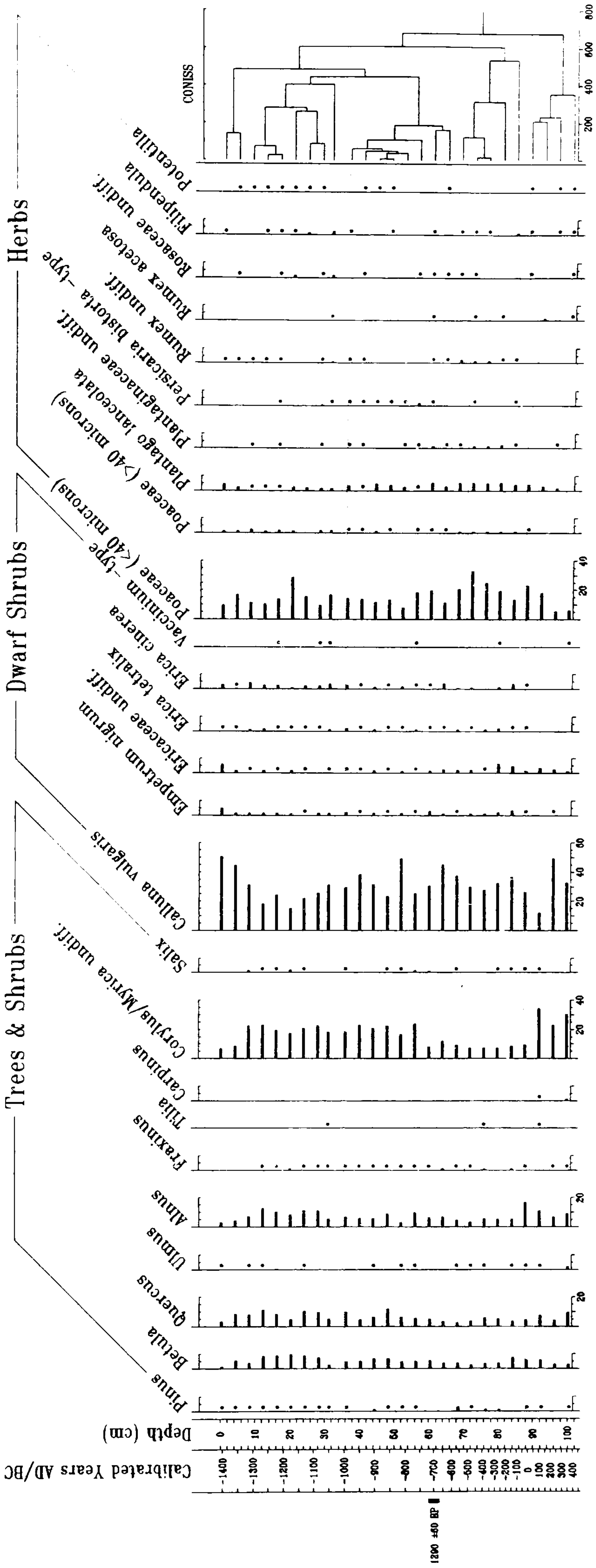
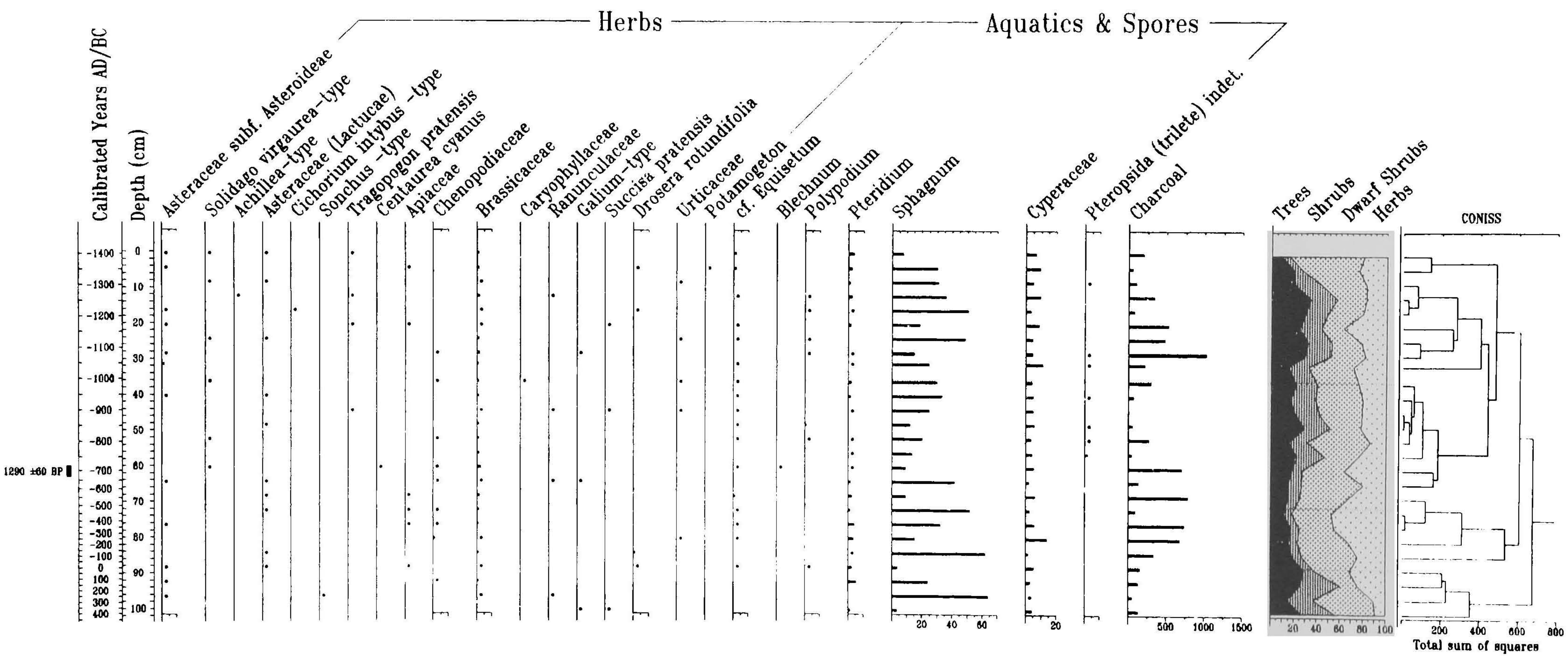


Figure 5.6. (part i). Pollen diagram from Bluewath Beck. Taxa are expressed as percentages of the pollen sum. Aquatics and spores are expressed as percentages of the pollen sum plus aquatics and spores. Circles signify frequencies amounting to less than 1% of the sum. Charcoal frequencies are expressed as the number of shards per 50 exotics. ^{14}C dates are expressed in years BP. The dendrogram presents the results of a sum of the squares cluster analysis.

Figure 5.6. (part ii).



1100. Tree pollen frequencies increase between cal. AD 1100 and 1300, before beginning a gradual decline towards the top of the profile. *Plantago lanceolata,* cereal pollen, Brassicaceae and wild grasses increase in abundance after *circa* cal. AD 1350, and remain abundant up to the top of the profile.

5.3 Synthesis of the regional vegetation history

The palynological history contained in the six palaeoecological profiles comprises a detailed picture of vegetation changes across the region during the last 2000 years. Summary diagrams expressing the relative abundance of trees, shrubs, mire shrubs and herbs from the six profiles are displayed in figure 5.7. The y-axis of figure 5.7 is re-scaled using the chronology derived for each site and the pollen profiles are correlated on the basis of the chronology. The profiles are divided into 500-year periods to facilitate comparison between the sites and the following synthesis of the vegetation and landscape history of the North York Moors is divided into these 500-year periods. The initial impression from figure 5.7 is that the palynostratigraphy is broadly similar across the region, which tends to support the hypothesis that the pollen profiles present a regional picture of the vegetation history.

Producing a regional vegetation history from a series of pollen profiles has a number of inherent methodological constraints. It is impossible to reconstruct the spatial distribution of the vegetation, because the pollen assemblages will be derived from local mire plants, vegetation surrounding the mire and also a wind-blown regional component. Despite this problem it may be possible qualitatively to assign vegetation changes to specific areas. The plant macrofossil stratigraphies indicate that the palaeoecological sites have been largely de-forested throughout the last 2000 years, and so the arboreal pollen present in the profiles must originate from the moorland periphery, and the dales and lowlands surrounding the North York Moors.

Frequencies of *Pinus*, a pollen type dispersed by wind typically over large distances, do not exceed 20% of the pollen sum in the surface layers at Fen Bogs. These low quantities are surprising considering the substantial plantations to the south of the North York Moors. Perhaps transfer of pollen from the surrounding lowlands and the southern hills, whilst important should not be overemphasised. This state of affairs also applied in the past, with high frequencies of non-mire pollen still relatively local in origin. Arable crops and weeds are not common on blanket mires and the pollen fossil record of these taxa probably reflects their abundance across the region. However this pollen could still be relatively local in origin reflecting agricultural exploitation of the moorland edge, thereby signifying exploitation at high altitudes. The

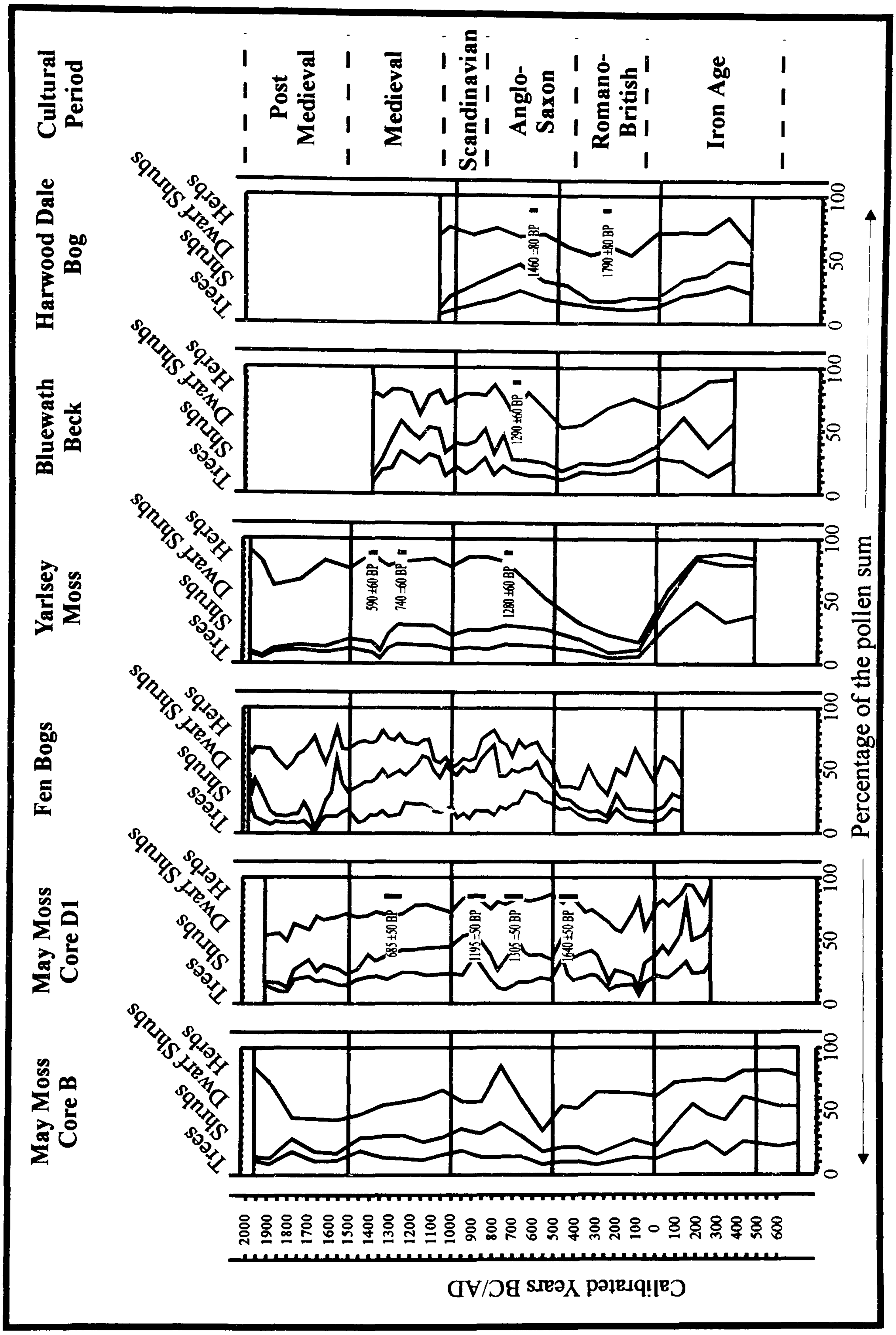


Figure 5.7. Correlation of the summary pollen diagrams, signifying the relative proportions of trees, shrubs, dwarf shrubs and herbs. The y-axis is a time series scaled in calibrated years AD/BC. The diagram is divided into 500 year segments, and is annotated with the main cultural and archaeological periods. Radiocarbon dates securing the palynostratigraphy are identified, listing the age estimates in radiocarbon years BP.

abundance of these arable indicators can be used to estimate the intensity of arable activity around the North York Moors. The pollen from mire plants, on the other hand, will for the most part be entirely local, admittedly with the exception of substantial quantities of wind-blown heather and moorland grass pollen.

In elucidating the factors controlling regional vegetation change, the range of ecosystems within a region must be taken into account. The non-moorland areas are likely to sustain a mixture of pastoral and arable activity, with non-agricultural land covered by woodland, scrub and heath. Fluctuations in the tree and shrub pollen fossil record probably reflect changes in the density and spatial extent of non-agricultural land, perhaps providing a semi-quantitative measure of the intensity of agricultural activity. Land-use on the North York Moors clearly falls into the category of marginal or frontier agriculture, because it has never been and probably never will be a prime site for agricultural endeavour. Higham (1985) identifies the North York Moors as a region in which environmental characteristics, for example altitude, soil type and climate, render pastoralism the most suitable land-use. However, arable cropping of barley and wheat is possible at lower altitudes on well drained soils receiving lower rainfall. This means that the southern limestone hills, well-drained areas of the dales and the surrounding lowlands offer the prime agricultural land.

The degree of agricultural exploitation on the North York Moors is unlikely to have remained constant throughout the last 2000 years, considering the region's demographic, political, and cultural history (Spratt, 1993; Spratt & Harrison, 1989). The evolution of the vegetated landscape of the North York Moors during the last 8000 years has broadly been in response to human activity, with the majority of vegetation changes during the last 2000 years almost certainly the product of anthropogenic activity. Previous palynological research on the North York Moors identifies three broad phases with reduced woodland, which have been attributed to human activity and specifically agricultural expansion (Simmons *et al.*, 1993). However a chronology for these vegetation changes was only available at Fen Bogs, which enabled these woodland reduction phases to be linked with the late Iron Age/Romano-British period, to the late Viking period and to a period of intensive agricultural activity in the early Medieval period. It should be noted that the chronology for these vegetation changes contains a considerable error, with the standard error of ±160 years on the ^{14}C date obtained for the Viking woodland decline.

The following sections discuss vegetation changes in the light of changes in human activity. The intensity of human impact on the landscape is controlled by a combination of, amongst other factors, environmental constraints on communities and economic activity, the political system, demographic change, technological developments and cultural traditions. Consequently interpretation and discussion of regional vegetation changes must draw on climatic, demographic, economic and social histories of the North York Moors.

500 cal. BC to cal. AD 0 (Iron Age)

The Iron Age palynological history identifies that great changes occurred on the landscape of the North York Moors, principally involving a massive reduction in the tree population. Evidence of this woodland clearance is present in all the pollen profiles and the cluster analyses signify that it represents one of the most significant changes in the palynostratigraphy at all the sites. The age of the base of this woodland clearance is secured to the middle of the first millennium cal. BC by ^{14}C dates at Fen Bogs and Harwood Dale Bog (Atherden, 1976a; 1989). The absence of dating on the higher altitude central moorland plateau is unfortunate, because assuming constant accumulation rates at Bluewath Beck the woodland clearance appears to occur later than at Fen Bogs and Harwood Dale Bog.

The decline in arboreal pollen is mirrored by an increase in herbs, particularly species associated with human activity. The most abundant herb taxa include the Poaceae, *Plantago lanceolata*, *Rumex* spp. and Chenopodiaceae, which have all been identified as indicators of pastoral activity (Turner, 1964; Behre, 1981). However some of these pastoral indicators typically associated with grasslands may have been grown as crops. *Pteridium* spores are also abundant, perhaps encouraged by increased grazing pressure within and near the edges of woodlands. Furthermore, some of these agricultural taxa, specifically cereals, Brassicaceae and Asteraceae pollen, have been proposed as diagnostic indicators of arable land-use (Turner, 1964; Behre, 1981). These arable indicators are present throughout the clearance phase, becoming increasingly abundant in the late Iron Age and during the Roman period.

Grazing pressure within and around the remaining woodland was probably a key mechanism responsible for the woodland decline, with herds grazing on young tree shoots, admittedly alongside physical felling and removal of trees to clear land for agricultural use. Additionally, trees would be felled to provide building materials and as a source of fuel. Wood was a valuable fuel for domestic use; furthermore it would have been converted into charcoal for the iron smelting industries clearly visible within the region's archaeological history (Spratt, 1993). Microscopic charcoal fragments in the Fen Bogs and May Moss peat stratigraphy may reflect the burning of wood to produce charcoal.

Spratt (1993) and Spratt & Harrison (1989) attribute the massive woodland decline to the activities of a substantial Iron Age population inhabiting traditional settlement sites on the North York Moors. Communities were distributed following spatial patterns initiated in the Neolithic, with concentrations in the lowlands surrounding the moors, in the broad flat dales, in Eskdale and with the largest populations on the better agricultural soils of the Tabular Hills. Traditionally, information about settlements, the population and land-use during the Iron Age has been difficult to find on the North York Moors. Elgee (1930) proposed that Bronze Age-type cultures persisted until the Roman period, but subsequent archaeological research and palaeobotanical evidence identifies that the Iron Age contains the most significant anthropogenic woodland clearances to have occurred on the North York Moors during the Holocene (Spratt, 1993; Simmons *et al.*, 1993).

Spratt (1993) synthesises Iron Age archaeological research carried out on the North York Moors, which reveals a relative paucity of material when compared with, for example, the Bronze Age. Concentrations of settlements are identified in the east of the Tabular Hills, at Levisham Moor, Cawthorn, Coombe Hill and Thornton Dale, and the agricultural activities of these communities would certainly have affected the pollen catchments of Fen Bogs, May Moss and Harwood Dale Bog. The pollen evidence identifies that a mixed arable and pastoral economy operated on the North York Moors throughout the Iron Age and the archaeological evidence tends to support this conclusion. Iron Age enclosures, probably used as livestock stockades, have been identified on Levisham Moor, Coomb Hill, Thornton Dale and Roxby (Spratt, 1993). Archaeological evidence of arable activity consists of numerous "Beehive Quern" finds, particularly concentrated in Eskdale and the Tabular Hills. These querns were used to grind grain indicating the presence of local arable cropping across the moors. Many of the querns were produced in local factories at Goathland, Spaunton Moor and Bransdale, although a large number came from further afield in the Pennines (Hayes *et al.*, 1980). Numerous querns across the region have been interpreted as indicating the intensification of agricultural activity in the late Iron Age and during the Roman period. Spratt (1993) suggests ninety-mile quern trade links to the Pennines indicate a vibrant agricultural economy.

A combination of arable and pastoral farming is probably responsible for much of the Iron Age decline in woodland, although industrial activity will also have affected the vegetated landscape. Iron ores are readily available on the North York Moors and three iron-working sites have been identified, at Levisham Moor, Roxby and Crown End on Westerdale (Spratt, 1993). These sites are probably all Iron Age and required wood resources to produce the charcoal that fired the primitive furnaces. The site at Levisham Moor would have drawn on the woodlands within the pollen catchment areas of Fen Bogs and May Moss.

In summary, the period 650 cal. BC to cal. AD 0 contains a vast woodland clearance, indicating an increase in the amount of land in agricultural production. Woodlands were under pressure from a variety of activities including increased in agricultural activity, increased grazing pressure on marginal agricultural land, and felling of trees for the iron smelting industry, domestic fuel and for building materials. Increased pressure on the woodland ecosystem arose, because a relatively large population was inhabiting the dales, the Tabular Hills and the lowlands surrounding the moors. A large or increasing population during the Iron Age is required to explain the vast reduction in woodland and this view is supported by a number of authors (Spratt, 1993; Fowler, 1978). Viewed in the context of demographic expansion at a national level, then population expansion in Northeast Yorkshire is not surprising.

Peat stratigraphic evidence from the North York Moors identifies substantially wetter conditions 600-200 cal. BC followed by drier conditions during the late Iron Age, *circa* 200 cal. BC. The combination of an expanding population and environmental conditions not really conducive for optimum agricultural production probably necessitated the use of more extensive areas of land. This process may have been compounded by land degradation in response to intensive exploitation and poor climatic conditions. Improved climatic conditions during the late Iron Age probably encouraged continued use of marginal land; however, it is implausible to attribute settlement and agricultural expansion into the marginal areas of Britain entirely to advantageous climatic conditions (Higham, 1985). The demographic expansion associated with this period probably necessitated exploitation of the agricultural frontier (Fowler, 1983), with a relatively warm and dry climate during the late Iron Age assisting the process of agricultural expansion around the North York Moors.

Cal. AD 0 to 500 (Romano-British Period)

The Romans arrived in northeast Yorkshire around AD 70, and largely without interruption politically controlled the region until AD410, when the Romans withdrew from Britain. The palynology indicates the Romans invaded a thriving mixed pastoral and arable landscape. Disruption of this mixed agricultural economy would be manifest in pollen profiles as increases in the abundance of trees, produced by limited regeneration of woodlands on marginal agricultural land. A detailed chronology of the vegetation changes during this period has previously been unavailable on the North York Moors. However this has been rectified by ^{14}C dating the later stages of the Romano-British period at Harwood Dale Bog. There is an absence of evidence of interference with the pastoral/arable economy around the time of the Roman invasion, which whilst not completely conclusive, implies the arrival of the Romans had little effect or only a short-lived impact on the native Brigantian communities.

Abundant weed species, specifically Poaceae, *Plantago lanceolata, Rumex* spp. and *Pteridium*, indicate pastoral activity continued to be an important land-use activity on the North York Moors. However cereal, Asteraceae and Brassicaceae pollen are more abundant during the Roman period, perhaps reflecting intensification of arable activity. The palynological evidence indicates the mixed pastoral and arable economy continued to thrive on the North York Moors, maintaining pressure on the remaining woodland. Exceptionally high frequencies of *Potentilla*, exceeding 10%, occur at Yarlsey Moss during the Romano-British period, which, given that species in the genus *Potentilla* are insect pollinated and a poor rate of dispersal, must reflect substantial local occurrences. The species of *Potentilla* likely to inhabit acidic peat bogs or moorlands are *Potentilla erecta* and *Potentilla palustris.* However *Potentilla erecta* is the more likely candidate inhabiting moorland, heaths and the drier areas of blanket bogs. Moore *et al.* (1986) found that the abundance and flowering of *Potentilla erecta* is enhanced by intensive sheep grazing, and so high frequencies of *Potentilla* pollen may indicate grazing on the moorlands and in the case of Yarlsey Moss grazing pressure at a relatively high altitude.

Circa cal. AD 500, a sharp increase in tree populations is evident in all the pollen profiles. This arboreal regeneration is at the expense of the agricultural weeds and crops. This event clearly represents a major land-use change, with a decline in arable and pastoral activity reducing the pressure on the remaining woodlands and allowing the regeneration of trees on marginal agricultural land. A consequence of this research is that the post-Roman woodland regeneration is now one of the most intensively dated horizons on the North York Moors, with ^{14}C dates from all the sites. These dates suggest that the woodland regeneration occurred during the 5th and 6th centuries cal. AD, linking the event with the aftermath of the departure of the Romans.

Assessing how this palaeoecological history conforms with other sources is difficult given the paucity of Roman archaeological remains on the North York Moors. The North York Moors were an economic backwater of Britain during the Roman period, and so the degree of romanisation would not have been great (Hartley, 1989). Hartley (1989; 1993) suggests little opposition was met during the invasion, to some extent supporting the palynological evidence of no major landscape changes. Furthermore the distribution of settlements probably was little different to the previous Iron Age patterns, concentrated in the Dales, Eskdale, the Tabular Hills and lowlands surrounding the moors. The small number of romanised settlements and the backwater nature of the North York Moors probably means the majority of sites were occupied by native Brigantian communities.

Military archaeological remains are the most visible symbols of Roman occupation, with the main forts at York and nearby Malton. On the North York Moors, military incursions were staged through forts at Lease Rigg (Hartley, 1993) and at Cawthorne (Richmond, 1930; Hartley, 1993). Both these forts were abandoned before the 2nd century AD, perhaps further testament to the peaceful nature of Roman occupation within the region. Other military installations include the coastal stations at Scarborough, Ravenscar, Goldsborough and Huntcliff, which were manned in response to raids from the continent around 367 AD (Hartley, 1989). Route-ways developed initially for military purposes would also have been of tremendous value to local communities, encouraging trade links. Wade's Causeway is one of the best exposed examples of a Roman road, which probably connected forts at Lease Rigg, Cawthorne and a terminal coastal fort, with a road between Malton and Hovingham (Hartley, 1993).

These military installations would have had little direct impact on the vegetated landscape. However, the development of route-ways, the presence of garrisons at Malton and periodic smaller units present at the other sites, may have created conditions ideal for a market economy. Musgrove (1990) suggests northern Britain thrived economically during the Roman period, which combined with palynological evidence of more intensive pastoral and arable farming, indicates a strong agricultural economy encouraged by a commercial outlook afforded by military grain markets at Malton. The peat stratigraphies at May Moss, Harwood Dale Bog and Yarlsey Moss all indicate that a dry mire surface persisted throughout the Romano-British period, which is interpreted as denoting a dry or warm climate. Favourable climatic conditions increase the agricultural potential of the North York Moors, perhaps rendering arable production more widely sustainable on suitable soils across the region.

The most significant changes in the vegetated landscape involve substantial increases in tree species. This event is identified by cluster analysis at all the sites and occurred *circa* cal. AD 400-500. The woodland expansion is broadly equivalent with the departure of the Romans. The withdrawal of the Romans around AD 410 caused the disruption of commercial agricultural markets, and perhaps forced a return to a subsistence agricultural economy. The loss of demand for agricultural produce probably resulted in a reduced scale of arable and pastoral activity. These changes are a useful mechanism for explaining the regeneration of woodland associated with this period. Existing woodlands could expand, and heliophytic trees and shrubs, *Betula* and *Corylus avellana*, were able to invade marginal agricultural land successfully, in the wake of a reduction in grazing pressure and clearance activity.

Cal. AD 500 to 1000 (Anglian and Scandinavian Periods)

Tree pollen frequencies continue the increases initiated around cal. AD 450, which are attributed to social, economic and political turmoil in the wake of the departure of the Romans. Previous research identified this woodland regeneration suggesting that it was initiated shortly after the Roman withdrawal and continued until the late Viking period (Atherden, 1976b). However it appears that this woodland regeneration was actually relatively short-lived, and after *circa* cal. AD 650 arboreal pollen frequencies at May Moss, Fen Bogs and Harwood Dale Bog begin to decline. The decline continues up to cal. AD 950-1100, when arboreal taxa at May Moss, Fen Bogs and Yarlsey Moss increase sharply in abundance. A similar sequence of events occurs at Bluewath Beck, although the chronology for this peat sequence is less secure. The increase in tree frequencies at May Moss occurs above a ^{14}C date of 1195 ±50 BP [cal. AD 700(870)975], equivalent to a horizon yielding a ^{14}C age of 1060±160 BP [cal. AD 655(955)1283] at Fen Bogs (Atherden, 1976a) and below a ^{14}C date of 740 ±80 BP [cal. AD 1170(1280)1400] at Yarlsey Moss, placing the woodland expansion firmly in the centuries around cal. AD 1000.

Poaceae, Brassicaceae, *Plantago lanceolata, Rumex acetosa* and *Pteridium* are the most abundant agricultural indicators throughout the period, and they are believed to be indicative of pastoral land-use (Turner, 1964; Behre, 1981). The arable indicators, cereals, Chenopodiaceae and Asteraceae, are distinctly less abundant than during the preceding Roman period, but they become more frequent after cal. AD 750. Furthermore *Potentilla* is distinctly less abundant at Yarlsey Moss perhaps reflecting a reduction in the intensity of grazing at higher altitudes. The balance of the evidence indicates that despite the collapse of the Roman economy and a return to a more subsistence based economy, pastoral and arable farming remained important land-use activities within the environs of the North York Moors.

A deterioration to a wetter climate *circa* cal. AD 400-500 is evident in the peat stratigraphies at May Moss, Yarlsey Moss, Harwood Dale Bog and Bluewath Beck. This climatic deterioration is discussed further in chapter 6. In a region marginal for arable production a climatic deterioration of this type may have rendered arable cropping untenable or at least difficult. Pastoral farming would also have been adversely affected. Environmental conditions unfavourable for agriculture, when combined with the political, economic and social disruption caused by the departure of the Romans, probably resulted in partial abandonment of marginal land. The better soils and sustainable agriculture in the Tabular Hills and lowlands surrounding the North York Moors offered a more suitable alternative. During the 7th and 8th centuries cal. AD there was a further decline in tree pollen frequencies and an increase in the abundance of arable indicator species probably produced by agricultural expansion, which continued until *circa* cal. AD 1000.

The period AD 500-1000 has been referred to as the Dark Ages, which is a reference to the lack of historical records rather than a comment about political, social and economic order. Archaeological remains are also scarce, especially during the 6th and 7th centuries. However abundant place-name evidence pertaining to this period implies the moors were well populated, with settlements concentrated in the traditional areas of the Tabular Hills, the Dales, the coastal fringe and lowlands surrounding the North York Moors (Lang, 1989). Yorkshire was a focus for Anglian and Scandinavian settlement of Northern England, however the relief, climate and inhospitable nature of North York Moors renders it likely that they would have remained an economic and cultural backwater.

In addition to continental immigration, Bede in his "Ecclesiastic history of the English people" records the arrival of Christianity and monastic settlements at Whitby in AD 657, Hackness after AD 657 and Lastingham in AD 659, perhaps providing early evidence of localised immigration and population expansion (Colgrave & Mynors, 1969). Demographic and agricultural expansion between cal. AD 650 and 850 overlaps with peat stratigraphic evidence of very dry mire surface conditions at May Moss and Yarlsey Moss, with cal. AD 650-850 containing perhaps the driest period during the last 2000 years. Although, a climate advantageous for agricultural endeavour probably encouraged expansion into the uplands, demographic growth during this period would have been the major factor behind increases in pastoral and arable activity (Lang, 1989).

The few Anglian settlements identified on the North York Moors at Wykeham, Seamer and Roxby, and burial sites at Saltburn and Robin Hood's Bay are all on former Romano-British sites. Lang (1989) warns against using this scant evidence to suggest continuity of settlement from earlier periods; however, using existing or former settlements probably appeared a sensible strategy to the population of Anglian Britain. The palaeoecological evidence hints at renewed intensity of agriculture during the 7th century, which is in keeping with the limited historical evidence; for example Gildas describes a British landscape populated with arable and pastoral communities (Winterbottom, 1978). This indicates the rural landscape continued relatively unaffected by political and economic trouble caused by the withdrawal of the Romans and wars with the Picts and the Scots. After *circa* AD 850, Scandinavian colonisation supplemented the population of the North York Moors, but probably with little impact on the distribution of settlements and land-use activity. Lang (1989) uses the profusion of churches and sculpture from this period as evidence of a population expansion during the 10th and 11th centuries, concentrated in the southern hills, on the coastal fringe and in the lowlands surrounding the North York Moors. The palynological evidence does not contradict this, with high frequencies of arable and pastoral indicators implying agricultural expansion (Behre, 1981), which probably reflects the activities of an expanding population (Fowler, 1983; Lang, 1989).

Cal. AD 1000 to 1500 (Medieval Period)

Vegetation changes during this period are recorded in pollen profiles at May Moss, Yarlsey Moss, Fen Bogs and Bluewath Beck. Unfortunately, the Harwood Dale Bog profile terminates shortly after cal. AD 1000. Tree species increase in abundance around cal. AD 1000, and although this is followed by a minor decline, tree pollen frequencies remain relatively high until around cal. AD 1500. Poaceae, *Plantago lanceolata, Rumex acetosa,* Brassicaceae, *Potentilla*-type and *Pteridium* increase in abundance between cal. AD 1000-1500, which is indicative of intensification of pastoral agriculture (Behre, 1981). Cereal and Asteraceae pollen also increase markedly during this period, reflecting expansion and intensification of arable farming.

It is difficult to gauge the extent of variations in agricultural land-use from the palaeoecological curves of arable and pastoral indicator species, other than to say a mixed arable/pastoral economy persisted on the North York Moors. Fortunately the abundance of woodland taxa also provides a measure of agricultural intensity. The remaining areas of woodland on the North York Moors in post-Norman Conquest England were limited to the steep valley-sides, the north facing scarp slopes of the Tabular hills and to the edges of the moors (Hodgeson, 1966). Consequently fluctuations in the amount of woodland may reflect expansion of agriculture into these marginal areas, which probably would only occur during economic and demographic boom periods. Therefore frequencies of tree pollen can tentatively be used to identify fluctuations between a less and more intensive agricultural economy. The chronology developed in previous research at Fen Bogs indicates that a woodland decline initiated in the late Viking period continues into the Medieval period, up to a subsequent woodland regeneration, which has been ^{14}C dated to 390±100BP [cal. AD 1331(1486)1954] (Atherden, 1976b).

The palynological history uncovered in this research indicates the picture maybe more complicated, which is not unexpected considering that the period AD 1000-1500 contains a series of demographic, political, economic and social fluctuations, which will have affected the landscape of the North York Moors. Documentary evidence pertaining to this period becomes increasingly abundant, providing a great deal of information about settlements, the population and land-use. The Domesday Book surveyed in AD 1085-86 shows that settlements were concentrated in the Tabular Hills, the dales, the coastal fringe and lowlands surrounding the North York Moors (Harrison, 1993; Harrison & Roberts, 1989; Hodgeson, 1966). The population of these settlements probably was engaged in a mixture of arable and pastoral farming, and although the central moorlands were not inhabited, they were annexed by surrounding settlements and exploited as summer grazing.

The period immediately after the Norman Conquest was a fraut time for the inhabitants of the North York Moors. The "scorched earth" policy, carried out by William I's army in the winter 1069-1070, devastated large areas of Yorkshire (Palliser, 1993; Harrison & Roberts, 1989). Additionally, the Anglo-Saxon Chronicles and William of Malmesbury's Chronicles record several incidents of pestilence, poor harvest and famine between AD 1066 and 1100 (James Menuge, 1997). A sequence of events of this magnitude would cause a decline in population and a reduction in intensity of agricultural activity especially in marginal areas. Landowners unaffected by this sequence of events would have moved their tenants to the better soils on the Tabular hills and at lower altitudes, to ensure the most productive land was fully exploited at the expense of marginal areas (Harrison & Roberts, 1989). This would encourage limited re-growth of trees and woodland expansion on the edges of the moors, on the steep valley sides and on north-facing slopes on the Tabular hills, perhaps accounting for the minor increases in tree frequencies identified in the pollen profiles.

The economic and demographic malaise of the late 11th century was followed by a period of revival during the 12th and 13th centuries (Hodgeson, 1966; Harrison & Roberts, 1989). Colonisation by tenant farmers on privately owned land and by monastic communities shortly after the Norman Conquest, transformed parts of the North York Moors into an intensively exploited landscape. Settlements admittedly were concentrated in the traditionally populated areas, but with frontier settlements on the moorland fringe up to altitudes of 240 m (Hodgeson, 1966; Harrison & Roberts, 1989). This expansion of population and agricultural activity may account for the increases in arable and pastoral indicator pollen taxa during this period. The expansion of cereal pollen indicates intensification of arable farming to a scale previously not seen within the region. This period of arable expansion is synchronous with a climatic period with conditions favorable for agricultural expansion, referred to as the Medieval Warm Period. Peat stratigraphies on the North York Moors signify that warm or dry conditions persisted between cal. AD 1200-1400. This period contains demographic, economic and climatic conditions that are all favourable for colonisation and agricultural expansion of the marginal agricultural frontier (Parry, 1976; 1978; Higham, 1985).

There are substantial reductions in tree pollen frequencies associated with this demographic and agricultural expansion; however, it is relatively short-lived with a further woodland expansion during the 14th and 15th centuries. This increase in tree pollen is probably caused by a reduction in agricultural activity in the wake of demographic collapse during the late 14th century. The Anonimalle Chronicle records a pestilence in AD 1346, and the first instance of the Black Death in AD 1348, with recurrences in AD 1361, 1369, 1373 and 1378 (Galbraith, 1927). The late 14th century is also the beginning of climatic deterioration that extends into the "Little Ice Age" *sensu stricto* (Grove, 1988). Peat stratigraphies across the North York Moors contain evidence of a broad deterioration in climate after cal. AD 1350.

The combination of the Black Death and the results of an unfavorable climate, which include failed harvests and famine (James Menuge, 1997), decimated the population of Yorkshire (Harrison & Roberts, 1989). Mackay & Tallis (1994) refer to a "Malthusian"-type crisis, affecting the population of the Forest of Bowland in Lancashire, which caused an increase in arboreal pollen frequencies, probably in response to a reduction in land-use pressure. The North York Moors are a similar marginal or frontier region and a demographic collapse could be responsible for increases in arboreal pollen frequencies on the North York Moors during the late 14th and the 15th century. There was a further reduction in woodland towards the end of the 15th century and continuing throughout the 16th century. This woodland decline is synchronous with increases in arable and pastoral indicators, reflecting further intensification of agriculture. Demographic and economic growth during the 16th century allowed the resumption of agricultural expansion associated with the 12th and 13th century boom period (Hodgeson, 1966).

Cal. AD 1500 to the present-day

Palaeoecological records pertaining to the last 500 years are available at May Moss, Fen Bogs and Yarlsey Moss. Frequencies of tree pollen are low at all the sites reflecting a reduction of woodland area across the North York Moors. Turton (1894) encountered numerous accounts of tree felling within the Royal Forest of Pickering between AD 1252 and 1707 in charters, forest records and Duchy of Lancaster estate records. Woodland clearance continued to such an extent that only unimproveable land on very steep valley sides remained wooded (McDonnell, 1989). The impoverished state of woodlands was the product of a combination of factors including commercial harvesting of trees for trade, agricultural expansion and the abandonment of positive forest management techniques associated with the decline of charcoal-burning iron furnaces. Industrial wood reserves and coppicing practices were no longer necessary and many of the coppiced woodlands were eventually cleared (McDonnell, 1989).

Herbaceous pollen types, particularly those of the arable or pastoral weeds and crops are very abundant, exceeding 50% of the pollen assemblages. The most abundant taxa are the Poaceae, *Plantago lanceolata* and *Rumex acetosa*, which are all indicative of pastoral activity (Behre, 1981). However cereal pollen and the arable weeds, the Asteraceae, are also very abundant, reflecting intensification and improvements within the arable sector. The balance between arable and pastoral agriculture is supported by tithe records of rural land-use from Eskdale, which indicate that two-thirds of agricultural land was used for pastoral farming, with the remaining third for arable crops. This balance is probably representative of agricultural land-use across the region during the 19th century (McDonnell, 1989), revealing that even with intensive exploitation of the landscape the North York Moors remained marginal for arable production (Higham, 1985).

The agricultural expansion evident within the pollen records is probably the result of a steadily increasing population and a more commercial approach to farming. The Dissolution of the Monasteries, after AD 1536, freed more agricultural land, which allowed established landowners and new freeholders to purchase land. Parliamentary Enclosure between AD 1748-1864 had a profound impact on much of Britain, but was less extensive on the North York Moors, which had experienced "assarting" and piece-meal enclosure since the Middle Ages (Harrison & Roberts, 1989; McDonnell, 1989; Harrison, 1993). Woodlands were not the only part of the vegetated landscape to give way to the agricultural economy, with attempts to turn moorland into agricultural production on Commondale Moor, Lockton Moor and around Langdale during the 17th and 18th centuries.

Moorland plants, particularly *Calluna vulgaris*, became very abundant during the 19th and 20th centuries. The expansion of moorland reflects management practices maintaining the moors, partly for grouse rearing and partly as rough grazing for sheep. Cyclical burning of the heather encourages young shoots which the grouse prefer, and has helped produce and maintain a virtual *Calluna vulgaris* monoculture on the central plateau since the 19th century. The most recent change in the landscape of the North York Moors, evident in pollen profiles, is an increase in tree frequencies during the 20th century. In the case of the deciduous trees- birch, oak, alder and ash- this represents the onset of positive woodland management techniques, as awareness of the conservation value of these habitats has increased during the late 20th century. However the most significant woodland expansion involves the conifer species, Pine, Spruce and Fir trees, which were introduced into the region in vast commercial plantations by the Forestry Commission, initially at Dalby, Bickley and Hackness during the 1920s (Statham, 1989).

5.4 Conclusions

The evidence presented in this chapter modifies the traditional view of vegetation changes on the North York Moors during the last 2000 years and contributes a substantial improvement to the independent chronology that is critical for the understanding of vegetation histories. All of the pollen profiles contain the woodland clearances initiated in the Iron Age, which clearly is the most significant anthropogenic vegetation change during the late Holocene (Atherden, 1976b; 1979; 1989). The dates obtained for the Romano-British period at Harwood Dale Bog indicates the arrival of the Romans had a less significant impact on the vegetated landscape, merely continuing the Iron Age trend of woodland decline. The woodland regeneration associated with the Roman withdrawal is now supported by a ^{14}C chronology from five sites on the North York Moors.

The vegetation history, uncovered for the period AD 500 to the present-day, appears to be substantially more complicated than revealed in previous research. Phases with reduced and extensive agricultural activity have left a clear imprint in both the pollen derived history of woodland expansion and contraction, and in the fossil record of arable/pastoral indicator taxa. Phases with a reduced scale of agriculture are linked to economic malaise in the aftermath of the Roman withdrawal, the devastation of the "harrying of the north" and demographic collapse during the 14th century. On the other hand, phases of increased agricultural activity are attributed to population expansion, favorable climatic conditions and an economic revival during the Anglian and Scandinavian periods; and to upland settlement, favorable climatic conditions, and economic and demographic growth during the 12th and 13th centuries, conditions that were resumed from the 15th century onwards. These results indicate that utilisation of the landscape of the North York Moors was controlled by a diverse array of factors, ranging from climatic conditions controlling the nature of agricultural endeavour to the economic, technological, demographic and political controls that affected the population of the North York Moors.

6

Reconstructing mire palaeohydrology

6.1 Introduction

Information about mire surface wetness is elucidated from testate amoebae, plant macrofossil and humification analysis of peat stratigraphies on the North York Moors. The results are presented on a site-by-site basis. In the case of May Moss three core sites were used, which at sites C and D involved more than one core profile. The May Moss data are also presented on a site-by-site basis. The results are presented in the order testate amoebae, plant macrofossil and then humification, if applied at each site. Results are presented independently for each core site, because a critical evaluation of the comparative performance of the techniques is an important objective of this research.

The palaeoenvironmental data are presented against both depth and time axes. The chronologies for May Moss sites B and D, Fen Bogs, Yarlsey Moss, Harwood Dale Bog and Bluewath Beck were defined in chapter five. The chronology for May Moss site C is based upon seven ^{14}C dated horizons. The AMS age estimates are used in preference to the parallel radiometric assays for reasons discussed in chapter seven. In addition a present-day age is applied to the mire surface, and the Iron Age/Romano-British woodland clearance occurs at depths of 180-190 cm in May Moss site C cores 2 and 3. These nine chronological horizons can be identified in the other cores at site C with a reasonable degree of confidence. It is acknowledged that there will be some error in correlation of the stratigraphy; consequently the correlated dates are applied to 10cm vertical intervals of peat and the eventual time series is only proposed as a tentative chronology for each undated core.

The chronologies for each site were produced by linear interpolation between the various chronological horizons for all the sites, transforming the palaeoenvironmental data into time series. Correlation analyses identify that a broadly linear age/depth relationship only exists for May Moss core B (r^2=0.9999), core D1 (r^2=0.989), and core D2 (r^2=0.992), and Harwood Dale Bog (r^2=0.998). A linear age/depth relationship is a prerequisite for direct time series analysis of palaeoenvironmental data, and so only the palaeohydrological information from these cores were susceptible to direct time series analysis. A further prerequisite to time series analysis is that the data should be of fine temporal resolution, otherwise the results will be of limited value. In the case of this research only the humification data at the above sites meet both these criteria and are subjected to time series analysis.

None of the palaeoenvironmental profiles is subdivided into faunal or environmental zones, which would be the conventional approach within palaeoecological research, because the number of cores and palaeoenvironmental procedures necessitates several zonation schemes for the same core. Instead the profiles are discussed using the chronologies as a means for comparison between cores and sites. To ease visual appreciation of the palaeoenvironmental data the diagrams are annotated with lines denoting the 500-year periods utilised for interpretation of the palynological data. The section presenting the results for each core site concludes with a synthesis, which highlights the comparative performance of the palaeoenvironmental procedures utilised. Furthermore the disparate palaeohydrological information is collated to produce a surface moisture history for each core site, which in the case of ombrogenous sites provides a proxy record of climate change. Whilst clearly the intention of this research is to uncover surface wetness histories, any evidence of other environmental changes is invaluable and is also discussed.

6.2 May Moss

The reconstruction of the palaeohydrology at May Moss draws upon investigation of the stratigraphy at three locations: site B, site C and site D. A single core was extruded from site B. Four peat cores were extruded at site C, which were evenly distributed along a five metre levelled transect. Two adjacent cores were extruded at site D. Three palaeoenvironmental procedures were used to elucidate hydrological histories. Radiocarbon dates have been obtained for cores C3 and D2.

The following sections present the palaeoecological and palaeohydrological data from each core, and this information is synthesised to produce a surface wetness history for sites B, C and D. The respective palaeohydrological histories generated for each core site are integrated, thereby contributing a detailed reconstruction of changes in the hydrological budget of May Moss. In the light of the ombrotrophic status of May Moss, the mire palaeohydrological history can be viewed a proxy record of climatic change. The use of several cores to elucidate the palaeohydrological information allows detailed assessment of the consistency of blanket mire peat stratigraphy and critical testing of the value of blanket peat as a source of palaeoclimatic information.

6.2.1 May Moss Site B

The site B peat core is 2.3m in length and was extracted with a 10×30cm Russian corer. A second core was extracted within one metre of core B, just to assess the consistency of the stratigraphy. A summary of the field stratigraphy is presented in table 6.1. The peat profile received sub-fossil testate amoebae, plant macrofossil and humification analysis.

Table 6.1. Peat stratigraphy recorded in the field at site B.

Mire surface	A dry hollow covered by *Calluna vulgaris* and *Eriophorum vaginatum*, with occasional *Eriophorum angustifolia*, *Erica tetralix*, and a ground flora of *Hypnum jutlandicum* and *Sphagnum capillifolium*.
0-20 cm	Poorly humified *Eriophorum vaginatum* and Ericaceae peat..
20-95 cm	Poorly humified *Sphagnum* and Monocotyledonous peat.
95-230 cm	Well humified Monocotyledonous peat, with occasional layers of Ericaceae remains.

6.2.1.1 Testate amoebae data

Quantitative analysis

The testate amoebae stratigraphy is presented in figure 6.1. The species scores on the first two axes of a detrended correspondence analysis of the sub-fossil data are displayed as an X/Y biplot in figure 6.2. The first two axes of the DCA have eigenvalues of 0.609 and 0.283 respectively, which signifies that they summarise the most significant structure within the dataset and that the amount of variation explained by further DCA axes is minimal. Correlation coefficients between the testate amoebae taxa and the DCA axes, listed on figure 6.2, identify the species involved in the most significant changes in the sub-fossil stratigraphy.

The most abundant testate amoebae species appear to be arranged along DCA axis 1 according to their tolerance of habitat wetness. Taxa that typically inhabit drier environments, for example *Hyalosphenia subflava*, occur at the opposite end of DCA axis 1 to species that prefer wetter conditions, for example *Amphitrema flavum* and *Amphitrema wrightianum* (Woodland, 1996; Woodland *et al.*, 1998). The correlation analysis supports this conclusion with DCA axis 1 summarising sub-fossil variations between a "wet environment" assemblage and a "dry environment" assemblage. The wet indicators are *Amphitrema flavum*, *Amphitrema wrightianum*, *Assulina muscorum* and *Assulina seminulum*, which all display a strong positive

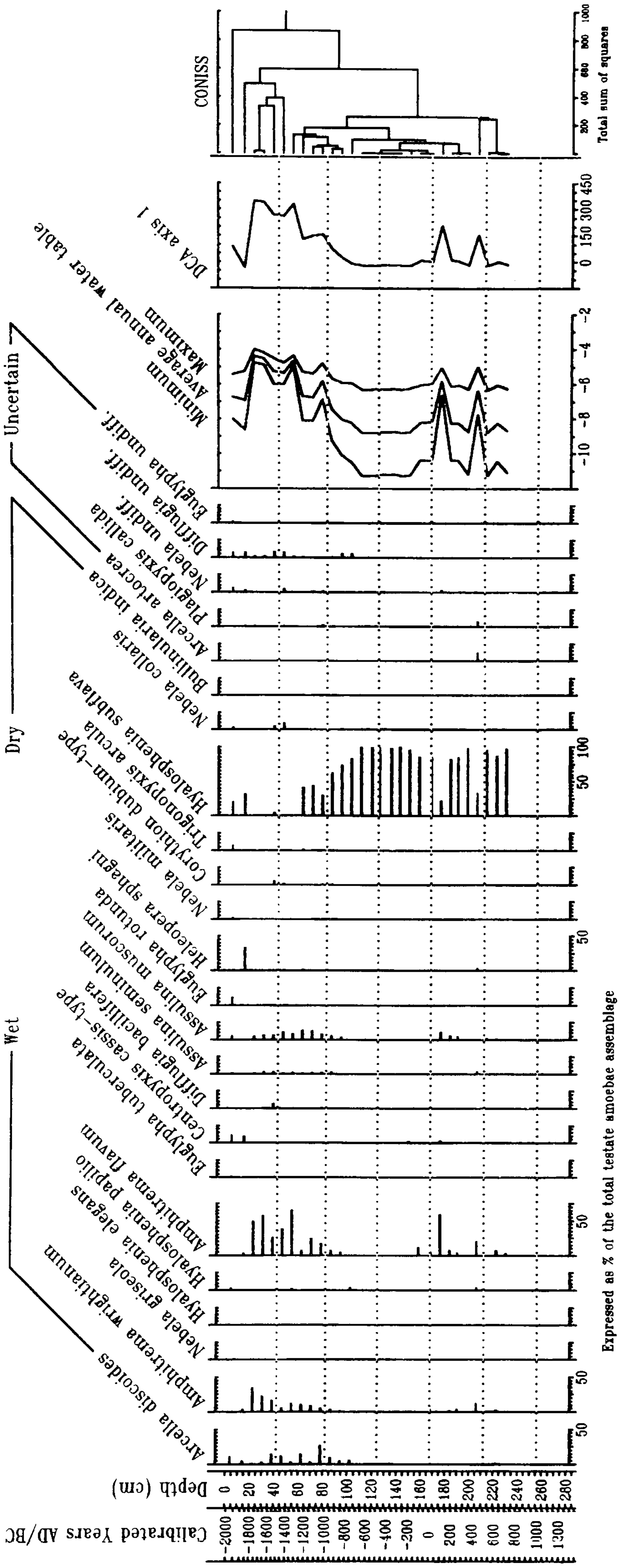
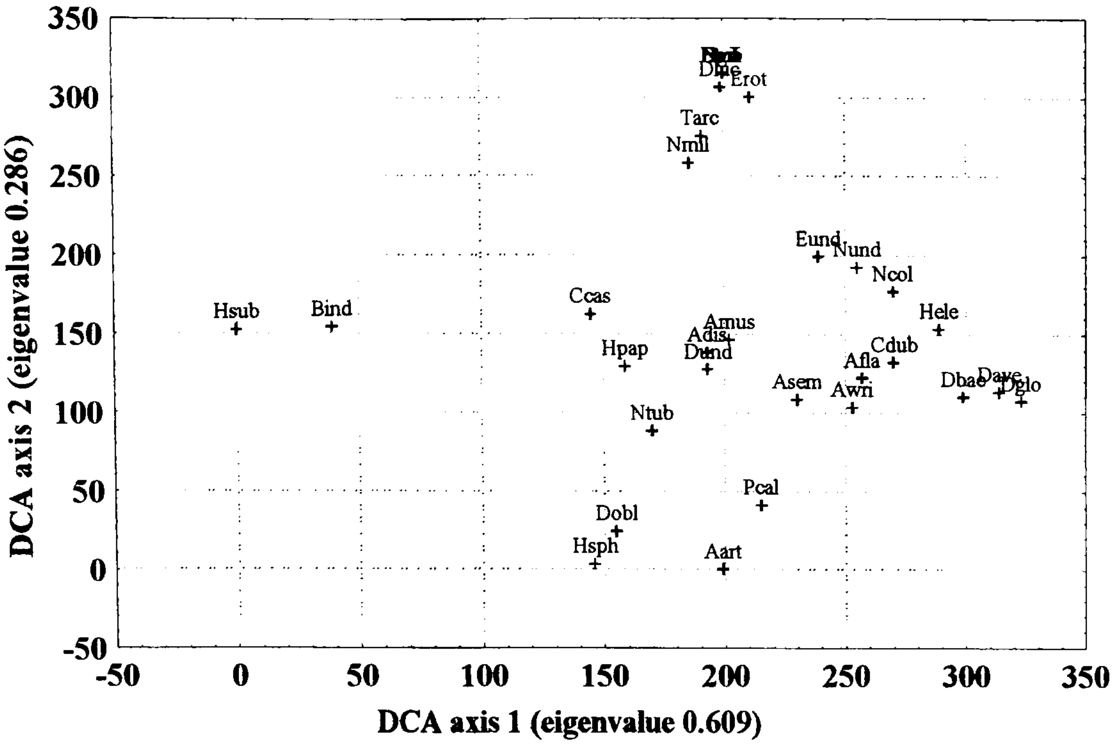


Figure 6.1. May Moss site B testate amoebae diagram. The species curves are arranged from left to right according to preference of habitat moisture conditions. On the far right the reconstructed mean annual water table depths are presented, including upper and lower limits based on the ranges tolerated by individual species; the sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

a).



b).

Testate Amoebae species	Graph label	DCA axis 1	DCA axis 2
Eigenvalue		0.609	0.286
% variance		33.25	12.17
Arcella artocrea	Aarc	0.147	0.508
Arcella discoides	Adis	0.371 [a]	0.184
Plagiopyxis callida	Pcal	0.275	0.655 [c]
Bullinularia indica	Bind	-0.143	-0.327
Trigonopyxis arcula	Tarc	0.037	0.206
Centropyxis cassis -type	Ccas	-0.086	0.463 [a]
Hyalosphenia subflava	Hsub	-0.912 [c]	-0.534 [c]
Hyalosphenia papilio	Hpap	0.141	0.426 [a]
Hyalosphenia elegens	Hele	0.392 [a]	0.012
Heleopera sphagni	Hsph	-0.154	0.648
Nebela undiff.	Nund	0.412 [a]	0.038
Nebela collaris	Ncol	0.382 [a]	0.113
Nebela griseola	Ngri	0.012	0.238
Nebela militaris	Nmil	0.048	0.181
Nebela tubulata	Ntub	-0.121	0.65 [c]
Nebela vitraea	Nvit	0.012	0.238
Difflugia undiff.	Dund	0.301	0.282
Difflugia avellana	Dave	0.285	0.062
Difflugia baccillifera	Dbac	0.414 [a]	0.114
Difflugia globulosa	Dglo	0.405	0.151
Difflugia lucida	Dluc	0.018	0.229
Difflugia oblonga	Dobl	-0.123	0.59 [c]
Difflugia oviformis	Dovi	0.012	0.238
Amphitrema flavum	Afla	0.913 [c]	0.196
Amphitrema wrightianum	Awri	0.807 [c]	0.478 [a]
Euglypha undiff.	Eund	0.359	0.298
Euglypha tuberculata	Etub	0.012	0.238
Euglypha rotunda	Erot	0.044	0.251
Assulina muscorum	Amus	0.683 [c]	-0.132
Assulina seminulum	Asem	0.715 [c]	0.4 [a]
Corythion dubium -type	Cdub	0.447 [a]	0.109

Figure 6.2. (a) Detrended correspondence analysis ordination diagram showing the species weighted averages on the first two axes for the site B testate amoebae data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the testate amoebae species. The correlations are not statistically significant unless annotated by either, [a] = significance at the 95% level, [b] = significance at the 99% level or [c] = significance at the 99.9% level.

correlation with DCA axis 1, whereas the dry indicator *Hyalosphenia subflava* displays a strong negative correlation.

The other DCA axes are difficult to interpret ecologically. DCA Axis 2 is negatively correlated with *Hyalosphenia subflava*, and positively correlated with nine taxa only abundant in isolated layers within the peat stratigraphy. The axis appears to summarise a relationship between the most abundant species and a series of occasional or outlier species. Further DCA axes individually only explain minor amounts of variation within the sub-fossil dataset. DCA axis 1 represents the most significant variation within the dataset and clearly appears to identify a moisture gradient. Consequently, mire surface wetness appears to be the most important environmental factor affecting sub-fossil testate amoebae at site B, and DCA axis 1 is proposed as a semi-quantitative model summarising fluctuations between wet and dry conditions at site B. The sample scores on DCA axis 1 are plotted stratigraphically on figure 6.1, with high values identifying wetter conditions and lower values drier conditions. The optimum, maximum and minimum mean annual water table depths tolerated by extant species were used to generate three palaeohydrological curves identifying the potential range of moisture conditions. These curves are displayed stratigraphically on figure 6.1. The fluctuations in mean annual water table depth and DCA axis 1 reveal an interesting palaeohydrological history at site B containing pronounced wet shifts and drier periods.

Palaeoecology

Of the twenty-four species encountered in the site B profile, only six occur in any great number: *Amphitrema flavum*, *Amphitrema wrightianum*, *Assulina muscorum*, *Assulina seminulum*, *Hyalosphenia subflava* and *Centropyxis cassis*-type. The sub-fossil record is characterised by fluctuations between two groups of species. The first group contains one species, *Hyalosphenia subflava*, which typically is associated with dry environments (Woodland, 1996). The second contains *Amphitrema flavum*, *Amphitrema wrightianum*, *Assulina muscorum* and *Assulina seminulum*, and these taxa are typically associated with wetter environments (Woodland *et al.*, 1998). The palaeoecology reveals that the sub-fossil testate amoebae community has been dominated by these two groups throughout the last 2500 years. Cluster analysis signifies that the most significant changes in the testate amoebae stratigraphy occurred *circa* 400 cal. BC, cal. AD 700, cal. AD 1400 and cal. AD 1900.

The stratigraphy between 600 cal. BC and cal. AD 700 is dominated by *Hyalosphenia subflava*, which appears to signify a period with broadly dry conditions. However *circa* 400 cal. BC

Amphitrema flavum and *Assulina muscorum* appear for the first time and this increase in diversity signifies wetter conditions. Between *circa* 100 cal. BC and cal. AD 700 species diversity is very low, with *Hyalosphenia subflava* the only species, perhaps signifying a return to drier conditions. *Hyalosphenia subflava* begins a sharp decline *circa* cal. AD 700, and there are corresponding increases in *Arcella discoides, Amphitrema wrightianum, Amphitrema flavum* and *Assulina muscorum*. These stratigraphic changes are augmented *circa* cal. AD 1400, with the most significant change in the testate amoebae stratigraphy, namely further increases in *Amphitrema wrightianum* and *Amphitrema flavum*, and a decline by *Hyalosphenia subflava*. The replacement of *Hyalosphenia subflava* dominated stratigraphy with comparatively high diversity communities is clearly a response to increased surface wetness. The final stratigraphic changes occurred *circa* cal. AD 1900, with *Amphitrema wrightianum, Amphitrema flavum* and *Assulina muscorum* declining sharply, replaced by *Hyalosphenia subflava*. This change near the mire surface appears to identify a shift to drier mire surface conditions during the last 100 years.

6.2.1.2 Plant macro-fossil analysis

Quantitative analysis

The plant macrofossil stratigraphy of the core B peat sequence is presented in figure 6.3. The scores of the main macrofossil components on the first two axes of a detrended correspondence analysis of the sub-fossil data are displayed as an X/Y biplot in figure 6.4. These first two axes of the DCA have eigenvalues of 0.534 and 0.193 respectively, signifying that they summarise the most significant structure within the dataset and that the amount of variation explained by further individual DCA axes is minimal. Correlation coefficients between the main components of the plant macrofossil stratigraphy and the first two DCA axes, listed in figure 6.4, identify the components involved in the most significant changes within the macrofossil stratigraphy.

The main macrofossil components appear to be arranged along axis 1 according to their tolerance of habitat wetness. Dry indicators such as Unidentified Organic Matter occur at the opposite end of DCA axis 1 to the wet indicator *Sphagnum* section *Cuspidata*. The correlation analysis supports this conclusion with DCA axis 1 summarising sub-fossil variations between a "wet environment" assemblage and a "dry environment" assemblage. The wet indicators are the Sphagnaceae, which all display a strong positive correlation with DCA axis 1, whereas the dry indicator Unidentified Organic Matter displays a strong negative correlation. This evidence identifies the most significant changes within stratigraphy are from well humified peat to poorly humified *Sphagnum*-dominated peat, which are stratigraphic changes typically associated with increased surface wetness. DCA axis 2 appears to summarise an inverse relationship between *Sphagnum imbricatum* and *Sphagnum* section *Rigida*, which are only abundant in isolated layers.

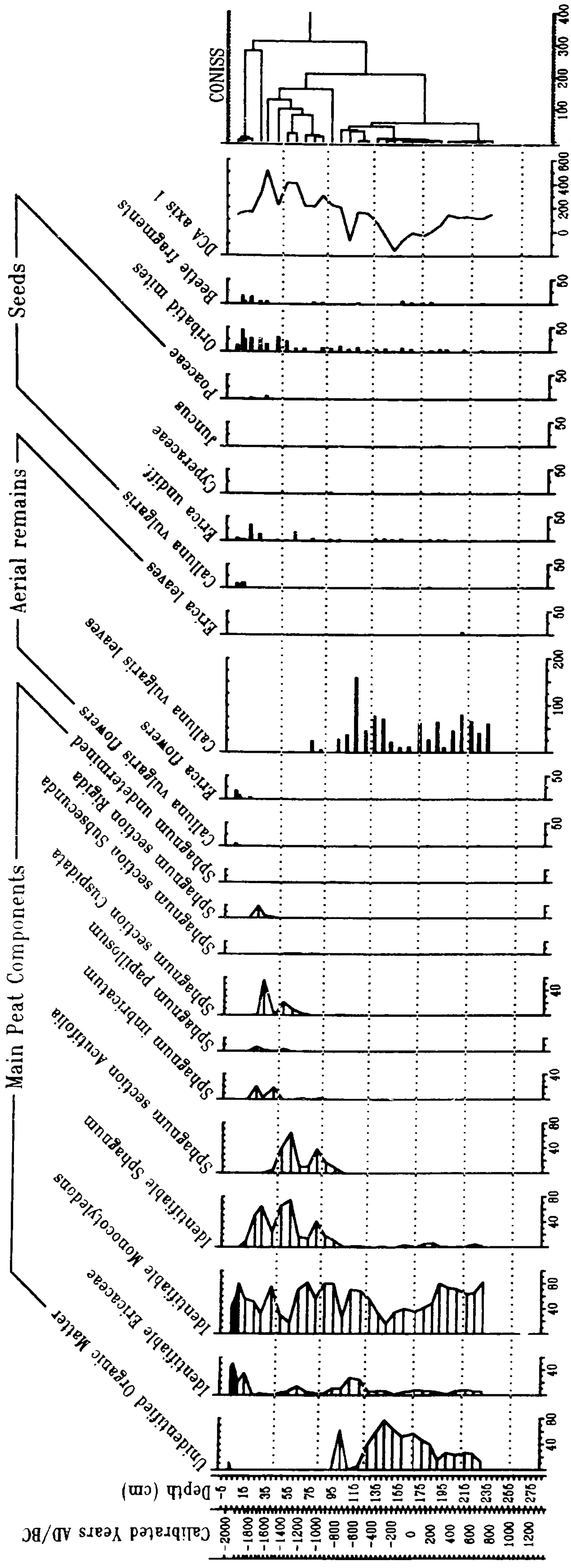
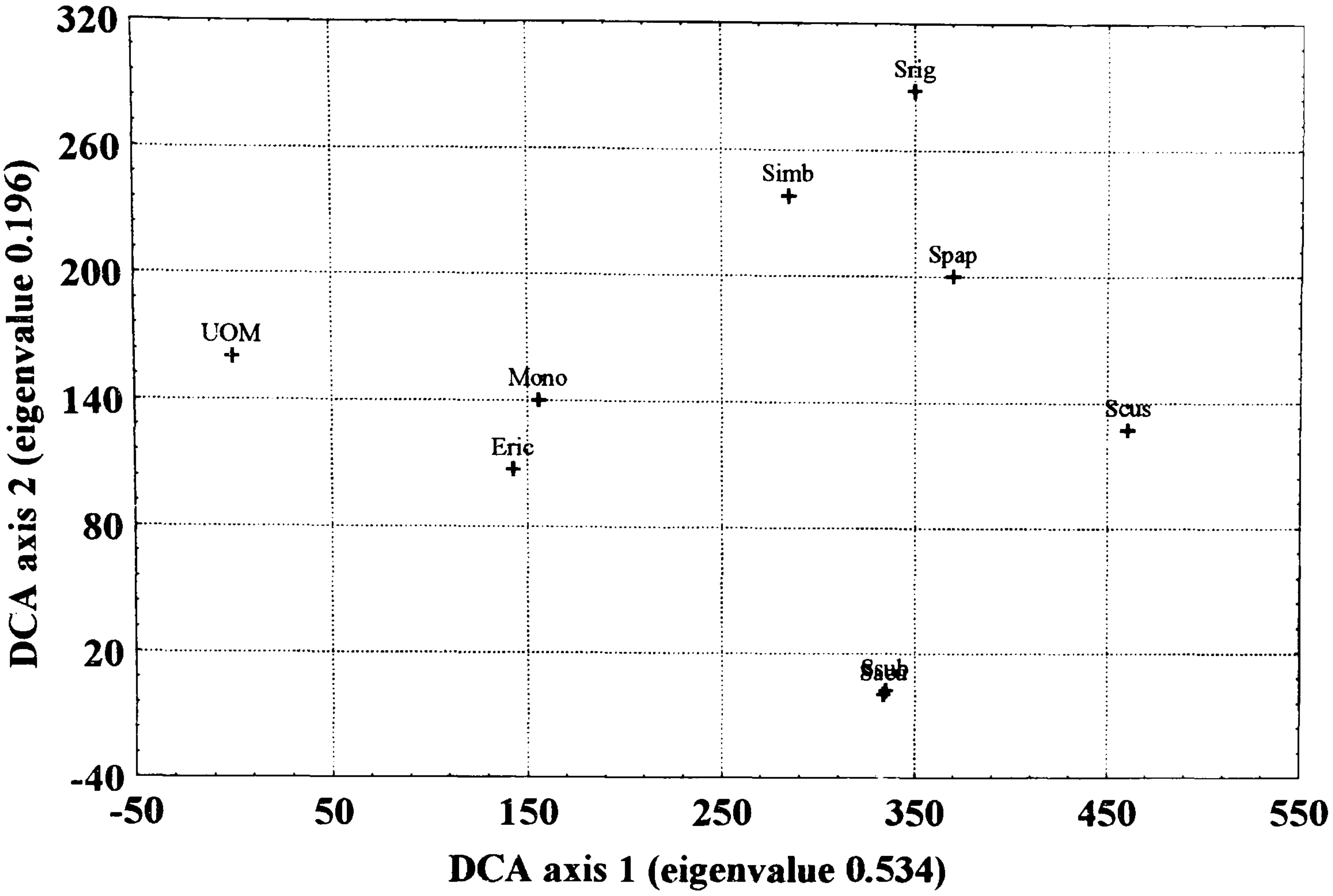


Figure 6.3. May Moss site B plant macrofossil diagram. Main peat components are expressed as percentages of the total volume of peat, with *Sphagnum* abundances based on leaf counts of a random selection of branch leaves (>100 per sample). The other curves display raw counts of leaves, seeds, flowers and selected insect remains. The sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

a).



b).

Macrofossil components	Graph label	DCA axis 1	DCA axis 2
Eigenvalue		0.534	0.196
% variance		33.25	12.17
Unidentified Organic Matter	UOM	-0.851 ^{c}	0.295
Monocotyledons	Mono	0.186	0.241
Ericaceae	Eric	-0.02	-0.321
Sphagnum section *Acutifolia*	Sacu	0.566 ^{c}	-0.794 ^{a}
Sphagnum imbricatum	Simb	0.303	0.452 ^{c}
Sphagnum papillosum	Spap	0.44 ^{a}	0.257
Sphagnum section *Cuspidata*	Scus	0.607 ^{c}	-0.022
Sphagnum section *Subsecunda*	Ssub	0.51 ^{c}	-0.701 ^{c}
Sphagnum section *Rigida*	Srig	0.306	0.457 ^{c}

Figure 6.4. (a) Detrended correspondence analysis ordination diagram showing the component weighted averages on the first two axes for the site B plant macrofossil data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the plant macrofossil components. The correlations are not statistically significant unless annotated by either, ^{a} = significance at the 95% level, ^{b} = significance at the 99% level or ^{c} = significance at the 99.9% level.

and other *Sphagnum* species. Further DCA axes individually only represent comparatively minor amounts of variation within the sub-fossil dataset.

DCA axis 1 represents the most significant variation within the dataset and appears to identify a moisture gradient. Consequently mire surface wetness may be the most important environmental factor affecting the plant macrofossil stratigraphy, and in theory DCA axis 1 could be used as a model summarising fluctuations between wet and dry conditions on the mire surface. The sample scores on DCA axis 1 are plotted stratigraphically on figure 6.3, with high values signifying wetter conditions and lower values drier conditions. There are problems with using DCA axis 1 in this manner, principally because the peat between 90-230 cm is dominated by Ericaceae and Monocotyledonous remains, with no discernible changes in the diversity and abundance of species. Macrofossil stratigraphy of this type is difficult to interpret in terms of changes in surface moisture conditions. Palaeohydrological interpretation of the DCA results can only be tentative, because DCA axis 1 solely models the main change within the macro-fossil stratigraphy, which is the arrival of *Sphagnum*.

Palaeoecology

Cluster analysis signifies that the most significant changes in the plant macrofossil stratigraphy occurred *circa* cal. AD 900, cal. AD 1600 and cal. AD 1800. The peat stratigraphy between 800 cal. BC and cal. AD 850 contains substantial quantities of UOM and is dominated by Monocotyledonous and Ericaceae remains, with *Calluna vulgaris* leaves particularly abundant. This evidence indicates the mire surface was relatively dry, sustaining a mixed community of *Calluna vulgaris*, *Eriophorum vaginatum* and other monocotyledonous taxa. The first significant change in the peat stratigraphy occurs *circa* cal. AD 900, with the expansion of *Sphagnum* section *Acutifolia*. However this expansion is relatively short-lived, followed by a decline in the abundance of *Sphagnum* section *Acutifolia* and expansion of Ericaceae remains between cal. AD 1150 and cal. AD 1400.

There were further increases in *Sphagnum* section *Acutifolia* and *Sphagnum* section *Cuspidata* after *circa* cal. AD 1400. *Sphagnum* section *Cuspidata* is a wet environmental indicator typically inhabiting pools, whereas *Sphagnum* section *Acutifolia* typically inhabit drier hummock-top sites. This association of taxa, combined with abundant Ericaceae remains, is in keeping with an environment consisting of a mixture of hummocks and hollows. *Circa* cal. AD 1600 *Sphagnum imbricatum* and *Sphagnum papillosum* increase in abundance at the expense of *Sphagnum* section *Cuspidata* and *Sphagnum* section *Acutifolia*. However, the decline of *Sphagnum* section *Cuspidata* is short-lived expanding again between cal. AD 1650-1800. During the last 150 years there is a further major change in the peat stratigraphy at site B, namely the decline of *Sphagnum*. All species of *Sphagnum* decline *circa* cal. AD 1800 and are replaced by Ericaceae remains, especially *Calluna vulgaris*. The composition of macrofossils in the surface layers of peat reflects the current mire flora, with a mixture of *Calluna vulgaris* and *Eriophorum vaginatum*, which reflects the current dry conditions at site B.

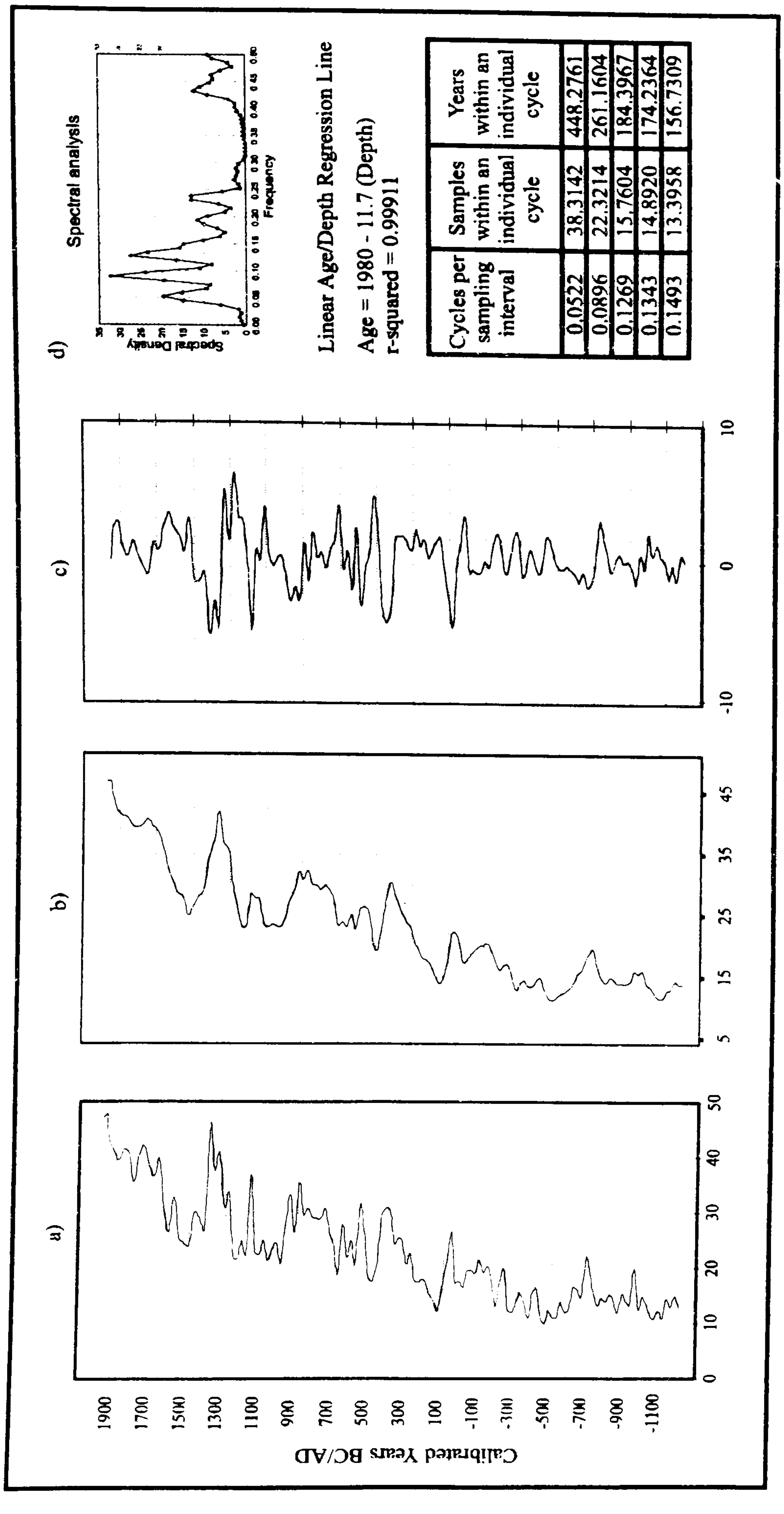
6.2.1.3 Humification analysis

The results of the humification analyses are displayed in figure 6.5. The humification profile contains seven significant shifts to poorly humified peat, which are interpreted as indicating changes to wetter conditions on the mire surface *circa* 700 cal. BC, 50 cal. BC, cal. AD 400, cal. AD 900, cal. AD 1100 and cal. AD 1300. Phases of well humified peat signifying comparatively dry conditions occur between 1100-800 cal. BC, cal. AD 0-400, cal. AD 700-900, cal. AD 1000-1100, cal. AD 1200-1300 and cal. AD 1500-1600.

Regression analysis of the age/depth model for the core B peat profile revealed a broadly linear relationship, and so the humification data was susceptible to time series analysis. The data series that produced the smoothed and high-pass filtered curve was subjected to spectral analysis using the Fourier transformation method and a Daniell smoothing window. The spectral density function displayed in figure 6.5(d) identifies several peaks, with the most significant two centred at 0.09 cpi (cycles per sampling interval) and 0.13 cpi. The linear age/depth model indicates these frequencies correspond to 260 and 185-year cycles respectively. A caveat to this analysis reiterates that the chronology for this core sequence is very tentative, based solely upon correlation of the palynostratigraphy and this analysis must be viewed in that context. However the periodicities identified in the humification changes are interesting and discussed further in later sections.

6.2.1.4 Reconstructing mire surface wetness

Palaeoecological investigation of the peat stratigraphy at site B reveals evidence of a changeable hydrological history. The fundamental problem with this palaeohydrological history arises from the chronology, which can only be regarded as tentative. Comparison of the hydrological signals yielded by the three palaeoenvironmental procedures identifies broad similarities. The evidence for wet shifts and unambiguously dry conditions present in the palaeoenvironmental data is summarised on figure 6.6, which demonstrates the correlation between the hydrological signal yielded by each technique. Humification shifts to poorly humified peat appear to occur slightly before equivalent changes in the testate amoebae and plant macrofossil stratigraphy. This is not unexpected, because if the main environmental control over humification, the depth of the average



Linear Age/Depth Regression Line

Age = 1980 - 11.7 (Depth)
r-squared = 0.99911

Cycles per sampling interval	Samples within an individual cycle	Years within an individual cycle
0.0522	38.3142	448.2761
0.0896	22.3214	261.1604
0.1269	15.7604	184.3967
0.1343	14.8920	174.2364
0.1493	13.3958	156.7309

Figure 6.5. Humification data from May Moss core B displaying; (a) the raw percentage light transmission values, (b) the raw data smoothed using an unweighted three point moving average, (c) the smoothed data series subjected to a high pass filter emphasising the key shifts. In all three curves higher values denote poorly humified peat and are interpreted as signifying wetter conditions. (d) Results of the time series analysis, which includes the spectral density function for the smoothed high-pass filtered data series displayed on graph (c). The table in part (d) converts the spectral peaks into years using the age/depth model derived for the peat profile.

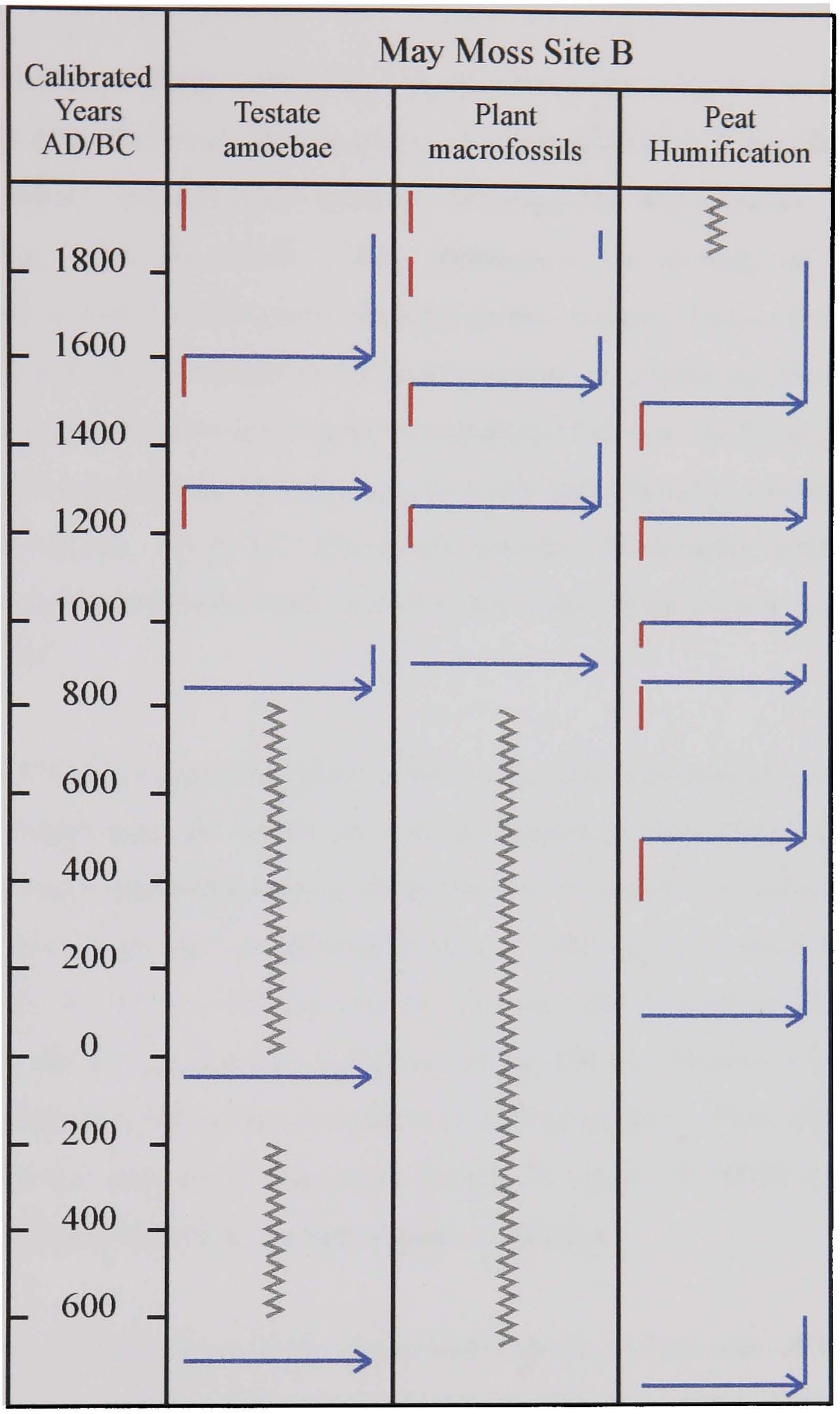


Figure 6.6. Summary of the moisture fluctuations signified in peat stratigraphies at May Moss site B. Red lines denote dry conditions and blue lines wet conditions. The blue arrows signify changes to wetter conditions. Grey zigzag lines denote stratigraphy with an ambiguous hydrological signal.

minimum summer water table, rises then previously accumulated acrotelmic peat will be absorbed by the rising catotelm, smearing evidence of the hydrological change within peat predating the event.

There are further problems, which centre on the stratigraphy pertaining to the period 800 cal. BC to cal. AD 800. The basal 180 cm of peat is comparatively well humified and dominated by Monocotyledons and Ericaceae remains. Consequently the turnover of identifiable plant macrofossils within the profile is low; furthermore the diversity of the testate amoebae assemblages is low. It is difficult to elucidate surface wetness changes from stratigraphy of this type. Fortunately the humification stratigraphy appears to contain evidence of moisture changes during this period, identifying relatively wet conditions between 700-50 cal. BC and from cal. AD 400-700. These wet phases are separated by a dry phase broadly concurrent with the Roman-British period, cal. AD 0-400. The testate amoebae stratigraphy corroborates part of this moisture history, identifying wetter conditions and a fluctuating shallow water table in the period 500-0 cal. BC.

The upper 120 cm of peat stratigraphy is better suited for palaeohydrological research, with both the plant macrofossil and testate amoebae stratigraphies characterised by a higher diversity community and a reasonable turnover of species. The balance of the ecological evidence indicates that the most important environmental factors affecting past plant and testate amoebae communities at site B is habitat wetness. The increase in diversity of the testate amoebae community and the expansion of *Sphagnum* are broadly synchronous, which is not unexpected because testate amoebae are more abundant on *Sphagnum* mires. These changes occurred around cal. AD 800-900 after a brief drier phase between *circa* cal. AD 700-800, and parallel a shift to wetter conditions identified in the humification stratigraphy.

There is a broad agreement in the palaeohydrological interpretation of the plant macrofossil, testate amoebae and humification stratigraphies after this major stratigraphic change. Wet conditions persist until *circa* cal. AD 1100, with reconstructed mean annual water table depths of *circa* 6 cm. Between cal. AD 1100-1300 the plant macrofossil and testate amoebae stratigraphies contained evidence of a broad drier phase. The period between cal. AD 1300-1900 appears to be broadly wet, evidenced by a reconstructed mean annual water table depth of *circa* 4 cm and plant communities dominated by *Sphagnum* section *Cuspidata*. There is evidence of a brief drier phase around cal. AD 1550 within the plant macrofossil, testate amoebae and humification stratigraphies. The final hydrological event involves changes in the plant macrofossil and testate amoebae stratigraphy pertaining to the last 100 years, signifying a drying trend in the surface layers of peat.

6.2.2 May Moss Site C

Introduction

Palaeohydrological investigation of the site C peat sequence is based on the analysis of four cores, which are all 2.1 metres in length. A summary of the field stratigraphy synthesised from the four cores is presented in table 6.2. Cores 1 and 4 received both plant macrofossil and testate amoebae analysis. Core 3 received plant macrofossil, testate amoebae and humification analysis, and yielded the samples for ^{14}C dating. Core 2 received both plant macrofossil and humification analysis. The results of the plant macrofossil, testate amoebae and humification data are graphed against both depth and a time series calculated using the methodology introduced in chapter four utilising the chronological horizons defined at the beginning of this chapter.

Table 6.2. Peat stratigraphy recorded in the field at site C.

Mire surface	A transact over a hummock and hollow sequence covered by *Calluna vulgaris* and *Eriophorum vaginatum*, with occasional *Eriophorum angustifolia* and *Erica tetralix*. The ground flora consists of *Hypnum jutlandicum* and *Sphagnum capillifolium*, with *Sphagnum* section *Cuspidata* in the hollows.
0-75 cm	Poorly humified *Sphagnum* and Monocotyledonous peat.
75-90 cm	Poorly humified *Eriophorum vaginatum* and Ericaceae peat.
90-145 cm	Poorly humified *Sphagnum* and Monocotyledonous peat.
145-210 cm	Well humified Monocotyledonous peat, with occasional layers of Ericaceae remains.

6.2.2.1 Testate amoebae data

Quantitative analysis

The testate amoebae diagrams are presented in figures 6.7-6.9. The species scores on the first two axes of a detrended correspondence analysis of the core 1, 3 and 4 sub-fossil data are displayed as X/Y biplots in figures 6.10-6.12. The eigenvalues for the first two DCA axes for each core are also listed on figures 6.10-6.12 and signify that the first two axes summarise the most significant structure within each sub-fossil dataset. The amount of variation explained by further DCA axes is small. Correlation coefficients calculated for each core between the testate amoebae taxa and the first two DCA axes are listed in figures 6.10-6.12. The correlation analysis identifies the species involved in the most significant changes in the testate amoebae stratigraphy.

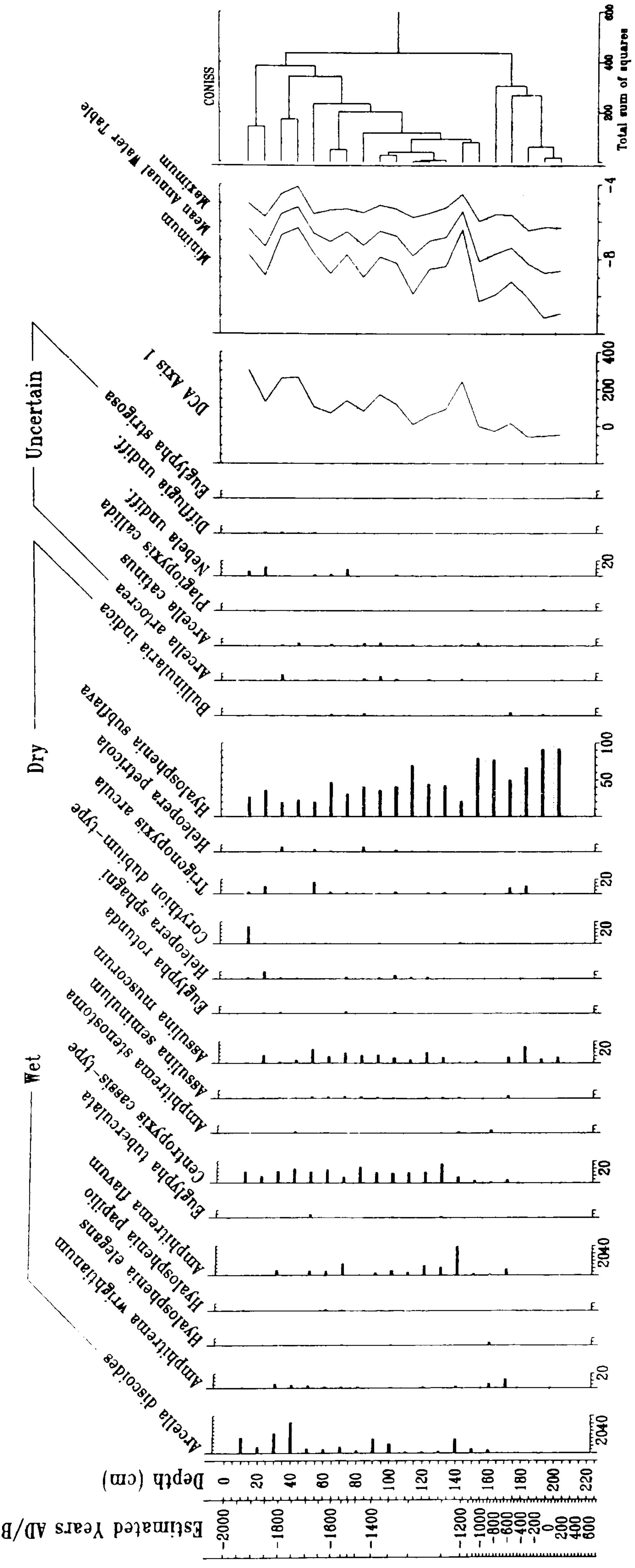


Figure 6.7. May Moss core C1 testate amoebae diagram. The species curves are arranged from left to right according to preference of habitat moisture conditions. On the far right the reconstructed mean annual water table depths are presented, including upper and lower limits based on the ranges tolerated by individual species; the sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

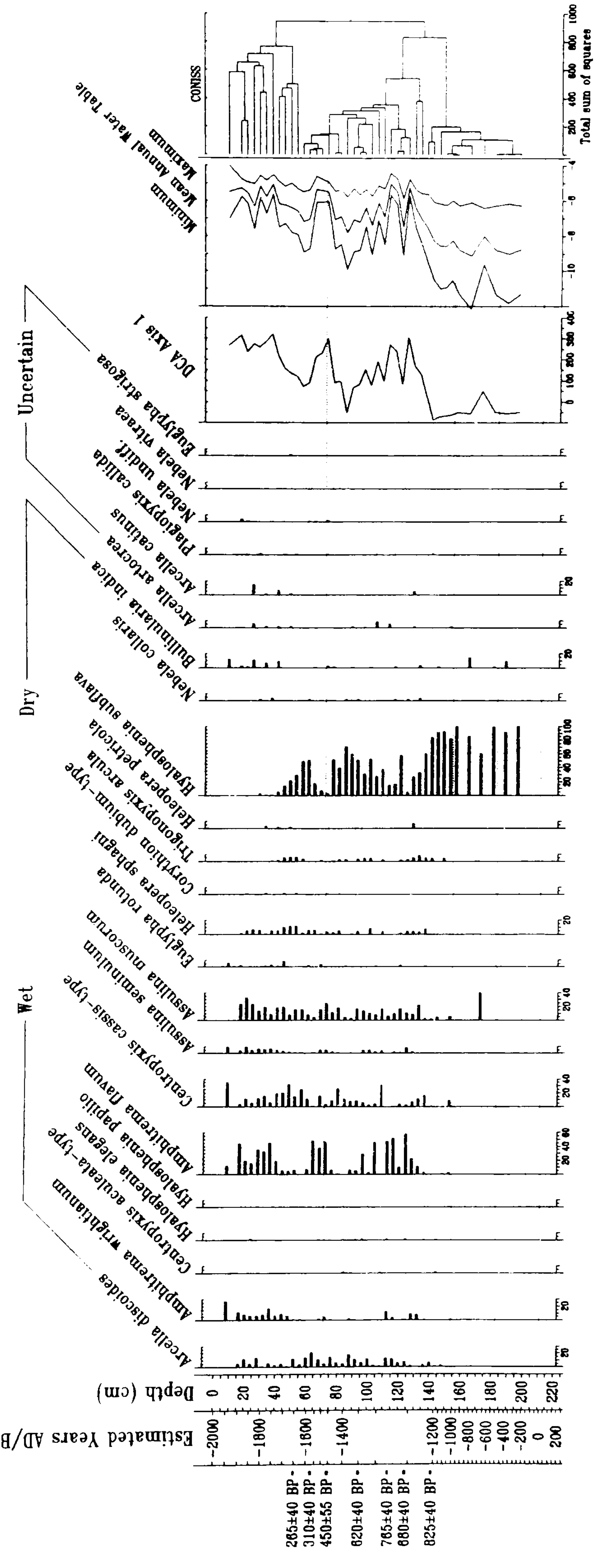


Figure 6.8. May Moss core C3 testate amoebae diagram. The species curves are arranged from left to right according to preference of habitat moisture conditions. On the far right the reconstructed mean annual water table depths are presented, including upper and lower limits based on the ranges tolerated by individual species; the sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

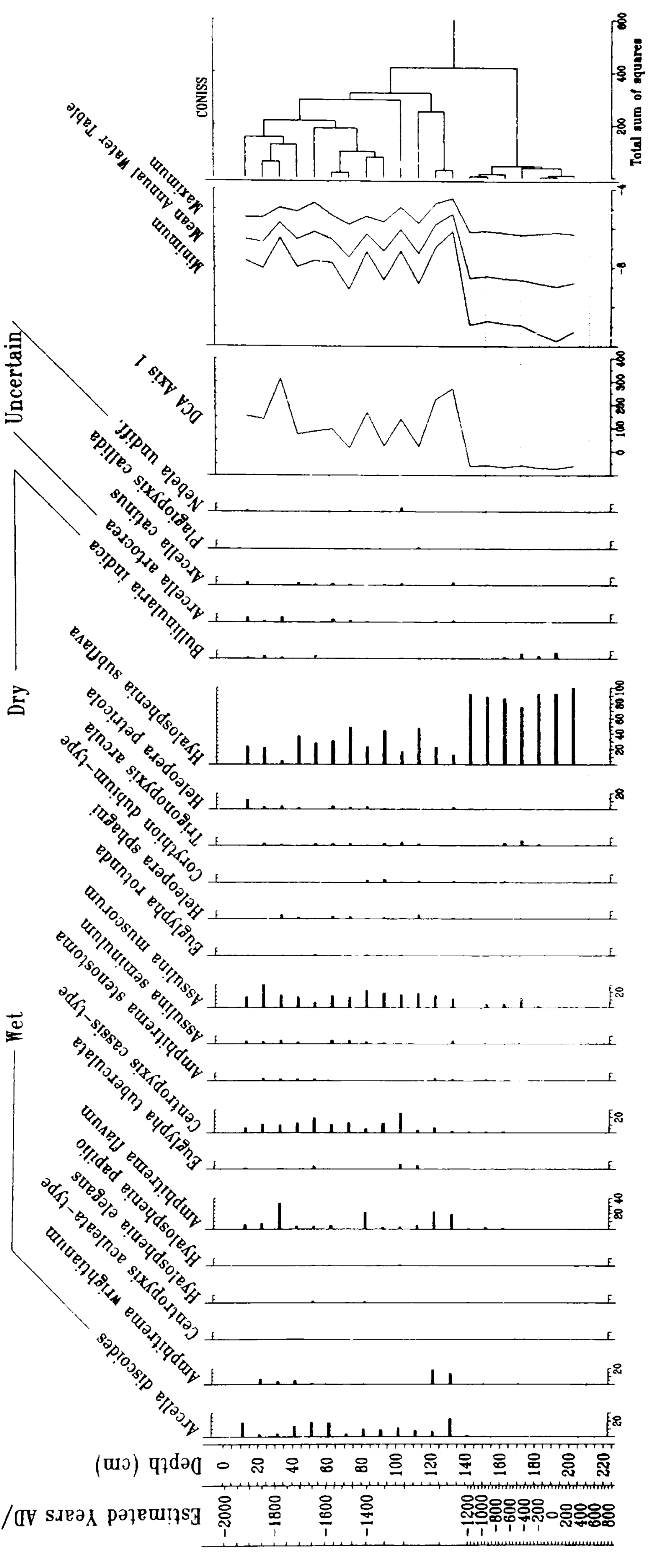
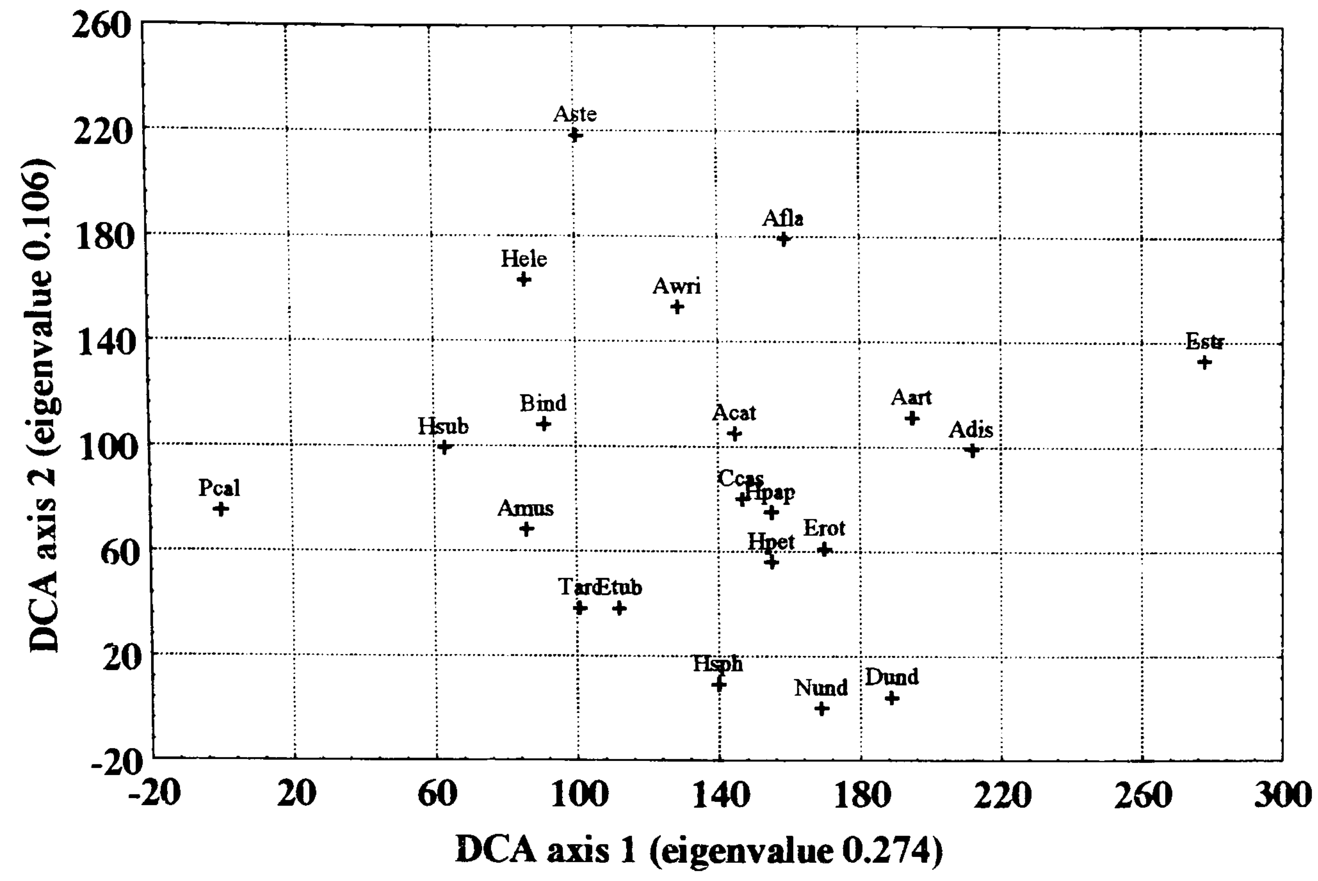


Figure 6.9. May Moss core C4 testate amoebae diagram. The species curves are arranged from left to right according to preference of habitat moisture conditions. On the far right the reconstructed mean annual water table depths are presented, including upper and lower limits based on the ranges tolerated by individual species; the sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

a).

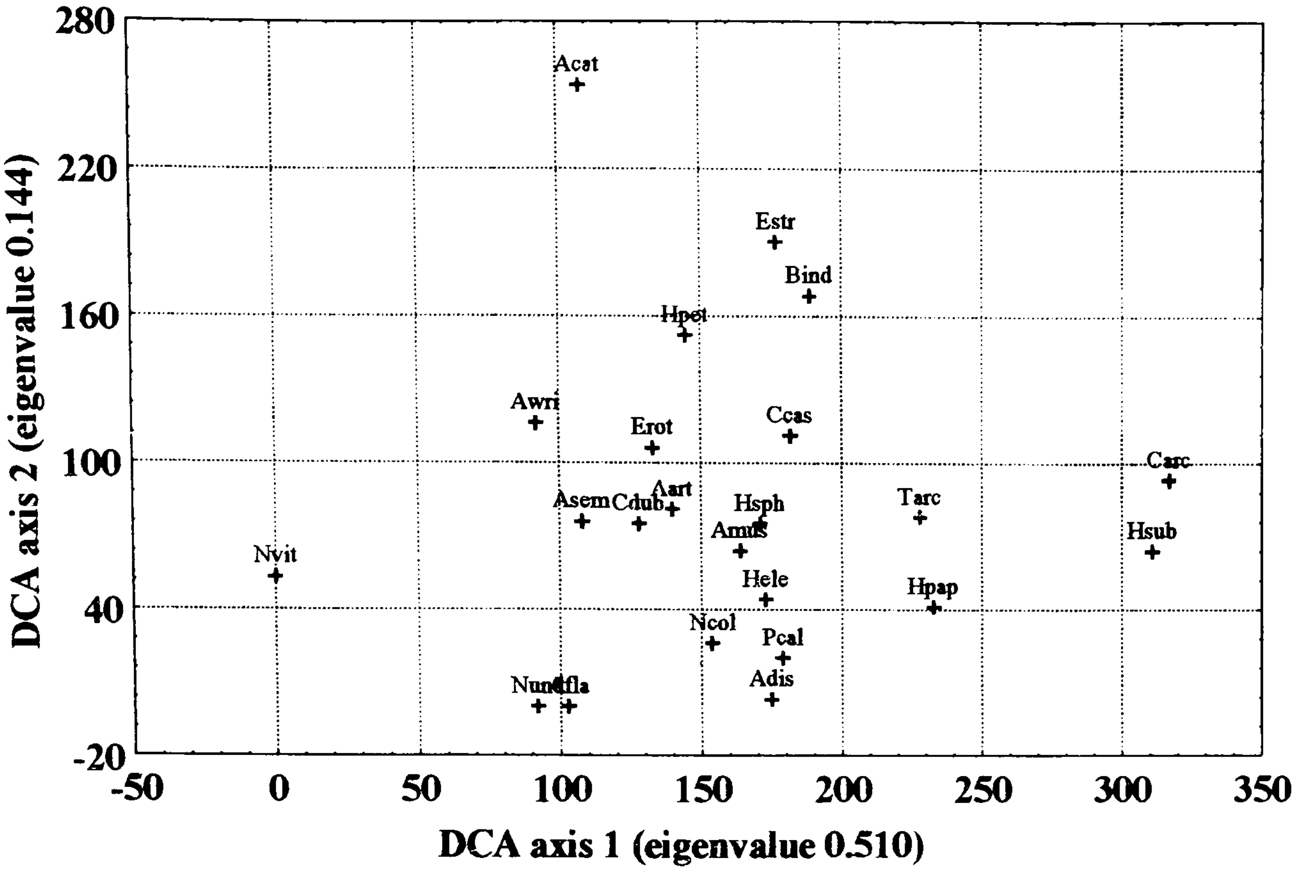


b).

Testate Amoebae species	Graph label	DCA axis 1	DCA axis 2
Eigenvalue		0.274	0.106
% variance		25.59	9.88
Arcella discoides	Adis	0.8522 ^{c}	0.0406
Arcella artocrea	Aarc	0.4307	0.0924
Arcella catinus	Acat	0.2794	0.0872
Centropyxis cassis -type	Ccas	0.5361 ^{a}	-0.2232
Plagiopyxis callida	Pcal	-0.3219	-0.0627
Bullinularia indica	Bind	-0.1057	0.0924
Trigonopyxis arcula	Tarc	-0.0522	-0.4348
Hyalosphenia subflava	Hsub	-0.8855 ^{c}	0.1050
Hyalosphenia papilio	Hpap	0.1749	-0.0818
Hyalosphenia elegans	Hele	-0.0865	0.2891
Heleopera sphagni	Hsph	0.1842	-0.5536 ^{a}
Heleopera petricola	Hpet	0.2337	-0.2126
Nebela undiff.	Nund	0.2933	-0.5133 ^{a}
Difflugia undiff.	Dund	0.4446 ^{a}	-0.5535 ^{a}
Amphitrema flavum	Afla	0.3449	0.6414 ^{b}
Amphitrema wrightianum	Awri	-0.0279	0.4934 ^{a}
Amphitrema stenostoma	Aste	0.1444	0.4545 ^{a}
Euglypha strigosa	Estr	0.3662	0.0924
Euglypha tuberculata	Etub	0.0139	-0.2343
Euglypha rotunda	Erot	0.3495	-0.2087
Assulina muscorum	Amus	-0.2934	-0.3856
Assulina seminulum	Asem	0.1200	0.2274
Corythion dubium -type	Cdub	0.4708 ^{a}	-0.2820

Figure 6.10. (a) Detrended correspondence analysis ordination diagram showing the species weighted averages on the first two axes for the core C1 testate amoebae data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the testate amoebae species. The correlations are not statistically significant unless annotated by either, ^{a} = significance at the 95% level, ^{b} = significance at the 99% level or ^{c} = significance at the 99.9% level.

a).

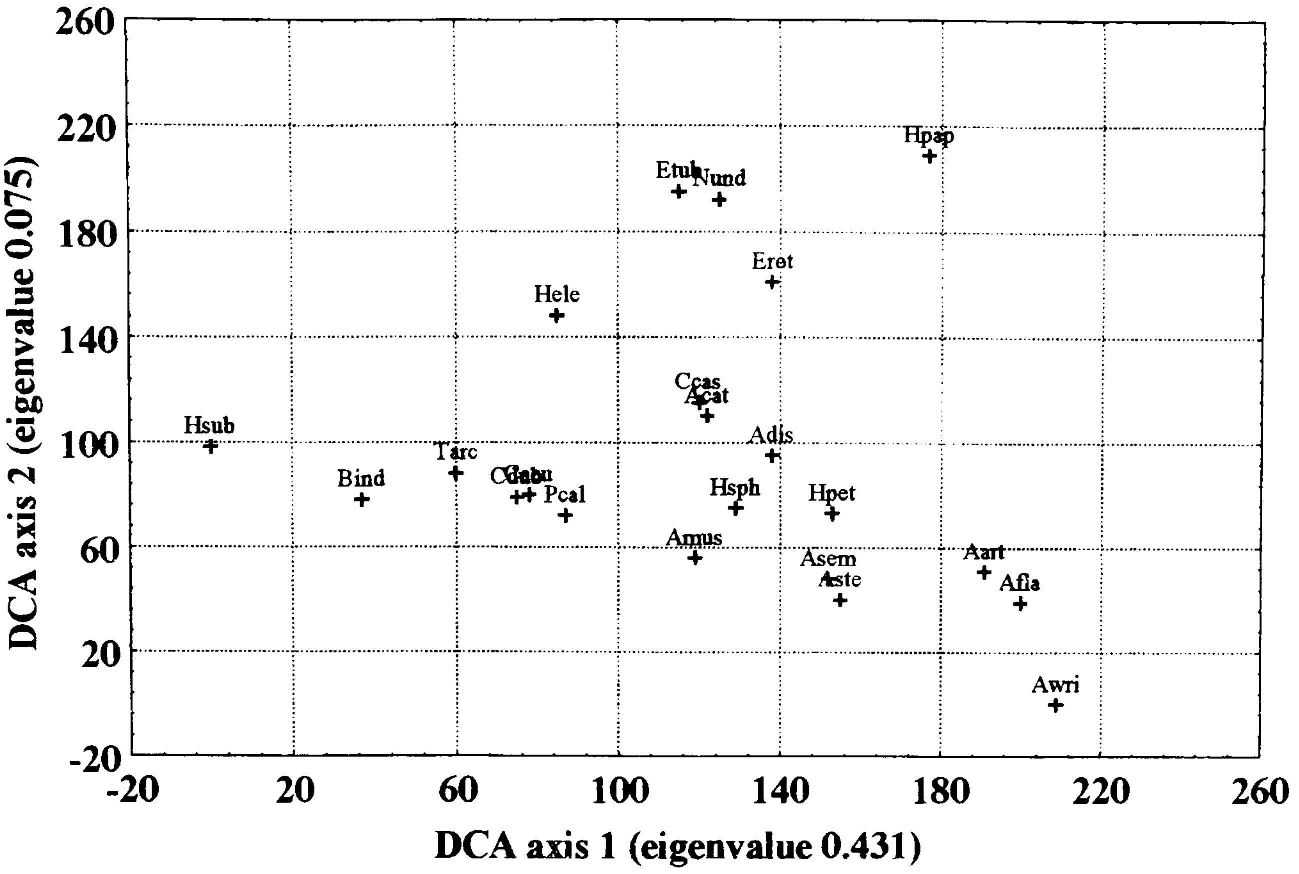


b).

Testate Amoebae species	Graph label	DCA axis 1	DCA axis 2
Eigenvalue		0.510	0.144
% variance		39.62	11.22
Arcella discoides	Adis	-0.3325 [a]	-0.6231 [c]
Arcella artocrea	Aarc	-0.2669	0.0940
Arcella catinus	Acat	-0.2457	0.5569 [c]
Plagiopyxis callida	Pcal	-0.1382	-0.2043
Bullinularia indica	Bind	-0.1047	0.5616 [c]
Trigonopyxis arcula	Tarc	0.0935	0.1417
Centropyxis cassis -type	Ccas	-0.2540	0.0923
Centropyxis aculeata -type	Cacu	0.2355	0.4954 [c]
Hyalosphenia subflava	Hsub	0.9805 [c]	0.0417
Hyalosphenia papilio	Hpap	0.0514	-0.0664
Hyalosphenia elegens	Hele	-0.1550	-0.0789
Heleopera sphagni	Hsph	-0.3012	0.1238
Heleopera petricola	Hpet	-0.1501	0.2475
Nebela undiff.	Nund	-0.3350 [a]	-0.2123
Nebela collaris	Ncol	-0.2499	-0.1843
Nebela vitraea	Nvit	-0.2738	-0.0131
Amphitrema flavum	Afla	-0.7895 [c]	-0.5427 [c]
Amphitrema wrightianum	Awri	-0.6365 [c]	0.3600 [a]
Euglypha rotunda	Erot	-0.3281 [a]	0.2295
Euglypha strigosa	Estr	-0.0602	0.2613
Assulina muscorum	Amus	-0.5039 [c]	0.0350
Assulina seminulum	Asem	-0.7582 [c]	0.1343
Corythion dubium -type	Cdub	-0.2609	0.0533

Figure 6.11. (a) Detrended correspondence analysis ordination diagram showing the species weighted averages on the first two axes for the core C3 testate amoebae data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the testate amoebae species. The correlations are not statistically significant unless annotated by either, ^{a} = significance at the 95% level, ^{b} = significance at the 99% level or ^{c} = significance at the 99.9% level.

a).



b).

Testate Amoebae species	Graph label	DCA axis 1	DCA axis 2
Eigenvalue		0.431	0.075
% variance		45.20	7.88
Arcella discoides	Adis	0.6045 [c]	0.1044
Arcella artocrea	Aarc	0.6621 [c]	-0.2557
Arcella catinus	Acat	0.3602	0.2290
Plagiopyxis callida	Pcal	0.0499	-0.0542
Bullinularia indica	Bind	-0.2193	-0.0717
Trigonopyxis arcula	Tarc	-0.0745	0.0208
Centropyxis cassis -type	Ccas	0.4409	0.3479
Centropyxis aculeata -type	Cacu	0.0165	-0.0162
Hyalosphenia subflava	Hsub	-0.9363 [c]	0.2201
Hyalosphenia papilio	Hpap	0.3566	0.5643 [b]
Hyalosphenia elegens	Hele	0.0583	0.3270
Heleopera sphagni	Hsph	0.4480 [a]	-0.1161
Heleopera petricola	Hpet	0.4342	-0.0883
Nebela undiff.	Nund	0.2187	0.5736 [c]
Amphitrema flavum	Afla	0.8528 [c]	-0.4196
Amphitrema wrightianum	Awri	0.6028 [c]	-0.5091 [a]
Amphitrema stenostoma	Aste	0.5230 [a]	-0.3875
Euglypha rotunda	Erot	0.2332	0.3502
Euglypha tuberculata	Etub	0.1893	0.6192 [b]
Assulina muscorum	Amus	0.6299 [c]	-0.5129 [a]
Assulina seminulum	Asem	0.5967 [c]	-0.3735
Corythion dubium -type	Cdub	0.0290	-0.0456

Figure 6.12. (a) Detrended correspondence analysis ordination diagram showing the species weighted averages on the first two axes for the core C4 testate amoebae data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the testate amoebae species. The correlations are not statistically significant unless annotated by either, [a] = significance at the 95% level, [b] = significance at the 99% level or [c] = significance at the 99.9% level.

Some of the most abundant testate amoebae species in core 1 appear to be arranged along DCA axis 1 according to their tolerance of habitat wetness. Dry indicator taxa such as *Hyalosphenia subflava* occur at the opposite end of axis 1 to the wet indicators *Arcella discoides*, *Amphitrema flavum* and *Amphitrema wrightianum* (Tolonen *et al.*, 1992; 1994; Woodland *et al.*, 1998). The correlation coefficients support this conclusion with axis 1 appearing to summarise sub-fossil variations between a "wet environment" assemblage and a "dry environment" assemblage. The wet indicators are *Arcella discoides and Centropyxis cassis*-type, which display a strong positive correlation with axis 1, whereas the dry indicator *Hyalosphenia subflava* displays a strong negative correlation. However, some of the species typically found in wetter environments are not correlated with axis 1, for example *Amphitrema* spp. and *Assulina muscorum*. DCA axis 1 appears to solely model the relationship between *Hyalosphenia subflava*, and *Arcella discoides* and *Centropyxis cassis*-type.

Although DCA axis 1 summarises the most significant structure, it only accounts for 25.59% of the total variation within the dataset. Although DCA axis 1 could be used as a model identifying a series of wet and dry phases, it is important to remember that the axis only really summarises the relationship between *Hyalosphenia subflava*, and *Arcella discoides* and *Centropyxis cassis*-type. A consequence of three species contributing the most significant structure, is that 74% of the variation is explained by further DCA axes. However, the amount of variation explained by these DCA axes becomes increasingly small. DCA axis 2 accounts for 9% of the overall structure and the correlation analysis identifies that it summarises the relationship between a wet environment assemblage containing *Amphitrema* spp. and a dry environment assemblage containing *Heleopera sphagni*, *Nebela* spp. and *Difflugia* spp.. The sample scores of DCA axis 1 are plotted stratigraphically in figure 6.7. and although it is of limited value as a palaeohydrological curve, it does identify the most significant changes in the sub-fossil stratigraphy.

The most abundant testate amoebae species in core 3 appear to be arranged along DCA axis 1 according to their tolerance of habitat wetness. The dry indicator taxon, *Hyalosphenia subflava*, occurs at the opposite end of axis 1 to the wet indicator, *Arcella discoides*, *Amphitrema flavum*, *Amphitrema wrightianum* and *Assulina* spp. (Tolonen *et al.*, 1992; 1994; Woodland *et al.*, 1998). The correlation coefficients support this conclusion with DCA axis 1 summarising sub-fossil variations between a "wet environment" assemblage and a "dry environment" assemblage. The wet indicators are *Arcella discoides*, *Amphitrema flavum*, *Amphitrema wrightianum* and *Assulina* spp., which display a strong positive correlation with axis 1, whereas the dry indicator

Hyalosphenia subflava displays a strong negative correlation. Further DCA axes individually explain less significant amounts of variation within the sub-fossil dataset, with DCA axis 1 accounting for 39.62% of the total. The axis appears to identify a moisture gradient; consequently, mire surface wetness appears to be the most important environmental factor affecting the sub-fossil testate amoebae stratigraphy. DCA axis 1 is proposed as a model summarising fluctuations between wet and dry conditions on the mire surface. The sample scores on DCA axis 1 are plotted stratigraphically in figure 6.8, with high values identifying wetter conditions and lower values drier conditions.

The most abundant testate amoebae species in core 4 also appear to be arranged along DCA axis 1 according to their tolerance of habitat wetness. Dry indicator taxa such as *Hyalosphenia subflava* occur at the opposite end of axis 1 to the wet indicators *Arcella discoides*, *Amphitrema flavum*, *Amphitrema wrightianum* and *Assulina* spp. (Tolonen *et al.*, 1992; 1994; Woodland *et al.*, 1998). The correlation coefficients support this conclusion with DCA axis 1 summarising sub-fossil variations between a "wet environment" assemblage and a "dry environment" assemblage. The wet indicators are *Arcella discoides*, *Amphitrema flavum*, *Amphitrema wrightianum*, *Amphitrema stenostoma* and *Assulina* spp., all displaying a strong positive correlation with DCA axis 1, whereas the dry indicator *Hyalosphenia subflava* displays a strong negative correlation.

Further DCA axes individually only explain minor amounts of variation within the sub-fossil dataset, with DCA axis 1 summarising 45.20% of the variation in the dataset. The axis appears to identify a moisture gradient. Consequently, mire surface wetness appears to be the most important environmental factor affecting the sub-fossil testate amoebae stratigraphy, and so DCA axis 1 is proposed as a model summarising fluctuations between wet and dry conditions on the mire surface. The sample scores on DCA axis 1 are plotted stratigraphically in figure 6.9, with high values identifying wetter conditions and lower values drier conditions.

Each DCA curve can only be viewed as a semi-quantitative model of moisture conditions. The DCA analyses indicate that the significant structure within the core 3 and 4 data, appears to reflect a clear response to surface wetness, whereas the link between the DCA axes and surface wetness is less apparent. Core 1 was extruded from beneath a hummock, whereas core 3 was extruded from beneath a hollow. The macrofossil stratigraphy at site C indicates that hummocks and hollows appear to be long-lived features, expanding and contracting in response to surface saturation. Assuming the surface topography at site C has been comparatively similar throughout during the last 2,000 years, then the testate amoebae stratigraphy beneath a hollow appears to record hydrological changes more clearly than stratigraphy beneath a hummock.

The optimum, maximum and minimum reconstructed mean annual water table depths tolerated by extant species were used to generate three palaeohydrological curves, which identify the potential range of moisture conditions for each core at site C. These curves are displayed stratigraphically in figures 6.7-6.9. The fluctuations in reconstructed mean annual water table depth signify a very changeable hydrological history at site C. The fluctuations in reconstructed mean annual water table depth are more pronounced in core 3 than in core 1, perhaps providing further evidence of a discrepancy between the testate amoebae stratigraphy beneath hummocks and hollows.

Palaeoecology

The testate amoebae stratigraphy at site C contains twenty three species, of which nine are particularly abundant. Two distinct sub-fossil assemblages of testate amoebae occur, with the first dominated by wet environment species, namely *Arcella discoides*, *Amphitrema wrightianum*, *Amphitrema flavum*, *Centropyxis cassis*-type and *Assulina* spp. (Woodland *et al.*, 1998; Tolonen *et al.*, 1992; 1994). The second is a dry environment assemblage dominated by *Hyalosphenia subflava*, with occasional *Trigonopyxis arcula*, *Corythion dubium*-type and *Bullinularia indica* (Woodland *et al.*, 1998).

The most significant changes in the testate amoebae stratigraphy identified by the cluster analyses occurred *circa* cal. AD 500, cal. AD 1100, cal. AD 1300, cal. AD 1500 and cal. AD 1700. The stratigraphy pertaining to the period 600 cal. BC to cal. AD 1200 is dominated by *Hyalosphenia subflava*, which is indicative of relatively dry conditions. *Assulina muscorum* and *Trigonopyxis arcula* are more abundant between cal. AD 400-800 perhaps reflecting increased surface wetness, which allowed a more diverse testate amoebae community to develop. However, between cal. AD 800-1000 the stratigraphy is dominated by *Hyalosphenia subflava* reflecting a return to drier conditions.

The most significant change in the testate amoebae stratigraphy occurs *circa* cal. AD 1100, and involves a marked increase in the diversity of testate amoebae at site C. Increases are displayed in the palaeoecological curves of *Arcella discoides*, *Amphitrema wrightianum*, *Amphitrema flavum*, *Centropyxis cassis*-type and *Assulina* spp. on all three cores, and there is a corresponding decline in the abundance of *Hyalosphenia subflava*. This event signifies a change to a wetter environment, which is below a ^{14}C date of 825±40 BP [cal. AD 1165(1230)1275]. Species particularly indicative of wet conditions, namely *Arcella discoides*, *Amphitrema wrightianum* and *Amphitrema flavum*, decline between cal. AD 1200-1300 and there is a resurgence in frequencies of *Hyalosphenia subflava*, identifying a return to drier conditions. This drier phase is short-lived, followed by increases in *Arcella discoides, Amphitrema wrightianum, Amphitrema flavum, Centropyxis cassis*-type and *Assulina* spp., reflecting a return to wetter conditions.

The beginning of this wetter phase is ^{14}C dated to 620±40 BP [cal. AD 1275(1295)1395] and the end is ^{14}C dated to 310±40BP [cal. AD 1475(1640)1665]. There is brief drier phase signified by a further expansion by *Hyalosphenia subflava*, particularly evident on core 3, which nestles between two ^{14}C dates of 310±40BP [cal. AD 1475(1640)1650] and 265±40 BP [cal. AD 1515(1650)1950]. After *circa* cal. AD 1650 a decline in *Hyalosphenia subflava* signifies a return to wetter conditions, a view corroborated by high frequencies of *Arcella discoides, Amphitrema wrightianum, Amphitrema flavum* and *Assulina* spp., and these broadly wet conditions persist to the present-day.

An important outcome of the analysis at site C arises from the consistency identified in the testate amoebae stratigraphy. The testate amoebae stratigraphy in all three cores located beneath both hummock and hollow environments is very similar, which indicates that microtopography appears to have little impact on the testate amoebae stratigraphy. This cannot be used to suggest that testate amoebae stratigraphies are consistent across a mire, because variations in testate amoebae communities in response to environmental differences will occur across a topographic mire. However, the consistency over short distances (*circa* 5 metres) indicates that cores from hummocks and hollows can provide a representative assessment of the testate amoebae stratigraphy at a particular location. This homogeneity contrasts with early research on testate amoebae ecology, which identified testate amoebae assemblages typical of hummock and hollow environments (Schönborn, 1963).

6.2.2.2 Plant macrofossil data

Quantitative analysis

The plant macrofossil stratigraphy from cores 1-4 are displayed in figures 6.13-6.16. The scores of the main macrofossil components on the first two axes of a detrended correspondence analysis performed on the sub-fossil data for each core are displayed as X/Y biplots in figures 6.17-6.20. The eigenvalues for the first two DCA axes generated for each core are also listed on figures 6.17-6.20 and signify that the first two DCA axes summarise the most significant structure within each individual data-set. The amount of variation explained by further individual DCA axes is small. Correlation coefficients between the main components of the plant macrofossil stratigraphy and the first two DCA axes generated for each core are listed on figures 6.17-6.20.

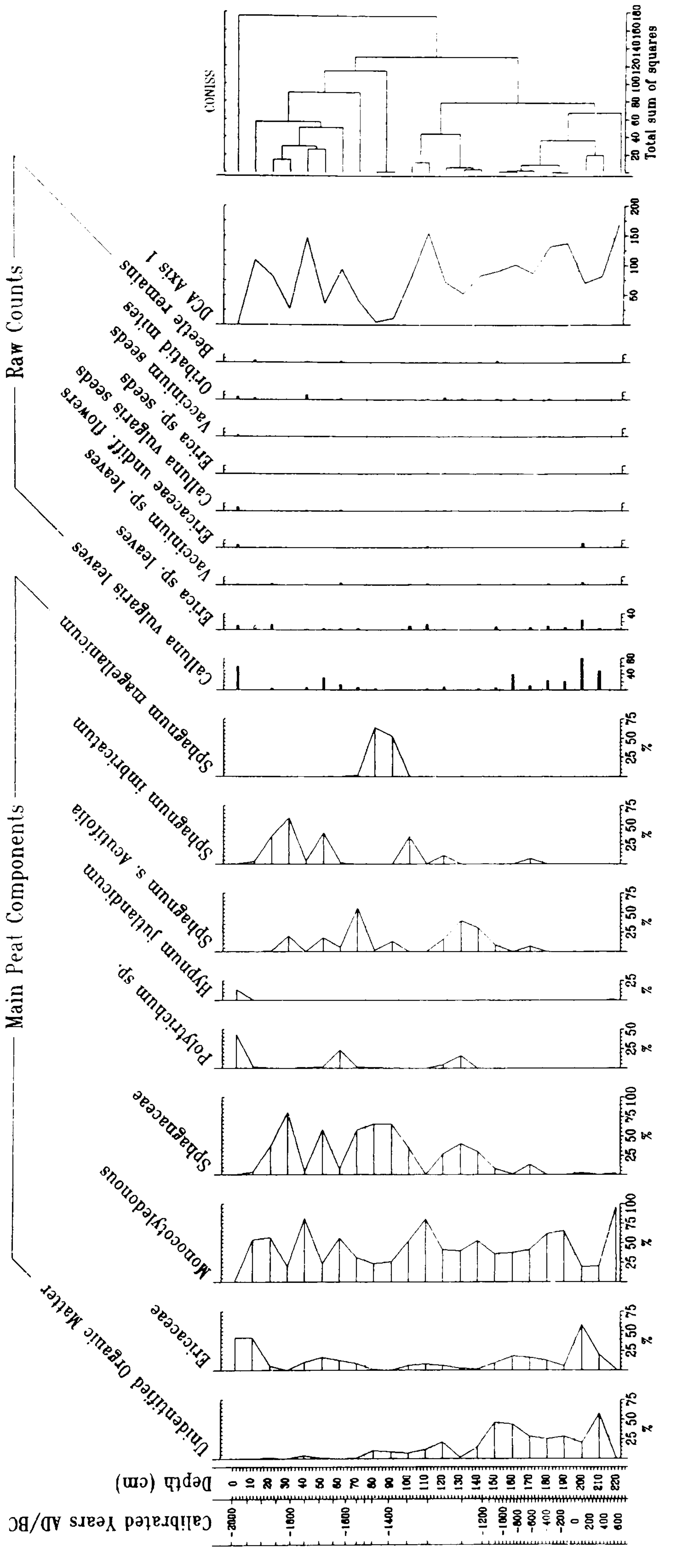


Figure 6.13. May Moss core C1 plant macrofossil diagram. Main peat components are expressed as percentages of the total volume of peat, with *Sphagnum* abundances based on leaf counts of a random selection of branch leaves (>100 per sample). The other curves display raw counts of leaves, seeds, flowers and selected insect remains. The sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

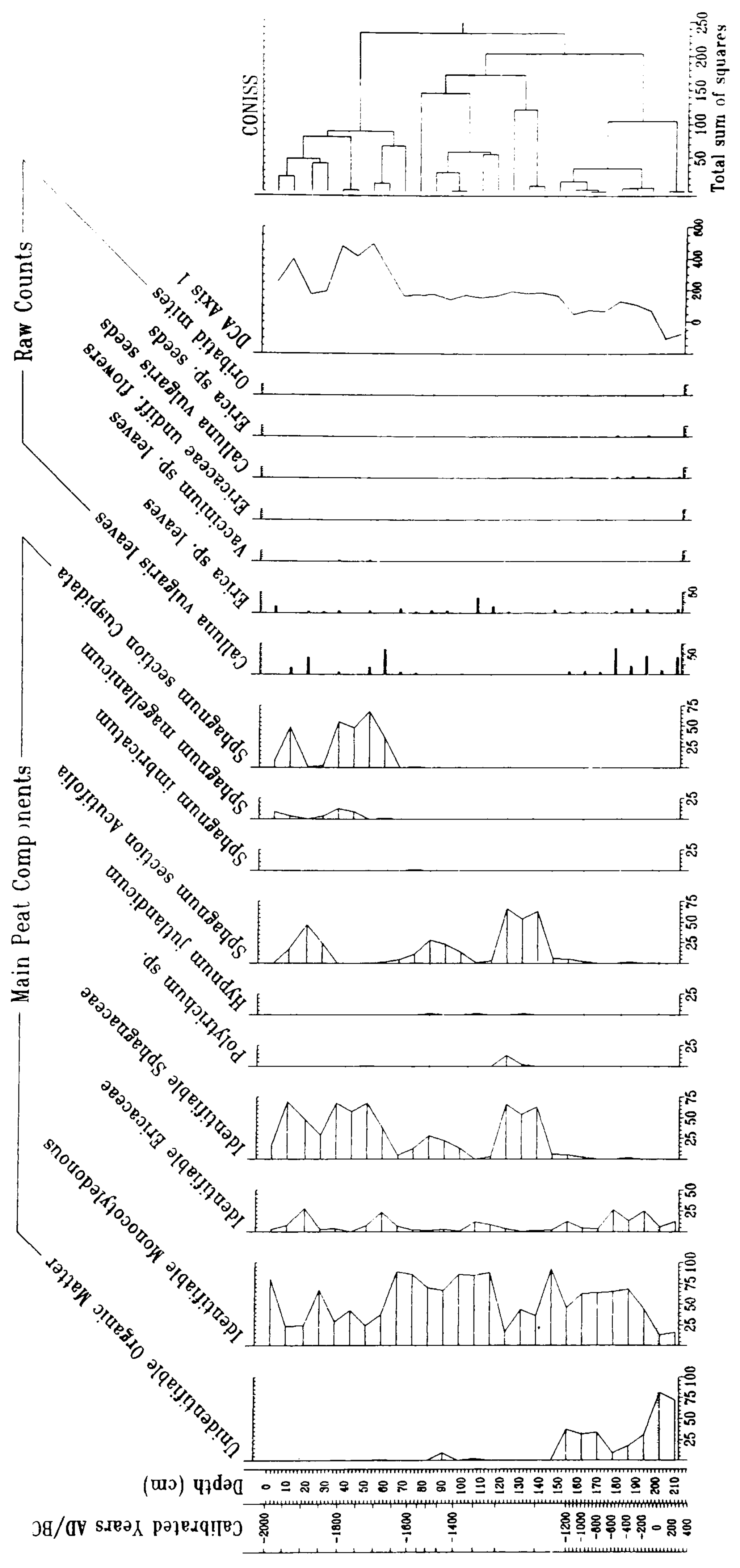


Figure 6.14. May Moss core C2 plant macrofossil diagram. Main peat components are expressed as percentages of the total volume of peat, with *Sphagnum* abundances based on leaf counts of a random selection of branch leaves (>100 per sample). The other curves display raw counts of leaves, seeds, flowers and selected insect remains. The sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

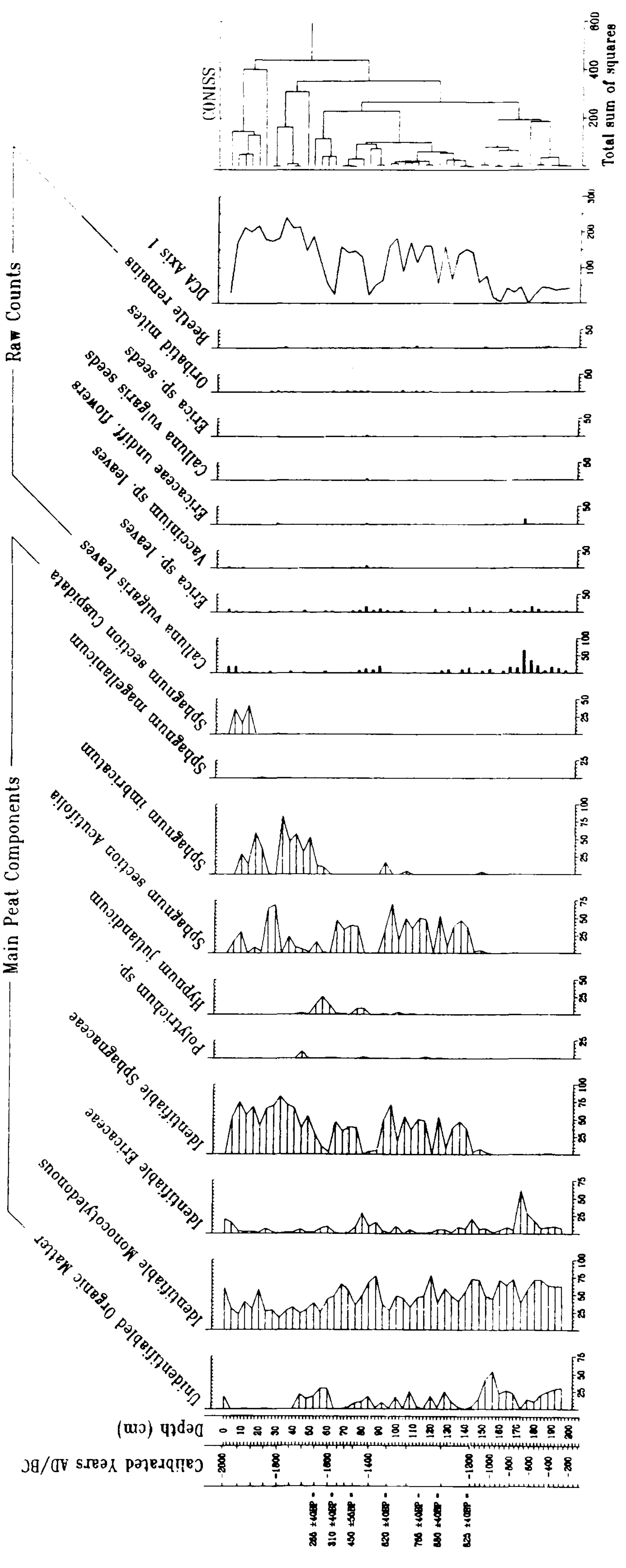


Figure 6.15. May Moss core C3 plant macrofossil diagram. Main peat components are expressed as percentages of the total volume of peat, with *Sphagnum* abundances based on leaf counts of a random selection of branch leaves (>100 per sample). The other curves display raw counts of leaves, seeds, flowers and selected insect remains. The sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

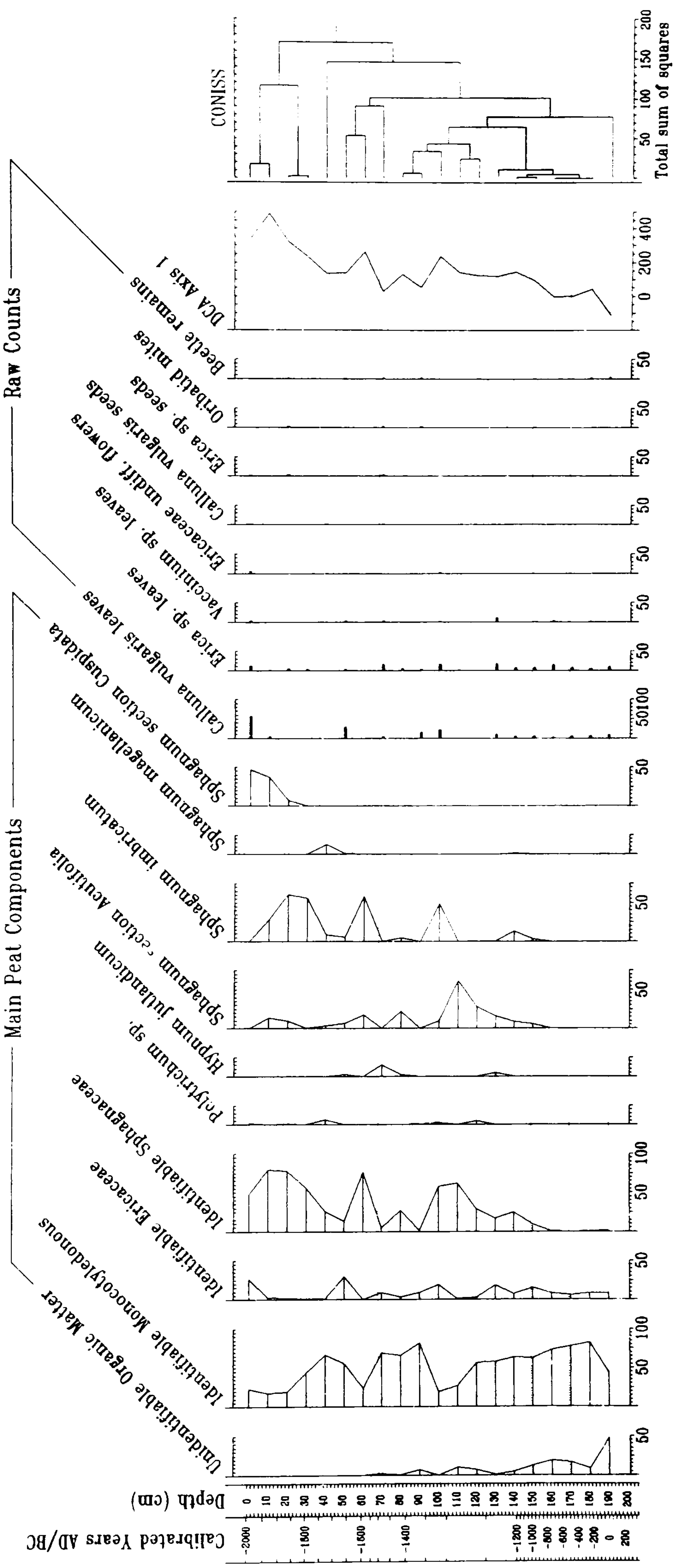
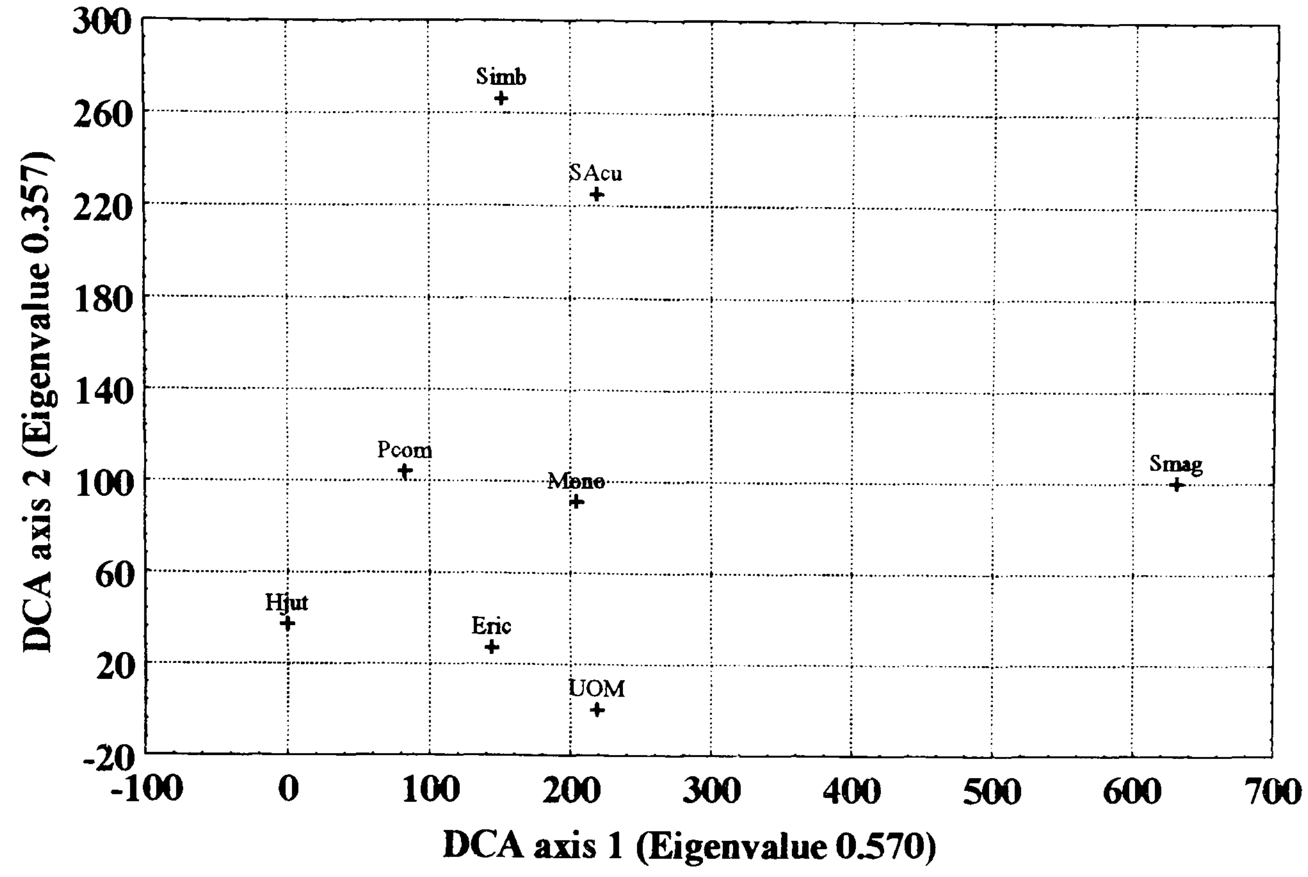


Figure 6.16. May Moss core C4 plant macrofossil diagram. Main peat components are expressed as percentages of the total volume of peat, with *Sphagnum* abundances based on leaf counts of a random selection of branch leaves (>100 per sample). The other curves display raw counts of leaves, seeds, flowers and selected insect remains. The sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

a).

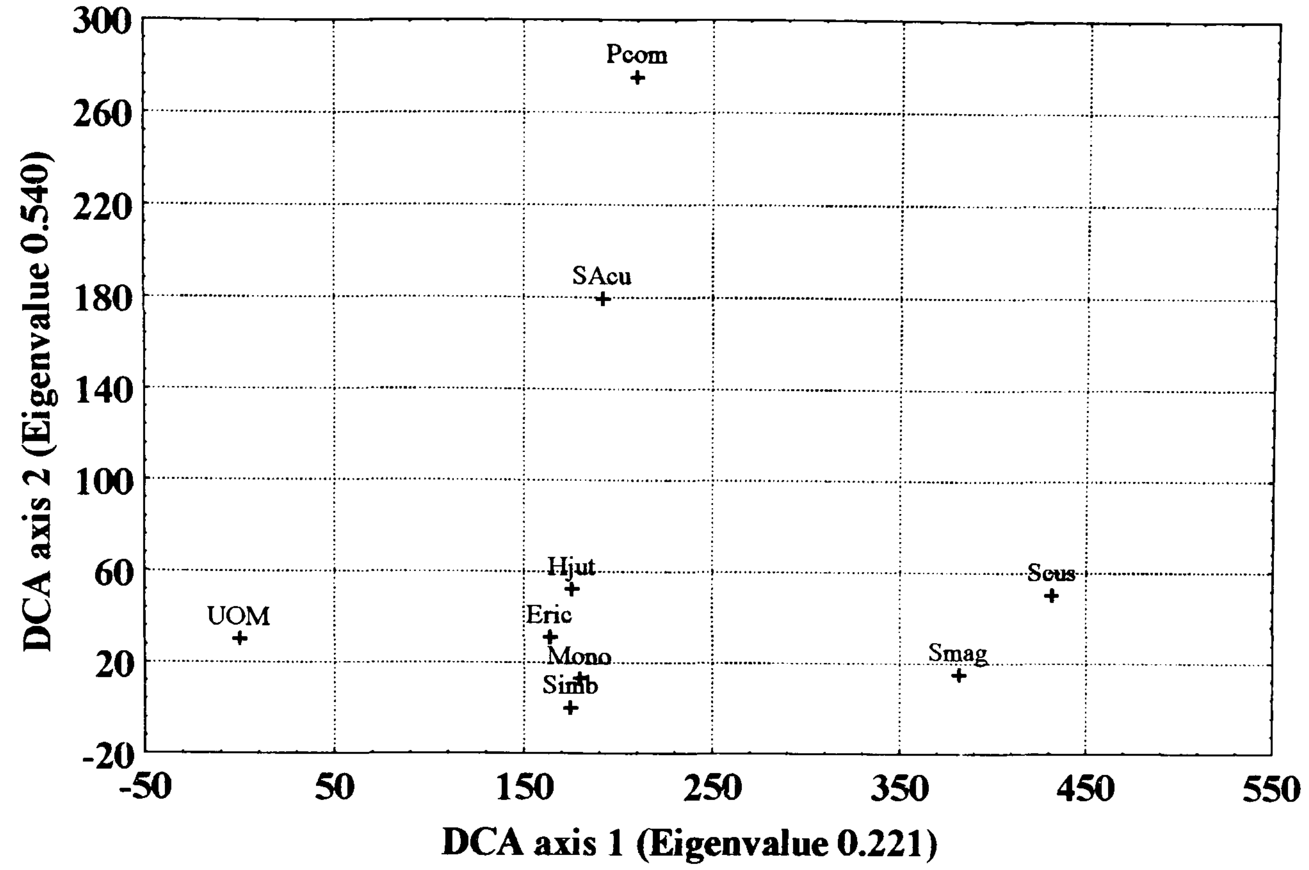


b).

Macrofossil components		DCA axis 1	DCA axis 2
Eigenvalue		0.570	0.357
% variance		29.83	18.68
Unidentified Organic Matter	UOM	0.0436	-0.6619 [c]
Monocotyledons	Mono	-0.0890	-0.1021
Ericaceae	Eric	-0.4367 [a]	-0.5013 [a]
Polytrichum commune	Pcom	-0.3673	0.0180
Hypnum jutlandicum	Hjut	-0.3417	-0.1091
Total identifiable *Sphagnum*	Spha	0.4746 [a]	0.8058 [c]
Sphagnum section *Acutifolia*	Sacu	0.0353	0.6498 [c]
Sphagnum imbricatum	Simb	-0.2238	0.6957 [c]
Sphagnum magellanicum	Smag	0.9432 [c]	0.0044

Figure 6.17. (a) Detrended correspondence analysis ordination diagram showing the component weighted averages on the first two axes for the core C1 plant macrofossil data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the plant macrofossil components. The correlations are not statistically significant unless annotated by either, [a] = significance at the 95% level, [b] = significance at the 99% level or [c] = significance at the 99.9% level.

a).

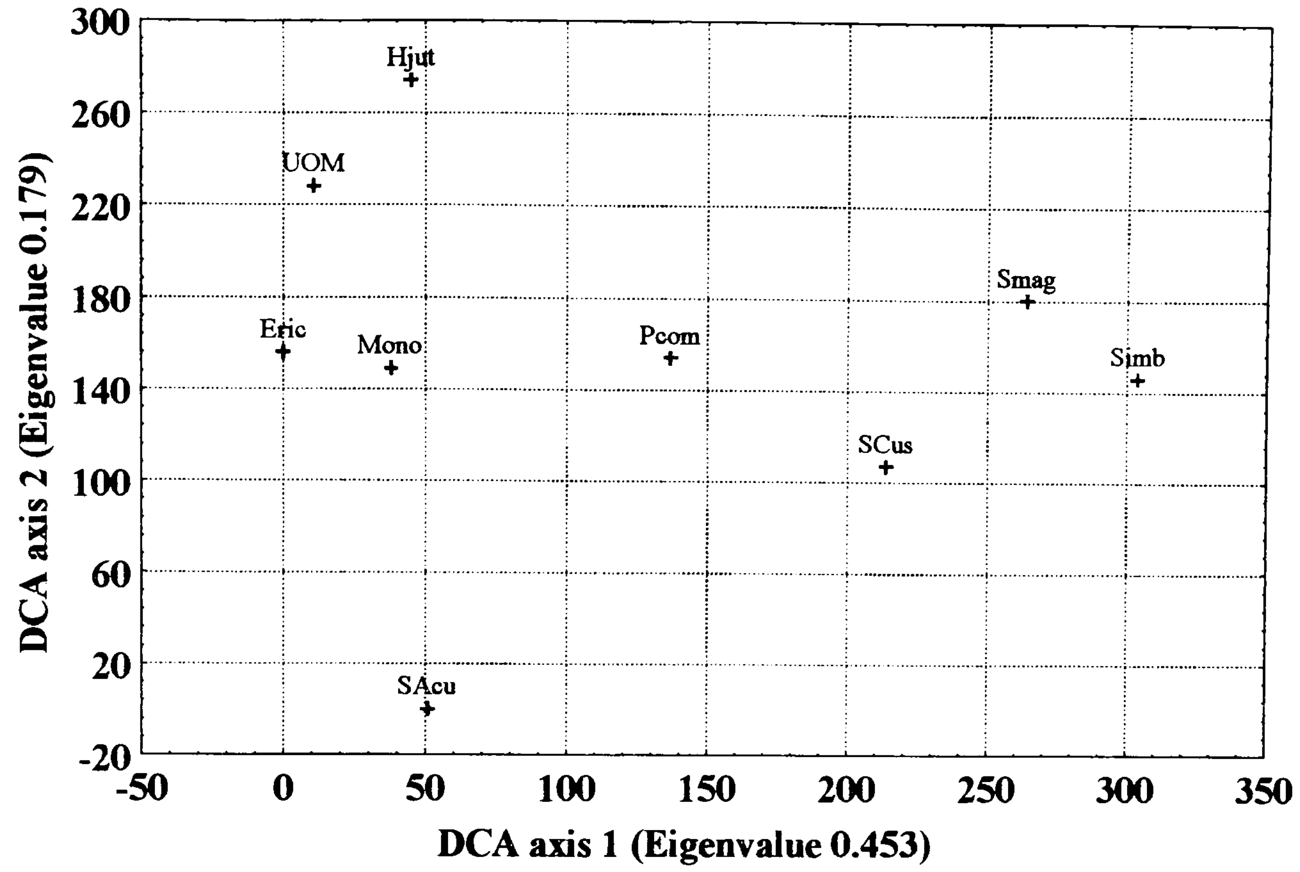


b).

Macrofossil components	Graph labels	DCA axis 1	DCA axis 2
Eigenvalue		0.540	0.221
% variance		35.55	14.53
Unidentified Organic Matter	UOM	-0.7250 [c]	-0.0768
Monocotyledons	Mono	-0.1031	-0.6453 [c]
Ericaceae	Eric	-0.1527	-0.1250
Polytrichum commune	Pcom	0.0392	0.5197 [b]
Hypnum jutlandicum	Hjut	-0.0277	0.0257
Total identifiable *Sphagnum*	Spha	0.7565 [c]	0.6862 [c]
Sphagnum section *Acutifolia*	Sacu	0.0258	0.8759 [c]
Sphagnum imbricatum	Simb	-0.0163	-0.0846
Sphagnum magellanicum	Smag	0.5886 [c]	-0.1198
Sphagnum section *Cuspidata*	Scus	0.8495 [c]	0.0266

Figure 6.18. (a) Detrended correspondence analysis ordination diagram showing the component weighted averages on the first two axes for the core C2 plant macrofossil data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the plant macrofossil components. The correlations are not statistically significant unless annotated by either, [a] = significance at the 95% level, [b] = significance at the 99% level or [c] = significance at the 99.9% level.

a).

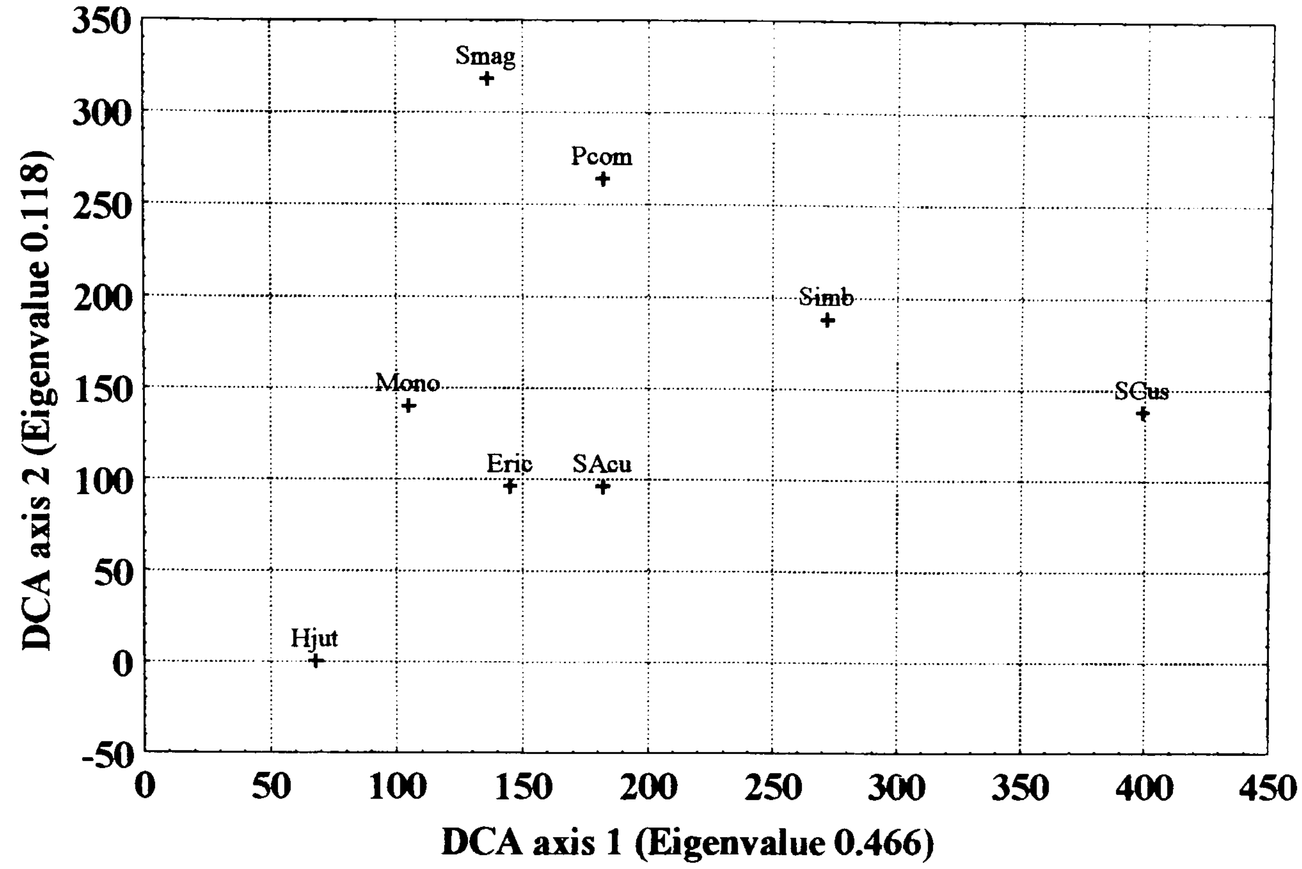


b).

Macrofossil components	Graph labels	DCA axis 1	DCA axis 2
Eigenvalue		0.453	0.179
% variance		29.52	11.67
Unidentified Organic Matter	UOM	-0.3801 [b]	0.7063 [c]
Monocotyledons	Mono	-0.5673 [c]	0.3870 [b]
Ericaceae	Eric	-0.3779 [b]	0.1442
Polytrichum commune	Pcom	0.1346	0.0423
Hypnum jutlandicum	Hjut	-0.0531	0.4136 [b]
Total identifiable *Sphagnum*	Spha	0.6901 [c]	-0.7103 [c]
Sphagnum section *Acutifolia*	Sacu	-0.0907	-0.9084 [c]
Sphagnum imbricatum	Simb	0.9408 [c]	0.0543
Sphagnum magellanicum	Smag	0.2331	0.0563
Sphagnum section *Cuspidata*	Scus	0.2921 [a]	-0.0489

Figure 6.19. (a) Detrended correspondence analysis ordination diagram showing the component weighted averages on the first two axes for the core C3 plant macrofossil data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the plant macrofossil components. The correlations are not statistically significant unless annotated by either, [a] = significance at the 95% level, [b] = significance at the 99% level or [c] = significance at the 99.9% level.

a).



b).

Macrofossil components	Graph labels	DCA axis 1	DCA axis 2
Eigenvalue		0.466	0.118
% variance		31.79	8.06
Unidentified Organic Matter	UOM	-0.6877 [c]	-0.0433
Monocotyledons	Mono	-0.7382 [c]	0.0317
Ericaceae	Eric	-0.0129	-0.4265
Polytrichum commune	Pcom	0.1342	0.6206 [b]
Hypnum jutlandicum	Hjut	-0.2141	-0.4736 [a]
Total identifiable *Sphagnum*	Spha	0.8722 [c]	0.1404
Sphagnum section *Acutifolia*	Sacu	0.1855	-0.2824
Sphagnum imbricatum	Simb	0.6177 [b]	0.3108
Sphagnum magellanicum	Smag	-0.0242	0.5128 [a]
Sphagnum section *Cuspidata*	Scus	0.6753 [c]	-0.0002

Figure 6.20. (a) Detrended correspondence analysis ordination diagram showing the component weighted averages on the first two axes for the core C4 plant macrofossil data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the plant macrofossil components. The correlations are not statistically significant unless annotated by either, [a] = significance at the 95% level, [b] = significance at the 99% level or [c] = significance at the 99.9% level.

The correlation analysis identifies the components involved in the most significant changes in the plant macrofossil stratigraphy.

A common problem with detrended correspondence analysis arises because the procedure is inherently susceptible to dominance by occasionally abundant or outlier species (Kovach, 1995). This is clearly evidenced by the core 1 stratigraphy, where *Sphagnum magellanicum* exceeds 60% of the assemblage for only 30 cm of peat. DCA axis 1 identifies these fluctuations as the most significant structure within the sub-fossil data; however, DCA axis 1 only summarises 30% of the total variation. DCA axis 2 summarises 19% of the overall structure and models an inverse relationship between a dry environment stratigraphy dominated by Unidentified organic matter and Ericaceae, and a wet environment stratigraphy dominated by *Sphagnum* species. Both these DCA axes emphasise stratigraphic changes that cumulatively contribute 50% of the overall structure in the plant macrofossil data, and these changes can be broadly related to fluctuating moisture conditions. Similar problems arise in plant macrofossil stratigraphy of all four cores, with DCA axis 1 primarily summarising the relationships between occasionally abundant components and it is difficult to link the DCA axes with a meaningful ecological gradient. Consequently, the DCA axes are not used as a semi-quantitative palaeohydrological model *sensu* Barber *et al.* (1994a). However, detrended correspondence analysis does identify and emphasise the most significant structure or changes within a dataset, and so DCA axis 1 is displayed stratigraphically in figures 6.13-6.16 to assist with interpretation of the peat stratigraphy.

Palaeoecology

An important feature of the plant macrofossil stratigraphies is that core sites 2 and 3 appear to have consistently sustained wetter communities than core sites 1 and 4. This is emphasised by a *Sphagnum* flora containing *Sphagnum* section *Cuspidata* at cores sites 2 and 3, a group of species that typically occur as submerged or floating vegetation in pools or hollows. Conversely the core 1 and 4 stratigraphy is dominated by the hummock-building Sphagna, namely *Sphagnum* section *Acutifolia* and *Sphagnum imbricatum*. The stratigraphic evidence appears to indicate that the topography currently at site C has been broadly similar since at least *circa* cal. AD 1100.

The most significant changes in the plant macrofossil stratigraphy identified in the cluster and detrended correspondence analyses occurred *circa* cal. AD 500, cal. AD 1100-1200, cal. AD 1400-1450, cal. AD 1600, cal. AD 1700 and around cal. AD 1800. The most significant change in the site C peat stratigraphy involves the expansion of a *Sphagnum* community *circa* cal. AD 1200. Prior to this event the stratigraphy is dominated by Monocotyledon and Ericaceae remains, mixed with substantial quantities of decomposed Unidentified organic matter. There is a comparatively minor expansion of *Sphagnum* in the cores (1 and 4) extracted from beneath present-day hummocks *circa* cal. AD 500, but this expansion is not evident in the core 2 and core 3 peat stratigraphy. The major expansion of *Sphagnum* occurs in all four cores, identifying substantially wetter conditions at site C below a ^{14}C date of 825 ±50BP [cal. AD 1165(1230)1275].

A drier phase between cal. AD 1250-1450 is also evident in all four cores, with the *Sphagnum* communities declining in the hollows and *Sphagnum* section *Acutifolia* surviving on the drier hummocks. This perception of a drier environment is enhanced by the presence of *Hypnum jutlandicum* and *Polytrichum*, which typically occur in the drier parts of blanket mires, with *Hypnum jutlandicum* perhaps covering the mire surface beneath a *Calluna vulgaris* canopy in drier locations. After cal. AD 1400 there is a return to wetter conditions evidenced by a further expansion of *Sphagnum*. This return to wetter conditions is ^{14}C dated to 450 ±55BP [cal. AD 1410(1445)1630]. A short-lived drier phase is evidenced by a decline by *Sphagnum magellanicum* in core 1, and the decline by *Sphagnum* species in general on the other cores *circa* cal. AD 1650. These dry conditions are corroborated by the expansion of Ericaceae and *Hypnum jutlandicum* communities. The chronology for this dry phase is secured by two ^{14}C dates of 310 ±40BP [cal. AD 1475(1640)1665] and 265 ±40BP [cal. AD 1515(1650)1950].

Subsequently, wet communities dominate the peat stratigraphy at site C, with *Sphagnum imbricatum* the dominant hummock-forming Sphagna and *Sphagnum* section *Cuspidata* in the hollows. These environmental conditions persist largely uninterrupted to the present-day, with the exception of a brief undated drier phase *circa* cal. AD 1800, which is evidenced by the expansion of *Sphagnum* section *Acutifolia* at the expense of *Sphagnum* section *Cuspidata*. This fluctuation is short-lived with *Sphagnum* section *Cuspidata* dominating the stratigraphy between *circa* cal. AD 1850 and the present-day. The final feature in the site C stratigraphy involves evidence for a change to drier conditions in the surface layers of peat. *Hypnum jutlandicum* and Ericaceae remains increase in abundance at the expense of the Sphagnaceae, perhaps reflecting a drying trend in the recent history of May Moss. This drying trend of the last 100 years affects both hummock and hollow habitats.

6.2.2.3 Humification data

The humification curves from cores 2 and 3 are displayed stratigraphically in figures 6.21 and 6.22 respectively. Comparison of the two profiles reveals that the stratigraphy is broadly identical, and this corroboration signifies that the profiles provide a representative assessment of the humification stratigraphy. The humification stratigraphy is derived from two hollow peat

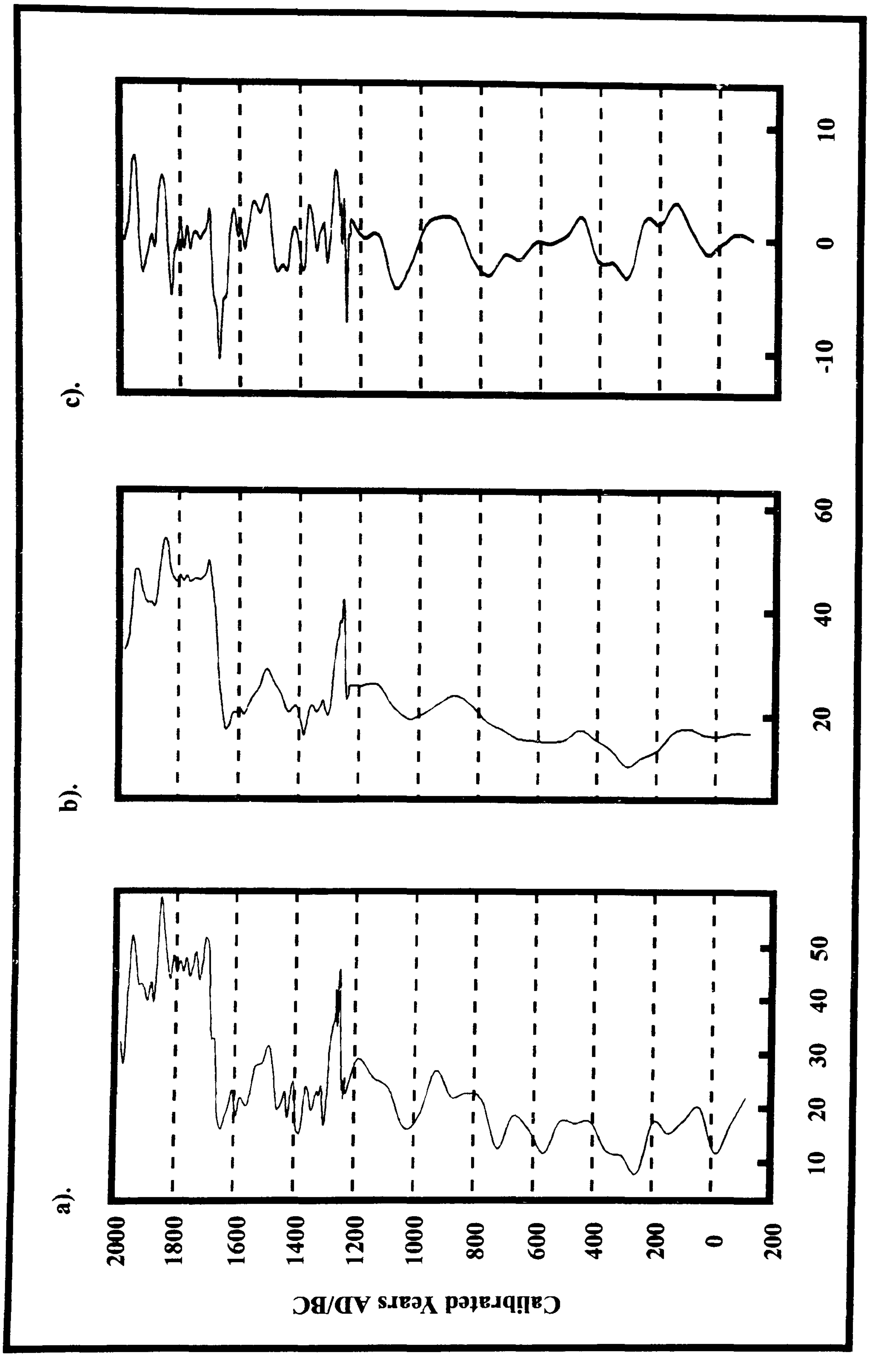


Figure 6.21. Humification data from May Moss core C2 displaying; (a) the raw percentage light transmission values, (b) the raw data smoothed using an unweighted three point moving average, (c) the smoothed data series subjected to a high pass filter emphasising the key shifts. In all three curves higher values denote poorly humified peat and are interpreted as signifying wetter conditions.

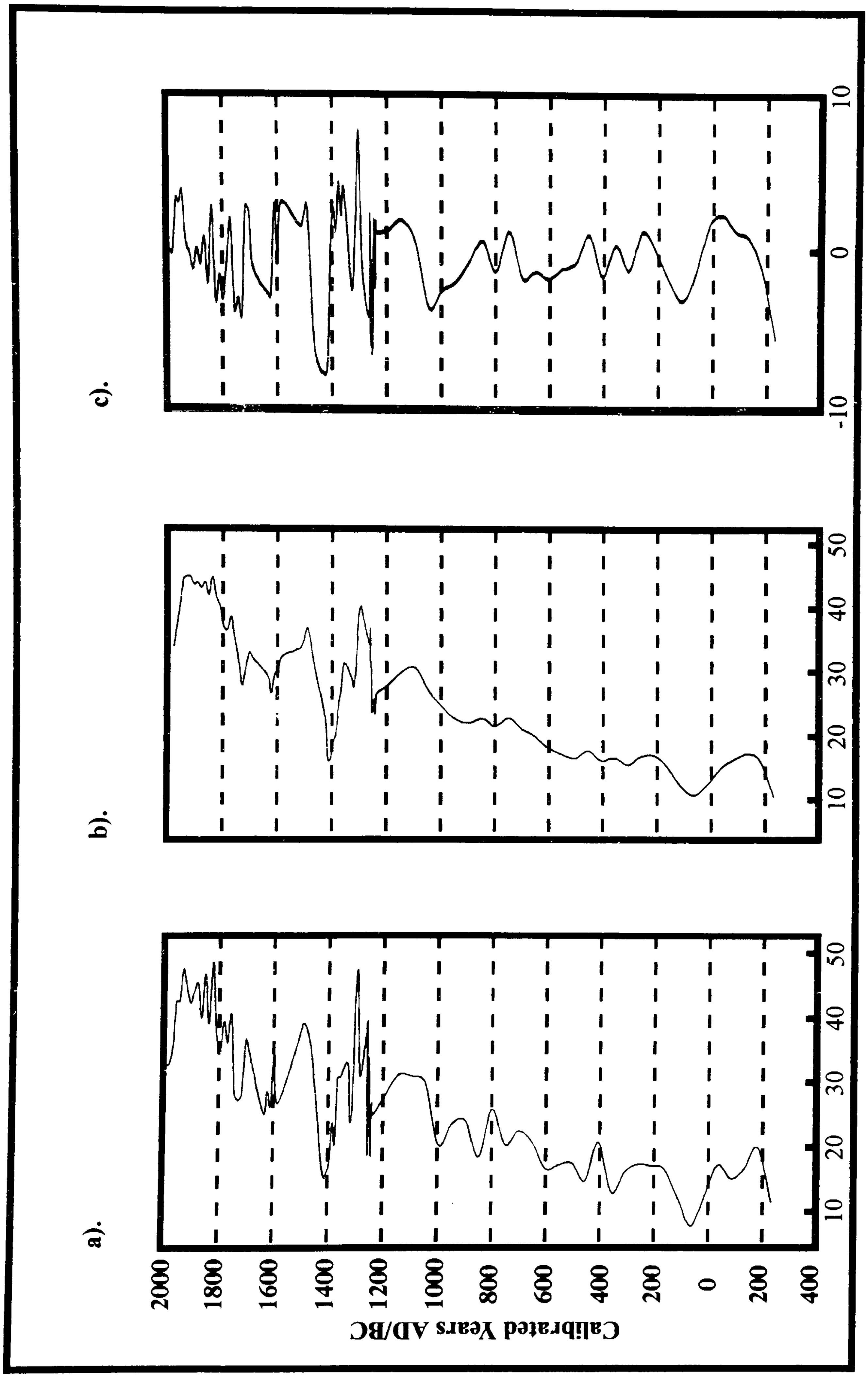


Figure 6.22. Humification data from May Moss core C3 displaying; (a) the raw percentage light transmission values, (b) the raw data smoothed using an unweighted three point moving average, (c) the smoothed data series subjected to a high pass filter emphasising the key shifts. In all three curves higher values denote poorly humified peat and are interpreted as signifying wetter conditions.

sequences, with each profile containing six major changes to poorly humified peat, which occur at similar depths within the peat sequence. The shifts to poorly humified peat are particularly well emphasised in graph (c), the smoothed and low-pass filtered data, and are interpreted as indicating changes to wetter conditions on the mire surface *circa* cal. AD 500, 800, 1100, 1400, 1625 and 1800. Phases of well humified peat signify comparatively drier conditions between cal. AD 200-450, 700-800, 950-1100, 1250-1400, 1550-1600 and 1725-1775.

6.2.2.4 Reconstructing mire surface wetness

The palaeohydrological history at site C draws upon evidence uncovered in all four cores. The chronology for the peat stratigraphy is secured by a series of ^{14}C dates on core 3. Utilising several cores and palaeoenvironmental procedures allows both the consistency of the peat stratigraphy and the comparative performance of each palaeoecological procedure to be assessed. The following synthesis of the palaeohydrology at site C places particularly emphasis on surface moisture changes identified by all the palaeoenvironmental procedures and changes evidenced in more than one core. The evidence for wet shifts and unambiguously dry conditions present in the palaeoenvironmental data is summarised on figure 6.23. Periods containing conflicting palaeohydrological indications are extremely important, because they identify stratigraphy produced under indeterminate moisture conditions and emphasise fallibilities within the palaeoenvironmental procedures.

The testate amoebae and plant macrofossil stratigraphy is very similar in all the site C cores. This broad uniformity of the stratigraphy occurs even though cores 2 and 3 were wetter environments throughout the period of peat accumulation. Consequently, it appears that both hummock and hollow peat sequences are useful for palaeohydrological research. However, it should be noted that a clearer hydrological history was elucidated from the core 3 testate amoebae stratigraphy than from cores 1 and 4, which tends to support a view that the hollow environment is more sensitive to hydrological changes and that hollow stratigraphy provides a clearer record of mire palaeohydrology (Barber, 1981). This opinion is not unanimously-held, Tallis (1994) asserts that hummock stratigraphy can provide a clear record of moisture fluctuations, with wet shifts signifying substantial changes in mire surface wetness. These views are equally valid, with both hollow and hummock stratigraphy capable of yielding meaningful palaeohydrological and palaeoclimate information. The boundary between a hummock and a hollow arguably should provide the clearest record of moisture changes, recording the expansion of dry and wet-indicating stratigraphy in response to climatic fluctuations.

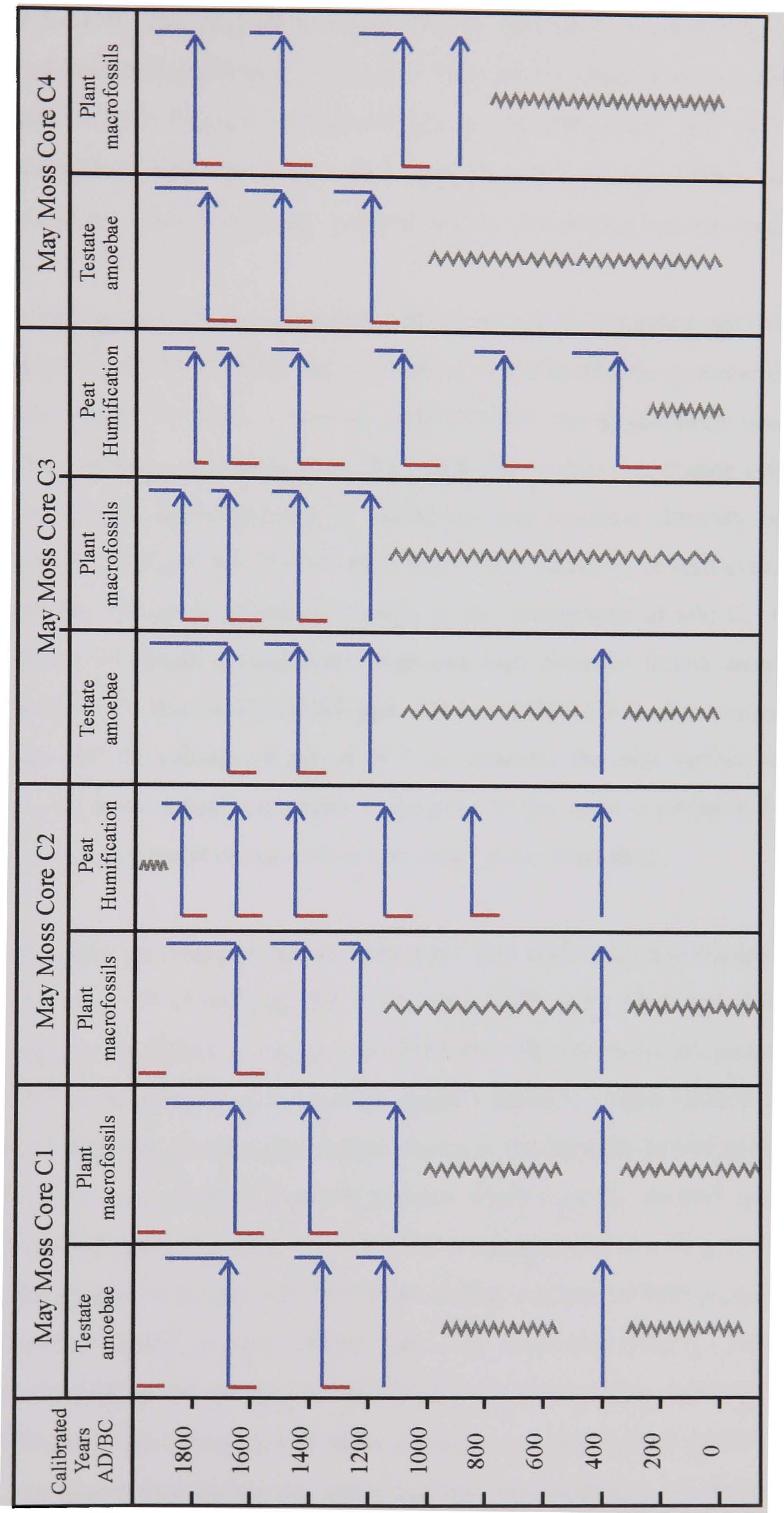


Figure 6.23. Summary of the moisture fluctuations signified in peat stratigraphies at May Moss site C. Red lines denote dry conditions and blue lines wet conditions. The blue arrows signify changes to wetter conditions. Grey zigzag lines denote stratigraphy with an ambiguous hydrological signal.

Figure 6.23 demonstrates that the hydrological indications, yielded by the different procedures are broadly identical. The obvious exception to this involves the stratigraphy pertaining to the period cal. AD 0-1150. The palaeohydrological history derived from the basal 80 cm of peat is interpreted from the humification stratigraphy, because the testate amoebae and plant macrofossil stratigraphy is hydrologically ambiguous. The stratigraphy above 140 cm is better suited for palaeohydrological research with a higher diversity and a greater turnover of plant and testate amoebae species, which importantly includes species with precise moisture requirements.

Notwithstanding the problems identified above there is clear correlation and uniformity within the hydrological signal at May Moss site C. There are significant shifts to wetter conditions, three of which have been ^{14}C dated. *Circa* cal. AD 400-500 the humification stratigraphy provides unequivocal evidence of a change to wetter conditions, with corroborating evidence provided by minor increases in the abundance of *Sphagnum* and increased diversity of testate amoebae communities. *Circa* cal. AD 750-800 there is a further undated wet shift evident in humification stratigraphies. The most significant change in the stratigraphy at site C, which involves the accumulation of *Sphagnum*-dominated peat and high diversity testate amoebae communities, occurs below a ^{14}C date of 825±40BP [cal. AD 1155(1220)1284]. A reconstructed mean annual water table for the subsequent period of 5 cm indicates the mire surface was very wet. The reconstructed mean annual water table curve prior to this point is probably flawed, because the reconstructions are based on one or two taxa which is far from ideal.

The stratigraphy pertaining to the period from cal. AD 1100 to the present-day contains three wet shifts: occurring 450 ±55BP [cal. AD 1407(1441)1627], 265 ±40BP [cal. AD 1521(1651)1954] and a further undated shift *circa* cal. AD 1750-1800. The reconstructed mean annual water table depths of 5-6 cm during these wet periods quantify moisture conditions on the mire. The periods after these shifts are probably the wettest phases in the palaeohydrological history, signified by abundant *Sphagnum* section *Cuspidata* remains, which typically are pool species. Dry events in the stratigraphy at site C prior to cal. AD 1000 are rather equivocal, largely due to the ambiguity of the stratigraphy. After cal. AD 1000 there is clear evidence of drier periods: 680 ±40BP [cal. AD 1264(1294)1396] to 450 ±55BP [cal. AD 1407 (1441)1627], 310 ±40BP [cal. AD 1477(1638)1664] to 265 ±40BP [cal. AD 1521(1651)1954] and an undated drier phase *circa* cal. AD 1700-1800. The reconstructed mean annual water table values signify water table depths only 2 cm deeper than during the wetter periods. The expansion of *Hypnum jutlandicum* and *Calluna vulgaris* during these three phases also signifies a comparatively dry environment.

The final event in the hydrological history occurs in the surface layers of peat, where the testate amoebae and plant macrofossil stratigraphy signify a change to substantially drier conditions. The decline in diversity of testate amoebae communities and higher frequencies of Ericaceae remains and *Hypnum jutlandicum* provide clear evidence of drying of the mire surface in recent years. This drying trend is more severely manifested in hummock stratigraphy than the hollows, which still sustain *Sphagnum* communities.

6.2.3 May Moss Site D

Palaeohydrological research at site D is based on the analysis of two cores, D1 and D2. Additionally three parallel cores were extruded, from within a 1.5×1.5 metre area during the sampling of the D1 core, to assess the consistency of the stratigraphy. Both the D1 and D2 cores were analysed to assess consistency of the palaeohydrological signal at site D. D1 was extracted with a 5×50 cm Russian corer and D2 with a 10×30 cm Russian corer. A summary of the field stratigraphy is presented in table 6.3.

Table 6.3. Field stratigraphy at May Moss site D.

Mire surface 0 - 12 cm	*Sphagnum recurvum* in the hollows, with *Sphagnum papillosum* and *Eriophorum vaginatum*. *Calluna vulgaris* and *Sphagnum capillifolium* covers the hummocks.
12 - 28 cm	5YR 4/4. Poorly humified *Sphagnum* and Monocotyledonous peat.
28 - 34 cm	5YR 3/4. Monocotyledonous peat.
34 - 70 cm	5YR 4/4. *Sphagnum* and Monocotyledonous peat.
70 - 85 cm	5YR 3/3. Monocotyledonous and Ericaceae peat.
85 - 110 cm	5YR 4/4. *Sphagnum* and Monocotyledonous peat.
110 - 130 cm	5YR 3/4. Monocotyledonous peat.
130 - 150 cm	5YR 3/4. *Sphagnum* and Monocotyledonous peat.
150 - 175 cm	5YR 4/4. Poorly humified *Sphagnum* peat.
175 - 275 cm	5YR 3/3. Well humified Monocotyledonous/Ericaceae peat.

The D1 peat profile received both plant macro-fossil and humification analysis. The D2 profile received testate amoebae, plant macro-fossil and humification analysis. Further analysis involved the construction of the D1 pollen profile presented in chapter 5.

6.2.3.1 Testate amoebae data

Quantitative analysis

The testate amoebae stratigraphy is presented in figure 6.24. The species scores on the first two axes of a detrended correspondence analysis of the sub-fossil data are displayed as a X/Y biplot in figure 6.25. The eigenvalues for the first two DCA axes are 0.505 and 0.051 respectively, which signify that they summarise the most significant structure within the dataset. The amount of variation individually explained by further DCA axes is minimal. Correlation coefficients between the actual abundance of testate amoebae taxa and the first two axes of the DCA are listed on figure 6.25. The correlation coefficients identify the testate amoebae species involved in the most significant changes in the sub-fossil stratigraphy.

The most abundant testate amoebae species appear to be arranged along DCA axis 1 according to their tolerance of habitat moisture conditions. Dry indicator taxa such as *Hyalosphenia subflava* occur at the opposite end of axis 1 to the wet indicators *Amphitrema flavum*, *Amphitrema wrightianum* and *Assulina* spp. (Tolonen *et al.*, 1992; 1994; Woodland *et al.*, 1998). The correlation coefficients support this conclusion with axis 1 summarising sub-fossil variations between a "wet environment" assemblage and a "dry environment" assemblage. The wet indicators, *Amphitrema flavum*, *Amphitrema wrightianum* and *Assulina* spp., are negatively correlated with axis 1, whereas the dry indicator *Hyalosphenia subflava* is positively correlated. Further individual DCA axes only explain minor amounts of variation, with DCA axis 1 accounting for 38.59% of the total structure. DCA axis 1 appears to identify a moisture gradient, and this appears to be the most important environmental factor affecting the sub-fossil testate amoebae. DCA axis 1 is proposed as a model summarising fluctuations between wet and dry conditions on the mire surface. The sample scores on DCA axis 1 are plotted stratigraphically on figure 6.24, with high values denoting drier conditions and lower values wetter conditions. The DCA palaeohydrological curve is only proposed as a semi-quantitative model of mire surface wetness.

The optimum, maximum and minimum reconstructed mean annual water table depths tolerated by extant species were used to generate three palaeohydrological curves, which identify the potential range of moisture conditions at site D. The curves are displayed stratigraphically on figure 6.24. The fluctuations in reconstructed mean annual water table depth signify a very changeable hydrological history. Figure 6.24 displays a broad agreement between DCA axis 1 and the depth to water table reconstruction. The significance of this agreement was tested using Spearman Rank correlation analysis for non-parametric data ($P \geq 0.0001$; correlation is significant at the 99.99% level), which indicates there is a strong agreement between the two signals. Assuming the

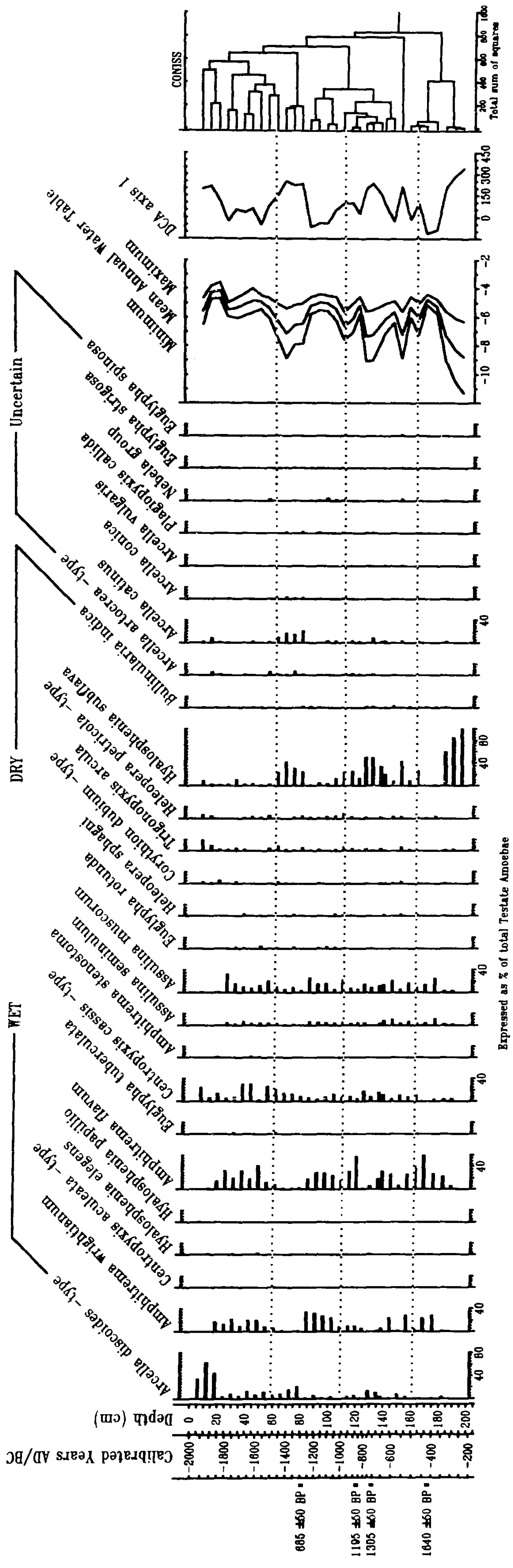
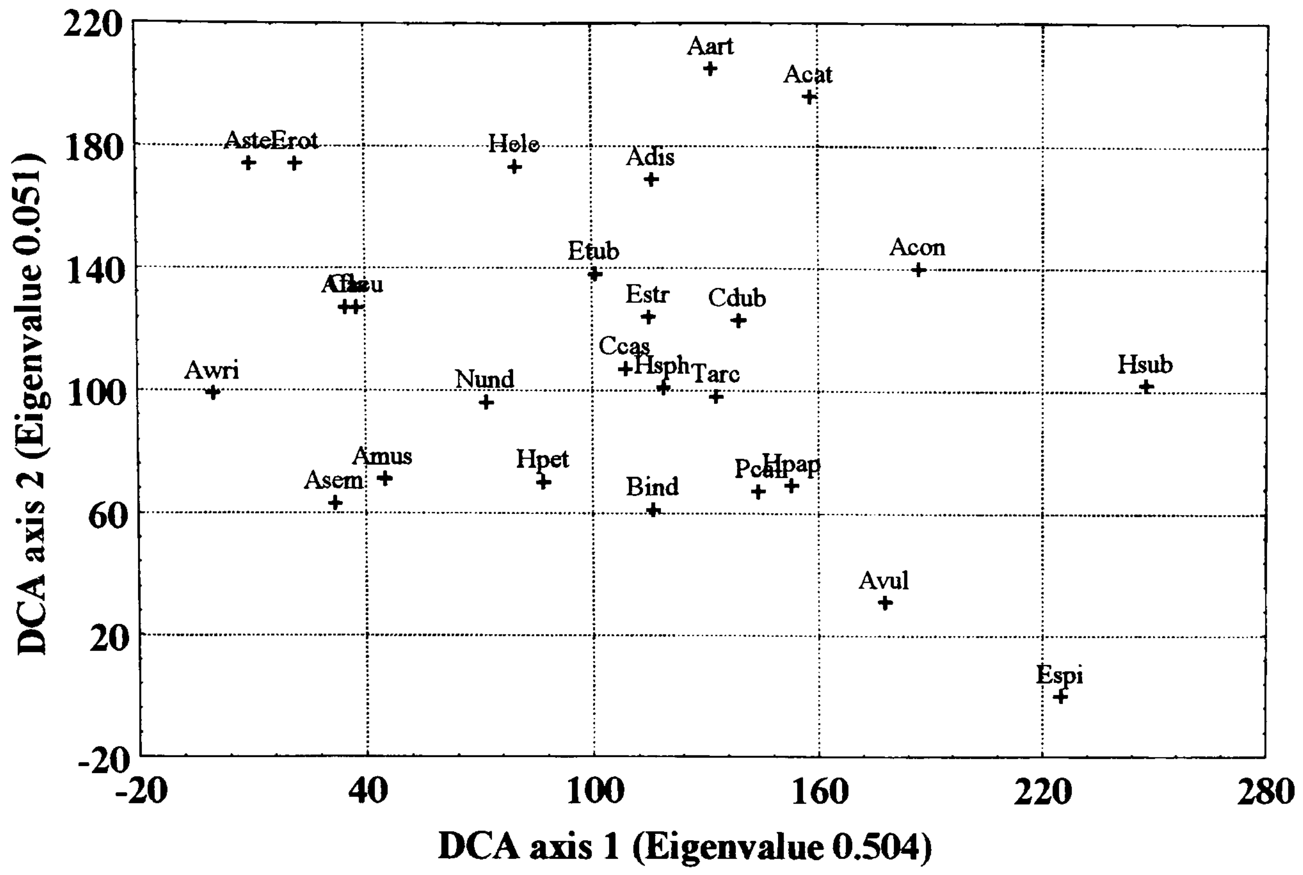


Figure 6.24. May Moss core D2 testate amoebae diagram. The species curves are arranged from left to right according to preference of habitat moisture conditions. On the far right the reconstructed mean annual water table depths are presented, including upper and lower limits based on the ranges tolerated by individual species; the sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

a).



b).

Testate Amoebae species	Graph label	DCA axis 1	DCA axis 2
Eigenvalue		0.504	0.051
% variance		38.59	3.94
Arcella discoides	Adis	-0.0078	0.5035 [c]
Arcella artocrea	Aarc	0.0589	0.4650 [c]
Arcella catinus	Acat	0.1714	0.4328 [c]
Arcella conica	Acon	0.1665	0.0811
Arcella vulgaris	Avul	0.1096	-0.1786
Centropyxis cassis -type	Ccas	-0.0818	-0.0652
Centropyxis aculeata -type	Cacu	-0.1761	0.0389
Plagiopyxis callida	Pcal	0.1082	-0.2174
Bullinularia indica	Bind	-0.0043	-0.3969 [a]
Trigonopyxis arcula	Tarc	0.0897	-0.0947
Hyalosphenia subflava	Hsub	0.8908 [a]	-0.0894
Hyalosphenia papilio	Hpap	0.0458	-0.0682
Hyalosphenia elegans	Hele	-0.1965	0.3801 [a]
Heleopera sphagni	Hsph	0.0130	-0.0925
Heleopera petricola	Hpet	-0.1951	-0.3244
Nebela undiff.	Nund	-0.1845	-0.0823
Amphitrema flavum	Afla	-0.7296 [c]	0.1602
Amphitrema wrightianum	Awri	-0.8627 [c]	-0.1167
Amphitrema stenostoma	Aste	-0.3013	0.2122
Euglypha strigosa	Estr	-0.0099	0.0654
Euglypha tuberculata	Etub	-0.0309	0.0575
Euglypha spinosa	Espi	0.1389	-0.1762
Euglypha rotunda	Erot	-0.3494 [a]	0.2738
Assulina muscorum	Amus	-0.6924 [c]	-0.4782 [c]
Assulina seminulum	Asem	-0.6944 [c]	-0.4867 [c]
Corythion dubium -type	Cdub	0.0975	0.0607

Figure 6.25. (a) Detrended correspondence analysis ordination diagram showing the species weighted averages on the first two axes for the core D2 testate amoebae data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the testate amoebae species. The correlations are not statistically significant unless annotated by either, [a] = significance at the 95% level, [b] = significance at the 99% level or [c] = significance at the 99.9% level.

reconstructed mean annual water table depths are accurate this provides further evidence that DCA axis 1 represents a moisture gradient and that the major control on testate amoebae communities is mire surface wetness.

Palaeoecology

Of the twenty-six species encountered in the peat profile, only nine occur in any great number: *Arcella discoides, Amphitrema flavum, Amphitrema wrightianum, Assulina muscorum, Assulina seminulum, Hyalosphenia subflava, Trigonopyxis arcula, Heleopera petricola* and *Centropyxis cassis*-type. The sub-fossil record is characterised by fluctuations between two groups of species. The first group is dominated by *Hyalosphenia subflava* and occasional *Trigonopyxis arcula,* which typically are associated with dry environments (Woodland, 1996). The second contains *Amphitrema flavum, Amphitrema wrightianum, Assulina muscorum* and *Assulina seminulum,* and these taxa are typically associated with wetter environments (Woodland *et al.*, 1998). The sub-fossil testate amoebae community has been dominated by these two groups throughout the last 2000 years. The most significant changes in the testate amoebae stratigraphy identified by the cluster and detrended correspondence analyses occurred *circa* cal. AD 400, 600, 1000, 1300, 1450 and 1900.

From cal. AD 0 to 400 testate amoebae are very sparse, and the number of tests counted occasionally fails to achieve a minimum of 100 tests. The diversity of species within these layers is also low, dominated by *Hyalosphenia subflava,* with occasional *Assulina muscorum, Amphitrema flavum* and *Centropyxis cassis*-type. Perhaps the most significant change in the sub-fossil fauna occurs *circa* cal. AD 400 and is an event synchronous with the initiation of *Sphagnum*-dominated stratigraphy at site D. Prior to this change the stratigraphy consisted of well humified peat dominated by monocotyledonous and Ericaceae remains. Testate amoebae become more abundant, and as the diversity of the assemblages increases *Hyalosphenia subflava* declines sharply and is replaced by *Amphitrema flavum, Amphitrema wrightianum, Assulina muscorum* and *Assulina seminulum.* This species association is joined by *Centropyxis cassis*-type, *Arcella discoides* and *Heleopera* spp. *circa* cal. AD 600. This assemblage of species is typically associated with a wet environment.

Circa 700 cal. AD *Amphitrema flavum, Amphitrema wrightianum* and *Assulina seminulum* decline, and *Hyalosphenia subflava* increases in abundance to dominate the sub-fossil community. *Centropyxis cassis*-type, *Trigonopyxis arcula, Bullinularia indica, Arcella catinus* and *Assulina muscorum* are also relatively abundant. *Hyalosphenia subflava* dominates the stratigraphy between cal. AD 700-900, which signifies comparatively dry conditions. Between cal. AD 1000-1250 *Hyalosphenia subflava* declines gradually, and *Amphitrema flavum*, *Amphitrema wrightianum*, *Assulina muscorum*, *Assulina seminulum* and *Centropyxis cassis*-type dominate the peat stratigraphy, reflecting a return to wetter conditions.

Between cal. AD 1300-1450 the previously diverse testate amoebae community is replaced by an association of *Hyalosphenia subflava* and *Arcella catinus*, with occasional tests of *Trigonopyxis arcula*, *Bullinularia indica*, *Assulina muscorum* and *Heleopera sphagni*. This assemblage is indicative of comparatively dry conditions. However, after cal. AD 1450 the *Hyalosphenia subflava* dominated community declines and is replaced by an association of *Amphitrema flavum*, *Amphitrema wrightianum*, *Assulina muscorum*, *Assulina seminulum* and *Arcella discoides*, which dominate the peat stratigraphy between cal. AD 1450-1900 and signify wet conditions. During the last 100 years *Amphitrema flavum*, *Amphitrema wrightianum*, *Assulina muscorum* and *Assulina seminulum* disappear from the fossil record. *Hyalosphenia subflava*, *Arcella catinus* and *Trigonopyxis arcula* increase in abundance and dominate the surface layers of peat signifying a drying trend in the recent hydrological history.

6.2.3.2 Plant macro-fossil data

Palaeoecology

The plant macro-fossil stratigraphy from D1 is displayed in figure 6.26 and D2 is displayed in figure 6.27. The scores of the main macrofossil components on the first two axes of a detrended correspondence analysis performed on the sub-fossil data of both cores are displayed as X/Y biplots in figure 6.28 and 6.29. The eigenvalues for the first two DCA axes generated for each core are also listed on figure 6.28 and 6.29, and signify that the axes summarise the most significant structure within both data-sets. The amount of variation explained by further individual DCA axes is minimal. Correlation coefficients between the main components of the plant macrofossil stratigraphy and the first two DCA axes generated for each core are also listed on figures 6.28 and 6.29. The correlation coefficients identify the components involved in the most significant changes in the macrofossil stratigraphy.

The main components of the plant macrofossil stratigraphy in D1 appear to be arranged along DCA axis 1 according to their tolerance of moisture conditions. Dry indicator components such as the Ericaceae and Unidentified Organic Matter occur at the opposite end of axis 1 to the wet indicators, the Sphagnaceae (Daniels & Eddy, 1990; Barber, 1981). The correlation coefficients support this conclusion with DCA axis 1 summarising variations between a "wet environment" stratigraphy and a "dry environment" stratigraphy. The wet indicators are the Sphagnaceae,

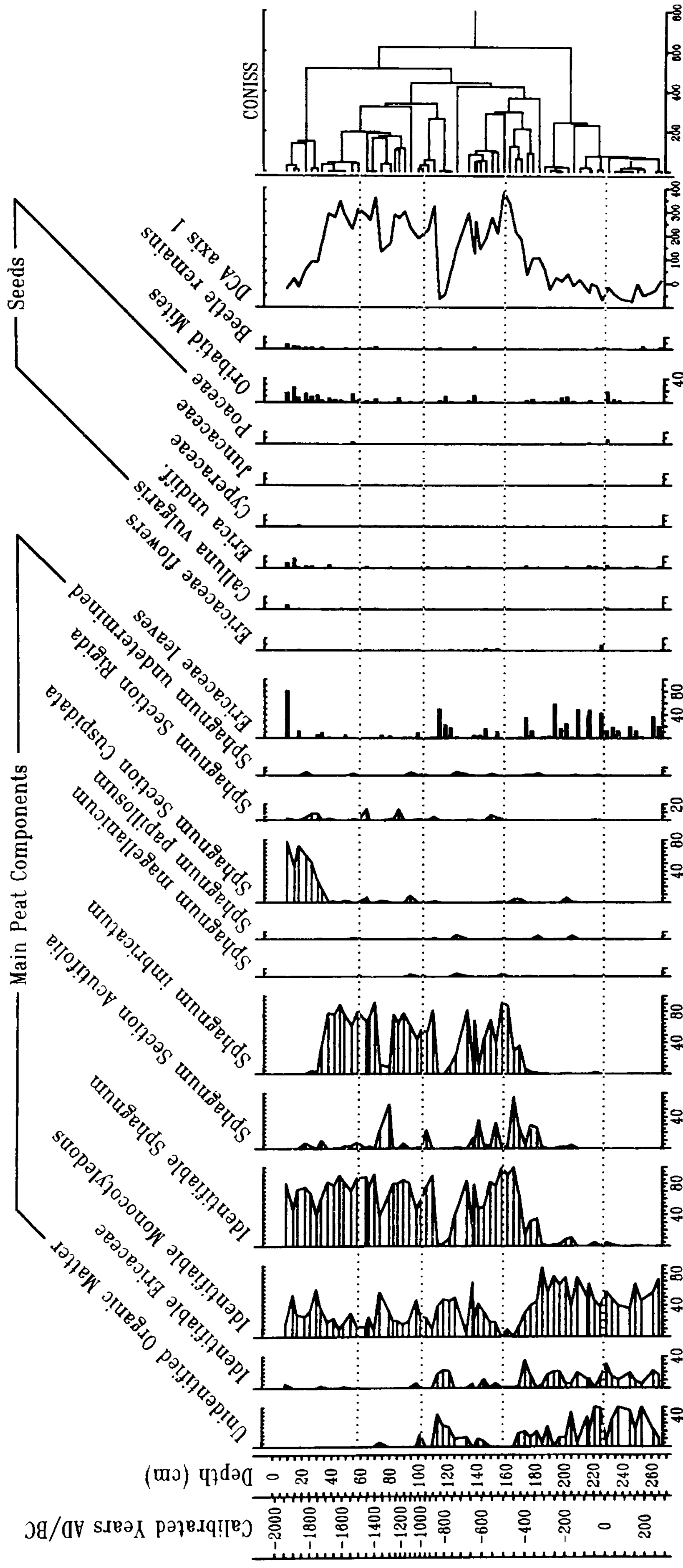


Figure 6.26. May Moss core D1 plant macrofossil diagram. Main peat components are expressed as percentages of the total volume of peat, with *Sphagnum* abundances based on leaf counts of a random selection of branch leaves (>100 per sample). The other curves display raw counts of leaves, seeds, flowers and selected insect remains. The sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

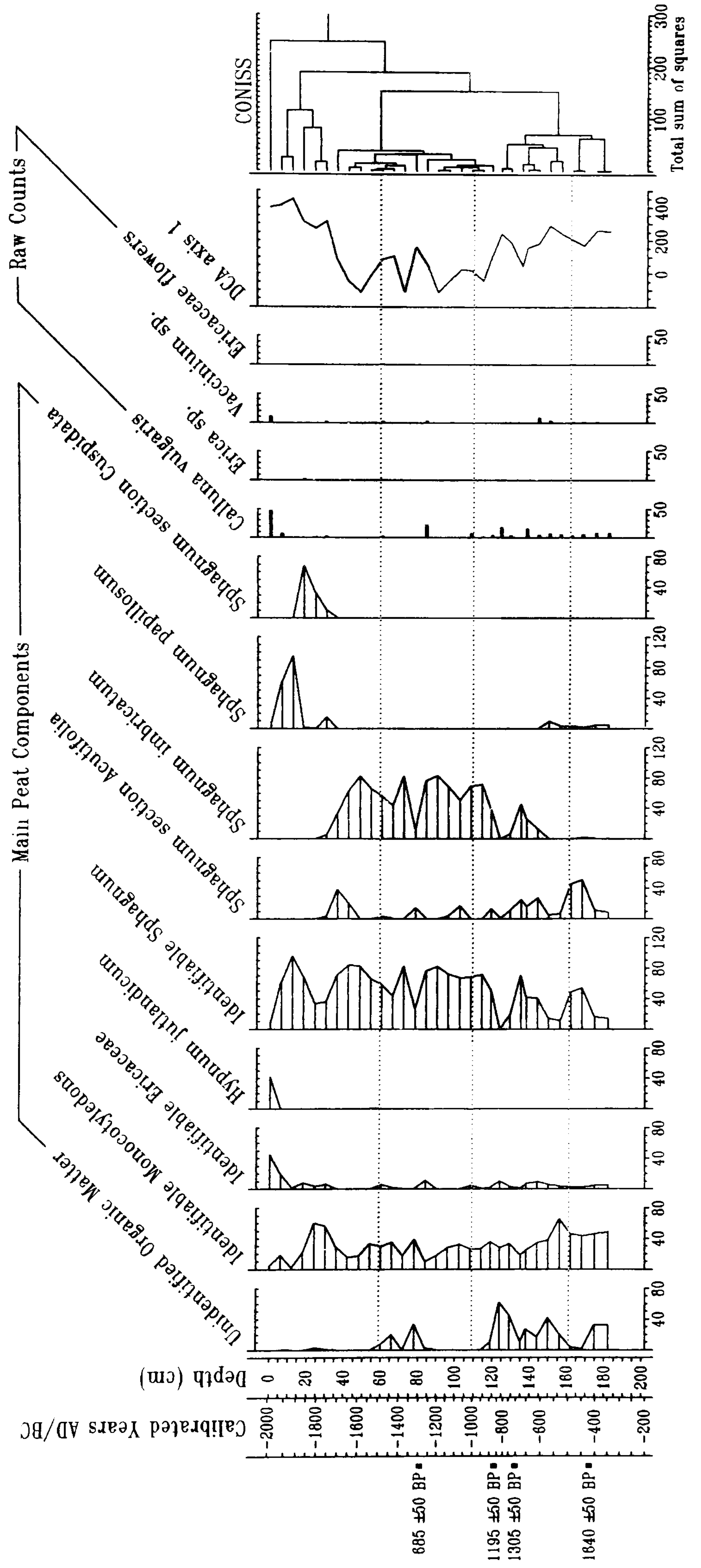
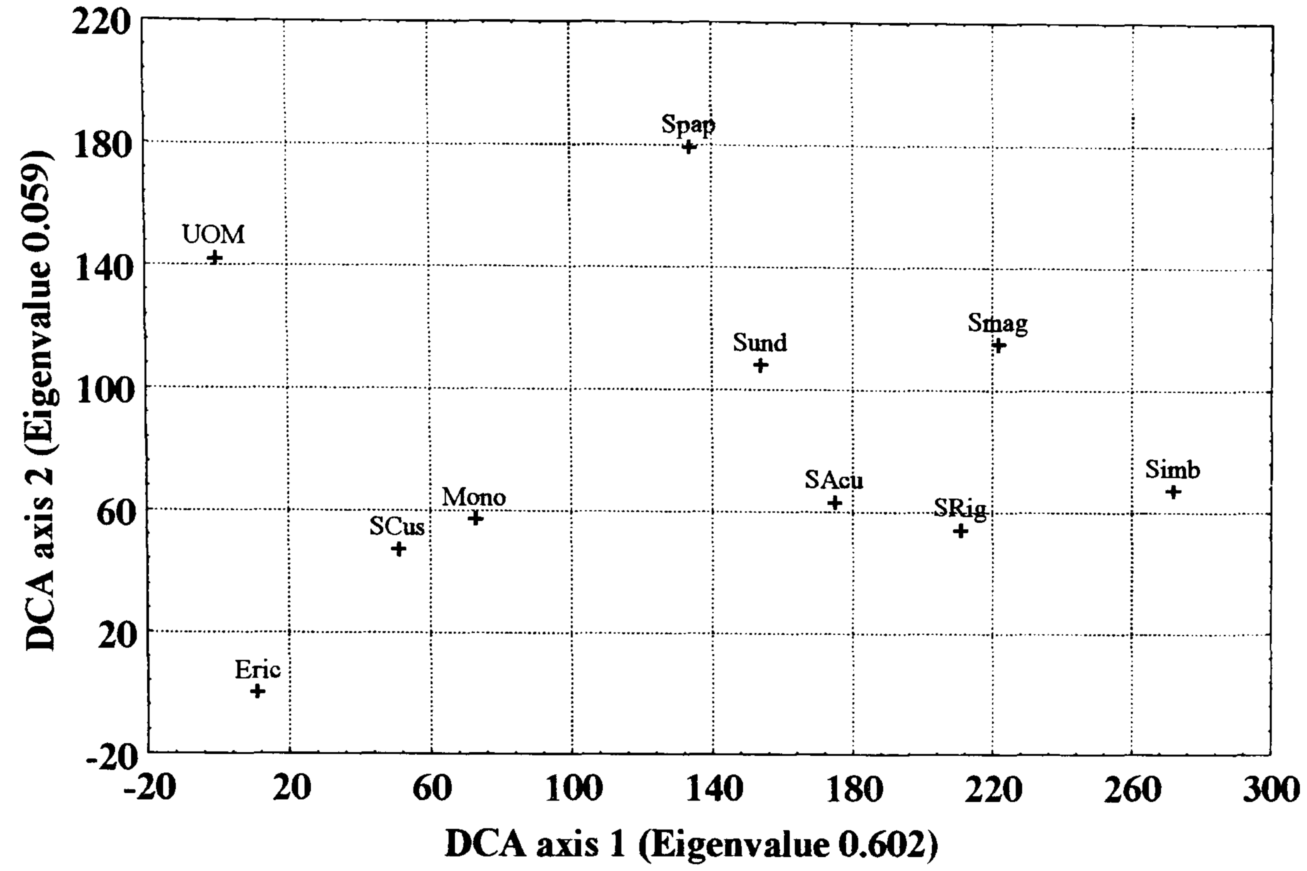


Figure 6.27. May Moss core D2 plant macrofossil diagram. Main peat components are expressed as percentages of the total volume of peat, with *Sphagnum* abundances based on leaf counts of a random selection of branch leaves (>100 per sample). The other curves display raw counts of leaves, seeds, flowers and selected insect remains. The sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

a).

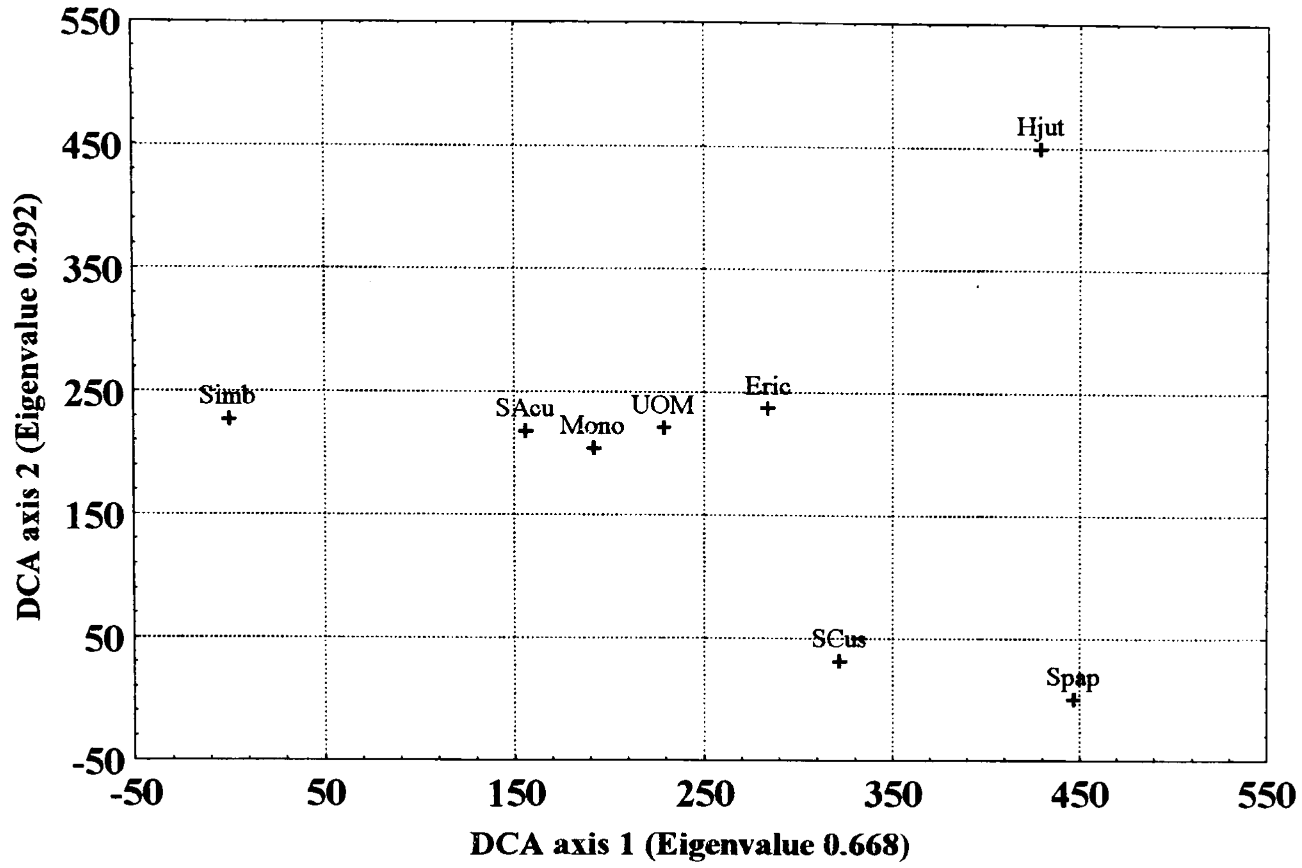


b).

Macrofossil components	Graph labels	DCA axis 1	DCA axis 2
Eigenvalue		0.602	0.059
% variance		34.39	3.36
Unidentified Organic Matter	UOM	-0.6937 [c]	0.5552 [c]
Monocotyledons	Mono	-0.6957 [c]	-0.1616
Ericaceae	Eric	-0.6363 [c]	-0.4889 [c]
Total identifiable *Sphagnum*	Spha	0.8762 [c]	-0.0299
Sphagnum section *Acutifolia*	Sacu	0.1719	-0.0176
Sphagnum imbricatum	Simb	0.9430 [c]	0.0045
Sphagnum magellanicum	Smag	0.1755	0.1252
Sphagnum papillosum	Spap	0.0135	0.3524 [c]
Sphagnum section *Rigida*	Srig	0.2544 [a]	-0.0513
Sphagnum section *Cuspidata*	Scus	-0.2084	-0.0720

Figure 6.28 (a) Detrended correspondence analysis ordination diagram showing the component weighted averages on the first two axes for the core D1 plant macrofossil data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the plant macrofossil components. The correlations are not statistically significant unless annotated by either, [a] = significance at the 95% level, [b] = significance at the 99% level or [c] = significance at the 99.9% level.

a).



b).

Macrofossil components	Graph labels	DCA axis 1	DCA axis 2
Eigenvalue		0.668	0.292
% variance		27.38	11.98
Unidentified Organic Matter	UOM	0.2974	0.1625
Monocotyledons	Mono	0.2873	0.0519
Ericaceae	Eric	0.5543 [c]	0.3018
Hypnum jutlandicum	Hjut	0.2755	0.4619 [c]
Total identifiable *Sphagnum*	Spha	-0.5518 [c]	-0.3099
Sphagnum section *Acutifolia*	Sacu	-0.0539	0.1144
Sphagnum imbricatum	Simb	-0.9207 [c]	0.2428
Sphagnum papillosum	Spap	0.5383 [c]	-0.6893 [c]
Sphagnum section *Cuspidata*	Scus	0.2369	-0.4694 [c]

Figure 6.29 (a) Detrended correspondence analysis ordination diagram showing the component weighted averages on the first two axes for the core D2 plant macrofossil data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the plant macrofossil components. The correlations are not statistically significant unless annotated by either, [a] = significance at the 95% level, [b] = significance at the 99% level or [c] = significance at the 99.9% level.

which display a strong positive correlation with DCA axis 1, whereas the dry indicators, Unidentified Organic Matter, Ericaceae and Monocotyledonous, display a strong negative correlation.

DCA axis 1 accounts for 34.29% of the total structure; consequently, further DCA axes individually explain less significant amounts of variation within the plant macrofossil stratigraphy. DCA axis 1 appears to identify a moisture gradient, which appears to be the most important environmental factor affecting the D1 stratigraphy. DCA axis 1 is proposed as a model summarising fluctuations between wet and dry conditions on the mire surface. In order to use the DCA axes as semi-quantitative moisture curves, the peat stratigraphy should ideally contain an interchange of species with specific environmental preferences. In the case of the site D1 plant macrofossil stratigraphy this does occur, and so the DCA axis 1 curve is a useful tool assisting with the interpretation of the palaeohydrological history. The sample scores on DCA axis 1 are plotted stratigraphically on figure 6.26.

The results of the detrended correspondence analysis of the D2 data are more complicated. The correlation coefficients identify that Ericaceae remains are positively correlated with DCA axis 1, whereas *Sphagnum imbricatum* is negatively correlated. The ecological relationship between these components is strongly affected by moisture conditions, with *Sphagnum imbricatum* indicative of wetter conditions. However, in this case the detrended correspondence analysis appears to be affected by components that are abundant in isolated layers; for example, *Sphagnum papillosum* is a significant component of the structure represented on DCA axis 1, but is only present in the top 20 cm of peat stratigraphy. The behaviour of three further outliers, *Hypnum jutlandicum*, *Sphagnum* section *Cuspidata* and *Sphagnum papillosum*, is represented on DCA axis 2 and is a significant component of the overall structure within the sub-fossil data.

In theory the DCA axis 1 generated for D2 models variations between a "wet environment" stratigraphy and a "dry environment" stratigraphy. However, the occasionally frequent components are a significant part of the structure identified by the DCA, which, combined with the fact that DCA axis 1 only summarises 27.38% of the overall structure, questions the validity of using DCA axis 1 as a hydrological model for the D2 data. Nevertheless detrended correspondence analysis does identify and emphasise the most significant structure or changes within a dataset; consequently the sample scores on DCA axis 1 are displayed stratigraphically on figure 6.27 to assist with interpretation of the peat stratigraphy.

Palaeoecology

Ecologically the *Sphagnum* taxa identified in the fossil record are associated with substantially different environmental micro-habitats. *Sphagnum* section *Cuspidata* contains pool species, *Sphagnum imbricatum* and *Sphagnum papillosum* typically form low dense hummocks or ridges, and *Sphagnum* section *Acutifolia* are typically hummock-top species. The D2 profile consistently contains taxa that typically would inhabit a position located further above the water table than D1. This evidence suggests that D2 has been a topographically higher palaeohabitat than D1 throughout the period of peat accumulation, which is in keeping with the current state of affairs at site D. The current flora at D1 is dominated by the pool species *Sphagnum recurvum* (*Sphagnum* section *Cuspidata*), and D2 is dominated by *Sphagnum papillosum*, *Hypnum jutlandicum* and Ericaceae, which are hummock-forming species, typically elevated above the water table. However, despite slight differences in the palaeohabitat yielding the cores, the plant macrofossil analysis has revealed a virtually identical sequence of stratigraphic changes.

The most significant changes in the plant macrofossil stratigraphy identified by the cluster and detrended correspondence analyses occurred *circa* cal. AD 400, 700-750, 900, 1250, 1400 and 1750. Between 300 cal. BC - cal. AD 350 the peat stratigraphy contains substantial quantities of Unidentified Organic Matter, and is dominated by Ericaceae and Monocotyledonous remains. Additionally the raw counts Ericaceae leaves are very high, identifying comparatively dry conditions. After cal. AD 400, *Sphagnum* section *Acutifolia* increase in abundance, dominating the peat stratigraphy. This expansion of *Sphagnum* is indicative of a wetter environment and is ^{14}C dated to 1640±50 BP [cal. AD 260(420)555] on the D2 profile. *Sphagnum imbricatum* replaces *Sphagnum* section *Acutifolia* in both cores, dominating the peat stratigraphy until *circa* cal. AD 750. Between cal. AD 550-650 there is a short-lived decline in the abundance of *Sphagnum*, and corresponding increases in Ericaceae and Monocotyledonous remains. After this fluctuation *Sphagnum imbricatum* appears for the first time in the D2 profile. Unidentified Organic Matter and Ericaceae dominate the peat stratigraphy between cal. AD 700-900, perhaps reflecting a return to drier conditions, an interpretation supported by the absence of *Sphagnum* remains during this period. The chronology of these changes is secured by a lower ^{14}C date of 1305±50 BP [cal. AD 650(690)860] and an upper ^{14}C date of 1195±50 BP [cal. AD 700(870)975], both obtained for the D2 core.

Between cal. AD 900-1200, *Sphagnum imbricatum* dominates the stratigraphy in both cores identifying a return to wetter conditions. Between cal. AD 1200-1300 *Sphagnum imbricatum* declines and is replaced by *Sphagnum* section *Acutifolia* and Ericaceae remains signifying a return to drier conditions. The beginning of this drier phase is ^{14}C dated to 1195±50 BP [cal. AD

1260(1295)1400]. Subsequently *Sphagnum imbricatum* dominates the D1 stratigraphy from cal. AD 1400 until *circa* cal. AD 1750; however, on D2 between cal. AD 1650-1750 *Sphagnum* section *Acutifolia* increases in abundance at the expense of *Sphagnum imbricatum*, identifying a brief drier phase. *Sphagnum* section *Cuspidata* dominates the D1 peat stratigraphy between cal. AD 1800 and the present-day. *Sphagnum* section *Cuspidata* dominates the D2 peat stratigraphy between cal. AD 1750-1900, after which it is replaced by *Sphagnum papillosum*. *Sphagnum* section *Cuspidata* is the wettest environmental indicator encountered at site D, and its presence in the stratigraphy pertaining to the period cal. AD 1750-1900 signifies the mire was very wet. The final event in the stratigraphy at site D involves the replacement of *Sphagnum* species by *Hypnum jutlandicum*, which signifies a drying trend in the surface layers of D2. There is no evidence of this drying trend in the D1 hollow sequence.

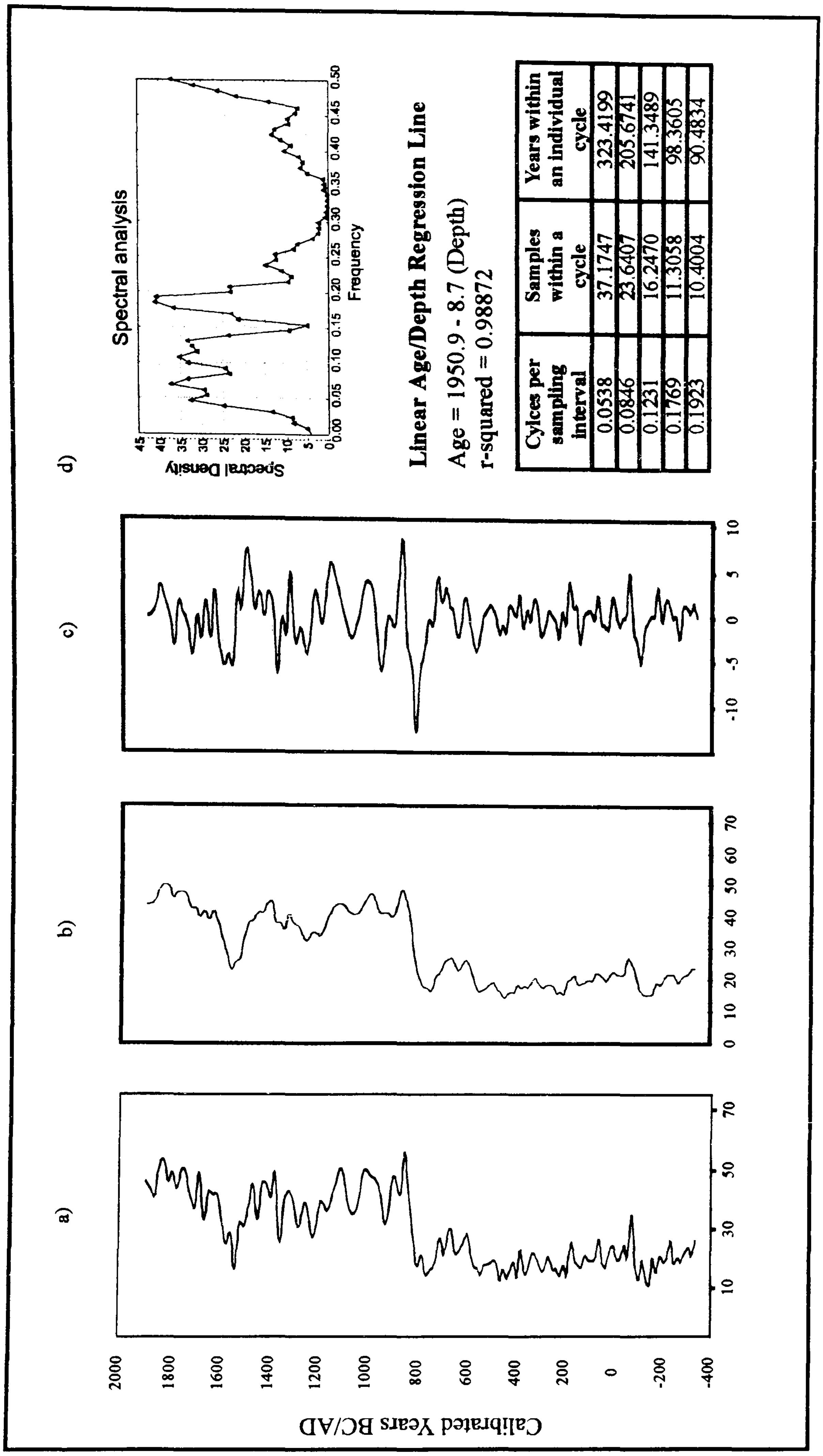
6.2.3.3 Degree of peat humification

The humification curves for cores D1 and D2 are displayed in figures 6.30 and 6.31 respectively. The humification stratigraphy contains several significant shifts to poorly humified peat, which signify changes to wetter conditions *circa* cal. AD 400, 600, 800-850, 1300, 1600-1650 and 1800. Phases of well-humified peat signifying comparatively drier conditions occurred *circa* cal. AD 100-400, 750-850, 1250-1300 and 1550-1600.

Regression analysis of the age/depth models for core D1 and D2 identified broadly linear relationships, and so both humification profiles were subjected to direct time series analysis. The smoothed and high-pass filtered data series displayed on graph (c) of figures 6.30-6.31 were examined with spectral analysis using the Fourier transformation method and a Daniell smoothing window. The spectral density function for D1, displayed in part (d) of figure 6.30, identifies several peaks, with the most significant centred on 0.08, 0.12 and 0.18 cpi (cycles per sampling interval). The linear age/depth model indicates these frequencies correspond to 205, 141 and 90-98 year cycles respectively. The spectral density function for D2, displayed in part (d) of figure 6.31, identifies several peaks, with the most significant centred on 0.2, 0.14 and 0.09 cpi (cycles per sampling interval). The linear age/depth model indicates these frequencies correspond to 92, 138 and 208-240 year cycles respectively. The time series analysis identifies virtually identical periodicities in two adjacent cores, which is clear endorsement of the identified cyclicity.

6.2.3.4 Reconstructing bog surface wetness

The palaeohydrology uncovered from peat stratigraphies at site D draws upon evidence from both cores. The chronology for the stratigraphy is secured by the ^{14}C dates on core D2. The evidence for shifts to wetter conditions and that for unambiguously dry conditions present within the



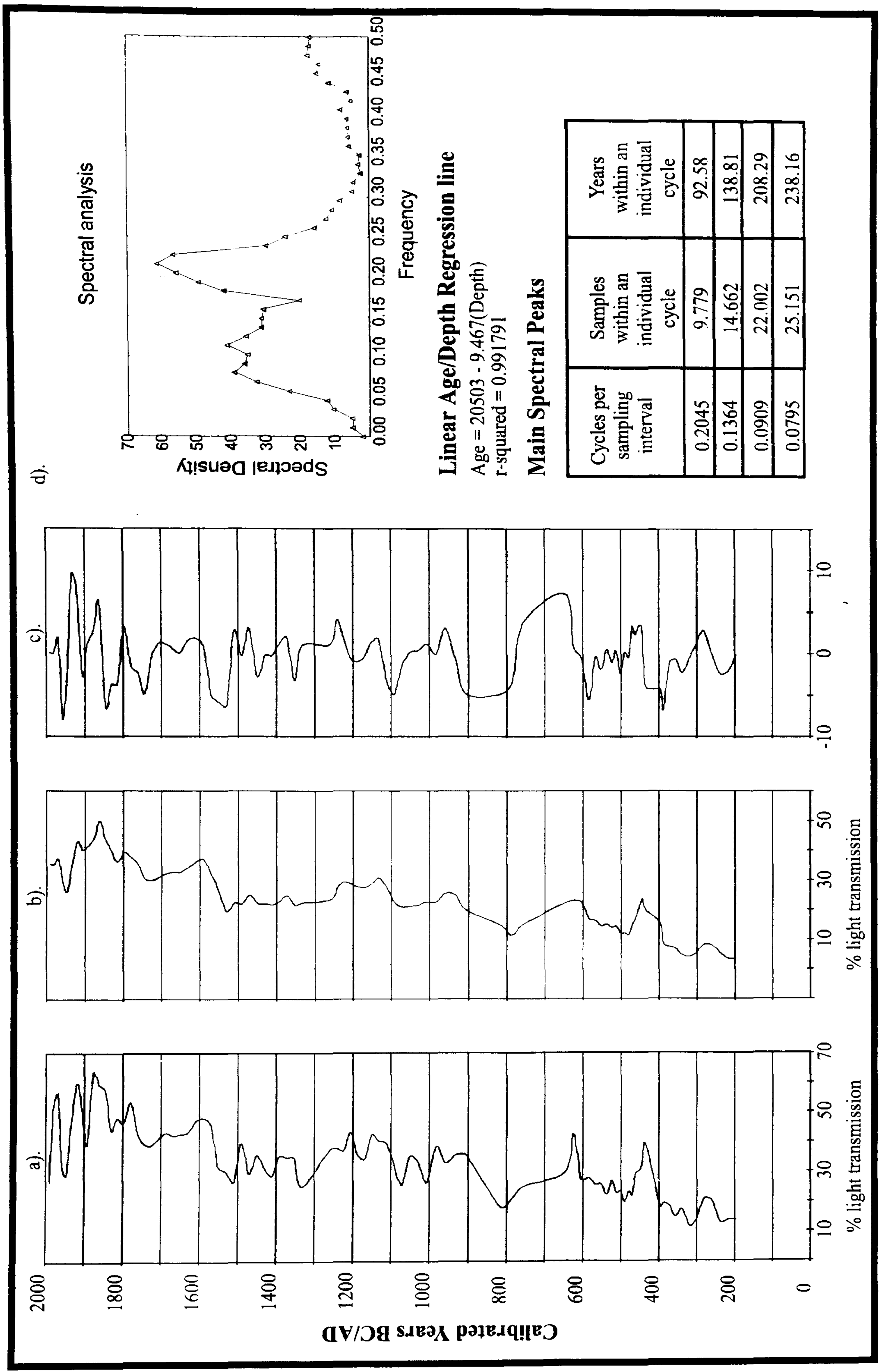
Linear Age/Depth Regression Line

Age = 1950.9 - 8.7 (Depth)

r-squared = 0.98872

Cylces per sampling interval	Samples within a cycle	Years within an individual cycle
0.0538	37.1747	323.4199
0.0846	23.6407	205.6741
0.1231	16.2470	141.3489
0.1769	11.3058	98.3605
0.1923	10.4004	90.4834

Figure 6.30. Humification data from May Moss core D1 displaying; (a) the raw percentage light transmission values, (b) the raw data smoothed using an unweighted three point moving average, (c) the smoothed data series subjected to a high pass filter emphasising the key shifts. In all three curves higher values denote poorly humified peat and are interpreted as signifying wetter conditions. (d) Results of the time series analysis, which includes the spectral density function for the smoothed high-pass filtered data series displayed on graph (c). The table in part (d) converts the spectral peaks into years using the age/depth model derived for the peat profile.



Linear Age/Depth Regression line

Age = 20503 - 9.467(Depth)
r-squared = 0.991791

Main Spectral Peaks

Cycles per sampling interval	Samples within an individual cycle	Years within an individual cycle
0.2045	9.779	92.58
0.1364	14.662	138.81
0.0909	22.002	208.29
0.0795	25.151	238.16

Figure 6.31. Humification data from May Moss core D2 displaying (a) the raw percentage light transmission values, (b) the raw data smoothed using an unweighted three point moving average, (c) the smoothed data series subjected to a high pass filter emphasising the key shifts. In all three curves higher values denote poorly humified peat and are interpreted as signifying wetter conditions. (d) Results of the time series analysis, which includes the spectral density function for the smoothed high-pass filtered data series displayed on graph (c). The table in part (d) converts the spectral peaks into years using the age/depth model derived for the peat profile.

palaeoenvironmental data is summarised in figure 6.32. Comparison of two cores and several procedures assesses the consistency of the stratigraphy and the performance of the palaeoenvironmental procedures. The macrofossil stratigraphy in both cores is broadly identical with the slight discrepancies attributable to differences in the location of the core sites in relation to the water table. Site D1 currently is a hollow and appears to have been consistently wetter than site D2, which was sampled from the edge of a *Sphagnum papillosum* hummock.

The humification stratigraphies are not consistent. Admittedly there are features common to both humification profiles, namely the wet shifts *circa* cal. AD 600-650, 800-850 and 1600-1650. However, the D1 humification stratigraphy between cal. AD 0 and 600 is hydrologically equivocal and fails to register a pronounced wet shift evident in all the other palaeoenvironmental records *circa* cal. AD 400. In addition the D2 stratigraphy between cal. AD 900 and 1400 is equally hydrologically ambiguous. This inconsistency poses questions about the reliability of the hydrological signal yielded by humification analysis and indicates that more than one profile should be used to investigate the humification stratigraphy of a peat sequence.

Despite these discrepancies figure 6.32 demonstrates that the hydrological signals yielded by the different procedures on both profiles are broadly consistent. The major stratigraphic change within the peat profile is ^{14}C dated to 1640±50BP [cal. AD 265(420)555], and appears to signify a change to substantially wetter conditions. The response of the testate amoebae and plant macrofossil stratigraphy is synchronous, although the wet shift is only recorded in the D2 humification stratigraphy. After this stratigraphic change a series of moisture fluctuations is recorded, with five wet shifts *circa* cal. AD 600-650, 800-850, 1300-1400, 1600 and 1800. Reconstructed mean annual water table depths during the wetter period of *circa* 5 cm indicate the mire surface was very wet. Unequivocally dry conditions are evident between cal. AD 200 and 400. A pronounced dry phase, which the palaeoecology signifies was perhaps the driest recorded in the stratigraphy, is evidenced by the decline of *Sphagnum* and a reconstructed mean annual water table depth of 8 cm. This dry period is delimited by ^{14}C dates of 1305±50BP [cal. AD 670(690)775] and 1195±50BP [cal. AD 700(870)975]. Three further dry phases occur *circa* cal. AD 1250-1400, 1550-1600 and 1750-1800, of which the later two fall within a long cal. AD 1400-1900 wet phase.

The final event in the hydrological history occurs towards the surface of D2, where the plant macrofossil and the testate amoebae stratigraphy to a lesser extent register a drying trend. This drying is not evident in D1, which indicates that at present pool or hollow stratigraphy is comparatively unaffected by this drying trend. The ability of hollows to be unaffected by a drying

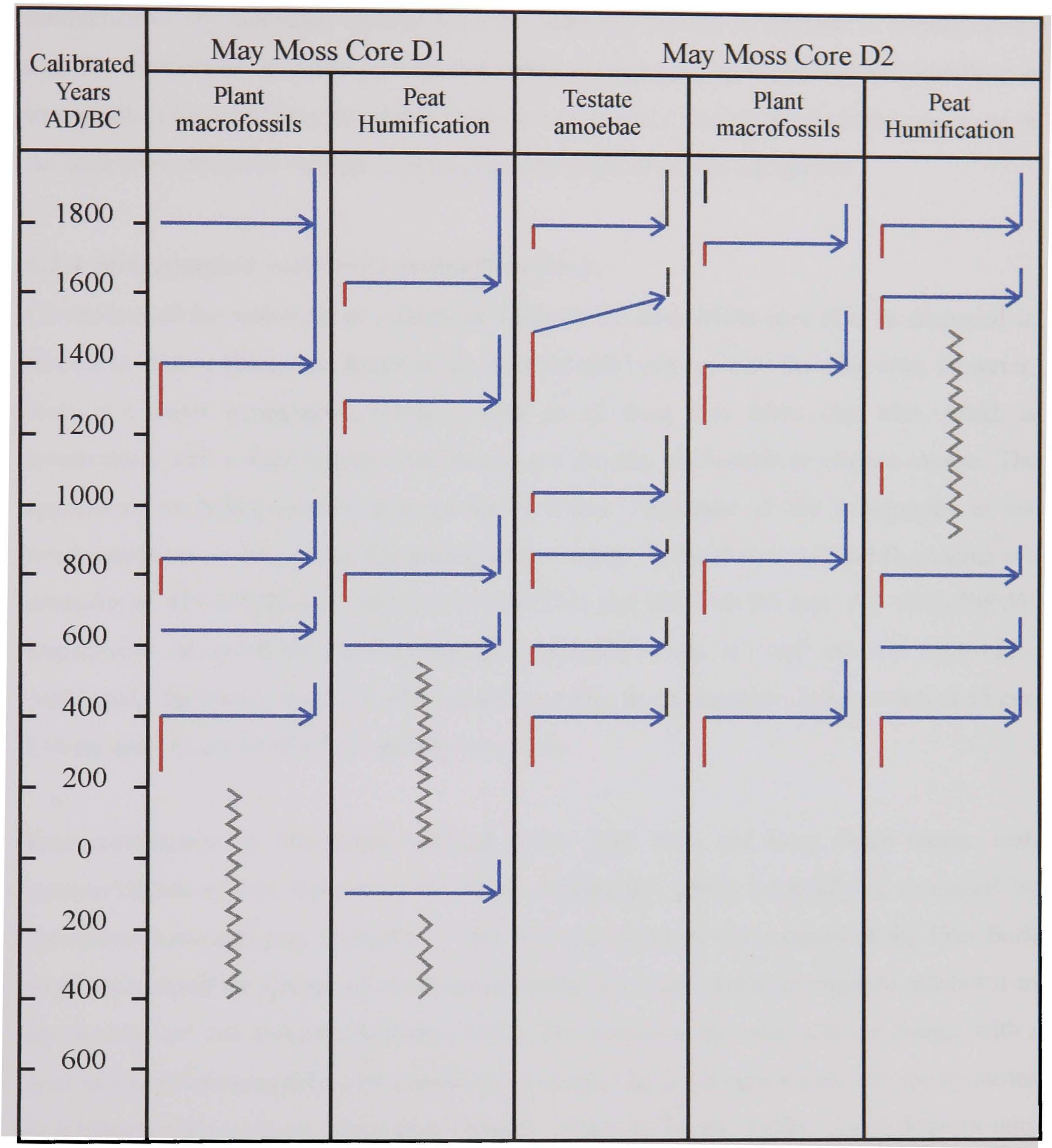


Figure 6.32. Summary of the moisture fluctuations signified in peat stratigraphies at May Moss site D. Red lines denote dry conditions and blue lines wet conditions. The blue arrows signify changes to wetter conditions. Grey zigzag lines denote stratigraphy with an ambiguous hydrological signal.

trend that is also evident at sites B and C, offers a possible explanation for some of the minor inconsistencies in the hydrological signal. The D1 hollow stratigraphy does not always record drier events and the subsequent wet shifts as well as D2. Perhaps sites located on the threshold between the hollow and hummock environment are well positioned for identifying expansion and contraction of dry hummock ecology from the hummock centres in response to climate-driven moisture fluctuations. It is also possible that testate amoebae, plant macrofossil and humification stratigraphies have differing thresholds before a wet shift is recorded, in which the case some of the comparatively minor discrepancies encountered at site D are not unexpected.

6.2.4 Stratigraphic variations across May Moss

Correlation of the hydrological indications between the May Moss core sites is discussed in relation to climate change in chapter seven, together with evidence from the other sites. However, there is a major stratigraphic change evident at all three May Moss core sites, which is synonymous with a hydrological event that is not directly attributable to climate change. The appearance of *Sphagnum*-rich peat as the dominant component of the stratigraphy is not synchronous across May Moss. The stratigraphic event is ^{14}C dated at sites C and D, yielding age estimates of 825 ±50BP [cal. AD 1165(1230)1275] and 1640 ±50BP [cal. AD 260(420)555] respectively. At site B the palynostratigraphy indicates an age of *circa* cal. AD 1100-1300. Additionally the change occurs at differing depths within the stratigraphy, being present at 95 cm, 140 cm and 180 cm at sites B, C and D respectively.

Peat accumulation at May Moss initiated in the Eller Beck and Long Grain basins, with monocotyledonous peat dominating the basal stratigraphy, which eventually is succeeded by *Sphagnum*-dominated peat (Atherden, 1979). Previous research in the centre of the Eller Beck basin encountered the *Sphagnum* expansion at depths of 195 cm, within stratigraphy attributed an age of *circa* cal. AD 400-500 (Atherden, 1979). This sequence represents a facies change, with a drier monocotyledonous-Ericaceae community succeeded by a *Sphagnum* mire ecotype by means of a process referred to as lateral paludification (Smith & Taylor, 1989). The *Sphagnum* mire facies expanded from the wet inhibited drainage of the Eller Beck basin over the surrounding watershed, reaching site D and eventually along a water-shedding ridge to sites C and B. This type of facies change is a feature of the evolution of a topographic blanket mire. Underlying topography is an important influence on blanket mire development, and is almost certainly responsible for the delayed arrival of *Sphagnum*-dominated stratigraphy at sites B and C, located away from the Eller Beck basin.

This facies expansion has implications for palaeohydrological interpretation of the peat stratigraphy, because this particular event must be treated with caution. However, the initiation of *Sphagnum* dominated stratigraphy at site D appears synchronous to that encountered in the centre of the Eller Beck basin. The initial formation of the *Sphagnum* mire facies is almost certainly in response to substantially wetter environmental conditions, which given the watershed location of May Moss may reflect wetter climatic conditions. The ^{14}C chronology at site D attributes the climatic deterioration an age of 1640 ±50BP [cal. AD 260(420)555].

6.3 Fen Bogs

Introduction

Palaeoecological research at Fen Bogs uses a 2.7 metres sequence sampled from the deepest peat in the centre of the mire. Three cores were extracted from within two metres of each other to assess the consistency of the stratigraphy. A summary of the field stratigraphy is presented in table 6.4. Fen Bogs differs from the other palaeoecological sites investigated in the course of this research, which are all plateau-top water-shedding ombrogenous mires. Fen Bogs is located at the headwaters of Newtondale forming the watershed between Eller Beck and Pickering Beck. The mire is located in a deeply incised gorge, with steep slopes rapidly rising 60 m from the flat mire surface. Fen Bogs receives a substantial amount of water as surface wash from the surrounding slopes. Consequently, Fen Bogs is not strictly an ombrotrophic mire, even though there are ombrogenous facies currently in the centre of the mire (Atherden, 1976b). Abundant *Phragmites australis* remains occur at depths of 1.4 m and deeper, which indicate that in the past the mire probably was a classic minerotrophic upland valley fen.

Peat-based palaeoclimate research relies on reconstructing mire surface wetness, which in the case of ombrotrophic localities can provide a "proxy" record of climate change. The Fen Bogs peat sequence cannot be used in this manner, because the site is not ombrotrophic. However, the mire is topographically and spatially located 1.5 km from and 100 metres below the edge of the hydrological catchment. Surface moisture conditions at Fen Bogs will reflect the antecedent climate within this relatively small area; consequently, the hydrological history of Fen Bogs may contribute information useful for the palaeoclimate research.

The Fen Bogs peat profile was only analysed for plant macrofossil content because of the limited value of a full palaeohydrological investigation and time constraints. Plant macrofossil analyses will not only provide useful palaeoenvironmental information, but also investigate vegetation changes on the mire surface contributing to the understanding of the sedimentary history of Fen Bogs. Humification analyses would be of limited value, because of difficulties in identifying the causes of water table fluctuations in minerotrophic valley mires, compounded by evidence of human interference at the site. Palaeohydrological reconstruction based on testate amoebae analysis would be complicated by other environmental controls on the composition of sub-fossil communities, namely nutrient and mineral supply, which typically are higher on mires receiving substantial quantities of surface run-off. The chronology of the Fen Bogs peat sequence defined in chapter five, relies largely upon correlation of palynological marker horizons with a ^{14}C chronology obtained in earlier research at Fen Bogs and with key historical events (Atherden, 1976b).

Table 6.4. Field stratigraphy at Fen Bogs.

Mire Surface	Surface vegetation of *Sphagnum papillosum, Eriophorum vaginatum, Calluna vulgaris and Erica tetralix.*
3-21 cm	Dark brown (5YR 3/2) well humified Monocotyledonous peat.
21-96 cm	Yellow brown (10YR 5/6) poorly humified *Sphagnum* and Monocotyledonous peat.
96-120 cm	Dark Brown (10YR 4/3) Monocotyledonous peat.
120-140 cm	Dark yellow brown (10YR 4/4) poorly humified *Sphagnum* and Monocotyledonous peat.
140-270 cm	Reddish brown (5YR 3/3) *Phragmites australis* peat.

6.3.1 Plant macrofossil analysis

The plant macrofossil stratigraphy is displayed in figure 6.33. Cluster analysis signifies that the most significant stratigraphic changes occurred *circa* cal. AD 1150, 1600, 1700 and 1850. Between 200 cal. BC and cal. AD 1100 the peat stratigraphy is dominated by Monocotyledonous remains, particularly *Phragmites australis* and *Eriophorum vaginatum.* The remains of other mire plants are not abundant. The most significant event in the plant macrofossil stratigraphy occurred *circa* cal. AD 1150. This change involves the first appearance of *Sphagnum*, which increases in abundance to exceed 50%. The most abundant *Sphagnum* species were *Sphagnum* section *Acutifolia* and *Sphagnum papillosum*, perhaps identifying the formation of *Sphagnum* hummocks within a *Phragmites*-Cyperaceae fen community. This expansion of *Sphagnum* is short-lived, declining between *circa* cal. AD 1200 and 1400.

Monocotyledonous remains, particularly *Eriophorum vaginatum* and *Phragmites australis* dominate the peat stratigraphy between cal. AD 1200 and 1400. A further significant change in the Fen Bogs macrofossil profile occurs around cal. AD 1400, when *Sphagnum papillosum*

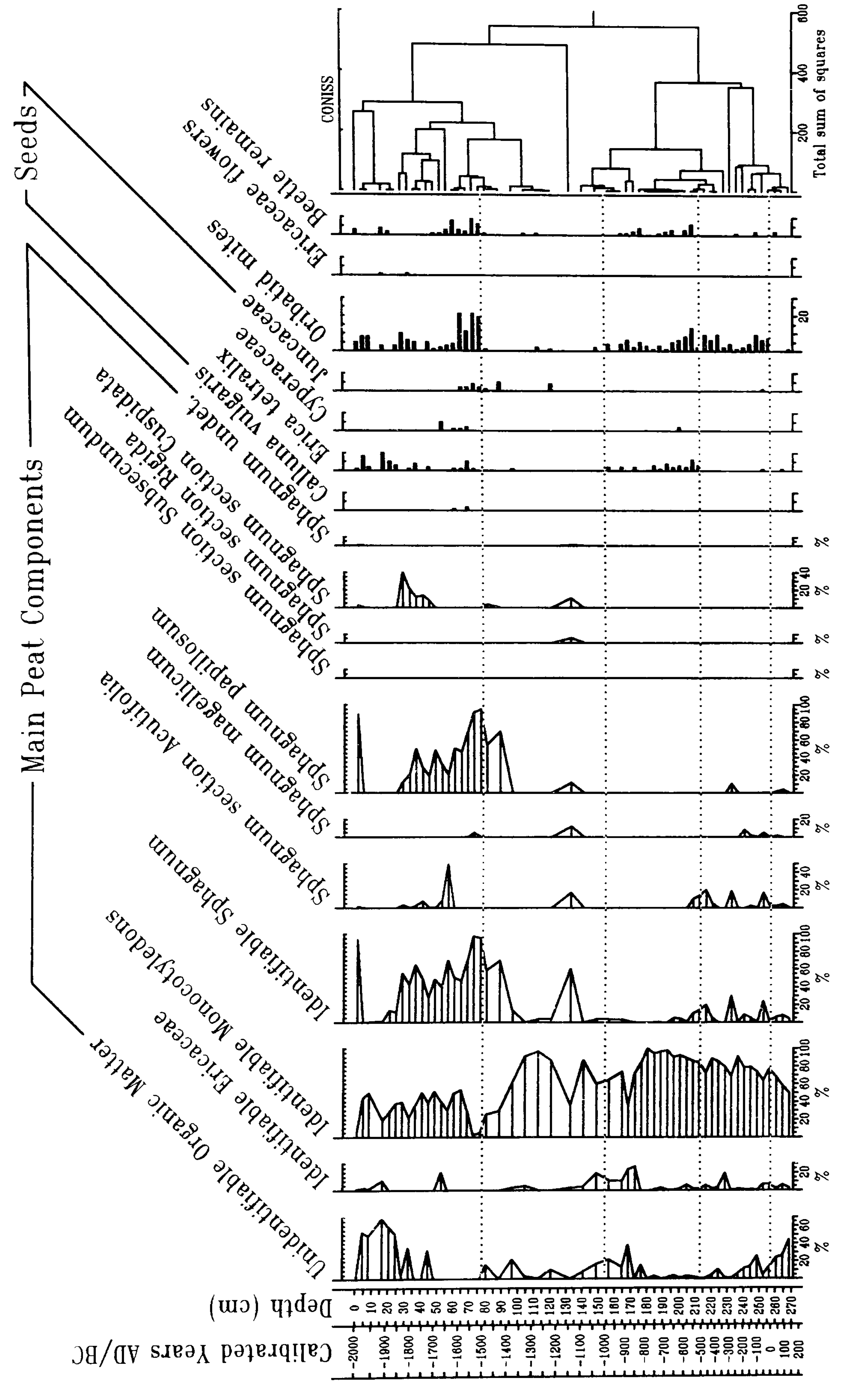


Figure 6.33. Fen Bogs plant macrofossil diagram. Main peat components are expressed as percentages of the total volume of peat, with *Sphagnum* abundances based on leaf counts of a random selection of branch leaves (>100 per sample). The other curves display raw counts of leaves, seeds, flowers and selected insect remains. The dendrogram presents the results of a sum of the squares cluster analysis.

replaces the *Eriophorum vaginatum* and *Phragmites australis* community. *Sphagnum papillosum* dominates the peat stratigraphy between cal. AD 1400-1600. *Sphagnum papillosum* can inhabit acidic fens, but it is only usually found where the peat surface is raised above the water table (Daniels & Eddy, 1990). Consequently, it is possible that the presence of *Sphagnum papillosum* in the fossil record signifies the occurrence of a locally ombrogenous flora and ombrogenous facies on the mire surface. This represents an important change in the history of Fen Bogs. The mixture of ombrotrophic and minerotrophic facies currently found on the mire surface might owe its existence to environmental changes during the 10th and 15th centuries.

Between cal. AD 1600 and 1700 *Sphagnum papillosum* declines and is replaced by *Sphagnum* section *Acutifolia*. After *circa* cal. AD 1700 *Sphagnum* section *Cuspidata* increase in abundance replacing *Sphagnum* section *Acutifolia*. *Sphagnum* section *Cuspidata* probably consists of the species *Sphagnum cuspidatum* and *Sphagnum recurvum* (Daniels & Eddy, 1990; Smith, 1978). In the surface layers of peat (5-30 cm), *Sphagnum* remains become virtually absent, before re-appearing on the mire surface. The decline of *Sphagnum* is not dated; however, the chronology developed for the peat sequence indicates that the changes probably occurred during the nineteenth century. This palaeoecological change is broadly synchronous with the construction of the Whitby to Pickering railway across the western edge of the mire in AD 1836. Drainage schemes associated with railway construction and perhaps physical damage of the mire surface may be responsible for the decline in *Sphagnum*. However, *Eriophorum vaginatum*, Ericaceae and *Sphagnum papillosum* become more abundant in the top 10-15 cm of peat, reflecting the recovery of a typical mire flora.

6.3.2 Reconstructing mire surface wetness

The stratigraphy pertaining to the period 100 cal. BC to cal. AD 1100 is dominated by *Phragmites australis* and sedges, which reveals very little information about moisture conditions on the mire surface other than to identify that the mire was a wet upland valley fen. The site is a more useful palaeohydrological archive after the mire was colonised by an ombrogenous mire flora *circa* cal. AD 1100. The expansion of *Sphagnum* between cal. AD 1100 and 1200 reflects this colonisation process. The decline in *Sphagnum* between cal. AD 1200 and 1400 could reflect a drying of the mire surface, a view supported by a minor expansion of Ericaceae and Monocotyledonous remains. The massive expansion of *Sphagnum papillosum circa* cal. AD 1400 is probably a response to increased availability of water on the mire surface. These relatively wet conditions persist between cal. AD 1400 and 1600, when the drier environment indicator *Sphagnum* section *Acutifolia* replaces *Sphagnum papillosum*, identifying a drier mire surface between cal. AD 1600 and 1700. *Sphagnum* section *Acutifolia* typically prefer drier habitats, with the section including a number of hummock-top species and have been interpreted in previous plant macrofossil research as a dry environment indicator (Barber, 1981; Stoneman, 1993).

The cal. AD 1600-1700 dry phase is relatively short-lived and terminates with a return to wetter conditions evidenced by the replacement of *Sphagnum* section *Acutifolia* with the wet environmental indicator, *Sphagnum* section *Cuspidata*, between cal. AD 1700 and 1850. The last 150 years of peat stratigraphy contains evidence of interference with the mire flora and the process of peat accumulation. This interference is almost certainly related to drainage schemes and the process of building the Whitby to Pickering railway in 1836 (Statham, 1989). Mires are an easily damaged environment and this unprecedented scale of human activity on the western edge of Fen Bogs could quite conceivably have had a catastrophic impact on the hydrology and flora. Human interference is the driving force behind changes in the uppermost peat stratigraphy and it is impossible to elucidate any evidence of climate-driven palaeohydrological change.

6.4 Yarlsey Moss

Introduction

The palaeoecological history reconstructed from the Yarlsey Moss stratigraphy is based on analysis of a peat core sampled with a 10x30cm Russian corer from the deepest peat in the centre of the mire. A summary of the field stratigraphy is presented in table 6.5. The 2.4 m peat profile was analysed for plant macro-fossil content, sub-fossil testate amoebae and for the degree of peat humification. Further analysis involved the construction of a pollen diagram. Three ^{14}C dates and further palynostratigraphic marker horizons were used to generate a time series for the peat sequence. The rationale behind the chronology was introduced in chapter five.

Table 6.5 Field stratigraphy at Yarlsey Moss.

Peat surface	Dry mire surface covered with a *Calluna vulgaris* monoculture.
5 - 130 cm	Poorly humified *Sphagnum* and Monocotyledonous peat, with bands of Monocotyledonous and Ericaceae peat between 20-28 cm and 44-54 cm.
130 - 152 cm	Well humified Monocotyledonous and Ericaceae peat.
152- 185 cm	Moderately humified *Sphagnum* and Monocotyledonous peat.
185 - 240 cm	Well humified Monocotyledonous and Ericaceae peat.

There are problems with the time series generated for the peat sequence, with a very slow rate of peat accumulation indicated in the chronology for the stratigraphy between 170-250 cm. Peat accumulation appears to have been initiated at Yarlsey Moss probably in response to woodland clearance during the Iron Age. The peat stratigraphy at Yarlsey Moss supports this theory, with well humified peat dominated by UOM and Ericaceae remains near the base of the peat profile. This sequence reflects the comparatively dry *Calluna vulgaris* heath with a shallow peaty-mineral soil being swamped by *Sphagnum* peat, which typically accumulates more rapidly.

Further uncertainty with the base of this time-scale is created by the possibility that the tree decline identified as an Iron Age and Romano-British woodland clearance event, may be limited solely to the Roman-British period. Pre-Roman woodland clearance clearly has affected the central plateau of the North York Moors encouraging peat accumulation at North Gill and Bluewath Beck (Simmons & Innes, 1988d); however, it is likely that the steep slopes bordering the central moorland and the land surrounding these early peat sites remained forested until the major Iron Age and Romano-British woodland clearances.

Unfortunately the ^{14}C dates of this woodland decline are obtained from lower altitude sites at Fen Bogs and Harwood Dale Bog (Atherden, 1976b; 1989). The massive reduction in tree pollen traditionally associated with Iron Age and Romano-British woodland clearances may be staggered across the North York Moors, with landscape exploitation gradually extending on to the higher moors, forced by demographic and economic growth. It is possible the tree pollen decline at Yarlsey Moss and elsewhere on the high moors may reflect pressure on remaining woodlands during the economic boom of the Roman-British period, perhaps associated with greater access to the uplands after construction of the nearby Wheeldale Roman road or the result of construction of the road itself. Further ^{14}C dates investigating the chronology of this major woodland clearance are required to test this hypothesis, particularly using higher altitude peat sequences.

6.4.1 Testate amoebae analysis

Quantitative analysis

The testate amoebae stratigraphy uncovered at Yarlsey Moss is displayed in figure 6.34. The species scores on the first two axes of a detrended correspondence analysis of the sub-fossil data at Yarlsey Moss are displayed on a X/Y biplot in figure 6.35. The first two DCA axes have eigenvalues of 0.594 and 0.052, which signify that they summarise the most significant structure within the dataset, and that the amount of variation explained by further DCA axes is minimal. Correlation coefficients between the actual abundances of testate amoebae taxa and the DCA axes, listed on figure 6.35, identify the species involved in the most significant changes in the sub-fossil stratigraphy.

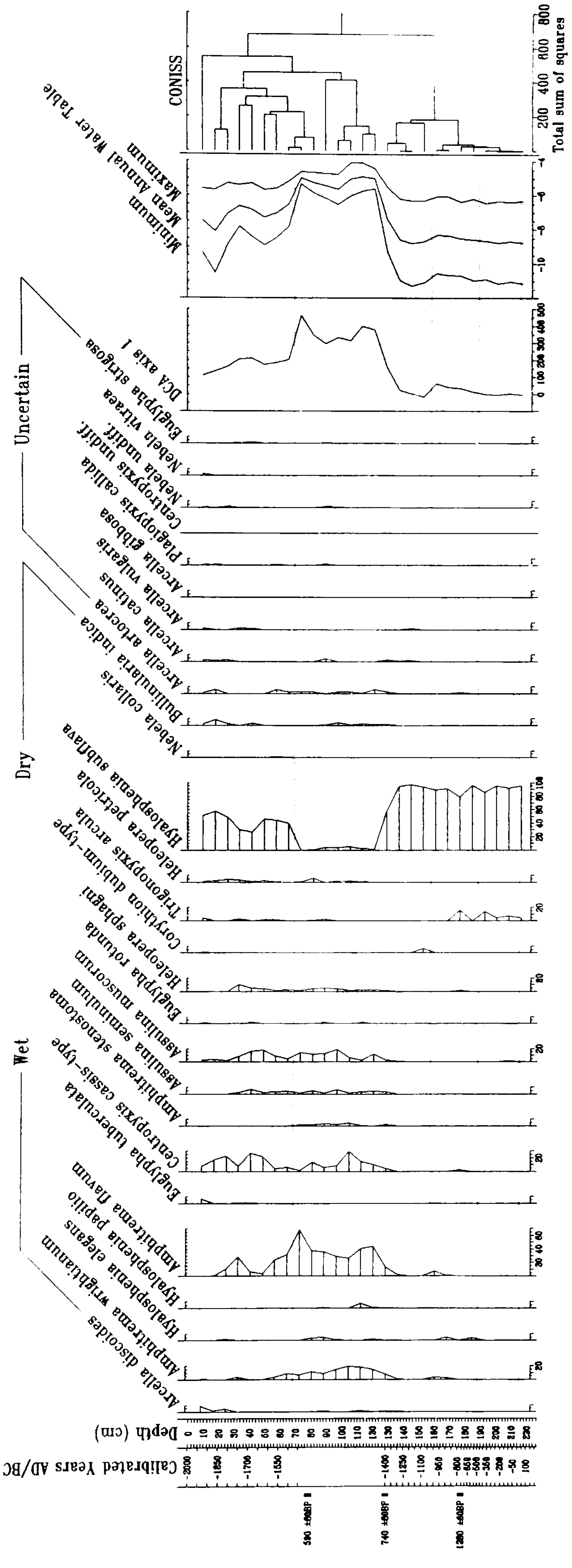
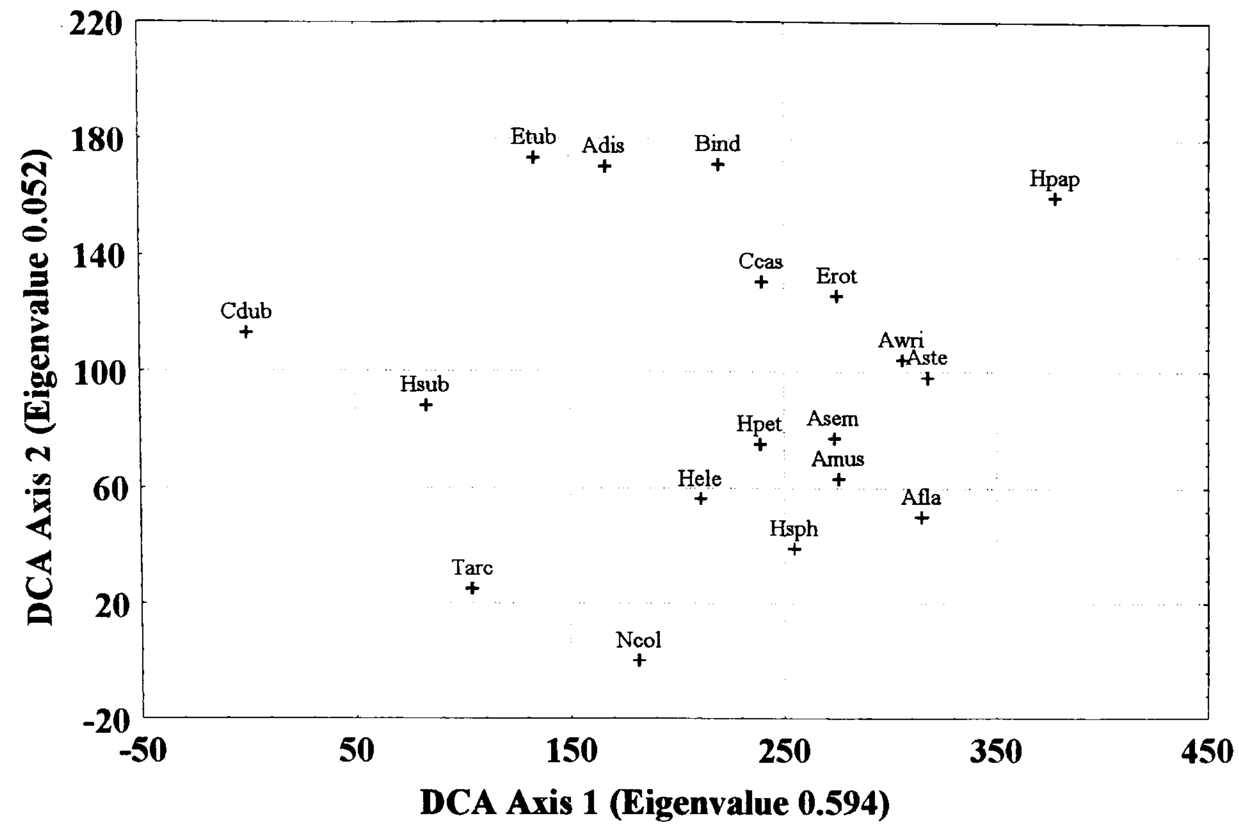


Figure 6.34. Yarlsey Moss testate amoebae diagram. The species curves are arranged from left to right according to preference of habitat moisture conditions. On the far right the reconstructed mean annual water table depths are presented, including upper and lower limits based on the ranges tolerated by individual species; the sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

a).



b).

Testate Amoebae species	Graph labels	DCA axis 1	DCA axis 2
Eigenvalue		0.594	0.052
% variance		48.96	4.30
Arcella discoides	Adis	0.037	-0.346
Arcella artocrea	Aarc	0.468 [a]	-0.398 [a]
Arcella catinus	Acat	0.062	-0.033
Arcella vulgaris	Avul	-0.027	0.321
Arcella gibbosa	Agib	0.078	0.207
Centropyxis cassis -type	Ccas	0.518 [b]	-0.221
Plagiopyxis callida	Pcal	0.144	0.010
Bullinularia indica	Bind	0.263	-0.400 [a]
Trigonopyxis arcula	Tarc	-0.206	0.205
Hyalosphenia subflava	Hsub	-0.959 [c]	-0.058
Hyalosphenia papilio	Hpap	0.414 [a]	-0.200
Hyalosphenia elegans	Hele	0.208	0.122
Heleopera sphagni	Hsph	0.537 [b]	0.677 [c]
Heleopera petricola	Hpet	0.385 [a]	0.095
Nebela undiff.	Nund	0.312	0.111
Nebela collaris	Ncol	0.047	-0.006
Nebela vitraea	Nvit	-0.054	-0.236
Amphitrema flavum	Afla	0.925 [c]	0.155
Amphitrema wrightianum	Awri	0.808 [c]	-0.243
Amphitrema stenostoma	Aste	0.613 [c]	-0.069
Euglypha strigosa	Estr	0.180	0.536 [b]
Euglypha tuberculata	Etub	-0.033	-0.128
Euglypha rotunda	Erot	0.348	0.131
Assulina muscorum	Amus	0.749 [c]	0.298
Assulina seminulum	Asem	0.656 [c]	0.167
Corythion dubium -type	Cdub	-0.254	-0.044

Figure 6.35. (a) Detrended correspondence analysis ordination diagram showing the species weighted averages on the first two axes for the Yarlsey Moss testate amoebae data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the testate amoebae species. The correlations are not statistically significant unless annotated by either, [a] = significance at the 95% level, [b] = significance at the 99% level or [c] = significance at the 99.9% level.

The most abundant testate amoebae species at Yarlsey Moss appear to be arranged along DCA axis 1 according to their tolerance of habitat wetness. Dry indicator taxa, such as *Hyalosphenia subflava* and *Trigonopyxis arcula*, occur at the opposite end of axis 1 to the wet indicators *Amphitrema flavum*, *Amphitrema wrightianum* and *Assulina* spp. (Tolonen *et al.*, 1992; 1994; Woodland *et al.*, 1998). The correlation coefficients support this conclusion, with axis 1 summarising sub-fossil variations between a "wet environment" assemblage and a "dry environment" assemblage. The wet indicators are *Amphitrema flavum*, *Amphitrema wrightianum*, *Assulina muscorum* and *Assulina seminulum*, which display a strong positive correlation with axis 1, whereas the dry indicator *Hyalosphenia subflava* displays a strong negative correlation.

DCA axis 2 only displays a significant correlation with four species, which are limited in occurrence to isolated layers within the fossil record. DCA axis 2 appears to summarise the behaviour of these occasionally frequent outlier species. DCA axis 1 clearly identifies a moisture gradient, which appears to be most significant environmental factor affecting sub-fossil testate amoebae at Yarlsey Moss. DCA axis 1 accounts for 48.96% of the total structure. Further DCA axes only explain minor amounts of variation within the sub-fossil dataset. DCA axis 1 is proposed as a semi-quantitative model summarising fluctuations between wet and dry conditions on the mire surface. The sample scores on DCA axis 1 are plotted stratigraphically in figure 6.34, with low scores identifying drier conditions and higher scores wetter conditions.

The optimum, maximum and minimum reconstructed mean annual water table depths tolerated by extant species were used to generate three palaeohydrological curves, identifying the potential range of moisture conditions at Yarlsey Moss. These curves are displayed stratigraphically in figure 6.34. The fluctuations in reconstructed mean annual water table depth reveal an interesting palaeohydrological history, with pronounced wet and dry phases. Figure 6.34 demonstrates the broad agreement between DCA axis 1 and the water table depths, which assuming the reconstructed mean annual water table values are accurate provides further evidence that DCA axis 1 represents a moisture gradient and that the dominant control on testate amoebae communities is mire surface wetness.

Palaeoecology

Cluster analysis signifies that the most significant changes in the testate amoebae stratigraphy occurred *circa* cal. AD 1100, 1300, 1600 and 1700. The basal peat deposits contain very low quantities of testate amoebae; furthermore the diversity of the testate amoebae communities between cal. AD 0 and 450 is very low and dominated by *Hyalosphenia subflava*, which signifies a comparatively dry environment. *Hyalosphenia subflava* is also the most abundant species between cal. AD 450 and 1300; however, additional low frequencies of *Trigonopyxis arcula*, *Heleopera sphagni* and *Amphitrema flavum* from cal. AD 450 to 1000 signify wetter conditions. These additional species are absent between cal. AD 1100 and 1300, with the peat stratigraphy solely dominated by *Hyalosphenia subflava* identifying a comparatively dry environment.

After cal. AD 1300 there is a major change in the testate amoebae stratigraphy as *Hyalosphenia subflava* declines, and *Arcella* spp., *Amphitrema flavum*, *Amphitrema wrightianum*, *Assulina muscorum*, *Assulina seminulum* and *Centropyxis cassis*-type increase in abundance cumulatively to dominate the peat stratigraphy reflecting substantially wetter conditions until *circa* cal. AD 1450. This major stratigraphic change is ^{14}C dated to 740 ±80BP [cal. AD 1170(1280)1400]. *Circa* cal. AD 1450 *Amphitrema flavum*, *Amphitrema wrightianum* and *Assulina muscorum* decline in abundance and are replaced by *Hyalosphenia subflava*.

Hyalosphenia subflava is the most abundant species between cal. AD 1450 and the present-day, which signifies a return to drier conditions. A subsequent decline by *Hyalosphenia subflava* and the expansion of an *Amphitrema flavum*, *Assulina muscorum* and *Centropyxis cassis*-type community signifies wetter conditions. This stratigraphic change is ^{14}C dated to 590 ±80 BP [cal. AD 1275(1400)1450]. This wet indicator suite of species is abundant until *circa* cal. AD 1850, when *Amphitrema flavum*, *Assulina muscorum* and *Assulina seminulum* decline and there is a further expansion of *Hyalosphenia subflava*, which signifies drier conditions between cal. AD 1800 and the present-day. This dry shift is corroborated by minor increases in the abundance of *Bullinularia indica*, *Trigonopyxis arcula* and *Arcella catinus*, which alongside *Hyalosphenia subflava* dominate the peat stratigraphy up to the mire surface.

6.4.2 Plant macro-fossil data

Quantitative analysis

The plant macrofossil stratigraphy is displayed in figure 6.36. The scores of the main macrofossil components on the first two axes of a detrended correspondence analysis performed on the Yarlsey Moss data are displayed on a X/Y biplot in figure 6.37. The first two axes of the DCA have eigenvalues of 0.449 and 0.214 respectively, signifying that they summarise the most significant structure within the data-set. Consequently, the amount of variation explained by further individual DCA axes is minimal. Correlation coefficients between the main components of the plant macrofossil stratigraphy and the first two DCA axes, listed on figure 6.37, identify the components involved in the most significant changes in the macrofossil stratigraphy.

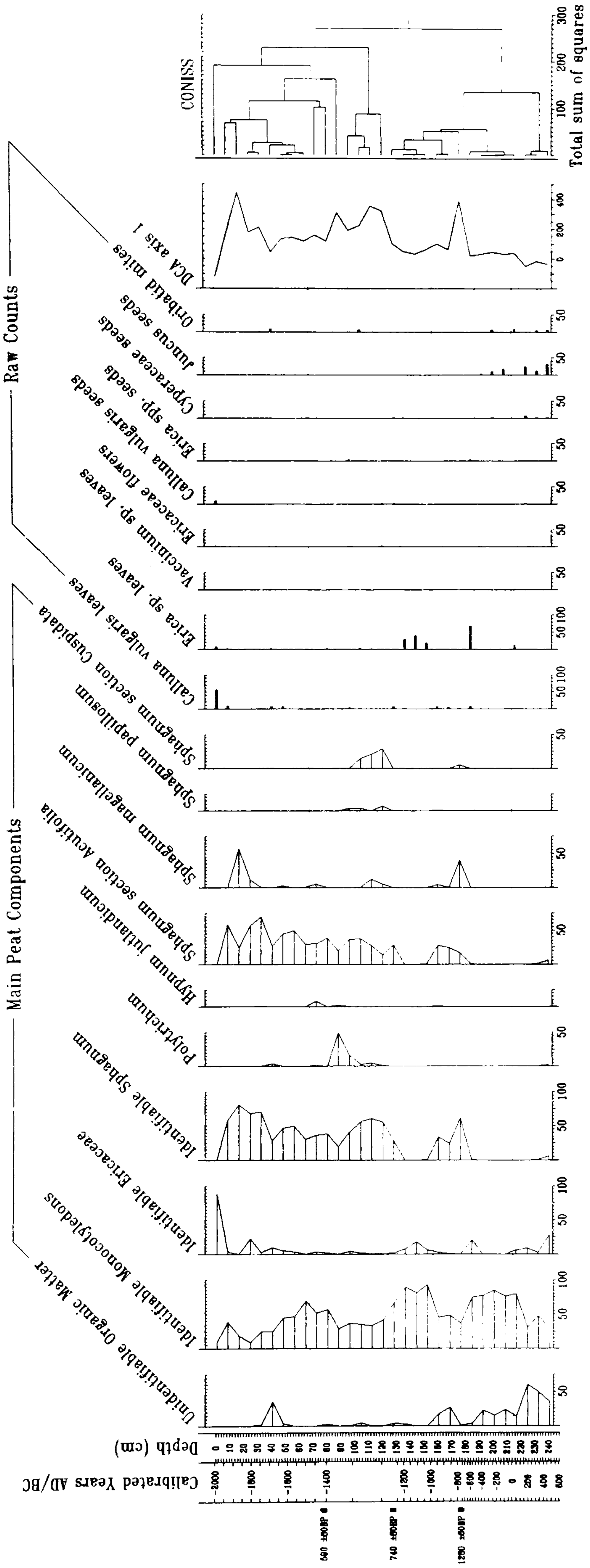
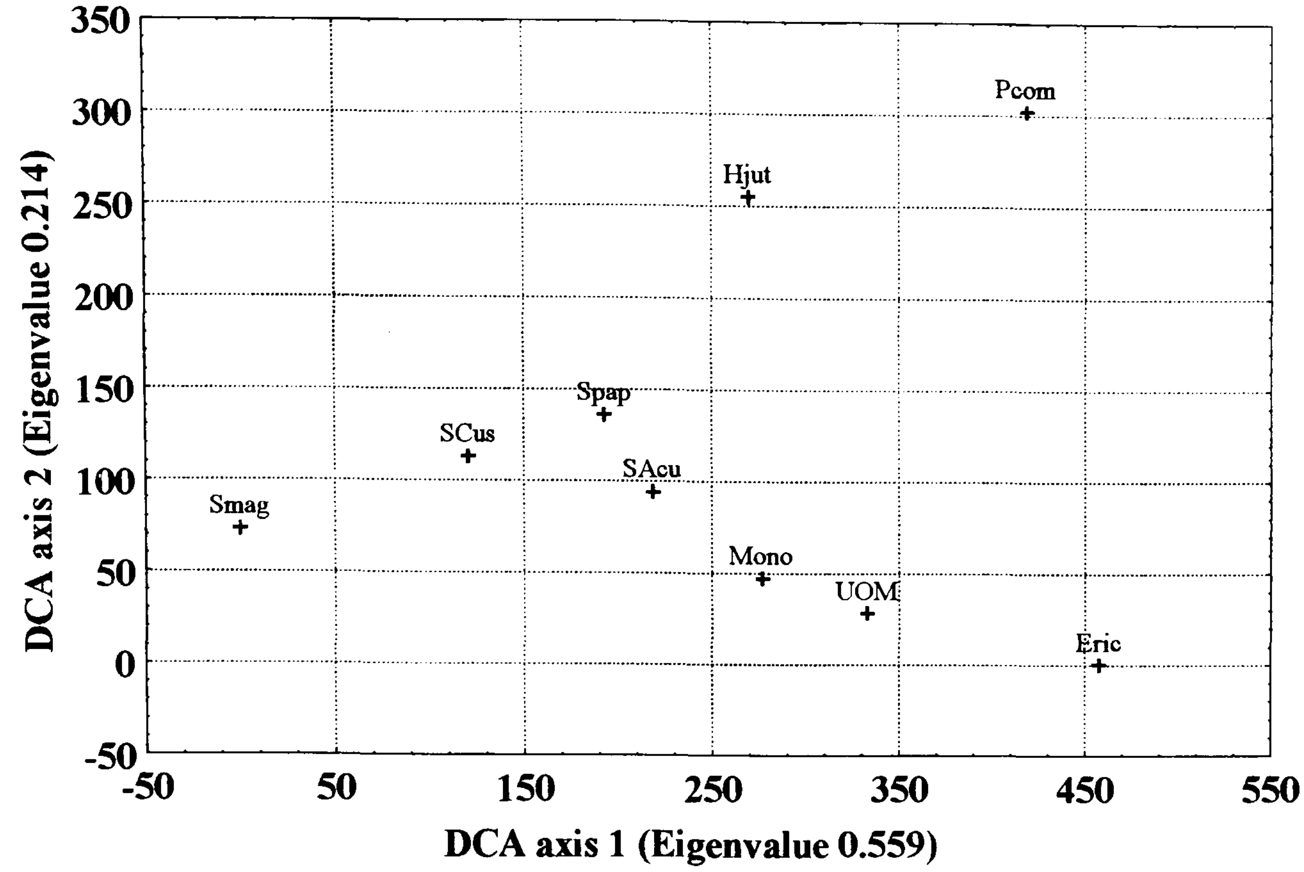


Figure 6.36. Yarlsey Moss plant macrofossil diagram. Main peat components are expressed as percentages of the total volume of peat, with *Sphagnum* abundances based on leaf counts of a random selection of branch leaves (>100 per sample). The other curves display raw counts of leaves, seeds, flowers and selected insect remains. The sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

a).



b).

Macrofossil components	Graph labels	DCA axis 1	DCA axis 2
Eigenvalue		0.559	0.214
% variance		31.11	11.92
Unidentified Organic Matter	UOM	0.234	-0.217
Monocotyledons	Mono	-0.099	-0.275
Ericaceae	Eric	0.667 [c]	-0.305
Polytrichum commune	Pcom	0.345	0.790 [c]
Hypnum jutlandicum	Hjut	-0.028	0.481 [b]
Total identifiable *Sphagnum*	Spha	-0.784 [c]	0.273
Sphagnum section *Acutifolia*	Sacu	-0.454 [b]	0.277
Sphagnum magellanicum	Smag	-0.704 [c]	0.033
Sphagnum papillosum	Spap	-0.223	0.231
Sphagnum section *Cuspidata*	Scus	-0.407 [a]	0.162

Figure 6.37 (a) Detrended correspondence analysis ordination diagram showing the component weighted averages on the first two axes for the Yarlsey Moss plant macrofossil data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the plant macrofossil components. The correlations are not statistically significant unless annotated by either, [a] = significance at the 95% level, [b] = significance at the 99% level or [c] = significance at the 99.9% level.

The main components of the Yarlsey Moss plant macrofossil stratigraphy appear to be arranged along DCA axis 1 according to tolerance of surface wetness. Components indicative of dry environments, such as the Ericaceae, occur at the opposite end of DCA axis 1 to the wet environment components, for example *Sphagnum* section *Cuspidata*. The correlation coefficients support this conclusion with DCA axis 1 summarising variations between a "wet environment" stratigraphy and a "dry environment" stratigraphy. The wet indicators include the Sphagnaceae, which display a strong negative correlation with DCA axis 1, whereas the dry indicator, the Ericaceae, displays a strong positive correlation. This evidence suggests the most significant stratigraphic changes are from an Ericaceae-dominated to a *Sphagnum*-dominated community, and ecologically this signifies a shift from a dry to a wet environment.

DCA Axis 2 is positively correlated with *Polytrichum commune* and negatively correlated with Unidentified Organic Matter, and appears to summarise the impact of two components that are only abundant in occasional layers within the peat stratigraphy. These outliers have a significant impact on the overall data structure (11.92%), but unfortunately DCA axis 2 appears to have little palaeoenvironmental value.

The first two axes account for 43% of the total structure and further DCA axes individually explain less significant amounts of variation within the plant macrofossil stratigraphy. DCA axis 1 appears to identify a moisture gradient, which may be the most important environmental factor affecting the plant macrofossil stratigraphy. DCA axis 1 is proposed as a semi-quantitative model summarising fluctuations between wet and dry conditions on the mire surface. The sample scores on DCA axis 1 are plotted stratigraphically in figure 6.36, with high scores identifying wetter conditions and lower scores drier conditions.

Palaeoecology

Cluster analysis signifies that the most significant changes in the plant macrofossil stratigraphy occurred *circa* cal. AD 0, 500, 1250, 1350, 1400 and 1900. The peat between the base of the profile and *circa* cal. AD 550 contains large quantities of Unidentified Organic Matter, and is dominated by Ericaceae and Monocotyledonous remains. *Juncus* seeds are also very abundant. This assemblage of macro-fossil remains indicates the mire was probably covered with a mixture of Ericaceae heath, with *Juncus* dominated soak-ways. After cal. AD 550 a more characteristic ombrogenous flora developed, evidenced by abundant Ericaceae, *Eriophorum vaginatum*, *Sphagnum* section *Acutifolia* and *Sphagnum magellanicum* remains. The appearance of *Sphagnum* is just below a ^{14}C date of 1280 ±60BP [cal. AD 650(720,735,760)885]. This suite of macrofossil remains dominates the peat stratigraphy between *circa* cal. AD 600 and 1100 reflecting a change to a wetter environment.

Sphagnum remains disappear between cal. AD 1000 and 1250, succeeded by Ericaceae and Monocotyledonous remains. *Sphagnum* species reappear above 130 cm, with *Sphagnum* section *Acutifolia* initially dominating the peat stratigraphy, but is later joined by a mixed community of *Sphagnum* section *Cuspidata*, *Sphagnum papillosum* and *Sphagnum magellanicum*. This reappearance of *Sphagnum* reflects a shift to wetter conditions and is ^{14}C dated to 740 ±80BP [cal. AD 1170(1280)1400]. This suite of *Sphagnum* species inhabits environments ranging from, pools and hollows in the case of *Sphagnum* section *Cuspidata*, low hummocks or lawns in the case of *Sphagnum papillosum* and *Sphagnum magellanicum*, to hummock-tops in the case of *Sphagnum* section *Acutifolia*. Yarlsey Moss displays the classic characteristics of an ombrotrophic mire, with an ombrotrophic flora distributed over a mosaic of hummocks and hollows.

The diversity of the *Sphagnum* flora declines after cal. AD 1350, with only *Sphagnum* section *Acutifolia* remaining. *Polytrichum commune* and *Hypnum jutlandicum* appear and increase in abundance between cal. AD 1350 and 1400. *Polytrichum commune* declines *circa* cal. AD 1400, and there is an expansion of Monocotyledonous remains and *Sphagnum* section *Acutifolia*. This expansion of *Sphagnum* is ^{14}C dated to 590 ±80BP [cal. AD 1275(1400)1450]. *Sphagnum* section *Acutifolia* and Monocotyledonous remains dominate the peat stratigraphy between cal. AD 1400 and 1600. Subsequently *circa* cal. AD 1600-1700 *Sphagnum* declines, replaced by Ericaceae and *Polytrichum commune* remains, perhaps reflecting a return to drier conditions. However, this change is short-lived, followed by increases in the abundance of *Sphagnum* section *Acutifolia* and *Sphagnum magellanicum*, which dominate the peat stratigraphy between cal. AD 1700 and 1900, signifying a return to wetter conditions. The surface layers of peat contain evidence of a further change, becoming dominated by *Calluna vulgaris* remains. These changes are consistent with the composition of the current flora at Yarlsey Moss.

6.4.3 Humification data

The results of the humification analyses are displayed in figure 6.38. The humification profile contains six major shifts to poorly humified peat, which are interpreted as identifying changes to wetter conditions *circa* 200 cal. BC, cal. AD 500, cal. AD 800, cal. AD 1200, cal. AD 1350 and cal. AD 1400. Phases of well humified peat signify comparatively dry conditions between cal. AD 0-500, 600-800, 1000-1100, 1250-1350 and 1600-1700.

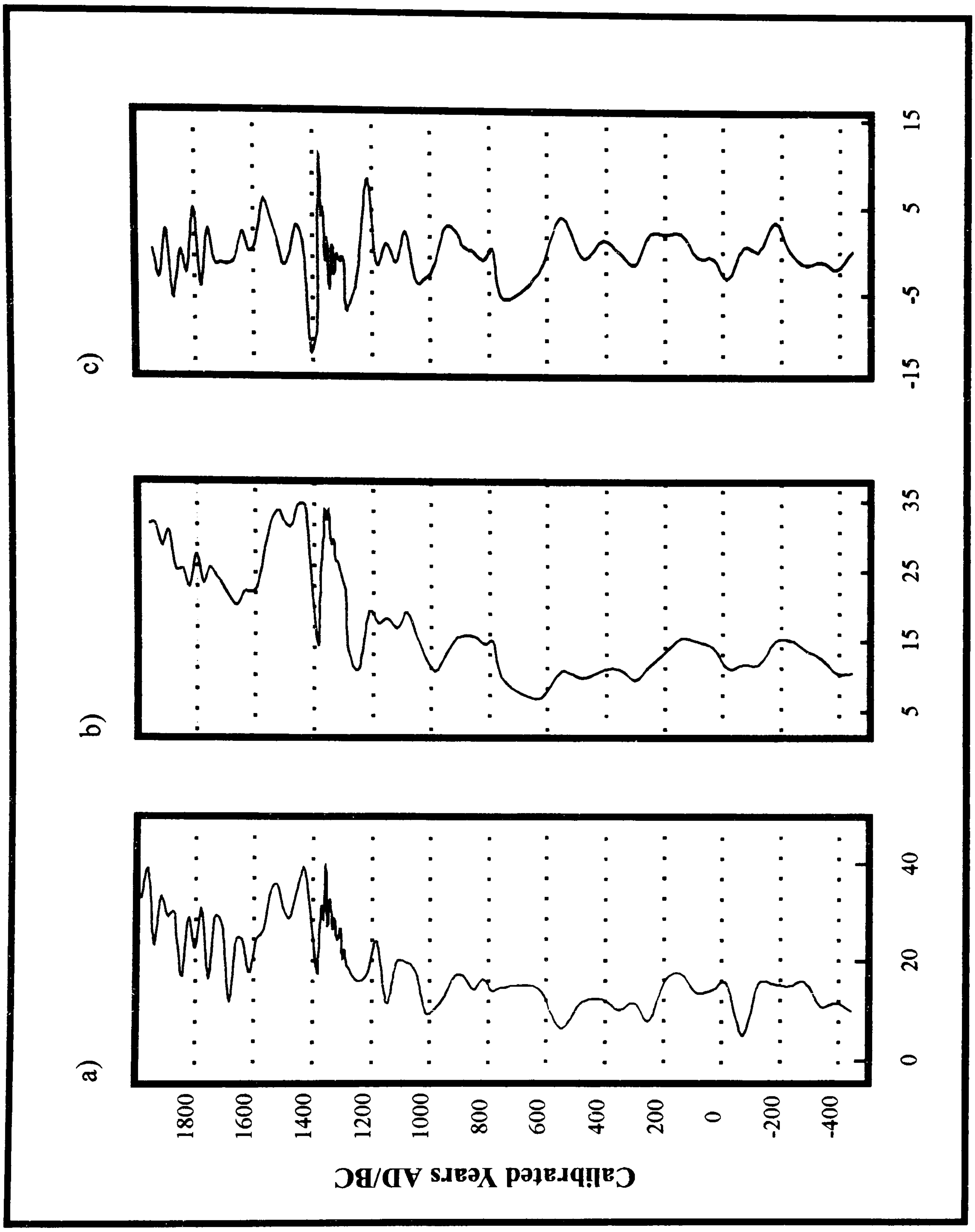


Figure 6.38. Humification data from Yarlsey Moss displaying; (a) the raw percentage light transmission values, (b) the raw data smoothed using an unweighted three point moving average, (c) the smoothed data series subjected to a high pass filter emphasising the key shifts. In all three curves higher values denote poorly humified peat and are interpreted as signifying wetter conditions.

6.4.4 Reconstructing mire surface wetness

Moisture changes are difficult to elucidate from the basal stratigraphy at the Yarlsey Moss. The stratigraphy reflects the early stages of peat accumulation at Yarlsey Moss, which initially consisted of Ericaceae and *Juncus* reed-swamp communities. After *circa* cal. AD 550 a more typical ombrogenous mire flora develops, containing *Sphagnum* species, *Eriophorum vaginatum* and Ericaceae. The initial expansion of *Sphagnum* and accumulation of *Sphagnum* peat could indicate a change to wetter conditions (Moore, 1986). However, it may equally be an early phase in the establishment of a blanket mire at Yarlsey Moss. The early history of testate amoebae at Yarlsey Moss is closely linked to the establishment of a *Sphagnum* flora, with higher frequencies of testate amoebae as the *Sphagnum* mire develops.

Subsequent hydrological changes at Yarlsey Moss are evidenced by fluctuations in the abundance of *Sphagnum*, changes in the diversity and composition of testate amoebae communities and humification changes. Hydrological indications in the peat stratigraphy are summarised on figure 6.39, which demonstrates the broad concordance between the three palaeoenvironmental procedures. The humification signal appears to recognise some moisture shifts before the other techniques, but this may reflect the impact of water table changes upon peat already within the acrotelm smearing evidence of the hydrological change several centimetres down the peat profile.

The stratigraphy pertaining to the period cal. AD 500-1000 accumulated very slowly and is difficult to interpret palaeohydrologically. The testate amoebae and plant macrofossil stratigraphy signify relatively wet conditions, but re-scaling the humification stratigraphy against time indicates the palaeohydrology maybe more complicated. The reconstructed mean annual water table values from Yarlsey Moss are problematic and should be treated with caution mainly because until cal. AD 1400 the diversity of sub-fossil communities is poor and dominated by *Hyalosphenia subflava*. The ecological transfer functions for this stratigraphy will solely be based on the environmental tolerance of the *Hyalosphenia subflava*, which is *circa* 11-6 cm (Woodland *et al.*, 1998). Using the reconstructed mean annual water table depths derived for stratigraphy of this type is unwise, probably both in terms of mathematics and ecology.

Evidence of shifts to wetter conditions occurs between cal. AD 400 and 600, with the establishment of a *Sphagnum* mire clearly synonymous with much wetter conditions. However, the causes of this event are integrally involved with the process of mire inception, which may or may not be climatically driven. Subsequent wet shifts occurred *circa* cal. AD 800, 1200-1400 and 1750-1800. The humification stratigraphy indicates hydrological conditions between cal. AD 1200 and 1400 may have been very changeable, with several clear wet shifts separated by drier

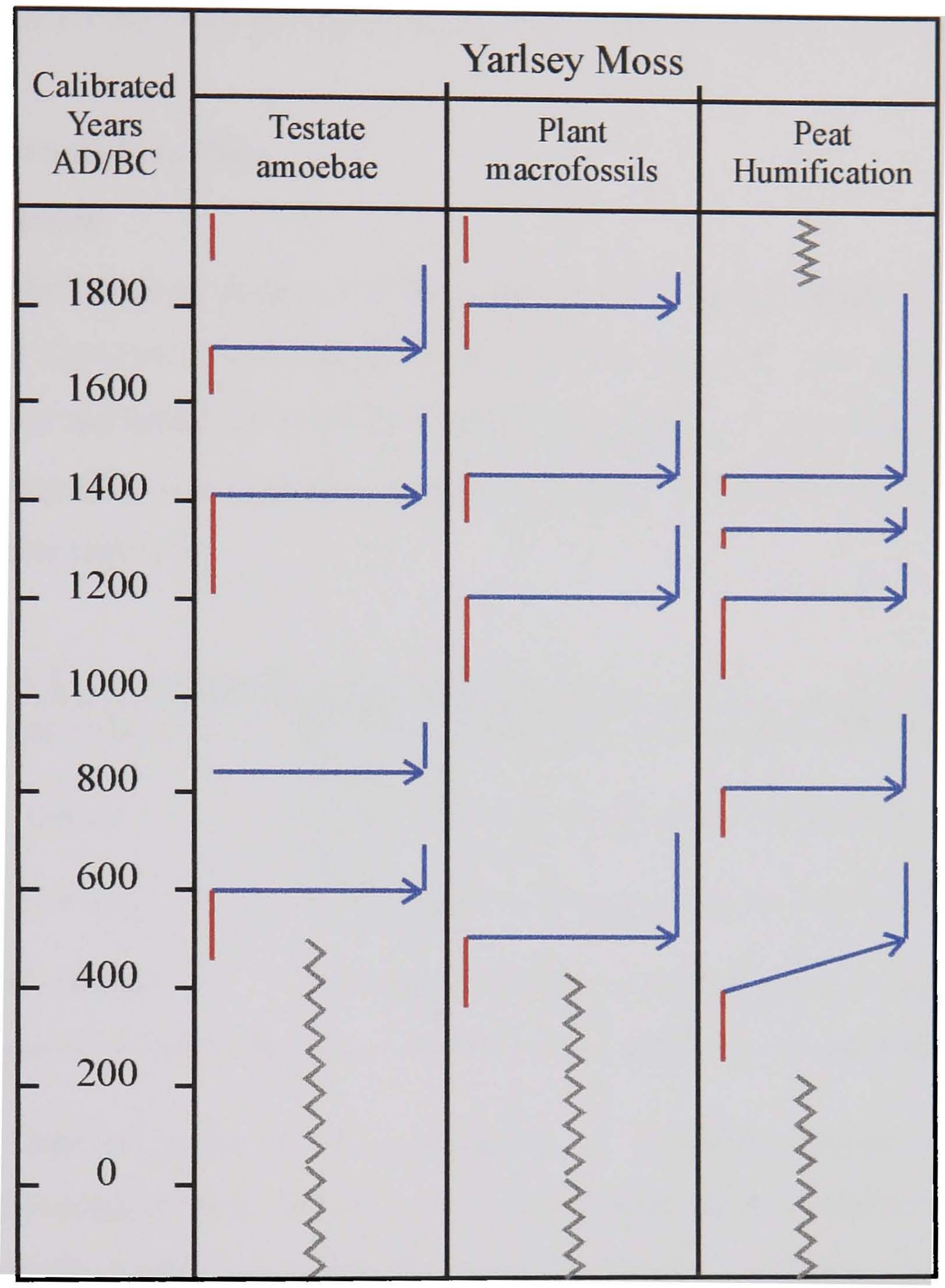


Figure 6.39. Summary of the moisture fluctuations signified in peat stratigraphies at Yarlsey Moss. Red lines denote dry conditions and blue lines wet conditions. The blue arrows signify changes to wetter conditions. Grey zigzag lines denote stratigraphy with an ambiguous hydrological signal.

phases. Evidence of drier conditions within the stratigraphy occurs *circa* cal. AD 1100-1200, 1350-1400 and 1650-1775. There is evidence of anthropogenic drying of the mire surface in the top 10 cm of peat, evidenced by the decline of *Sphagnum* and the expansion of Ericaceae. These changes reflect management of the moors for grouse during the last 100 years, which is responsible for the *Calluna vulgaris* monoculture covering Yarlsey Moss today.

6.5 Harwood Dale Bog

Introduction

Palaeohydrological investigation of the Harwood Dale Bog stratigraphy utilises a series of four monoliths (10×10×30 cm) sampled from the fresh face of a peat cutting, and entailed plant macrofossil and humification analysis. Visual examination of the exposed face demonstrated the peat stratigraphy was consistent along the cutting. A summary of the field stratigraphy is presented in table 6.6.

Table 6.6. Field stratigraphy at Harwood Dale Bog.

Peat surface	Dry mire surface covered with *Calluna vulgaris* and *Eriophorum vaginatum*.
0-6 cm	Fresh humus dominated with *Calluna vulgaris* rootlets, leaves and stems.
6-60 cm	Poorly humified *Sphagnum* and *Eriophorum vaginatum* peat.
60-108 cm	Well humified Ericaceae and *Eriophorum vaginatum* peat.

Further analysis involved the construction of a pollen diagram. Two ^{14}C dates and palynostratigraphic marker horizons were used to generate a chronology for the peat sequence. The rationale behind the chronology was introduced in chapter five. Correlation analysis identifies that a broadly linear age/depth relationship exists for the Harwood Dale Bog sequence ($r^2 = 0.998$). This linear age/depth relationship renders the palaeoecology and any eventual palaeohydrological reconstruction from Harwood Dale Bog susceptible to time series analysis.

6.5.1 Plant macrofossil data

Palaeoecology

The plant macrofossil stratigraphy is displayed in figure 6.40. The scores of the main macrofossil components on the first two axes of a detrended correspondence analysis performed on the Harwood Dale Bog data are displayed on a X/Y biplot in figure 6.41. The first two axes have eigenvalues of 0.479 and 0.192 respectively, signifying that they summarise the most significant structure within the data-set. The amount of variation explained by further individual DCA axes

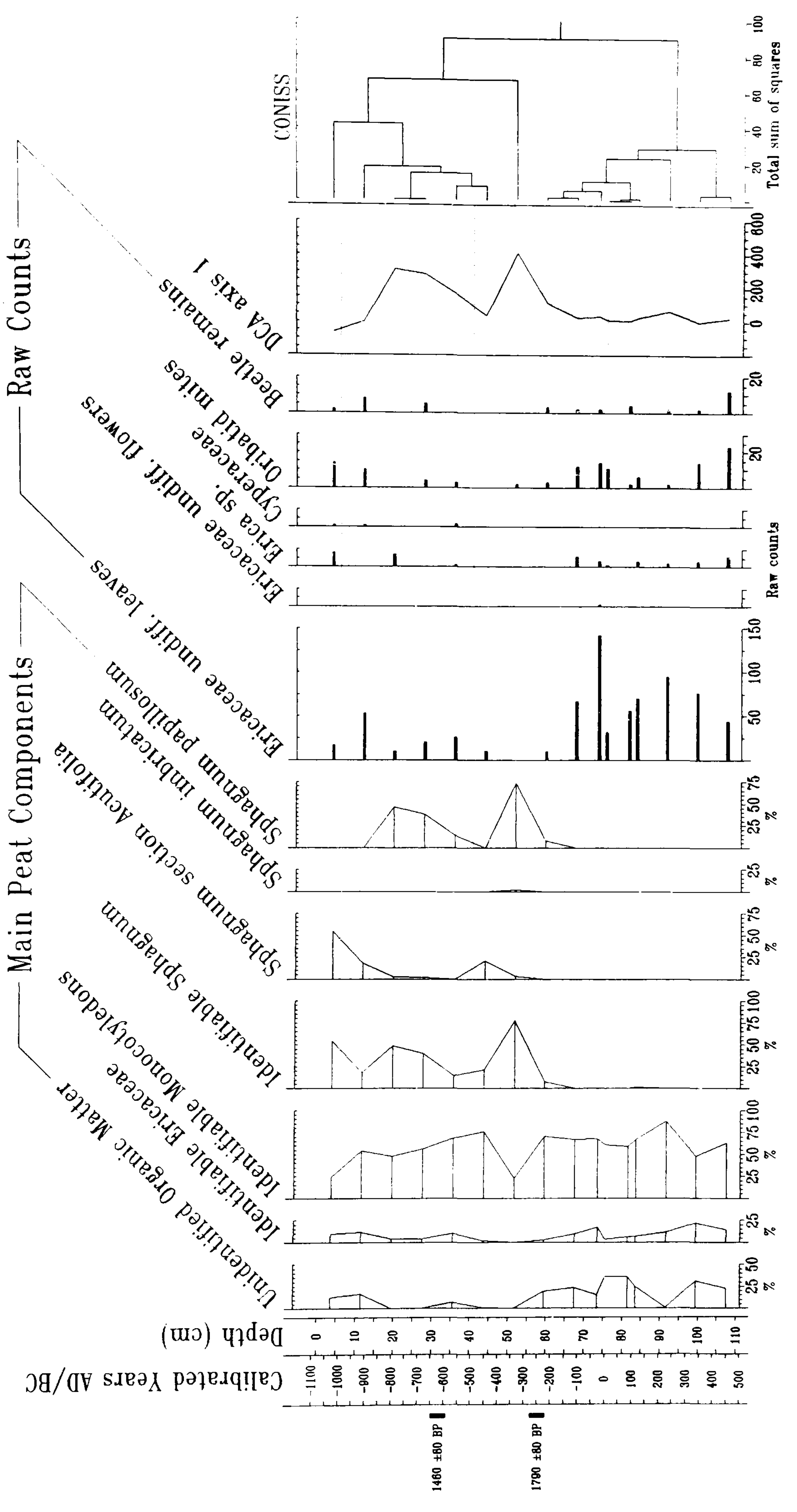
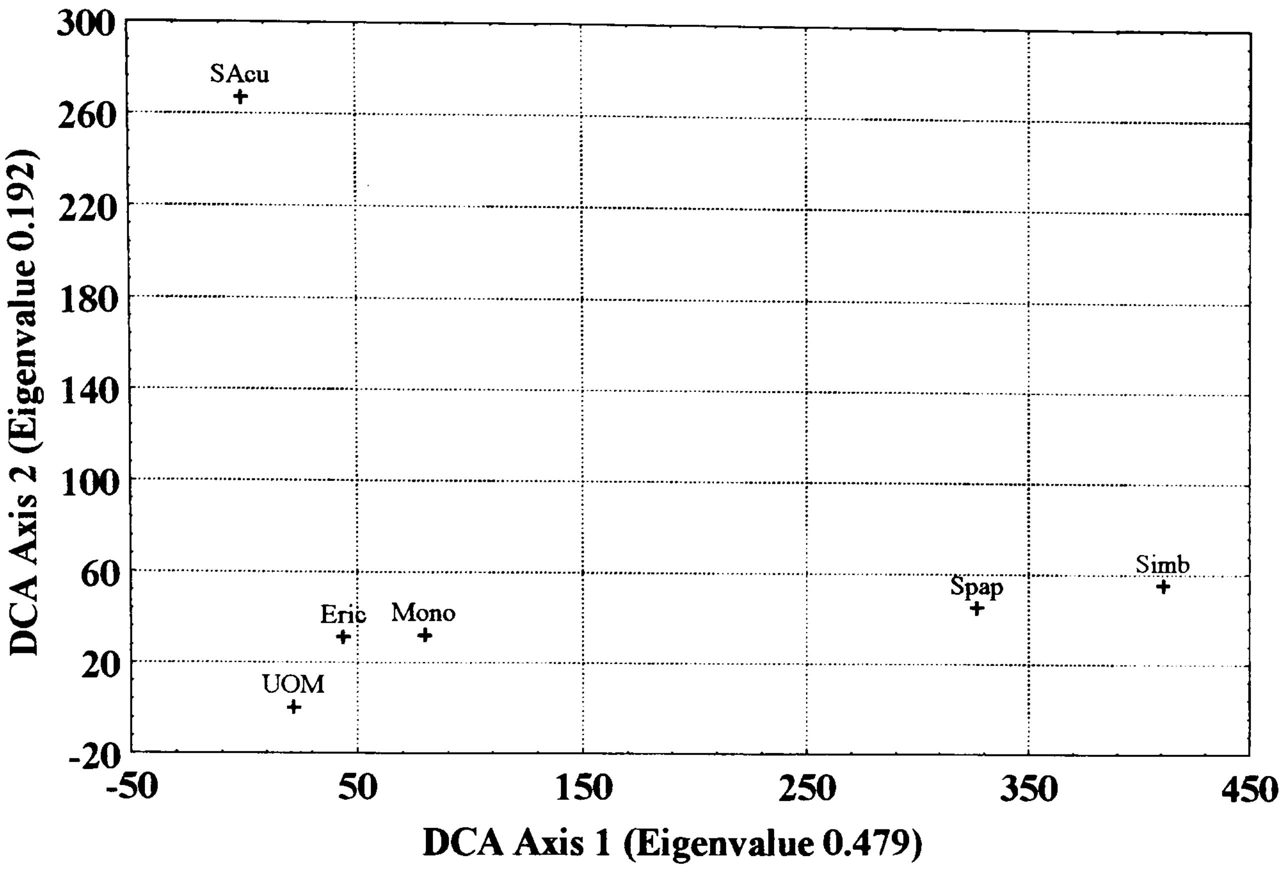


Figure 6.40. Harwood Dale Bog plant macrofossil diagram. Main peat components are expressed as percentages of the total volume of peat, with *Sphagnum* abundances based on leaf counts of a random selection of branch leaves (>100 per sample). The other curves display raw counts of leaves, seeds, flowers and selected insect remains. The sample scores on the first axis of a DCA are expressed in standard deviation units (×100); and the dendrogram presents the results of a sum of the squares cluster analysis.

a).



b).

Macrofossil components	Graph labels	DCA axis 1	DCA axis 2
Eigenvalue		0.479	0.192
% variance		52.58	21.04
Unidentified Organic Matter	UOM	-0.649 ^{b}	-0.482
Monocotyledons	Mono	-0.519 ^{a}	-0.164
Ericaceae	Eric	-0.304	-0.350
Total identifiable *Sphagnum*	Spha	0.682 ^{b}	0.541 ^{a}
Sphagnum section *Acutifolia*	Sacu	-0.317	0.913 ^{c}
Sphagnum imbricatum	Simb	0.636 ^{b}	0.026
Sphagnum papillosum	Spap	0.961 ^{c}	0.005

Figure 6.41 (a) Detrended correspondence analysis ordination diagram showing the component weighted averages on the first two axes for the Harwood Dale Bog plant macrofossil data. The axes are scaled in standard deviation units ×100. **(b)** Identifies the species labels on part (a), lists the eigenvalues for and percentage variation explained by each DCA axis and lists the correlation coefficients between DCA axes and the plant macrofossil components. The correlations are not statistically significant unless annotated by either, ^{a} = significance at the 95% level, ^{b} = significance at the 99% level or ^{c} = significance at the 99.9% level.

is minimal. Correlation coefficients between the main components of the plant macrofossil stratigraphy and the first two DCA axes, listed on figure 6.41, identify the components involved in the most significant changes in the macrofossil stratigraphy.

The main components of the Harwood Dale Bog plant macrofossil stratigraphy appear to be arranged along DCA axis 1 according to tolerance of surface wetness. Components indicative of dry environments, such as the Ericaceae, occur at the opposite end of DCA axis 1 to the wet environment components, for example *Sphagnum* section *Cuspidata*. The correlation coefficients support this conclusion with DCA axis 1 summarising variations between a "wet environment" stratigraphy and a "dry environment" stratigraphy. The wet indicators included the Sphagnaceae, which display a strong negative correlation with DCA axis 1, whereas the dry indicators, such as Unidentified Organic Matter and the Ericaceae, display a strong positive correlation.

The ecological status of *Eriophorum vaginatum* is more complicated, because the species is capable of tolerating a range of moisture conditions (Heathwaite *et al.*, 1993a). *Eriophorum vaginatum* tussocks also have a reputation for being very resilient and long-lived (Barber, 1981; Heathwaite *et al.*, 1993a). These characteristics render palaeoenvironmental interpretation using *Eriophorum vaginatum* difficult, because dense layers of *Eriophorum vaginatum* within the fossil record have an uncertain palaeoenvironmental status. This is particularly pertinent with regard to the stratigraphy between 60-110 cm on the Harwood Dale Bog peat profile. The palaeoenvironmental discussion in the following section treats *Eriophorum vaginatum* cautiously, with surface wetness reconstructions based on the other five components.

The balance of the evidence suggests that the most significant stratigraphic changes are from Ericaceae- and Unidentified Organic Matter dominated to a *Sphagnum*-dominated stratigraphy, and ecologically this signifies a shift from a dry to a wet environment. DCA axis 1 accounts for 52.58% of the total structure; consequently, further DCA axes individually explain less significant amounts of variation within the plant macrofossil stratigraphy. DCA axis 1 identifies a moisture gradient, which appears to be the most important environmental factor affecting the Harwood Dale Bog plant macrofossil stratigraphy.

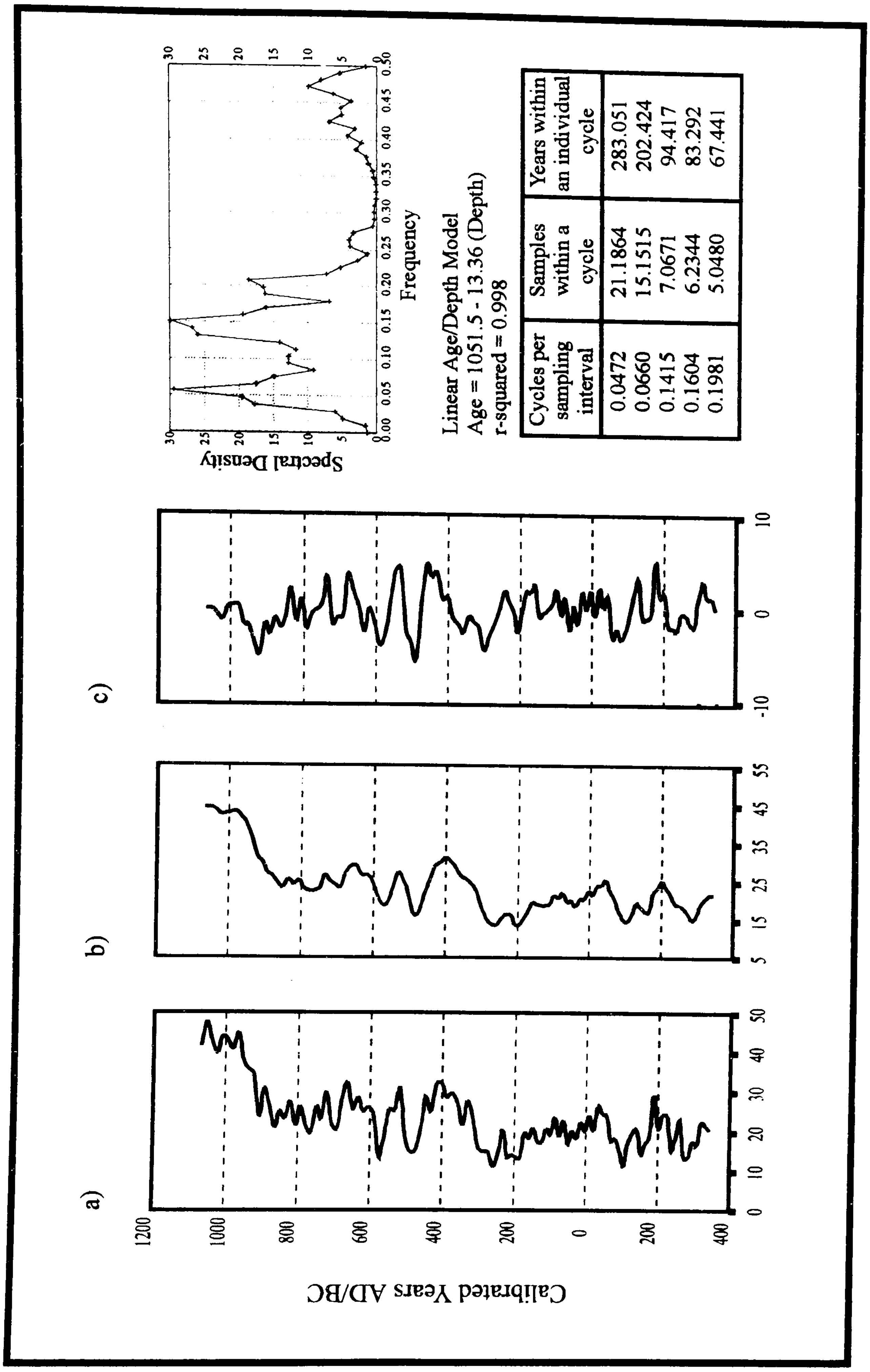
DCA axis 1 is proposed as a semi-quantitative model summarising fluctuations between wet and dry conditions on the mire surface. The sample scores on DCA axis 1 are plotted stratigraphically in figure 6.40, with high scores signifying wetter conditions and lower scores drier conditions. There are problems with using DCA axis 1 as a proxy palaeohydrological curve, because detrended correspondence analysis is more ecologically interpretable on profiles containing a greater interchange of species and larger number of samples than encountered at Harwood Dale Bog. It is possible the detrended correspondence analysis on the Harwood Dale Bog data just identifies the appearance of *Sphagnum*, and whilst this may be related to a moisture change, using the detrended correspondence analysis axes *sensu* Barber *et al.* (1994a; 1994b) is not appropriate. In subsequent discussions of the palaeohydrology at Harwood Dale Bog, changes in mire surface wetness are largely identified by qualitative ecological interpretation of the macrofossil stratigraphy, with reference to the DCA axis 1 curve.

Palaeoecology

Cluster analysis signifies that the most significant changes in the peat stratigraphy occurred *circa* cal. AD 300, 500 and 950. Between 400 cal. BC and cal. AD 300 the peat stratigraphy is dominated by Unidentified Organic Matter, Monocotyledons and Ericaceae. The raw counts of Ericaceae leaves, particularly *Calluna vulgaris*, are high, indicating the mire probably was comparatively dry. The most significant change in the Harwood Dale Bog peat stratigraphy involves the expansion of *Sphagnum* at the expense of Monocotyledons and Ericaceae remains between cal. AD 300-500. The expansion of the *Sphagnum* flora initially involves *Sphagnum papillosum*, although *Sphagnum* section *Acutifolia* succeeds *Sphagnum papillosum* between cal. AD 400-500. *Sphagnum* section *Acutifolia* are typically associated with drier habitats than *Sphagnum papillosum*, and this change maybe indicative of a shift to drier conditions. After cal. AD 500 *Sphagnum papillosum* expands signifying a return to wetter conditions until *circa* cal. AD 900. The upper 20 cm of peat stratigraphy is dominated by *Sphagnum* section *Acutifolia* signifying a return to drier conditions between cal. AD 900 and the top of the peat profile, *circa* cal. AD 1100.

6.5.3 Degree of peat humification

The results of the humification analyses are displayed in figure 6.42. The humification stratigraphy contains three shifts to poorly humified peat, which are attributed to changes to wetter conditions, *circa* 200 cal. BC, cal. AD 400 and cal. AD 500. Well humified peat signifies periods of comparatively dry conditions *circa* cal. AD 100 to 400 and cal. AD 850 to 1100. The smoothed and high-pass filtered humification data, displayed on graph (c) of figure 6.42, was subjected to spectral analysis using the Fourier transformation method and a Daniell smoothing window. The spectral density function, displayed in part (d) of figure 6.42, identifies several peaks with the most significant two centred at 0.15 cpi (cycles per sampling interval) and 0.06 cpi. The linear age/depth model indicates these frequencies correspond to 94-83 and 202 year cycles respectively.



Linear Age/Depth Model
Age = 1051.5 - 13.36 (Depth)
r-squared = 0.998

Cycles per sampling interval	Samples within a cycle	Years within an individual cycle
0.0472	21.1864	283.051
0.0660	15.1515	202.424
0.1415	7.0671	94.417
0.1604	6.2344	83.292
0.1981	5.0480	67.441

Figure 6.42. Humification data from Harwood Dale Bog displaying; (a) the raw percentage light transmission values, (b) the raw data smoothed using an unweighted three point moving average, (c) the smoothed data series subjected to a high pass filter emphasising the key shifts. In all three curves higher values denote poorly humified peat and are interpreted as signifying wetter conditions. (d) Results of the time series analysis, which includes the spectral density function for the smoothed high-pass filtered data series displayed on graph (c). The table in part (d) converts the spectral peaks into years using the age/depth model derived for the peat profile.

6.5.4 Reconstructing mire surface wetness

Figure 6.43 presents the hydrological indications in the plant macrofossil and humification stratigraphy. Comparison of the two palaeoecological techniques identifies a problem with the interpretation of plant macro-fossil stratigraphies. When stratigraphy is dominated by resilient long-lived taxa, in this case *Eriophorum vaginatum*, palaeoenvironmental changes can be masked within peat layers dominated by a single species. This is exemplified by the humification shifts between *circa* 400 cal. BC and cal. AD 200, which occur within peat dominated by *Eriophorum vaginatum* and containing no plant macrofossil evidence of hydrological changes. Clearly there are methodological advantages in applying more than one palaeoecological technique to a fossil sequence, because comparison of approaches highlights discrepancies, thereby entailing a more rigorous assessment of environmental change.

Figure 6.43 summarises the broad concordance within the remainder of the stratigraphy. The palaeoecology contains evidence of a series of wet and dry phases, which are delimited by marked shifts to wetter or drier conditions. The earliest change in moisture conditions is only evidenced in the humification curve, with a shift to wetter conditions *circa* 200 cal. BC clearly not evident within the *Eriophorum vaginatum*-dominated plant macrofossil stratigraphy. The shallowing of the mean summer minimum water depth responsible for the humification change appears to have had little impact on the surface vegetation. Wet conditions persist until there is an increase in the degree of peat humification signifying drier conditions, which persist between cal. AD 0 and 350. The most significant stratigraphic change involves the appearance of *Sphagnum papillosum* and a shift to poorly humified peat. These changes are attributed to a substantially wetter mire surface, which is ^{14}C dated to 1790 ±80 BP [cal. AD 85 (245) 415].

This wetter period is relatively short-lived, with an expansion of *Sphagnum* section *Acutifolia* and a return to well humified peat, signifying drier mire surface conditions between cal. AD 400 and 500. There is a further wet shift evidenced by poorly humified *Sphagnum papillosum*-dominated peat just below a ^{14}C date of 1460 ±80 BP [cal. AD 430 (620) 695]. Wet conditions persist up to cal. AD 850, when *Sphagnum* section *Acutifolia* dominates the macrofossil assemblages signifying an expansion of drier habitats. The humification curve contains little evidence of this moisture shift; however, the palaeohydrological signal maybe obscured by subsequent interference with the surface layers of peat. This change to drier conditions has not been ^{14}C dated, but the chronology developed for the peat sequence indicates that it occurred between *circa* cal. AD 800-900.

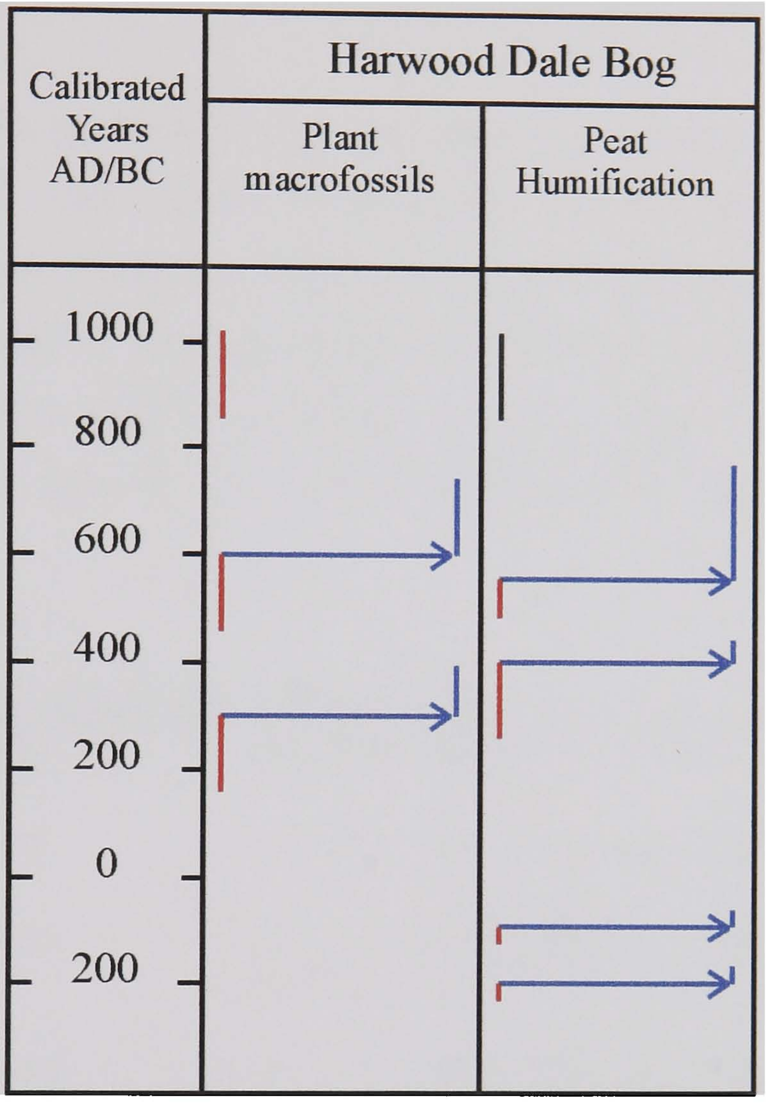


Figure 6.43. Summary of the moisture fluctuations signified in peat stratigraphies at Harwood Dale Bog. Red lines denote dry conditions and blue lines wet conditions. The blue arrows signify changes to wetter conditions. Grey zigzag lines denote stratigraphy with an ambiguous hydrological signal.

6.6 Bluewath Beck

The palaeoecological history of the Bluewath Beck peat sequence is reconstructed from a profile sampled from extensive peat cuttings near the headwaters of the catchment. The peat was sampled in five monolith tins (10×10×30cm) from the fresh face of a peat cutting. Field examination of the exposed face demonstrated the peat stratigraphy was consistent along the cutting. A summary of the field stratigraphy is displayed in table 6.7. Palaeoenvironmental analysis entailed an assessment of the plant macrofossil and the peat humification stratigraphy. Further analysis entailed the construction of a pollen diagram.

A chronology for the Bluewath Beck peat sequence is developed in chapter 5. This chronology is based on a ^{14}C dated horizon and correlation with three palynological marker horizons dated elsewhere on the North York Moors. The time series was produced by linear interpolation between the various chronological horizons transforming the palaeoecological data into time series. Correlation analysis identifies that a linear age/depth relationship does not exists for the Bluewath Beck sequence, and so the palaeoecology is not susceptible to direct time series analysis.

Table 6.7. Field stratigraphy at Bluewath Beck.

Peat surface	Dry mire surface covered with *Calluna vulgaris*.
0-22 cm	Poorly humified *Sphagnum* and Monocotyledonous peat.
22-159 cm	*Eriophorum vaginatum* peat, with occasional layers of Ericaceae and *Sphagnum*.
159-259 cm	Very well humified black peat, containing occasional wood remains.

6.6.1 Plant macrofossil data

The plant macrofossil stratigraphy is displayed in figure 6.44. Cluster analysis signifies that the most significant changes in the peat stratigraphy occurred *circa* 200-0 cal. BC, cal. AD 450-550, 900-1000 and during the Medieval period. The entire Bluewath Beck macrofossil profile is dominated by Monocotyledonous remains, which consistently contribute over 50% of the assemblage. The plant macrofossil stratigraphy does not contain the turnover of species essential for semi-quantitative palaeohydrological interpretation, and so Detrended Correspondence Analysis was not performed on the plant macrofossil stratigraphy. Quantities of Unidentified Organic Matter are also relatively high throughout the profile. Despite the dominance of Monocotyledonous remains, there are layers of Ericaceae and *Sphagnum*, which may be of palaeoenvironmental significance.

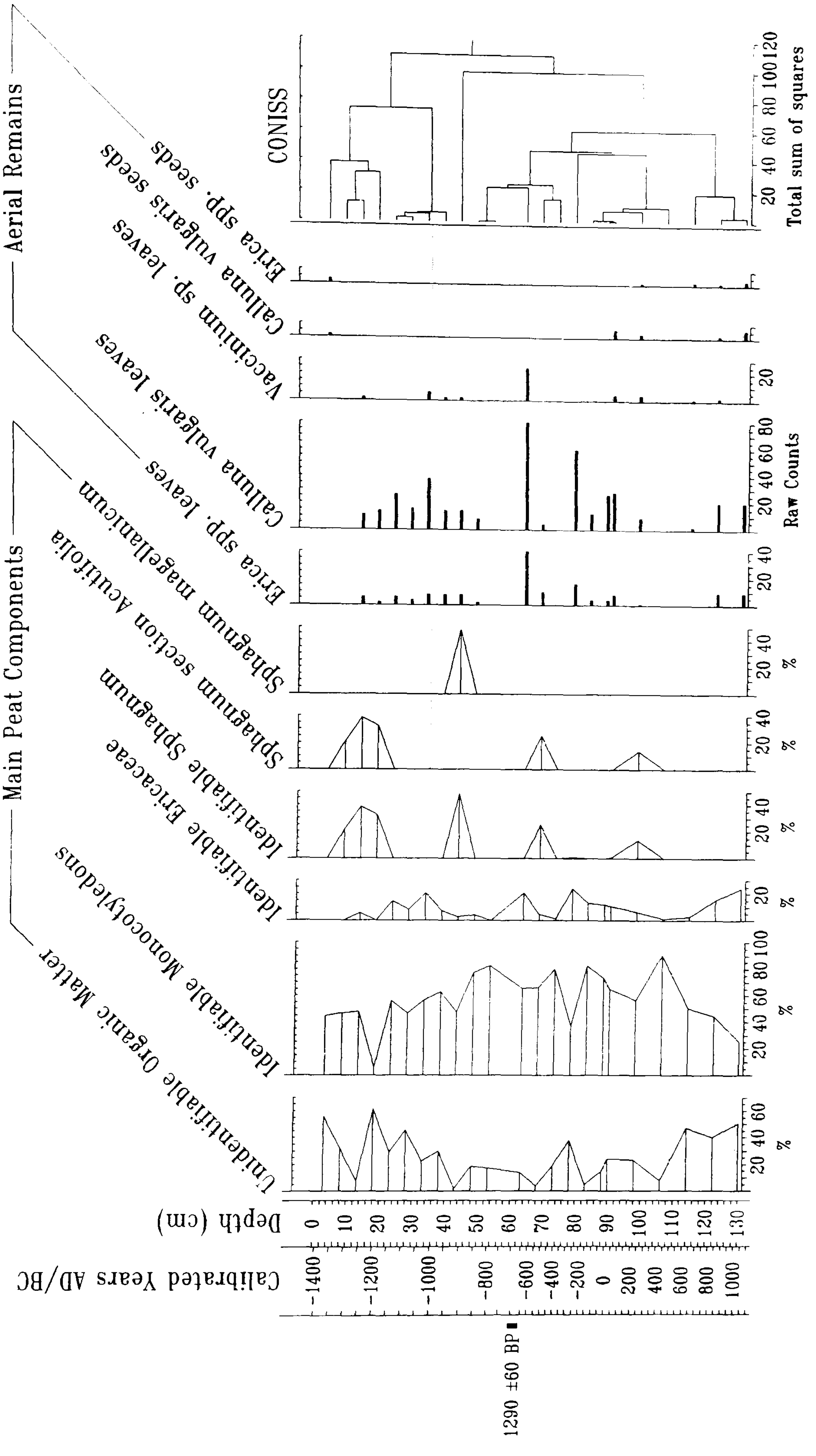


Figure 6.44. Bluewath Beck plant macrofossil diagram. Main peat components are expressed as percentages of the total volume of peat, with *Sphagnum* abundances based on leaf counts of a random selection of branch leaves (>100 per sample). The other curves display raw counts of leaves, seeds, flowers and selected insect remains. The dendrogram presents the results of a sum of the squares cluster analysis.

Sphagnum-dominated stratigraphy is typically associated with wetter conditions than Ericaceae-dominated stratigraphy. The *Sphagnum*-rich layers may signify wetter conditions *circa* 300-0 cal. BC, cal. AD 400-600, cal. AD 900-1000 and cal. AD 1200-1400. The intervening periods are dominated by either Ericaceae or Monocotyledonous remains, and whilst not providing equivocal evidence of dry conditions, the indications are that the environment was almost certainly less wet. Peat deposits blanketing the Bluewath Beck catchment have been affected by peat cutting and the peat profile appears to terminate during the late Medieval period. Unfortunately the chronology of the upper stratigraphy is not secured by independent dating of the peat, and so the chronology of palaeohydrological history can only be regarded as tentative.

6.6.2 Peat humification data

The results of the humification analyses are displayed in figure 6.45. The humification stratigraphy contains three shifts to poorly humified peat, which are attributed to changes to wetter conditions, *circa* cal. AD 400, 600, 900 and during the late Medieval Period. Phases of well humified peat signify comparatively dry conditions between cal. AD 100-350, 700-900 and 1000-1200.

6.6.3 Reconstructing mire surface wetness

There are two major problems with the palaeoecological record at Bluewath Beck, but despite this the stratigraphy manages to yield useful palaeohydrological information. The first problem stems from difficulties in elucidating palaeoenvironmental information from plant macrofossil stratigraphy dominated by a single fossil group and containing little interchange of species. The second problem arises from uncertainties regarding the chronology of the Bluewath Beck profile. Although a ^{14}C date does anchor the chronology developed for the profile, the remainder is largely estimated from palynological marker horizons that are less clear than at the other sites. Despite these problems, a series of fluctuations in mire surface wetness is evidenced in the peat stratigraphy and summarised on figure 6.46.

Comparison of the hydrological indications identifies a broad agreement between the palaeoenvironmental procedures. *Sphagnum*-rich stratigraphy *circa* 300-50 cal. BC signifies wetter conditions during the Iron Age. Subsequently well humified Ericaceae-rich peat identifies comparatively dry conditions during the Roman period. *Circa* cal. AD 400-500 a shift to poorly humified peat and the expansion of *Sphagnum* signify a wetter environment. *Circa* cal. AD 600-700 well humified Ericaceae-rich peat appears to identify drier mire surface conditions. There are a series of shifts to poorly humified peat between cal. AD 700 and 1000, with the most

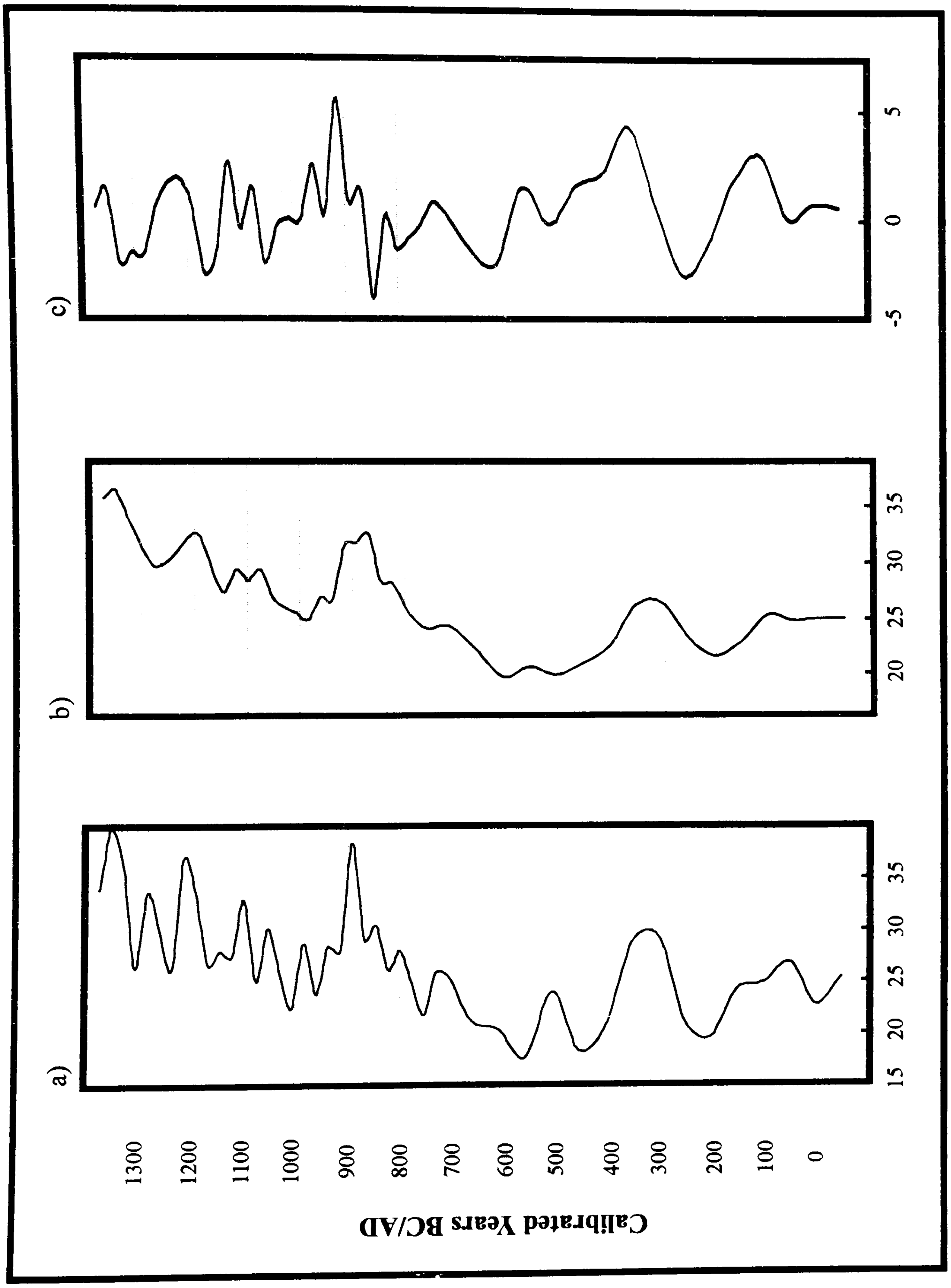


Figure 6.45. Humification data from Bluewath Beck displaying; (a) the raw percentage light transmission values, (b) the raw data smoothed using an unweighted three point moving average, (c) the smoothed data series subjected to a high pass filter emphasising the key shifts. In all three curves higher values denote poorly humified peat and are interpreted as signifying wetter conditions.

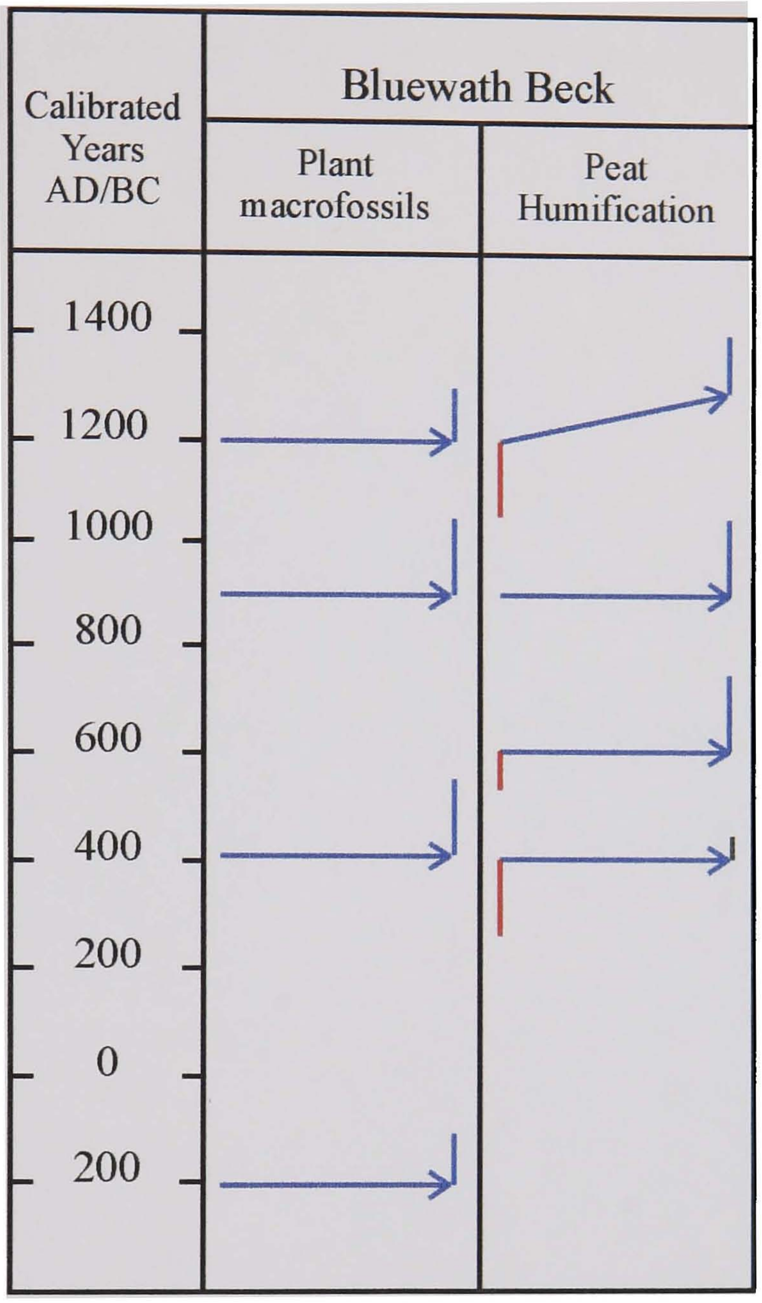


Figure 6.46. Summary of the moisture fluctuations signified in peat stratigraphies at Bluewath Beck, Glaisdale Moor. Red lines denote unequivocal dry conditions and blue lines wet conditions. The blue arrows signify changes to wetter conditions. Grey zigzag lines denote stratigraphy with an ambiguous hydrological signal.

significant change *circa* cal. AD 900. The humification plateau and abundant Ericaceae remains may signify a drier phase between cal. AD 650 and 900. Stratigraphy dominated by *Sphagnum magellanicum* provides evidence of a change to wetter conditions supported by the humification change *circa* cal. AD 900. Well-humified Ericaceae-rich peat signifies a drier phase during the early Medieval period. A subsequent expansion of *Sphagnum* section *Acutifolia* and shift to poorly humified peat signifies a return to wetter conditions during the late Medieval Period. This phase with a relatively wet mire surface continues up to the surface of the peat profile, which is believed to terminate *circa* cal. AD 1400-1500.

7

Proxy evidence of climate change

7.1 Introduction

The palaeohydrological history developed for the North York Moors in chapter six was elucidated using the peat stratigraphy of five mires. With the exception of Fen Bogs these mires are all ombrotrophic; consequently, fluctuations in mire surface wetness for the most part will reflect a response to climatic wetness or more accurately "effective precipitation". Theoretically, interpretation of the palaeohydrological record derived for each site should provide an invaluable record of climate change, but in practice the interpretative procedure is far more complex. These complexities are mostly unavoidable, involving uncertainties with;

- inferring palaeohydrology from peat stratigraphy, and uncertainty in the link between mire hydrology and climate;
- problems with the chronologies generated for the peat sequences and particularly problems with ^{14}C age determinations.

Testate amoebae, plant macrofossil and humification stratigraphies not only combine to produce a palaeohydrological history for a particular location on a mire, but double as a quality assurance exercise to assess the comparative performance of each palaeoenvironmental technique. This process should identify circumstances and types of stratigraphy in which the palaeoenvironmental procedures record little or no hydrological information. Palaeoenvironmental research utilising peat stratigraphy is hampered at the outset by the lack of analytical procedures that can reconstruct a specific climatic or environmental parameter, for example precipitation. There are limitations to all the palaeoenvironmental procedures and they constrain palaeohydrological interpretation of peat stratigraphy. Precision of palaeohydrological interpretation of peat stratigraphy is traditionally limited to identification of fluctuations between wet or dry conditions. It is difficult to envisage methodological developments that will substantially alter these circumstances.

Utilising the hydrological histories of several ombrogenous mires to identify climatic fluctuations is a well established procedure. It is tempting in the wake of this wealth of published research to ignore other causes of hydrological change, which include mire drainage either through human activity, mire erosion or bog-bursts; the accumulation of peat altering the surface topography, for example in-filling of hollows and migration of soak-ways; and features integral to the development of a mire, for example transgressive hydrological events associated with mire expansion. In the case of blanket mires some of the above factors are controlled to some extent by sub-surface topography and can be identified by careful interpretation of the sedimentary history of a mire. The hydrological indications derived from several mires are integrated to produce a palaeoclimate history for the North York Moors. However, there are problems with correlation of peat sequences, because the correlations rely upon independent chronologies derived for each peat sequence, and unfortunately there are uncertainties with ^{14}C dating of peat sequences.

Despite the problems introduced above the evidence from peat sequences on the North York Moors is drawn together producing a climate history for the region. This climate history bears interesting comparison with previous peat stratigraphic research, especially from mires experiencing a wetter climate than the North York Moors. Comparison with other types of palaeoclimatic information is also of interest, involving a variety of sources that reconstruct specific climatic variables, for example temperature or precipitation. The discussion of other types of palaeoclimate evidence focuses upon climate variations identified in north-west Europe. Finally the issue of the causes of climate change is discussed, with the 2000-year effective precipitation history derived for the North York Moors displaying extremely interesting parallels with hypothesised forcing agents of global and regional climate change.

7.2. Palaeohydrological interpretation of peat stratigraphy

The principal method of obtaining quality assurance in peat stratigraphic research involves using several analytical procedures and several core profiles to corroborate the stratigraphic history. The use of replicate profiles and several palaeoenvironmental procedures addresses several important issues, which include

- is any individual or combination of palaeoenvironmental procedures essential for uncovering the hydrological history of a blanket mire?
- are there circumstances in which moisture changes fail to leave an imprint within the testate amoebae, plant macrofossil and humification stratigraphy?
- does a particular technique perform better than the others, either consistently or in specific circumstances?
- should the variability of blanket peat stratigraphy be assessed? and how many sites are required to uncover the hydrological history of a blanket mire?

Investigations at May Moss uncovered significant stratigraphic differences across a blanket bog, and some of these variations cannot be solely linked to climatic forcing of mire palaeohydrology. The expansion of *Sphagnum*-rich peat over monocotyledonous and Ericaceae peat spreading from accumulating centres in the Eller Beck and Long Grain catchments is a stratigraphic change that does not solely occur in response to climate change. The expansion of *Sphagnum*-rich peat, *circa* cal. AD 400, could have been triggered by climate, but the continued expansion of the *Sphagnum* mire facies entails a hydrological change that is not directly related to a climatic fluctuation (Heathwaite *et al.*, 1993a; Smith & Taylor, 1989). Lateral paludification of *Sphagnum* peat in this case over a mor humus soil also affects the basal stratigraphy at Yarlsey Moss.

Blanket mires differ from raised mires in that topography plays a greater role in controlling peat stratigraphy. Raised mires are dome-shaped lowland features that expand over the surrounding landscape by lateral paludification from the mire centre. The initial centres for peat accumulation are typically flat and poorly drained. Upland blanket peat also initially accumulates in poorly drained areas, for example in basins and in low gradient channels. As peat accumulates the mire expands from these centres by lateral paludification over an undulating topography and subsequent changes in mire facies may operate in a similar manner. Clearly the subsurface topography of blanket mires is an important factor that will affect the eventual stratigraphy, because it controls local drainage and governs the lateral paludification process.

In summary, substantially different stratigraphic records can be produced from different locations across a blanket mire. Consequently, an understanding of the sedimentary evolution of a mire is critical and the location of core sites is an important decision for palaeoenvironmental research. In the case of Yarlsey Moss, Bluewath Beck and Harwood Dale Bog hydrological histories are based upon a single peat profile, and corroboration of the stratigraphy is provided by using several analytical procedures and by thoroughly assessing the stratigraphy in the field.

Four adjacent peat profiles at May Moss site C reveal a broadly identical sub-fossil testate amoebae and plant macrofossil stratigraphy, which indicates that a single peat profile is capable of yielding a representative assessment of the stratigraphy at that particular location. This uniformity of the stratigraphy supports the findings of previous plant macrofossil analysis of blanket peat sequences in the south Pennines (Tallis, 1994). However, this type of replicate analysis has not previously been applied to testate amoebae analysis and the uniformity of the stratigraphy encountered at May Moss is reassuring. Despite the broad uniformity of sub-fossil stratigraphy, there are distinct differences in the clarity of the moisture signal available from hollow and hummock peat sequences. Moisture changes are less evident in hummock stratigraphy, perhaps reflecting the topographic buffer afforded by a hummock.

The subdued nature of fluctuations in sub-fossil stratigraphies beneath hummocks supports a widely held view that hollow peat sequences are more suitable for palaeohydrological research (Aaby, 1976; Barber, 1993; Stoneman, 1993). Water table fluctuations are controlled by a combination of moisture availability and the hydrological capacity of the mire; consequently, the level of the water table is partially controlled by permeability of the acrotelm (Ingram, 1983). Flat water tables tend to occur within mires with a highly permeable acrotelm, whereas mires with lower and variable permeability of the acrotelm have an undulating water table (Ingram 1983). At May Moss dense *Sphagnum capillifolium* hummocks, perhaps with a less permeable acrotelm, are surrounded by *Sphagnum papillosum* and *Sphagnum recurvum* hollows with a more permeable acrotelm, providing circumstances that could produce an undulating water table (Ingram, 1983; Eggelsmann *et al.*, 1993).

Fluctuations in sub-fossil testate amoebae assemblages reflecting moisture changes appear more clearly in hollow peat sequences, with *Hyalosphenia subflava* abundant in hummock stratigraphy whatever the conditions. Local topographic control of testate amoebae communities is not a new idea. Grospietsch (1958) erected habitat categories distinguishing between hummock and hollow testate amoebae communities. Investigations at May Moss support this to some extent, even though water table depth and the hydrological balance of the entire mire are the dominant factors controlling both hummock and hollow testate amoebae stratigraphy. Mire topography exerts a similar control over the distribution of plant species, with *Sphagnum capillifolium*, *Sphagnum papillosum* and *Sphagnum imbricatum* dominating the stratigraphy beneath hummocks and *Sphagnum recurvum* mosty occurring within stratigraphy beneath present day hollows.

A similar degree of uniformity does not occur in the humification stratigraphy. The majority of humification changes at May Moss are evident in adjacent profiles; however, occasionally humification shifts are present in one core and not present or are of a different magnitude in the other: for example the shift to poorly humified peat *circa* cal. AD 500 is not represented in both cores at site C and there are differences between the two humification profiles before cal. AD 800 at site D. Localised variations in rates of acrotelmic decay and imprecision in the measurement procedure could explain these inconsistencies. Errors could arise from differential rates of decay between certain plant species, although this should not be to the detriment of the palaeohydrological record (Blackford & Chambers, 1993). In any case the plant macrofossil stratigraphy is very similar in profiles at May Moss sites C and D, alongside these inconsistencies in the humification stratigraphy.

Percentage light transmission through an alkali extract of humic acid is only a semi-quantitative estimation of the degree of peat humification, and the complexity of humic compounds renders it difficult to envisage improvements to the analytical procedure. Blackford & Chambers (1993) rigorously tested the alkali extraction procedure finding the methodology capable of producing sound replicable results, a view confirmed in this research. Adjacent blanket peat sequences in western Eire yielded broadly identical humification stratigraphies, although the magnitude and character of some of the humification shifts is clearly variable (Blackford & Chambers, 1995). Caseldine *et al.* (1998) encountered a deterioration to wet climatic conditions *circa* 2200 cal. BC, contemporaneous with the Hekla 4 volcanic ash layer, in humification stratigraphies from Corlea raised mire, county Longford, Eire (Caseldine *et al.*, 1998). However, the humification shift is not evident in all peat profiles, and further research on an adjacent mire encountered similar inconsistencies with Iron Age humification stratigraphies (Caseldine *et al.*, 1998; unpublished).

It is difficult to account for the discrepancies encountered in the humification stratigraphy at May Moss. However, it is possible that local circumstances including variations in the permeability of the acrotelm, topographic variations of the water table, and fluctuations in the abundance of micro-organisms and bacteria, could be responsible for these inconsistencies in the humification stratigraphy of a mire. The potential for variations in humification stratigraphy indicate that a minimum of more than one core should be used to uncover the humification stratigraphy of a particular location.

Comparison of testate amoebae, plant macrofossil and humification stratigraphies within a single core reveals slight discrepancies in the response to moisture changes. There is a broad degree of parallelism between the moisture signal within testate amoebae, plant macrofossil and humification stratigraphies, exemplified by the association between abundant *Sphagnum* remains and high diversity testate amoebae communities. The majority of testate amoebae species typically inhabit *Sphagnum* mires (Tolonen, 1986; Tolonen *et al.*, 1992), and so this association is not unexpected. However, the testate amoebae sub-fossil record occasionally appears to be affected by moisture shifts, when no significant change is recorded in the plant macrofossil stratigraphy.

The timing of the moisture shifts appears to vary slightly between techniques, although by no means consistently. The humification signal in many cores appears to respond before the other techniques. However, this may be illusory, because water table fluctuations and movements of the acrotelm/catotelm boundary will affect peat that has already accumulated. This means a hydrological change may affect the degree of humification of peat predating the hydrological event. Discrepancies in the timing of moisture shifts between the techniques reflect;

- the ability of plants and organisms to tolerate adverse environmental conditions;
- variations in the speed of response to hydrological changes;
- differences in the environmental parameters that affect the testate amoebae, plant macrofossil and humification stratigraphies.

Testate amoebae are seasonally active, and they potentially are susceptible to rapid environmental changes. Plants and notably some *Sphagnum* species are capable of surviving adverse conditions, recovering after seasonal desiccation (Daniels & Eddy, 1990). Furthermore changes in plant communities typically take time (Wheeler, 1993), whereas changes in testate amoebae communities can occur rapidly (Buttler *et al.*, 1996). Humification changes occur in a completely different manner, because the degree of peat humification reflects several decades spent under aerobic conditions in the acrotelm; consequently, the humification signal reflects average moisture conditions over several years. Clearly differences in the speed of ecological and diagenetic response to moisture fluctuations affects the consistency of the moisture signal within a single core, indicating that several palaeoenvironmental procedures should be used to analyse a peat sequence.

The degree of peat humification broadly reflects fluctuations in the acrotelm/catotelm boundary, which typically is located at the depth of the mean minimum summer water table (Ingram, 1978; Clymo, 1984). Consequently, humification analysis semi-quantitatively models changes in the depth of the summer water table. The hydrological changes elucidated from plant macrofossil stratigraphy are only qualitative, derived using the environmental preferences of specific plant species. The occurrence of testate amoebae species is controlled by water table depth and this association is used quantitatively to model the depth of mean annual water table. The hydrological link between testate amoebae communities and mean annual water table bears further scrutiny. Testate amoebae communities are active between May and October, with the reproductive cycle occurring during summer months. Mean annual water table depths inferred from testate amoebae stratigraphy (*sensu* Woodland *et al.*, 1998), could be improved by using seasonal mean water tables, because testate amoebae communities are more likely to be affected by environmental conditions during summer months.

Nevertheless, the reconstructed mean annual water table depths inferred from testate amoebae stratigraphy are the most precise of the environmental reconstructions presented in this thesis. However, precision and accuracy are not the same thing, and the reconstructed mean annual water table values are perhaps best regarded as a semi-quantitative indication of moisture conditions. Water table reconstructions generated for stratigraphy dominated by a single species, as occurs in drier stratigraphy on the North York Moors, should be treated cautiously. The accuracy of the estimated values can also be challenged, because average water table depths during the active part of their life cycle are more likely to control the abundance of testate amoebae species than annual averages, especially with mires affected by pronounced seasonal water table fluctuations.

Reservations over the accuracy of the water table values do not detract from their palaeoenvironmental value as a semi-quantitative tool, and clearly confidence is increased when the reconstructed mean annual water table depths are derived from more diverse sub-fossil assemblages. Plant macrofossil and humification analysis only provide semi-quantitative and qualitative information about past moisture conditions, which is perhaps why palaeoclimate histories uncovered from peat stratigraphy concentrate upon major hydrological changes, the wet shifts (Barber, 1981; Barber *et al.*, 1994a; 1994b; 1994c; Blackford & Chambers, 1991; 1995; Tallis, 1994).

Dry events are particularly clearly represented in peat stratigraphies on the North York Moors. Dry conditions are evidenced by either abundant *Sphagnum* section *Acutifolia* remains or the replacement of *Sphagnum* dominated stratigraphy with Ericaceae-Monocotyledonous peat, with occasional *Hypnum jutlandicum* remains. Drier conditions are evidenced the testate amoebae sub-fossil record by low diversity communities dominated by *Hyalosphenia subflava*. All the peat sequences contain evidence of a series of fluctuations between wet- and dry-indicating stratigraphy. Peat bogs on the North York Moors appear to be particularly affected by drier periods, with radical changes in the testate amoebae and plant macrofossil communities. The evidence for drier conditions *circa* cal. AD 200-400, 700-800, 1100-1200, 1300-1400 and 1550-1600 is particularly clear. These changes are too severe to be caused by autogenic bog growth and almost certainly are the product of climate change.

Moisture shifts to particularly dry conditions of this magnitude have been encountered elsewhere in the British Isles, but they are under-used in terms of elucidating climate histories. The reasons for this are understandable, because under stable climatic conditions a mire should grow gradually and it is possible that the rising mire surface may outpace corresponding upward movement of the water table, and the stratigraphy produced will be very similar to that signifying a change to a drier climate (Aaby, 1976; Blackford, 1993). This cautious approach is particularly pertinent at sites with stratigraphy that only allows the application of a single palaeoenvironmental procedure; for example, well humified peat will have few discernible macrofossils, where humification analysis may be the only possible methodology capable of elucidating meaningful palaeohydrological information. In the case of poorly humified peat, rich with plant macrofossils, testate amoebae and other micro-fossils, the wealth of fossil evidence and comparatively excellent chronological resolution of the stratigraphy enables the nature of drier events to be investigated. Rapid expansion of vegetation and testate amoebae communities which prefer drier environments are more likely to arise in response to climate changes. The humification signal, particularly in mires with a season of unwaterlogged surface conditions, should also identify phases of wetter and drier climate (Blackford, 1993).

Unfortunately the identification of wet and dry events polarises palaeohydrological interpretation of peat stratigraphy to fluctuations between moisture extremes, and albeit indirectly, this avoids the issue of periods with average moisture conditions. However, at present the precision of palaeohydrological information hampers fine-tuning the hydrological signal, with, accepting the problems discussed above, the reconstructed mean annual water table depths available from testate amoebae analysis providing the clearest and most precise evidence of moisture conditions. Ostensibly the best approach for elucidating climatic information from ombrogenous peat deposits is to use as many techniques as possible, uncovering the environmental history of the mire. This process can only be aided by including as many components of the mire ecosystem and diagenetic history in the palaeoenvironmental assessment.

The scale of the investigations at May Moss has implications for future research using blanket peat stratigraphy. The broad uniformity of the hydrological signal encountered in adjacent cores indicates that a single profile should be sufficient to provide a hydrological assessment of a site, with hollow stratigraphy providing the clearer record. However, minor discrepancies and the fallibilities of palaeoenvironmental procedures indicate that assessment of the uniformity of the stratigraphy is prudent. This can be achieved either by corroboratory analysis of an adjacent core or by recording the field stratigraphy in detail. Analysis of adjacent cores obviously increases confidence in the eventual hydrological interpretation of the stratigraphy. The investigations at May Moss identify a complex evolutionary history, which demonstrates that stratigraphic changes are produced within the process of mire development. Understanding the sedimentary history of a mire is critical, particularly if the intention is to link hydrological changes with climate. The hydrology of upland blanket mires can be affected by factors other than climate;

consequently, a knowledge of the development of a mire is critical, because topographically controlled mire expansion and probably erosion will have an impact on peat stratigraphy.

Testate amoebae, plant macrofossil and humification analysis as palaeohydrological tools are not without problems and all have circumstances when the yielded hydrological signal is unclear; for example, testate amoebae are less abundant and the communities less diverse in peat lacking *Sphagnum* remains and perhaps of more concern humification stratigraphies are occasionally and inexplicably inconsistent. In essence the multiple technique approach provides several lines of evidence and is the best option. In terms of the precision of the hydrological signal the reconstructed mean annual water table derived from sub-fossil testate amoebae is best, and although palaeohydrological value of testate amoebae, plant macrofossil and humification stratigraphies are all subject to limitations, they all provide indications of wet and dry conditions.

7.3 ^{14}C dating blanket peat sequences

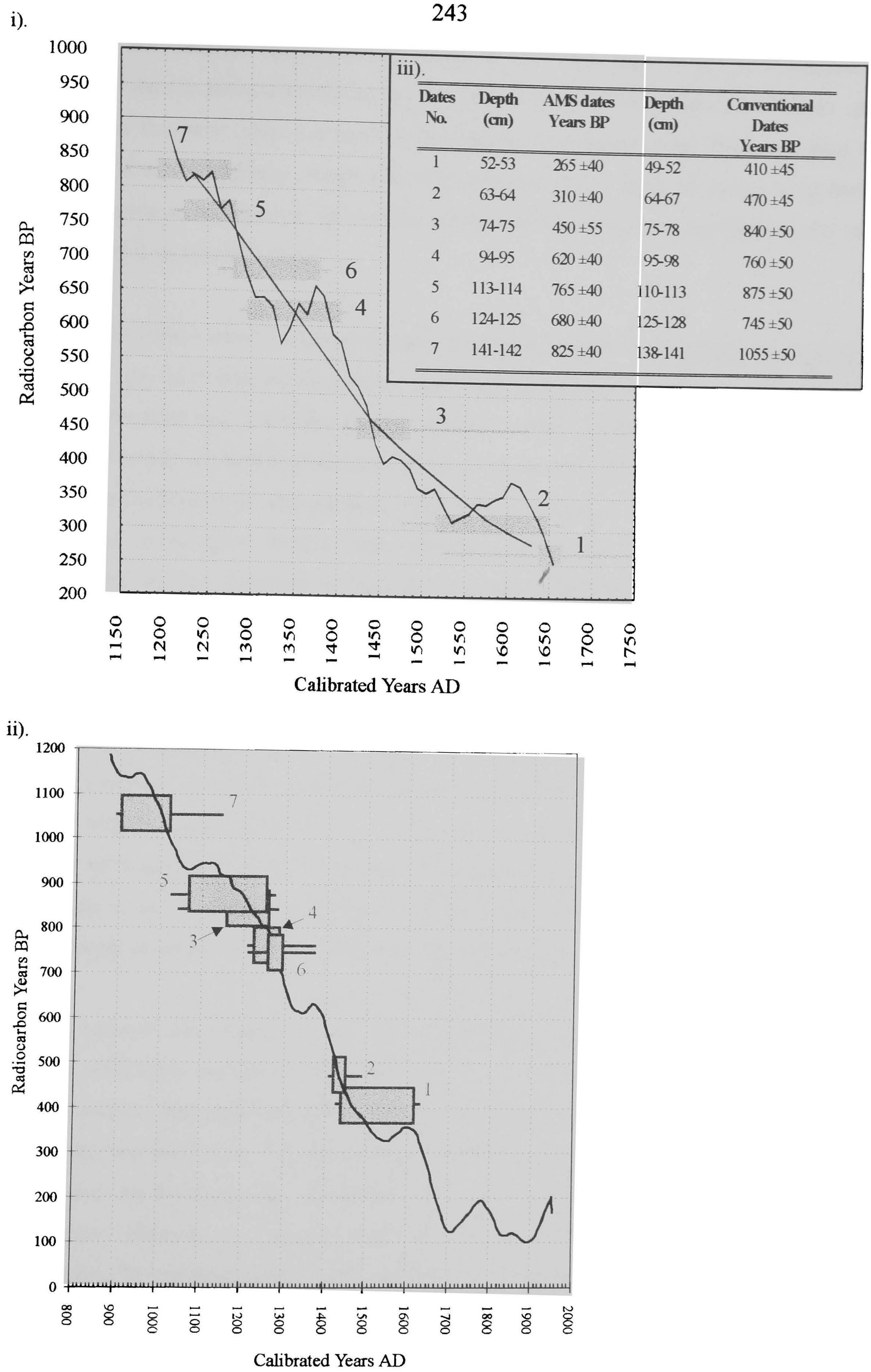
The time series generated for peat sequences on the North York Moors are secured by ^{14}C age determinations. However, as a geochronological procedure ^{14}C dating of peat has attracted critical reappraisal in recent years. This reappraisal questions both the accuracy and precision within conventional applications of the ^{14}C procedure. Three different ^{14}C methodologies have been utilised in this research. The ^{14}C age determinations on peat from Yarlsey Moss, Harwood Dale Bog and Bluewath Beck were radiometric decay assays utilising the alkali- and acid-insoluble humin fraction of bulk peat samples. The ^{14}C age determinations on May Moss cores C3 and D2 were radiometric decay assays utilising the acid-insoluble fraction of bulk peat samples, which includes both humic acid and the humin fraction.

A further suite of ^{14}C age determinations from May Moss core C3 were AMS assays analysing virtually pure hand-picked *Sphagnum* remains (*circa* 99%). Both radiometric and AMS ^{14}C age determinations on May Moss core C3 were from the same horizons, differing only in that the radiometric dates utilised a 3 cm vertical interval of peat, with the AMS dates utilising a 1 cm vertical interval from immediately above or below the conventional sample. The reasons for obtaining the AMS dates were introduced in chapter four. Basically this approach assesses whether dates obtained upon *Sphagnum* remains differ from ^{14}C age determinations on bulk peat samples. Peat is a heterogeneous sediment and dating *Sphagnum* remains may signify whether the relative ages of different components affects the accuracy of radiometric dates on bulk peat samples. Should discrepancies occur then a formal and comprehensive assessment of ^{14}C dating of peat may be in order.

The ^{14}C dates are listed and displayed graphically against a dendrocalibration curve in figure 7.1, which compares the radiometric and AMS age determinations. Comparison of the two suites of dates from May Moss core C3 reveals substantial differences, with only the ^{14}C age determinations from horizon six overlapping at the 1 sigma error. There are fundamental problems with the set of ^{14}C age determinations, with the radiometric dates between 65-390 years older than the AMS determinations. These discrepancies cannot really be explained by the differences in sample size and minor differences in the stratigraphic location of the samples. Furthermore assays 3-6 overlap within their respective 2 sigma range, which indicates that the differences between the assays are not statistically different. The radiometric ^{14}C age determinations are also not in a chronological order. The AMS ^{14}C age determinations behave better in terms of chronological order, with assay six out of sequence. The 2-sigma ranges of AMS ^{14}C age determinations four, five and six also overlap, indicating that there is little statistical difference between the age estimates.

Accounting for these inconsistencies is not easy, although they almost certainly arise because peat is a heterogeneous sediment. Basically different components within a unit of peat can yield substantially different age estimates. Radiometric ^{14}C age determinations on the fulvic acid, humic acid and humin fractions within bulk peat samples identify that fulvic acid typically produces age estimates younger than the horizon of accumulation, because fulvic acid is highly mobile and can be leached down peat profiles (Dresser, 1970; Shore *et al.*, 1995). However, this should not affect the radiometric ^{14}C age determinations in this research, because the samples were pre-treated with an acid wash removing this acid-soluble highly mobile component. The humin and humic acid fractions of bulk peat samples have also yielded substantially different ^{14}C age determinations (Dresser, 1970; Shore *et al.*, 1995). This has implications for the ^{14}C age determinations on May Moss cores C3 and D2, which utilise the acid-insoluble fraction containing both the humic acid and humin fraction; however, unfortunately there was insufficient peat to assess this problem and analyse all three components (fulvic acid, humic acid and humin). Consequently it is stressed that the radiometric ^{14}C age determinations at May Moss are based upon the analysis of two components that could individually yield substantially different age estimates.

Components that are not contemporaneous with the horizon of accumulation can be introduced to a peat sample in several ways. Downward penetration of roots is an obvious source of younger material, and these rootlets will eventually decompose contributing both humin and humic acid younger than the horizon of accumulation. Stem fragments of long-lived plants, for example *Calluna vulgaris*, are a further source of non-contemporaneous material being older than the



iii).

Dates No.	Depth (cm)	AMS dates Years BP	Depth (cm)	Conventional Dates Years BP
1	52-53	265 ±40	49-52	410 ±45
2	63-64	310 ±40	64-67	470 ±45
3	74-75	450 ±55	75-78	840 ±50
4	94-95	620 ±40	95-98	760 ±50
5	113-114	765 ±40	110-113	875 ±50
6	124-125	680 ±40	125-128	745 ±50
7	141-142	825 ±40	138-141	1055 ±50

Figure 7.1. 14C age estimates for May Moss core C3 displayed against the decadal dendrocalibration curve (Stuiver & Becker, 1993). i). AMS age estimates on virtually pure *Sphagnum* remains. ii). Radiometric age estimates on bulk peat samples. iii). Table of the age estimates identifying the horizon number signified on the dendrocalibration graphs.

horizon of accumulation (Pilcher, 1995). Mires on the North York Moors have experienced substantial climatic fluctuations during the last 2000 years, which has had a clear impact upon the depth of the water table. It is impossible to assess what impact water table movement has upon the ^{14}C ages of different components of blanket peat. Fulvic acids are known to be mobile within peat sequences; however, the mobility of humic acid particularly in the light of water table fluctuations is an unknown factor.

Kilian *et al.* (1995) identify a further problem that may afflict the ^{14}C procedure. Comparison of AMS ^{14}C age determinations on samples containing pure *Sphagnum* remains and samples of mostly *Sphagnum* with 2-4% fine *Calluna vulgaris* rootlets identified that samples containing fine *Calluna vulgaris* rootlets yield ages 100-150 years too old. Kilian *et al.* (1995) do not offer a conclusive explanation for this problem, which they refer to as a "reservoir effect", tentatively linking the chronological disparity with alternative sources of carbon. Trace gases, carbon dioxide and methane, produced at depth in mires are an obvious source of old carbon. They suggest methane is a more likely cause, and in theory, en route to the surface methane could be oxidised by bacteria near the acrotelm/catotelm boundary, providing a "reservoir" of older carbon in the root zone. Methane could be fixed by the mycorrhizal fungi associated with Ericaceae roots. However, Kilian *et al.* (1995) indicate that unpublished AMS measurements on living *Calluna vulgaris* and *Erica tetralix* yield modern age determinations, which conflicts with this theory. Methane need not be fixed by living rootlets, with the methane-derived carbon simply utilised by fungi (Kilian *et al.*, 1995). Largely taxonomically unknown fungi are found in massive quantities in peat sequences (van Geel, 1978), and could produce this reservoir effect, although AMS dating of fungal remains is essential to test this hypothesis (Kilian *et al.*, 1995).

Fungal remains were encountered within the stratigraphy at most of the sites, and the remains were counted *sensu* van Geel (1978) in the May Moss core D1 revealing substantial quantities of fungal remains. Non-pollen palynomorphs were not counted at all sites, because the taxonomic uncertainty involved in the analysis of these remains currently reduces their palaeoenvironmental value and the technique was abandoned in favour of more profitable palaeoenvironmental procedures. However, a reservoir effect of this type could contribute uncertainty to the radiometric ^{14}C age determinations obtained in the course of this research, but it should not affect the AMS ^{14}C age determinations on virtually pure *Sphagnum* remains. This provides a tentative explanation as to why the radiometric bulk assays are up to 300 years older than the AMS assays.

In terms of confidence in the contemporaniety of the dated material with each horizon of accumulation, the AMS ^{14}C age determinations are clearly the better option, negating many of the problems associated with the heterogeneous nature of peat deposits. The problems highlighted above could explain the absence of a correct chronological order in both the radiometric and AMS ^{14}C age determinations on May Moss core C3. However, it is probably unreasonably optimistic to expect seven ^{14}C age determinations within a 500-year period to produce age estimates in a chronological order. Discussion at the beginning of this section highlighted the overlap of the 2-sigma range of the ^{14}C age determinations. Furthermore AMS ^{14}C age determinations four to six overlap at the 1 sigma range, which means there is little difference between the age estimates. Providing a chronology at this resolution may only be possible by means of wiggle-match dating; however, this would require a substantially larger number of dates, probably a similar interval to that obtained for May Moss site C, but spread over a longer period.

Further chronological uncertainty stems from the absence of a dynamic equilibrium between the decay of ^{14}C and production of ^{14}C in the high atmosphere. Unfortunately the production of ^{14}C has not been constant owing to variations in the intensity of cosmic rays reaching the Earth, with the variations controlled by changes in sunspot activity (Stuiver & Brazuinas, 1993; 1994). Linking the ^{14}C chronology with the calendrical chronology of tree-rings can correct for variations in ^{14}C production. The dates obtained in the course of this research have been calibrated either using a decadal tree-ring dataset or a smoothed version of the decadal tree-ring dataset (Stuiver & Becker, 1993). The ^{14}C age determinations are plotted on calibration curves in figures 7.1 to 7.4. The important implication of the calibration procedure is that a single ^{14}C age determination clearly could represent a wide range of true ages. Throughout this thesis the 2-sigma range is given when referring to calibrated ^{14}C age estimates.

Despite the problems the AMS ^{14}C age determinations provide a chronology for the May Moss site C peat sequence. Linear interpolation between these dates, excluding horizon six, was used to generate an age/depth model for the peat sequence, which is used in subsequent interpretation. The ^{14}C age determinations from May Moss core D2 are in a chronological order; however, they may suffer the same problems that afflict the radiometric assays from May Moss core C3. The radiometric ^{14}C age determinations from the other sites, Yarlsey Moss, Harwood Dale Bog and Bluewath Beck, analyse the acid- and alkali-insoluble humin fraction of bulk peat samples, which Dresser (1970) suggests with blanket peat is more likely to reflect the true age of the horizon of accumulation. However, Shore *et al.* (1995) encountered discrepancies between the humin and humic acid fractions of bulk peat samples, and recommend obtaining ^{14}C age determinations for

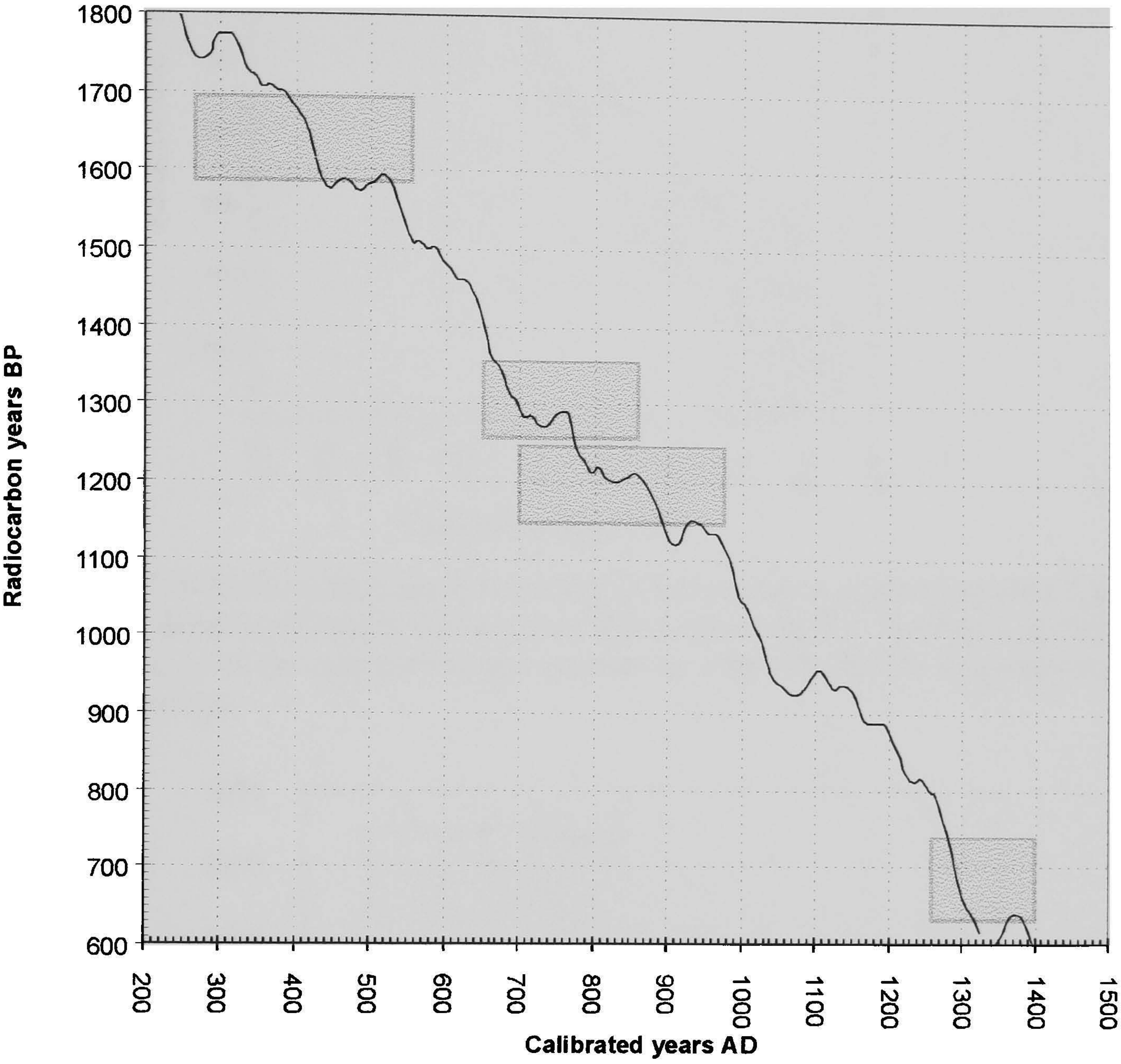


Figure 7.2 ^{14}Cage estimates for May Moss core D2 graphed against a smoothed decadal dendrocalibration curve (Stuiver & Becker, 1993). The boxes identify the 1-sigma range of the ^{14}C age estimate in years BP and the 2-sigma range of the calibrated ages.

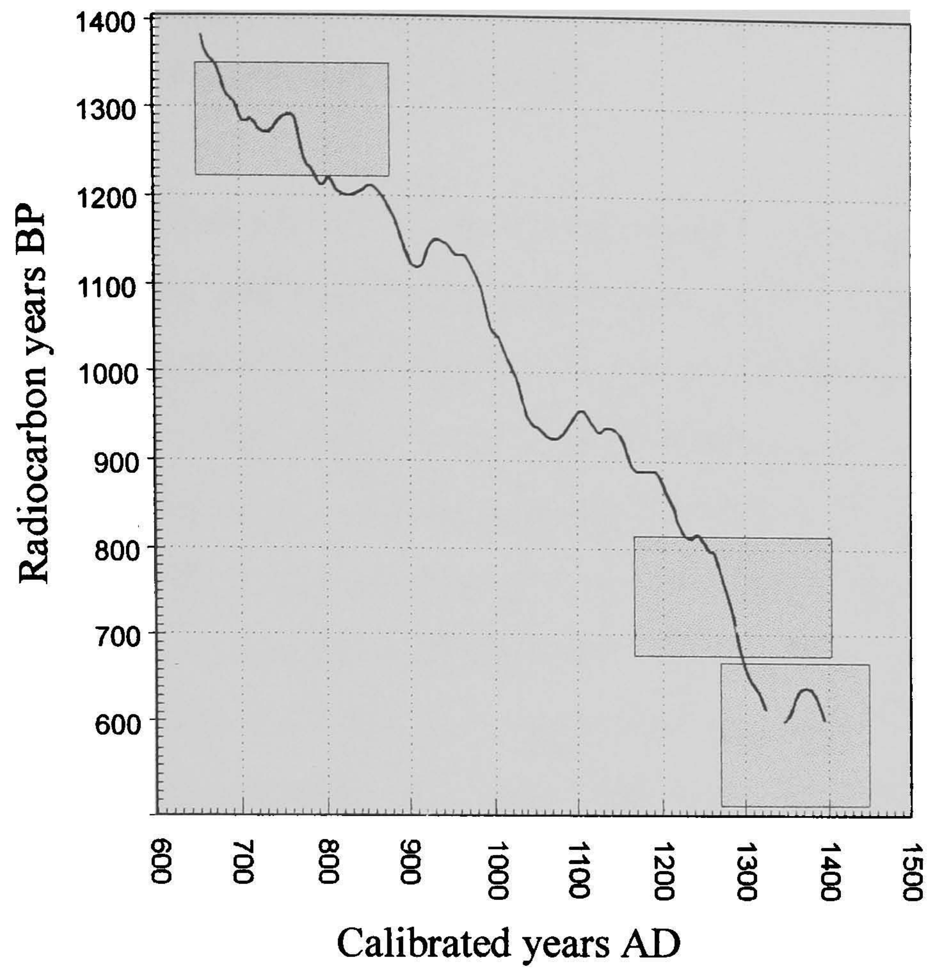


Figure 7.3. Radiocarbon age estimates for Yarlsey Moss graphed against a smoothed decadal dendrocalibration curve (Stuiver & Becker, 1993). The boxes identify the 1-sigma range of the radiocarbon age estimate in years BP and the 2-sigma range of the calibrated age.

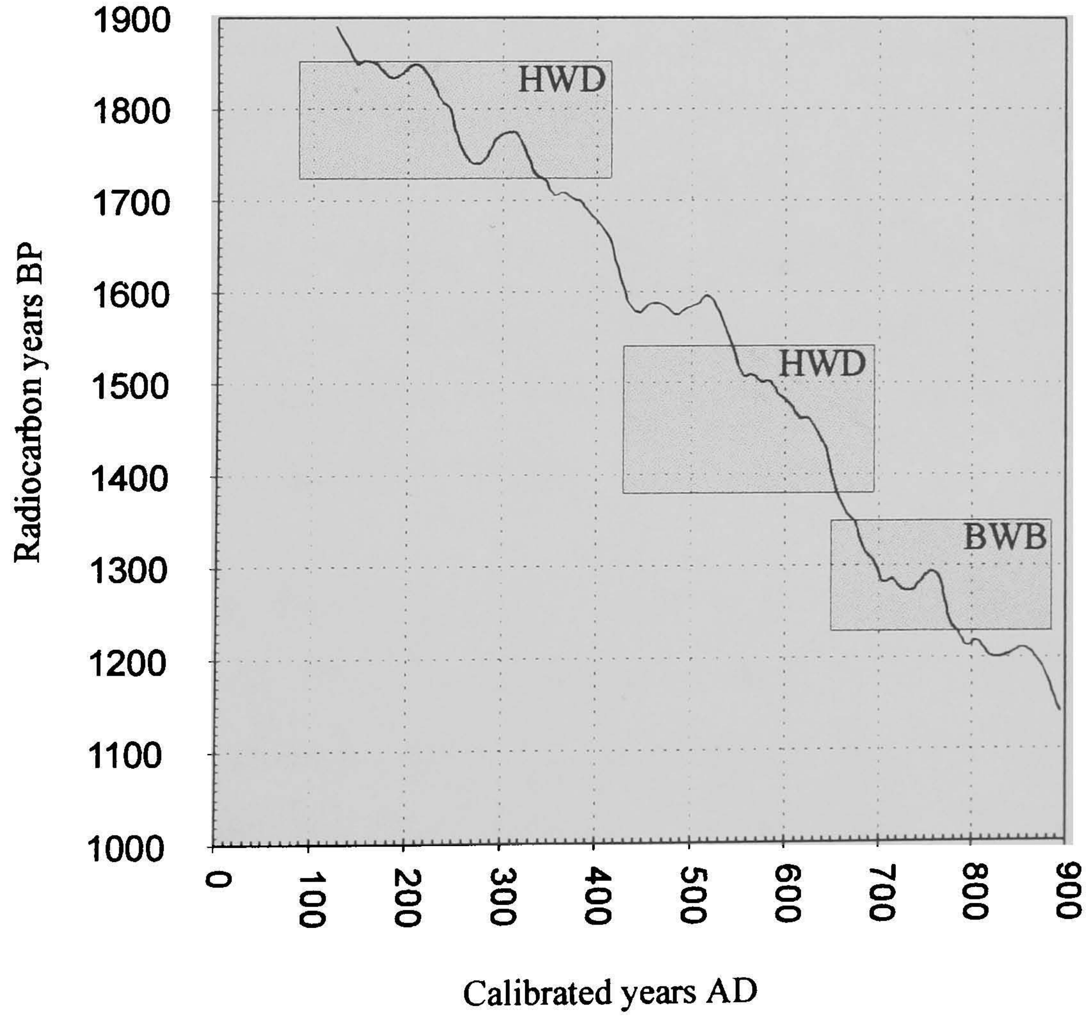


Figure 7.4. Radiocarbon age estimates for Harwood Dale Bog (HWD) and Bluewath Beck (BWB) graphed against a smoothed decadal dendrocalibration curve (Stuiver & Becker, 1993). The boxes identify the 1-sigma range of the radiocarbon age estimate in years BP and the 2-sigma range of the calibrated age.

all fractions within bulk peat samples, which would allow a more complete assessment of the ^{14}C procedure. Unfortunately this approach was not possible in this research owing to budgetary constraints and the size of the sample available.

The comparison of radiometric ^{14}C age determinations on acid-insoluble residues and AMS ^{14}C age determinations on hand-picked *Sphagnum* remains, supports a view gaining increasing weight in the scientific community, that great care should be taken with ^{14}C dating of peat (Dresser, 1970; Shore *et al.*, 1995; Kilian *et al.*, 1995; Oldfield *et al.*, 1997). The implication of the analyses at May Moss is that material should be selected for ^{14}C dating only if it is likely to be contemporaneous with the horizon of accumulation. Short-lived above-ground components are the best material and if *Sphagnum* remains are available, then pure hand-picked samples of *Sphagnum* leaves and stems are the most suitable material for ^{14}C dating peat. With the development of AMS technology, analysis of this type is becoming economically feasible and in the future may be the only approach scientifically.

7.4 Climate change on the North York Moors

The hydrological budget of a mire is a balance between moisture gained and moisture shed. There is no evidence of natural changes in mire drainage at any of the sites, for example bog-bursts or extensive gully systems. There is also no evidence of drainage initiatives associated with agricultural improvement at most of the mires, with the obvious exception of Fen Bogs where there is considerable evidence of human inference, associated with the construction of a railway opened in 1836 and improvement of southern sections of the mire creating land suitable for agriculture. In conclusion, it appears likely that the hydrological signal recorded in the peat stratigraphies will reflect changes in effective precipitation. Replication of the moisture signal at several sites across the region implies a regional phenomenon is responsible for surface wetness changes, with climate the most likely candidate.

Analysis of blanket peat from upland sites on the North York Moors has produced detailed palaeohydrological records for the last 2,600 years. The clarity and precision of the record is better during the last 1500 years, because at most sites the stratigraphy pertaining to this period is more suitable for palaeohydrological research. The hydrological changes are summarised in figure 7.5, which demonstrates that the moisture changes are evident in the stratigraphy at most sites. Notwithstanding the problems inherent in ^{14}C dating the chronologies for the peat sequences introduced in chapters five and six are used to generate a climate history for the North York Moors. These chronologies must be viewed against a backdrop of problems with ^{14}C dating; however, at present it is the only means of ageing the peat sequences.

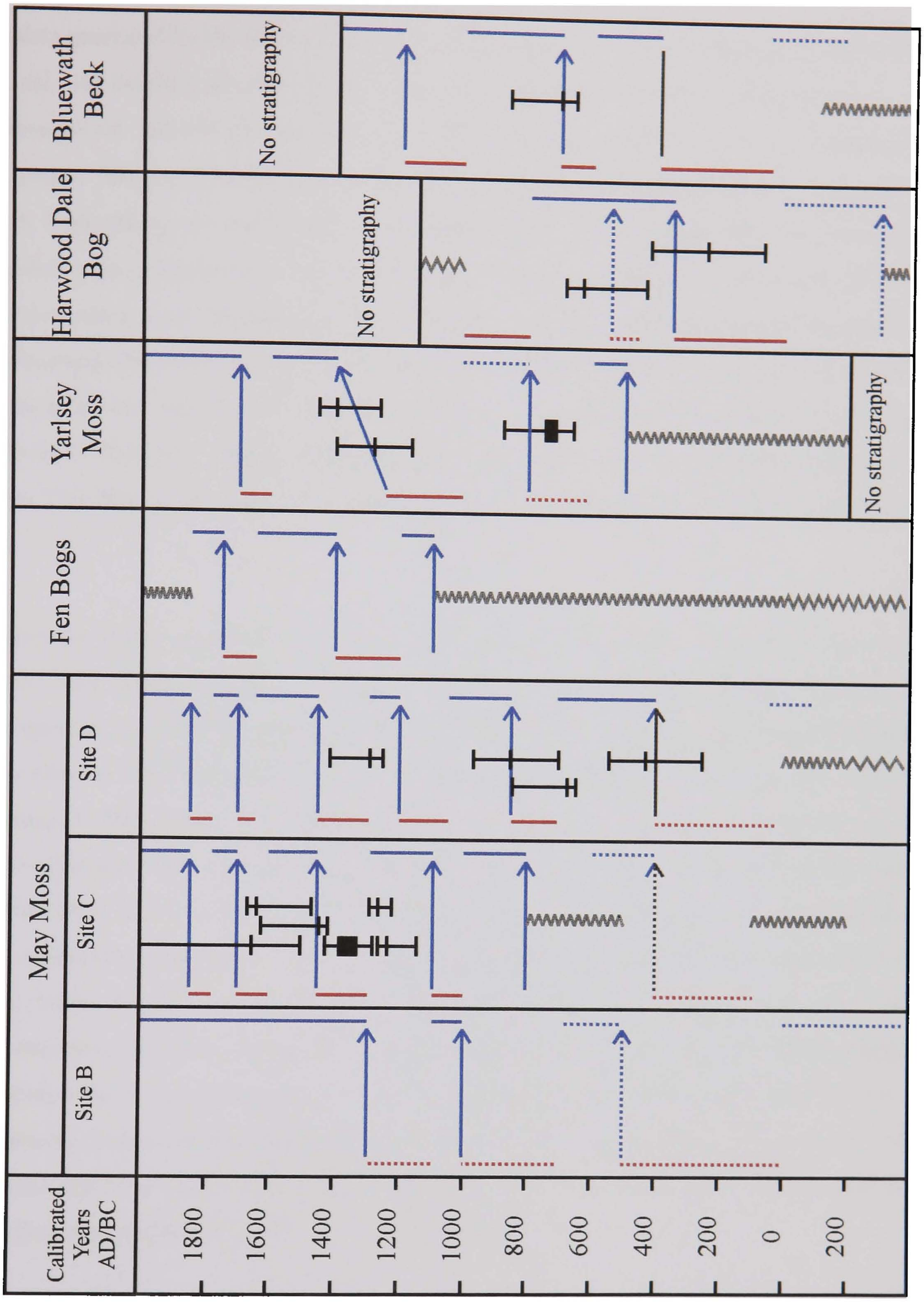


Figure 7.5. Summary of the moisture fluctuations signified in peat stratigraphies on the North York Moors, displayed against the timescale derived for each peat sequence (Years AD/BC). Solid lines denote moisture conditions signified by several techniques. Dotted lines denote less certain moisture conditions only evidenced by a single palaeoenvironmental procedure. Red lines denote dry conditions and blue line wet conditions. Grey zigzag lines denote stratigraphy with an ambiguous hydrological signal. ^{14}C age determinations obtained in during this research are signified in Calibrated Years AD/BC, identifying the intercept or the range of intercepts with the calibration curve and the 2-sigma range.

The data generated for the North York Moors imply changes to wetter climate *circa* 500-400 cal. BC, cal. AD 400-600, 800-900, 1000, 1250-1300, 1400-1450, 1600-1650 and 1800-1850 , and of these the cal. AD 400-600, 800-900 and 1400-1450 events are most marked. In addition to the wet phases that are the traditional focus for peat-based palaeoclimate research, mires on the North York Moors are well suited for the identification of drier conditions. The driest phase recorded in peat stratigraphies occurred cal. AD 700-800, evidenced by *Calluna vulgaris* and *Hypnum jutlandicum* communities, low diversity testate amoebae communities dominated by *Hyalosphenia subflava* and by well humified peat. Subsequent drier phases do not appear as severe as the cal. AD 700-800 event, but are clearly signified *circa* cal. AD 1100-1200, 1550-1600 and 1750-1800. Earlier events are less clearly represented in peat stratigraphies on the North York Moors, although dry conditions are signified during the Roman period, cal. AD 200-400.

Despite the broad agreement in the palaeohydrological signal from the different sites across the North York Moors signified on figure 7.5, there are some discrepancies. Some of the discrepancies could reflect uncertainties in the chronologies; however, the palaeohydrology at May Moss is more complicated than at the other sites between cal. AD 1000 and 1400. The sequence at May Moss, of a dry phase *circa* cal. AD 1000-1100, wetter conditions cal. AD 1100-1200 and drier conditions cal. AD 1200-1400, is at odds with the palaeohydrology at Yarlsey Moss and Fen Bogs, which signify a single dry phase during the first three centuries of this millennium. This discrepancy could reflect the greater stratigraphic resolution available at May Moss. Furthermore at this time Yarlsey Moss had only recently become a typical ombrotrophic blanket mire and the ombrotrophic status of Fen Bogs is clearly debatable. Consequently, it is possible that the climatic changes between AD 1100 and 1400 had no discernible impact on the stratigraphy at Yarlsey Moss and Fen Bogs. However, it is also possible the hydrological fluctuations recorded at May Moss arose from climatic change of insufficient magnitude to be recorded at the other sites.

The climate history for the North York Moors is compared in figure 7.6 with previous palaeohydrological investigations of peat stratigraphy. Comparison with previous peat-based palaeoclimate research in eastern England is limited, because the only studies available are from Harold's Bog on the North York Moors (Blackford & Chambers, 1991; in press) and the Humberhead Levels (Smith, 1985). The palaeohydrological indications at these sites corroborate the *circa* 500 cal. BC, cal. AD 400-600, 800-900 and 1600-1650 shifts to a wetter climate signified in this research. However, the climate history presented in this thesis is more

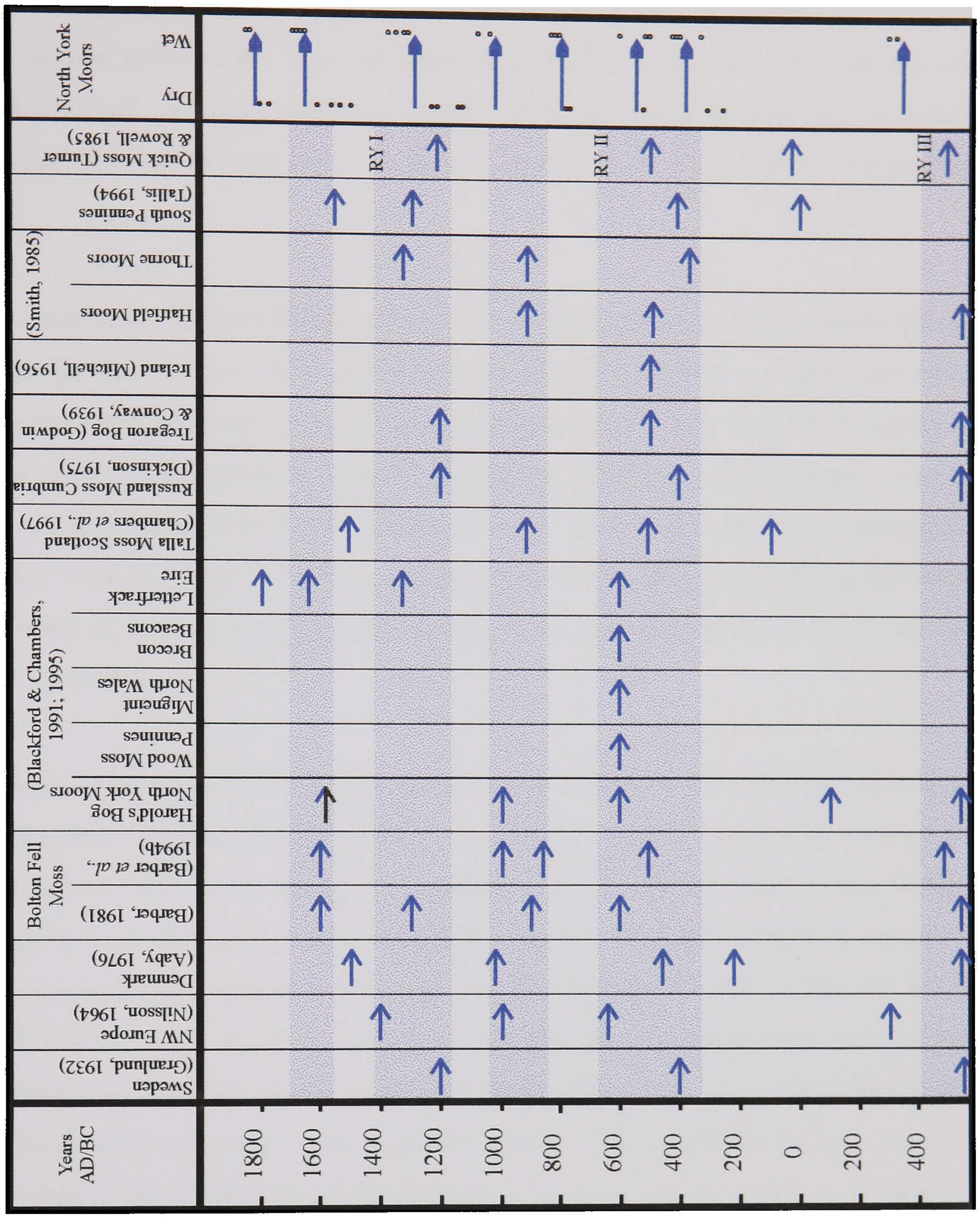


Figure 7.6. Comparison of moisture fluctuations signified on the North York Moors with evidence of wet shifts identified within peat stratigraphies across north-west Europe. The data for the North York Moors is expressed as incidences of unequivocal wet shifts and extremely dry conditions. The arrows signify regionally significant wet shifts, which only include events evidenced at more than one site. Correlation of moisture shifts across north-west Europe is emphasised by blue shading identifying coincident wet shifts. Three of these are broadly equivalent with recurrence surfaces RY III, RY II and RY I (*sensu* Granlund, 1932).

complicated with further short-lived shifts to a wetter climate *circa* cal. AD 1000, 1300 and 1800. Furthermore comment about drier conditions is scarce, with Blackford & Chambers (1991; in press) avoiding the issue on the grounds that drier shifts are more ambiguous than wet shifts, because continual growth away from the water table producing well humified peat can occur under stable as well as drying conditions. Smith (1985) identifies drier conditions immediately prior to an cal. AD 400-500 wet shift, with further dry periods *circa* cal. AD 700-900 and 1000-1300.

The point made about the hydrological ambiguity of dry stratigraphy is valid; however, the driest events signified on the North York Moors are severe and more likely to reflect drier climatic conditions than autogenic bog growth. Peat stratigraphies on the North York Moors signify drier conditions *circa* cal. AD 200-400, 700-800, 1100-1200, which are contemporaneous with drier events recorded in Humberhead raised mire peat stratigraphies (Smith, 1985). The stratigraphies at both May Moss and Yarlsey Moss in contrast to the Humberhead mires, Thorne and Hatfield Moors, extend up to the present day, and identify two further drier events *circa* cal. AD 1550-1600 and 1750-1800.

Palaeoclimate information has also been elucidated from other raised mires and blanket mires distributed across Northwest Europe. Figure 7.6 shows that a large number of moisture shifts identified on the North York Moors are contemporaneous with wet shifts across Northwest Europe and this corroboration supports the belief that they represent changes in climate. The changes to a wet climate signified on the North York Moors *circa* 500-400 cal. BC, cal. AD 400-600 and 1250-1300 stand out in this regard, because they are contemporaneous with recurrence surfaces RYIII, RYII and RYI (*sensu* Granlund, 1932). Using recurrence surfaces as a rationale for correlating peat sequences is an outdated concept, although these features are clearly associated with a shift to a wetter climate and appear broadly contemporaneous in ^{14}C dated peat sequences (Dickinson, 1975; Rowell & Turner, 1985; Smith, 1985).

Clearly the palaeohydrological history for the North York Moors also contains shifts that do not conform to the traditional sequence of recurrence surfaces. Elucidation of continuous proxy climate records from peat stratigraphy has only really occurred since the 1970s, and so the potential high-resolution moisture signal available in peat stratigraphy has only begun to be realised during the last twenty years. Continuous palaeoclimate histories have been elucidated from raised mire peat stratigraphies across north-west Europe, but with a particular concentration upon mires in Cumbria and southern Scotland (Haslam, 1987; Stoneman, 1993). Changes to a wetter climate have been the principal focus; however, the plant macrofossil analyses integral to these researches are capable of identifying drier phases. Stratigraphies at Bolton Fell Moss and Walton Moss contain clear evidence of drier phases *circa* cal. AD 70-400, 700-800 and 1345-1450.

There are clear differences between the palaeoclimate signal on the North York Moors and the long established record from Cumbria. The sites on the North York Moors are blanket mires, with a less pronounced interchange of *Sphagnum* species. Drier events on the North York Moors are evidenced either by a decline in *Sphagnum* or by abundant *Sphagnum* section *Acutifolia*. Cumbrian raised mires are characterised by a more complex suite of changes in the *Sphagnum* flora, within which moisture shifts can be difficult to interpret. However, drier climatic periods on the North York Moors are signified by a combination of testate amoebae, plant macrofossil and humification stratigraphies, which increases confidence in the moisture signal. The majority of peat-based climate research until recently typically has utilised a single palaeoenvironmental procedure- for example plant macrofossil analysis (Stoneman, 1993) or humification analysis (Blackford & Chambers, 1991)- whereas using several procedures on the North York Moors has produced clearer hydrological histories.

The comparative simplicity of the stratigraphic changes on the North York Moors oscillating between *Sphagnum*-rich to *Sphagnum*-poor peat renders identification of drier phases easier. The sites on North York Moors are all blanket mires, which could explain the differences with the palaeoclimate histories elucidated from raised mires, except that the stratigraphy consists of poorly humified peat that has accumulated at a similar rate to lowland raised mires. The sites on North York Moors are not typical slowly accumulating shallow blanket mires, but comparatively deep rapidly accumulating sites with stratigraphy containing a diverse range of fossils. The stratigraphy at these sites is not that dissimilar to raised mire peat stratigraphy. The main reason for the variance between the palaeoclimate signal on the North York Moors and that from raised mires in western Britain is probably due to the climatic differences between the regions. The North York Moors is one of the driest peat-forming areas in Europe, and as such, the mires are susceptible to pronounced ecological changes during drier periods. This is clearly evident on the moors today, with contraction of *Sphagnum* habitats and expansion of *Hypnum jutlandicum* at May Moss reflecting the current dry climate.

In addition to the climate archive elucidated from raised mire stratigraphies, in recent years upland blanket peat sequences have yielded continuous palaeoclimatic information. Palaeoclimatic evidence from the south Pennines is of particular interest, because this research is unusual in investigating the plant macrofossil stratigraphies of upland blanket peat sequences

(Tallis, 1994). *Sphagnum*-rich and *Sphagnum*-poor layers of peat were used to signify shifts to wetter conditions *circa* cal. AD 470, 1300 and 1550, with drier phases cal. AD 200-450, 1150-1275 and 1450-1550. This sequence of events is in agreement with the sequence proposed for the North York Moors.

Humification analysis has been utilised to investigate well humified slowly accumulated peat sequences from most upland areas of Britain including the North York Moors, south Pennines, Brecon Beacons, Snowdonia and Letterfrack, western Ireland (Blackford & Chambers, 1991; 1995) and southern Scotland (Chambers *et al.*, 1997). The well humified condition of the stratigraphy at these renders them unsuitable for plant macrofossil analysis. Testate amoebae analysis is a possibility in stratigraphy of this type, but it is more likely to be useful in *Sphagnum*-dominated stratigraphy or former *Sphagnum*-dominated stratigraphy currently in a highly decomposed condition. There is clear evidence of shifts to wetter conditions at all the sites listed above, with a cal. AD 400-600 climatic deterioration a particularly significant event that is signified in stratigraphies across the North York Moors. Subsequent wet shifts are also signified *circa* cal. AD 900-1000 and 1500-1600, which also correspond with wet shifts on the North York Moors.

Of the blanket mires mentioned above, the Letterfrack site in western Ireland warrants further comment, because it has been used to elucidate a detailed climate history for the last 2000 years extending up to the present day (Blackford & Chambers, 1991; 1995). In addition, within the British Isles it offers a complete contrast in terms of climate with mires on the North York Moors. The chronology for the sequence is only secured by two ^{14}C dates and a present-day age of the mire surface on each of two separate peat profiles. However, the stratigraphy reveals clear evidence of changes to wetter conditions *circa* cal. AD 500-700, 1050, 1300-1400, 1660-1720 and 1800-1850, with evidence of drier conditions cal. AD 1230-1380, 1560-1650 and 1730-1780. This sequence of events displays an excellent correlation with the climate history derived for the North York Moors. The North York Moors climate history obviously has the advantage that the palaeohydrological information is derived from five sites and uses a suite of palaeoenvironmental techniques upon stratigraphy ideally suited for the identification of dry periods.

The corroboration for the North York Moors palaeoclimate history provided by previous peat stratigraphic research is reassuring, because it indicates that the climate changes are regional phenomena. It must be emphasised that the chronologies for all these palaeoclimate records are based upon ^{14}C dated peat profiles and are inherently susceptible to errors from a variety of sources. The imprecision of ^{14}C dating hampers correlation of peat stratigraphy, a view exemplified by the wide spread of ages obtained for the *Grenzhorizont* recurrence surface. Whilst the horizons dated as the Grenzhorizont may not have been the same feature, the spread of ^{14}C ages may also be the result of a plateau in the radiocarbon calibration between 800 and 400 cal. BC (Pilcher, 1991). Notwithstanding the problems with ^{14}C dating and the tentative nature of correlation between wet shifts signified in the previous discussion, there is evidence of national climate changes within the peat stratigraphies across the British Isles.

The stratigraphic resolution of the palaeohydrological data for the North York Moors means that only the humification stratigraphies are susceptible to time series analysis. The four to eight centimetre sampling intervals of the plant macrofossil and testate amoebae analyses are equivalent to a chronological interval of 20 to 40 years, which negates the value of time series analysis within a 2000-year period. Fine resolution testate amoebae analysis would circumvent this problem, but this was not possible within the time constraints of this research. A further constraint is that a uniform sampling interval and a uniform sediment accumulation rate are essential for direct time series analysis, accordingly the humification stratigraphies at May Moss site B and D, and Harwood Dale Bog were the only data receiving time series analysis.

The dominant periodicities identified at Harwood Dale Bog and May Moss site D are centred on 80-95 and 200-240 year cycles. Previously published time series analyses of peat-based palaeoclimate histories are not abundant. Aaby (1976) identified an, as yet, unreplicated 260-year periodicity in a 5,500-year humification record from Draved Moss, Denmark. However, the main spectral peak in the 2600-year humification stratigraphy from May Moss site B signifies a 260 year periodicity. Chambers *et al.* (1997) encounter a 210-year periodicity in a 5000-year humification stratigraphy at Talla Moss, southern Scotland, which is similar to the most significant periodicity identified on the North York Moors. The fine resolution 6500-year plant macrofossil history from Bolton Fell Moss appears to contain an 800-year periodicity. A periodicity of this magnitude was unlikely to be encountered on the North York Moors, because the peat profiles for the most part are only 2000 years in duration. All these previous investigations only utilise the highest peak within the spectral density function, and do not discuss other peaks or the composite nature of certain peaks (Barber *et al.*, 1994a; Chambers *et al.*, 1997). It must be emphasised that the time series analyses of the North York Moors data and analysis in previous research are inherently constrained by the limitations of ^{14}C dating. Despite this, two periodicities are clearly represented in the humification stratigraphies at several sites on the North York Moors, centred on 80-95 and 200-240 years.

In summary the palaeohydrological record in peat stratigraphies from the North York Moors sheds new light upon the climate history for the last 2000 years. Some of the hydrological changes have been evidenced elsewhere in the British Isles, which gives further credence to the view that they represent significant changes in regional climate. The susceptibility of stratigraphy on the North York Moors to ecological changes in response to drier conditions gives the climate history considerable clarity and highlights differences with peat stratigraphic research elsewhere. The climate history appears far more complicated than previously encountered. Climatic conditions signified in peat stratigraphies on the North York Moors are summarised in figure 7.7, which also identifies the main climate changes and the ^{14}C ages obtained for these changes.

7.5 Late-Holocene climate history

In addition to peat stratigraphic research a variety of approaches has been utilised to uncover Holocene climate histories for north-west Europe. Sources of regional climate information include instrumental measurements, historical documents, the width of tree rings, a history of glacial advances, movements in the altitude of the tree line, water levels in lakes and records of heightened geomorphic activity, to name but a few. These data sources are based upon research across Europe from areas currently experiencing distinctly different climatic conditions; consequently, there are variations between these climate histories. A further potential source of variance arises from the climate variable reconstructed by a particular analytical approach. Palaeohydrological indications in ombrogenous peat are used to infer a history of effective precipitation, and can only distinguish between cold or wet and hot or dry conditions. Beyond these coarse indications the peat stratigraphic climate signal cannot really be more specific.

Other sources of Holocene climate histories reconstruct different variables. Instrumental measurements record quite specific climatic variables, but they are only available for the last 200-300 years. Precipitation and temperature measurements provide some of the longest records, with temperature measurements in central England between 1659 and 1973 (Manley, 1974), and equivalent precipitation measurements between 1760 and 1980 (Wigley *et al.*, 1984; Jones & Bradley, 1995a). Climatic information in historical documents can be very variable, often providing information about extreme events. Dendroclimatology allows the reconstruction of climatic variables that control tree growth. In Scandinavia the limiting factor is temperature (Briffa *et al.*, 1990), whereas in arid areas precipitation is a more important factor. In Britain and other areas with an oceanic climate tree growth is controlled by a combination of precipitation, temperature and other edaphic factors. The altitude of the tree line and the position of glacial margins in the Alps and in Scandinavia are clearly controlled by temperature. This array of

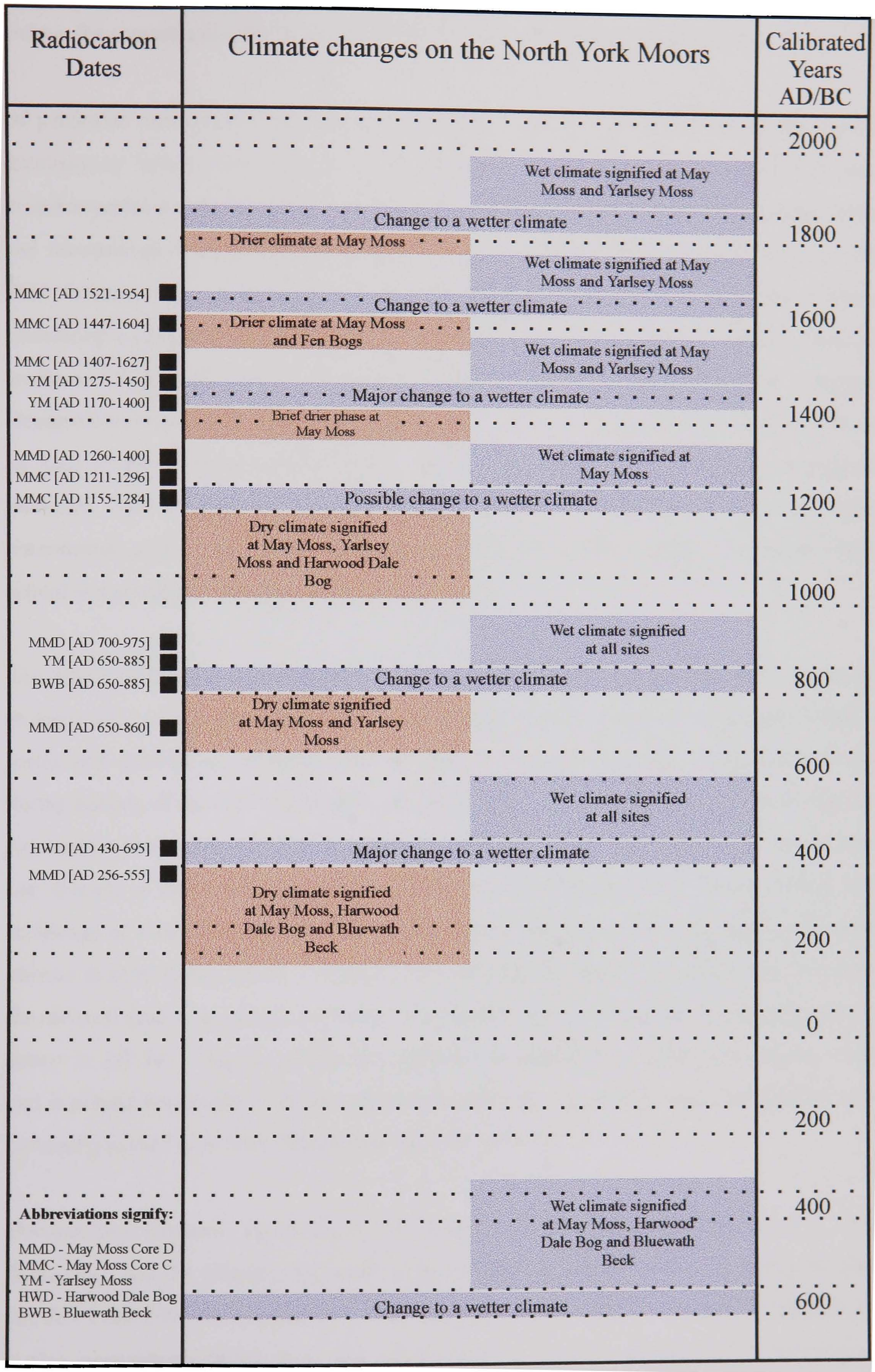


Figure 7.7 Summary of the climate changes signified on the North York Moors.

climatic variables elucidated in research focusing upon the Holocene provides an invaluable archive for comparison with the palaeoclimate history generated for the North York Moors.

Of particular pertinence to the palaeoclimate history generated in this thesis is the archive of documentary information collated by Nöel Menuge. This archive draws upon documentary evidence pertaining to the North York Moors specifically, collated in an unpublished database and summarised in PLACE Research Centre Occasional Paper No. 1 (James Menuge, 1997). This database is a parallel component to this thesis, forming a research project aimed at elucidating a climate history for the North York Moors. The documentary evidence, summarised on figure 7.8, provides some flesh to the skeleton climate history derived from peat stratigraphy. Documentary evidence is available for the period AD 458 to the present day, but is constrained by gaps where the historical information is either not available, is unreliable or is difficult to interpret. The sources of evidence include chronicles; ecclesiastical histories; monastic chartularies; estate, court, forest and tithe records; and a diverse range of personal, farming, school and newspaper records (James Menuge, 1997).

The nature of the climatic information is diverse and includes incidents of extreme events, for example heavy snow and great storms; and indirect climatic information elucidated from crop yields and occurrences of famine and diseases, for example murrain which afflicts livestock during periods of drought. The database is constrained by gaps in the historical record and by the regionally non-specific nature of the evidence until the eleventh and twelfth centuries. In records not specific to the North York Moors, Bede and the Annals of the Britons record several incidences of severe drought during the eighth century, which coincide with evidence of a very dry climate in peat stratigraphies. Documentary evidence pertaining to the period from the ninth to the eleventh century is lacking in climatic information, with the exception of reference to a severe winter in AD 991. This exemplifies the problem of regionally unspecific documentary evidence and it proved impossible to discern meaningful climatic information from documentary sources pertaining to the North York Moors between AD 800-1050.

Documentary evidence pertaining to the period AD 1050-1300 signifies several climatic fluctuations and the palaeohydrological evidence does not contradict this, signifying dry climate cal. AD 1100-1200, wet climate cal. AD 1200-1300 and dry climate cal. AD 1300-1400. There is also inconsistency within these wet and dry periods, possibly arising from differences in the ecological response to moisture change and uncertainties inherent in histories based upon ^{14}C chronologies. If the climate was changeable the peat stratigraphies produced under these conditions might reflect this, with variations present between the stratigraphies at different sites.

Period	Quality and quantity of climatic information	Crop failure / famine	Severe winter	Cold winter	Great storm	Heavy snow	Wet weather	Flooding	Pestilence	Drought	Murrain	Hot summer	Good crop yield
AD 458 -600	7 entries containing generalised information not specific to the region and only 3 references to climate.				515		458						540
AD 600 -700	11 entries with no reference to climate. The plague in AD 664 or 682, in response to crop failure and famine, could have been triggered by either an extremely wet or dry summer.												
AD 700 -800	11 entries with 4 references to climate. Incidents of drought and dysentery, a disease more commonly associated with warmer climes, in AD 721, 737, 741 and 759-761.								759	759 741		721	
AD 800 -900	3 entries containing no reference to climatic conditions.												
AD 900 -1000	5 entries identifying a famine in AD 976 and disease amongst cattle in AD 986. The winter of AD 991 was unusually severe, wet and cold.		991	991	991				986				
AD 1000 -1100	17 references to climate - some specific to the region. The data identifies a country blighted by cold and wet weather, which produced famine and poor crop yields.	1005 1070 1086 1087 1088 1093 1095	1047	1047	1047 1086		1092 1094 1096 1097		1086 1087				
AD 1100 -1200	122 entries mostly specific to the region, but concentrating upon the landscape with only 14 references to climate.	1103 1104 1111 1123	1111	1111 1115	1120 1121		1115 1117	1124			1111 1131		
AD 1200 -1300	42 entries mostly specific to the region, which identify a climate fluctuating between wet winters and dry summers.	1238 1241 1252 1257 1258 1271		1246 1258	1251		1236 1237 1257	1237 1253 1257 1271	1254	1238 1240 1241 1242 1252 1253		1236 1248 1262 1265 1266 1270 1272 1273	1239 1240 1244 1245 1247 1248 1251 1254 1255 1272 1273
AD 1300 -1400	21 entries concentrating upon the landscape and plagues, with only 5 references to the climate.	1315		1395		1395	1315 1325			1325			
AD 1400 -1500	8 entries containing information about land-use, with no reference to climate.												
AD 1500 -1600	13 entries containing information about livestock and the landscape, but with no reference to climate.												
AD 1600 -1700	18 entries containing information about livestock and the landscape, but only 3 references to climate.	1621-1623		1619 1621-1623 1641 1642		1641 1642							
AD 1700 -1800	7 entries, with specific references to climate and the earliest meteorological records - AD 1788-1792.		1782 1783	1788 to 1792									
AD 1800 -1900	43 entries containing specific references to climate and the early meteorological records from Whitby.			1800 to 1802			1841 to 1843 1867 to 1895	1857		1842			
AD 1900 -1996	Good regional coverage and continuous meteorological records. Alternating wet and dry weather throughout the century, but with a concentration of wet and cold events AD 1900-1950.			1900 to 1940			1900 to 1940						

Figure 7.8 Summary of the climatic information pertaining to the North York Moors collated from documentary sources (James Menuge, 1997; unpublished).

It is not possible to attribute the minor discrepancies between the palaeohydrological records from different mires definitively to either changeable climate, variations in the ecological response to climate change or to uncertainties in correlation between sites arising from the ^{14}C chronologies.

The fourteenth to sixteenth centuries are not well served in terms of climatic information, with documentary records focusing upon landscape and woodland management. After AD 1600 there is more in the way of regionally specific climate information, with a wet or cold climate between AD 1620 and 1640, which supports the palaeohydrological evidence of wet or cold conditions between cal. AD 1600 and 1700. There is further evidence of very cold and wetter climate in the latter half of the nineteenth century, after a comparatively dry or warm first quarter (Tuke, 1800), and this sequence of events strongly supports the palaeohydrological evidence. In conclusion, notwithstanding the gaps in and limitations of the documentary evidence, and the chronological uncertainty inherent in the peat stratigraphic record, there is good agreement between the historical and palaeoenvironmental evidence for climate change on the North York Moors.

The expansion and contraction of glaciers, combined with other indications of climatic fluctuations, including the altitude of the tree line and water levels in Alpine lakes, have been used in the Alps and Scandinavia to elucidate Holocene climate history (Grove, 1988; Lamb, 1977). In fact, the broad subdivision of the Holocene into warm and cold phases has been largely based on histories of ice advance. Climate histories of this type are inherently of poor chronological resolution, because, although ice advances can be identified by the geomorphology at the maximum extent of the glacier and in the recent past from historical records, little information is gathered about climate fluctuations within a phase of ice advance. A climate history based upon identification of high-magnitude events will include the major changes, but miss finer detail and short duration events.

Research in Scandinavia (Karlén & Kylenstierna, 1996) and from the Alps (Grove, 1988; Magny, 1993; 1995) identifies colder climate signified by phases with advanced glacial margins and high lake levels *circa* 800-300 BC, AD 300-1000 and AD 1300-1900, with intervening warm periods. This sequence of events conforms with syntheses of late-Holocene climate research (Lamb, 1977; Grove, 1988), which identify warm climate during the Roman occupation of Britain, cooler climate between AD 400 and 1000, and a pronounced Medieval warm period AD 1100-1300 followed by climatic cooling into the Little Ice Age. The Little Ice Age is poorly defined chronologically, covering the period AD 1200/1300 to 1900 if viewed purely in terms of advanced glacial margins (Magny, 1993; 1995; Karlén & Kuylenstierna, 1996). Lamb (1977) and Grove (1988) confine the Little Ice Age to the period AD 1550-1850, with a main phase AD

1550-1700. The period 800-300 BC is also a widely identified cooler or wetter period, with evidence of a deterioration in climate provided by advanced glacial margins (Magny, 1993; 1995; Karlén & Kuylenstierna, 1996), by higher tree lines (Bridge *et al.*, 1990; Karlén & Kuylenstierna, 1996), evidence of wetter mire surface conditions across Northwest Europe (van Geel *et al.*, 1996) and by heightened geomorphic activity in upland Britain (Ballantyne, 1991; 1993).

The climate history derived for the North York Moors is in agreement with the established perception of late-Holocene climate (Lamb, 1977). The main changes to a wetter climate *circa* 600 cal. BC, cal. AD 400 and cal. AD 1200-1400 clearly correspond with the beginning of phases of colder climatic conditions 800-300 BC, AD 300-1000 and AD 1300-1900. However, the finer resolution of climate histories derived from peat stratigraphy contains considerably more variations. The most notable of these variations involve a pronounced drier phase cal. AD 700-800. The Medieval warm period appears more complicated than the established definition of a AD 1100-1300 warm or drier period, with wetter conditions until *circa* cal. AD 1000, warmer or drier conditions cal. AD 1000-1200, a wetter or cooler phase cal. AD 1200-1300 and a short-lived drier or warm phase cal. AD 1300-1400 followed by a pronounced major deterioration to wetter or cooler conditions. The cooler and wetter period cal. AD 1400-1900 has obvious parallels with the traditionally defined Little Ice Age; however, the peat stratigraphic signal indicates the climate history for this period is more complicated. There are pronounced wetter phases cal. AD 1400-1550, 1625-1750 and 1800-1900, separated by periods with warmer or drier conditions *circa* cal. AD 1550-1625 and 1750-1800. Clearly the resolution of the peat-based palaeohydrological record for the North York Moors signifies a climate history of greater complexity than traditionally defined.

Peat stratigraphies are not alone in discerning greater complexity within late-Holocene climate history. A recent synthesis of research investigating climate during the last 500 years, drawing upon historical, ice core and tree ring evidence, also indicates the broad 400-500 year Little Ice Age has greater complexity than previously envisaged (Bradley & Jones, 1995). Tree rings like peat stratigraphy can yield fine-resolution climate information and are ideally suited for elucidating structure within the broad divisions of late-Holocene climate. Briffa *et al.* (1990) using detailed palaeotemperature records derived from tree rings, signified that the warmest periods during the last 1500 years occurred AD 749-768, 1087-1106, 1158-1106, 1551-1570 and 1748-1767, which correspond with dry indications on the North York Moors *circa* cal. AD 700-800, 1000-1200, 1550-1600 and 1750-1800. The coolest periods recorded in the dendroclimatology are AD 795-814, 848-867, 1344-1363 and 1601-1620 (Briffa *et al.*, 1990;

Briffa & Schweingruber, 1994), and are contemporaneous with significant wet shifts on the North York Moors *circa* cal. AD 800, 1300 and 1600. A comparatively dry and warm climate during the Little Ice Age is also evident in long instrumental measurement temperature records from central England (Manley, 1974), which signify a warm climate AD 1780-1850 during a broadly cooler period.

The climatic information derived from peat stratigraphy on the North York Moors clearly conforms with the established history of late-Holocene climate. However, this proxy record of effective precipitation reveals greater complexity within the climate history for the last two millennia. This complexity may be beyond the resolution possible with traditional approaches to elucidating Holocene climate. Palaeohydrological interpretation of peat stratigraphy is one of a number of sources of palaeoclimate information, alongside tree rings, ice cores and historical sources, capable of producing fine resolution climate histories. The peat stratigraphic record differs from the published dendroclimatology derived in Fennoscandinavia in that it records climatic wetness opposed to temperature, which is the dominant control upon tree growth in cooler climate regions. Despite the oceanic climate of the British Isles and the comparative aridity of the North York Moors within this climatic region, the proxy effective precipitation record has a great deal in common with both continental and global climate histories. However, the susceptibility of peat stratigraphy on the North York Moors to drier climatic events is invaluable, elucidating warm or dry phases within the cooler climatic conditions of the post thermal optimum late-Holocene.

7.6 Forcing of late-Holocene climate change

Notwithstanding some inherent uncertainties mainly stemming from the ^{14}C chronology, the climate history generated for the North York Moors can be used to address the causes of climate change during the last two millennia. The dominant force controlling the climate on Earth is the Sun (Trenberth *et al.*, 1995). The amount of solar energy received by the Earth has been far from constant and this is an obvious origin for climate changes during the late-Holocene. The solar constant, or perhaps more appropriately inconstant, is modulated by a variety of factors that operate over distinctly different periodicities and by completely different mechanisms. Orbital forcing is an important control upon climatic fluctuations throughout geological time moderating the solar constant; however, orbital parameters operate over longer periodicities than the 2000 year focus of this research.

Changes in the intensity of the Earth's dipole and non-dipole magnetic field occur at similar periodicities (2300 years) to climatic changes throughout the Holocene (Magny, 1993). Changes of this frequency will not be discernible within the 2000-year focus of this research; furthermore a plausible theory and mechanism for a geomagnetic influence on climate is not available. Having indicated that it is difficult to discern periodicities of climate change attributable to Milankovitch scale forcing or to geomagnetic fluctuations, changes in these factors may affect climate during the late-Holocene. Changes in orbital parameters have been linked with the 9000-6000 BP Holocene thermal optimum and the subsequent late-Holocene climatic deterioration, which prevails throughout the chronological focus of this research (Harvey, 1979).

Decadal and centennial variations in the solar energy received by the Earth, basically entail increased energy associated with periods containing a large number of sunspots and less energy associated with sunspot minima (Eddy, 1976). This periodic modulation of solar energy or efficiency has been proposed as a cause of climate change (Eddy, 1976; Magny, 1993; 1995; Stuiver *et al.*, 1995). Further modulation of solar efficiency involves the impact of volcanic aerosols and greenhouse gases, which are hypothesised causes of regional and global climate change (Hammer *et al.*, 1980; Bradley and Jones, 1995). Variations in the production of solar energy occur independently of the Earth's climate system. However, this system is complex, and there are features and feedback mechanisms that also affect regional and global climate. Comparatively minor changes in a single feature can trigger a series of feedback mechanisms affecting a much greater climate change. In fact, researchers supporting solar forcing of Holocene climate invoke feedback mechanisms to amplify the comparatively minor ±0.12°C temperature fluctuation directly attributed to oscillations between sunspot minima and maxima (Stuiver & Brazuinas, 1993).

Understanding of variations in sunspot activity is based upon a number of sources. Direct measurements exist only for the last 15 years and historical records of sunspot frequencies exist for the last 300 years (Eddy, 1976). Consequently the Holocene history of solar activity is inferred from cosmogenic isotopic records in tree-rings and ice cores. The amount of atmospheric ^{14}C ($\Delta^{14}C$) is affected by solar modulation of ^{14}C production, and this information is accessed by ^{14}C analysis of tree-rings. Corroboration of a solar control upon $\Delta^{14}C$ is provided by comparison with the historical record for the last 300 years and additional comparison with the abundance of cosmogenic ^{10}Be recorded in ice cores (Stuiver & Quay, 1980; Oeschger *et al.*, 1987). Both the $\Delta^{14}C$ tree ring and ^{10}Be ice core records unambiguously reconstruct fluctuations in solar magnetism, and by inference sunspot activity (Oeschger *et al.* 1987; Stuiver & Braziunas 1993).

The $\Delta^{14}C$ record derived from bidecadal tree-ring data (Stuiver & Braziunas, 1993a; 1993b) is compared in figure 7.9 with the palaeoclimate history elucidated for the North York Moors. Blue

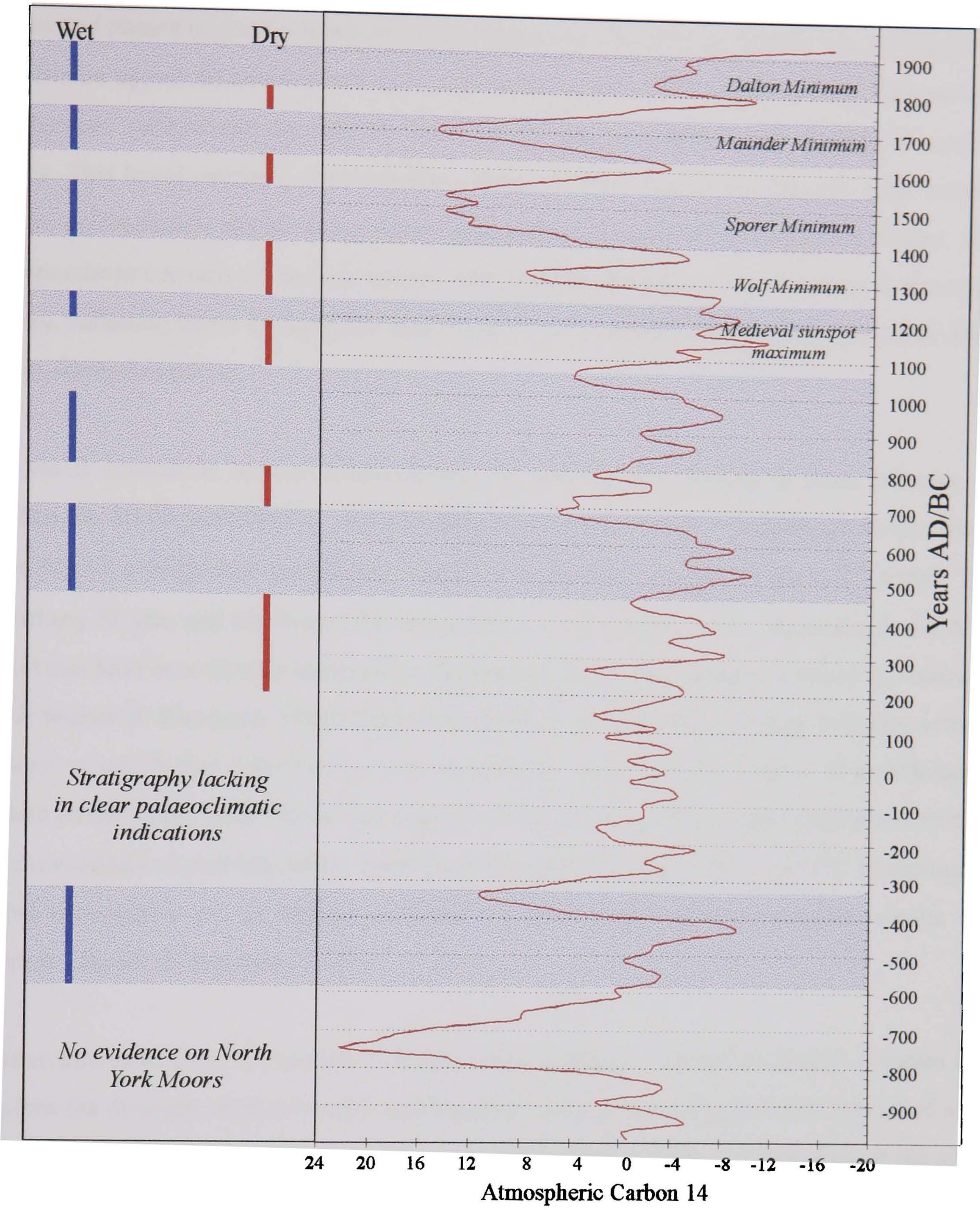


Figure 7.9 Tentative correlation between the atmospheric 14C variations (14C) and moisture indications in peat sequences on the North York Moors. The 14C fluctuations are derived from a smoothed decadal dendrocalibration curve (after Stuiver & Becker, 1993) and are believed to reflect a response to changing frequencies of sun-spots, with high values denoting sun-spot minima and low values sunspot maxima (Stuiver & Brazuinas, 1993). The main named sun-spot periods are annotated. Significant wet shifts and unequivocal evidence of dry conditions from all five sites are signified by blue and red lines respectively. Concentrations of wet events evidenced at several sites are highlighted with blue shading to assist comparison with the solar record.

shading denotes the wet climatic periods and red lines signify drier phases, and in addition the main named phases of solar activity are clearly annotated. The climatic fluctuations on the North York Moors appear to coincide with the solar record. Cool or wet shifts coincide with periods with reduced sunspot activity and the warm or dry phases coincide with heightened sunspot activity. This broad overlap provides tentative evidence for a relationship between solar activity and the palaeoclimate record derived from peat stratigraphies on the North York Moors. The correspondence between the records appears better for the last millennium; however, this may be illusory, reflecting better stratigraphic resolution of the palaeoclimate signal for the North York Moors during this period.

The visual correlation between solar activity and mire palaeohydrology is clear; however, in addition the 80-90 and 200-240 year periodicities identified in peat stratigraphies on the North York Moors overlap with periodicities signified in spectral analysis of the $\Delta^{14}C$ signal. The Gleissberg 88-year and the Suess 208-year cycles are components of the harmonics in the $\Delta^{14}C$ record that have been directly attributed to fluctuations in the solar constant (Damon & Jirikowic, 1992; Stuiver & Braziunas, 1993). This concordance between palaeohydrology and solar activity appears to signify that solar forcing may be partially responsible for forcing of late-Holocene climate on the North York Moors. The main *caveat* to this association, apart from anxieties over the chronologies of peat sequences, stems from the view that only a *circa* ±0.12°C fluctuation in global temperature can be directly attributed to the difference between sunspot minima and maxima (Stuiver & Brazuinas, 1993).

If solar fluctuations are forcing late-Holocene climate change, mechanisms within a system that involves the atmosphere, hydrosphere and biosphere must be amplifying the net impact of solar fluctuations. A complete discussion of the complexities of the climate system is beyond the scope of this thesis; however, the discussions in Stuiver & Braziunas (1993) and Chambers *et al.* (in press) identify a number of theories providing a mechanism for amplifying the impact of solar fluctuations have been postulated:

- A small change in the properties of clouds could have a considerable impact upon global and regional climate (Karlén & Kuylenstierna, 1996). Solar activity affects the global magnetic field with a knock-on impact upon cloud physics, which could affect the global albedo (Tinsley, 1994).
- Fluctuations in solar ultra-violet radiation also affect the production of ozone. Ozone fluctuations have been linked to climate change (Hood *et al.*, 1993).

- Minor changes in global irradiance can cause a resilient temperature change of 0.1-0.3°C, which could affect North Atlantic circulation, triggering thermohaline oscillations. Any change in North Atlantic oceanic circulation could have a knock-on impact upon atmospheric circulation, thereby causing or amplifying climate change (Stuiver & Brazuinas, 1993).

The literature on this subject is far from conclusive and this prohibits complete confidence in the association between late-Holocene climate and the solar record (Chambers *et al.*, in press). It is probable that several of these mechanisms and a series of as yet unknown factors combine to control climate in north-west Europe. Fluctuations in the abundance of volcanic aerosols and greenhouse gases also affect global climate. Greenhouse gases are inherently linked to the climate system and increased water vapour has already been identified as a mechanism for amplifying the impact of solar oscillations upon climate (Tinsley, 1994). Carbon dioxide is one of the most significant greenhouse gases and is apparently linked to anthropogenic global warming (Houghton *et al.*, 1990). However, CO_2 fluctuations are of insufficient magnitude to account for the climatic variations identified during the last two millennia, with the obvious exception of changes in the twentieth century (Bradley & Jones, 1993).

The climatic impact of volcanic aerosols has long been acknowledged (Lamb, 1970), but there is considerable debate about the duration and magnitude of climate changes in the wake of volcanic eruptions (Bradley & Jones, 1995; Rampino & Self, 1984). Climatic changes directly attributed to volcanic eruptions appear very short-lived, with temperature variations undetectable from background noise after 2-3 years. A more complete understanding of volcanic history, particularly identifying SO_2 rich eruptions, is essential before the contribution volcanic aerosols make to global and regional climate can be properly addressed. Zielinski *et al.*, (1994) encountered a 4-5 year impact by forty-three climatically significant eruptions during the last two millennia in the $\delta^{18}O$ temperature record in the GISP2 ice core. These eruptions are believed to cause an average 1°C fall below mean temperature for the last two millennia (Stuiver *et al.*, 1995). Hammer *et al.* (1980), in a record that is not without detractors, identified periods with intensive volcanic activity using acidity peaks in Greenland ice cores, AD 500-850, 900-1050, 1300-1700 and 1800-1900, which broadly overlap with wet periods on the North York Moors. Volcanic eruptions ejecting large quantities of sulphur dioxide into the stratosphere may cause cooler wetter climatic conditions; however, analysis of eruptions during the last 300 years indicates the intensity of the climatic impact is variable and short-lived (Rampino & Self, 1984). Nevertheless, the climatic impact of a volcanic eruption of the right magnitude, in the right location and at the right time could combine with other factors including solar forcing and feedback mechanisms within climate systems, effecting a greater and sustained climate change.

The discussion above highlights the complexities of regional climate and the scale of uncertainty in understanding forcing of palaeoclimate. There is a clear parallel between climate change on the North York Moors and solar forcing, which appears a likely factor behind climate change in north-west Europe. However, other factors will obviously affect this relationship, with feedback mechanisms inherent in ocean, atmosphere and biosphere interactions further clouding this issue, and volcanic eruptions unequivocally contributing to climate fluctuations in north-west Europe. At present it is not possible to link climate histories definitively to particular forcing agents. Furthermore, in balancing the complexity of the climate system against both spatial and temporal inadequacies, and the imprecision inherent within proxy climate histories, conclusive identification of the forcing agents behind climate change may never be entirely possible.

8 Synthesis

8.1 Implications and directions for future research

The conclusions of this thesis in relation to the vegetation and climate history for the North York Moors during the last two millennia are presented in chapters five, six and seven respectively. However, the ramifications of this research go beyond vegetation history and palaeoclimate research. The wealth of analysis on the North York Moors has implications for;

- future palaeoenvironmental research on the North York Moors;
- ^{14}C dating of peat sequences;
- future peat-based palaeoclimate research and predicting future climate change;
- moorland management.

Furthermore, as with all research, the process of investigation uncovers as many questions as it provides answers. There are a number of areas of research that clearly require further analysis, and these areas broadly occur within the four categories listed above.

8.2 Future palaeoenvironmental research on the North York Moors

The principal discoveries of palaeoenvironmental research on the North York Moors presented in chapters five, six and seven, entail a greater complexity to the regional vegetation history and the development of a 2000-year climate history. One of the main improvements on previous research this thesis has contributed is through the judicious use of ^{14}C dating to secure the palaeoenvironmental histories. A further advantage involves the availability of an archive of documentary material pertaining to the last 1500 years, which is an invaluable source of landscape and climatic information (James Menuge, 1997).

The pollen analyses uncovered evidence of a sequence of events reflecting changes in the demographic, cultural, economic and climatic history of the North York Moors. These events include woodland expansion as the result of reduced agricultural activity in the wake of population declines due to the Roman withdrawal from England, the 'harrying of north' and the Black Death. Furthermore, there is clear evidence of increased agricultural exploitation of the uplands as the results of a more commercial approach to farming during the Roman-British period, population expansion during the Anglo-Scandinavian period and due to concerted attempts to develop the North York Moors for agriculture during the 12-13th and 15-16th centuries. The climatic history discussed in chapter seven is the first attempt to elucidate palaeoclimate information from peat stratigraphies located across the eastern North York Moors.

Despite the concerted effort to develop a comprehensive vegetation and climate history for the last two millennia, there is still potential for further research on the North York Moors. Within the time constraints of this thesis fine-resolution palaeoecological analysis was not possible; However, the sequence of events uncovered in the pollen, testate amoebae and plant macrofossil analyses indicates this maybe a worthwhile approach. Fine-resolution analysis at sampling intervals of *circa* 1-3mm through significant events would improve understanding of the process and nature of change. This approach could target features like the woodland expansions linked to the Roman withdrawal or to the Black Death or particularly severe climatic fluctuations, and assess the speed of palaeoecological change and the structure within changes. Fine-resolution analysis may identify differential response by certain testate amoebae or plant species to climatic changes, that are not visible at the current resolution of analysis.

If fine-resolution palaeoecology could be coupled with judicious use of ^{14}C dating, notwithstanding the problems encountered with ^{14}C dating in this research, it would contribute greatly to understanding of environmental changes on the North York Moors. The great potential for research of this type lies with coupling the palaeoecology with the archive of historical information (James Menuge, 1997). The chronological accuracy of palaeoecological histories could be improved by recognising the pattern of ^{14}C wiggles, which reflect variations in atmospheric ^{14}C activity, in time series generated by fine resolution AMS ^{14}C dating of peat deposits (Kilian *et al.*, 1995; van Geel & Mook, 1989). If particular wiggles or plateaux occur in the time series generated from peat deposits, these can be directly correlated with the dendrocalibration record of atmospheric fluctuations in ^{14}C. Wiggle-match dating potential could greatly improve the accuracy of palaeoenvironmental histories elucidated from peat stratigraphy. In summary, there is still great potential for palaeoenvironmental investigation of peat stratigraphies on the North York Moors, particularly targeting specific events or features with a combination of fine-resolution palaeoenvironmental analysis and wiggle-match AMS ^{14}C dating of peat deposits.

In addition to a focus on the finer structure within the climate and vegetation histories elucidated in this research, there are other spatial and temporal gaps within the body of palaeoenvironmental research on the North York Moors. Pollen analysis of profiles within the southern hills of the North York Moors would investigate the vegetation changes in an important agricultural area.

Virtually all previous vegetation history research on the North York Moors utilised profiles from the central moorland, which are not prime land for agriculture. Sites located in the agricultural areas would be invaluable and provide more information about past land-use around the North York Moors, but unfortunately there is little peat remaining in the southern hills. In terms of climate history research, the only sites used for palaeoecological investigation are those in this thesis from the eastern and central North York Moors and the site utilised by Blackford & Chambers (1991) on East Bilsdale Moor. There are further potential sites on the central plateau of the North York Moors, which includes deep peat sites on the North Gill to Bluewath Beck plateau, and parts of Westerdale and East Bilsdale Moors. However, these sites may not necessarily yield stratigraphy pertaining to the late Holocene.

The other gap within palaeoclimate research on the North York Moors involves stratigraphy pertaining to the remainder of the Holocene, which, with the exception of the profile from East Bilsdale Moor (Blackford & Chambers, 1991), have not been investigated before. Much of early- and mid-Holocene stratigraphy is well humified and is not the *Sphagnum*-rich peat likely to contain large quantities of identifiable plant macrofossils or testate amoebae. Palaeohydrological analysis of stratigraphy of this type is likely to be limited to humification analysis. However, there are profiles covering the mid- and late Holocene in water-shedding locations across the North York Moors, in particular the basal stratigraphy at May Moss and Harwood Dale Bog, and peat sequences on the North Gill/Bluewath Beck plateau and on East Bilsdale Moor.

8.3 The future for radiocarbon dating peat sequences

Preliminary assessment of the contemporaniety of different components within peat at May Moss highlights the heterogeneous nature of the sediments and indicates there are problems with radiometric assays obtained upon bulk peat samples. The principal recommendation of this research is that components should be selected from peat on the basis of contemporaniety with the horizon of accumulation. Furthermore, pure *Sphagnum* remains, if present, are perhaps the most suitable materials for dating peat. Unfortunately this analysis at May Moss is only a preliminary assessment of the impact that the heterogeneity of peat has upon the ^{14}C age of a sample of peat. Future research further addressing this problem is essential and should analyse humic, humin and fulvic fractions and a bulk peat sample by the radiometric method. In addition, AMS dates should be obtained for all components identifiable and extractable within each selected horizon. Comparison of the variations in ^{14}C ages obtained in this may formally identify the most suitable material for ^{14}C dating peat and identify the level of inaccuracy present within existing ^{14}C age determinations. Ideally, research investigating this problem should utilise a range of different peat sequences, including raised mires, blanket mires and fens. Selecting sites with other means of ageing the peat sequences would enhance a formal test of this type. Volcanic ash layers, if present, within the stratigraphy offer this opportunity, as would ^{210}PB, ^{241}Am and ^{137}Cs dating the surface layers of actively accumulating mires as a part of an integrated geochronological strategy.

8.4 Future peat-based palaeoclimate research

The most important outcome of this research in terms of the process of elucidating climate history from peat stratigraphy, is the broad consistency of the hydrological signal yielded by the three approaches. There are circumstances when the hydrological signal yielded by a particular technique was ambiguous, with humification stratigraphy occasionally and inexplicably variable. The multi-proxy approach, utilising several palaeoecological procedures, represents the future for peat-based palaeoclimate research, because there is greater clarity and confidence in a hydrological signal derived by several lines of inquiry. The performance of testate amoebae as a palaeohydrological tool is excellent, with the broad degree of consistency between hollow and hummock sequences indicating a single peat profile is capable of providing an assessment of the sub-fossil testate amoebae stratigraphy at a particular location.

Research at May Moss provides further evidence that hollow stratigraphy is more suitable for palaeohydrological investigation than hummock stratigraphy. The location of the core sites is also critical for research on blanket mires. Topography and differential mire development over this topography can produce pronounced variations in the stratigraphy across a mire. Understanding the sedimentary history is critical for deciding upon core sites. For palaeoclimate research the core site should be located within ombrogenous facies on the mire watershed; however, the stratigraphy can still be affected by changes elsewhere on the mire. At May Moss the expansion of a *Sphagnum*-dominated facies from the Eller Beck basin has affected the stratigraphy on the mire watershed. An understanding of mire evolution is critical for interpreting stratigraphic changes with topographically controlled upland blanket peat.

Using poorly humified rapidly accumulated blanket peat sites, containing a wealth of macro- and micro-fossils, has advantages over palaeoclimate research utilising typical comparatively shallow well humified slowly accumulated blanket peat. Clearly a greater chronological resolution is available from rapidly accumulated stratigraphy. Furthermore the comparative wealth of fossil evidence favours a range of palaeoenvironmental procedures increasing confidence in the eventual palaeohydrological signal. Peat sequences formed under the oceanic climate of the British Isles are well suited for palaeoclimatic research, whereas peat sequences experiencing a continental climate in central Europe appear to record less in the way of climate change (Haslam, 1987). Within the British Isles there are considerable variations in climate, and research on the North

York Moors reveals peat stratigraphies from drier regions are well suited for the elucidation of climate history, particularly for identifying dry periods.

The benefits of palaeoclimate research utilising upland blanket peat sequences have only been realised during the last decade, and there is a large resource still to be utilised. This thesis signifies that future research should target;

- poorly decomposed rapidly accumulating upland ombrogenous peat sequences, because of the wealth of sub-fossil material within the peat and the potential for using several techniques to elucidate hydrological and climate history;
- sites in the drier parts of the British Isles clearly warrant further attention, because the oceanic nature of the British climate and the comparative aridity of eastern Britain appears a particularly fruitful combination for palaeoclimate research.

Further testing of the multi-proxy approach is warranted, because the testate amoebae, plant macrofossil and humification analyses utilised in this thesis could be supplemented with non-pollen micro-fossils (fungi, algae, etc.) (van Geel, 1978) and isotope geochemistry (van Geel & Middledorp, 1988). Basically, future improvements to the process of elucidating climate information from peat stratigraphy must entail both improving the precision of palaeohydrological interpretation of mire palaeoecology, and assessing the accuracy of temperature and precipitation values elucidated by means of isotopic analysis of cellulose within peat.

Improving the precision within reconstructions of mire hydrology may involve testate amoebae analysis, because it is the only technique currently allowing the quantitative estimation of environmental parameters. Environmental reconstructions using testate amoebae could be improved by ecological research quantifying the environmental parameters controlling the occurrence of testate amoebae from different regions across the globe. Furthermore, the link between the occurrence of testate amoebae and mean annual water tables can be challenged, because testate amoebae are only active during the summer months; consequently, mean depth of the summer water table may be more appropriate. Isotopic analysis of cellulose within peat is the only approach with the ability to produce tentative estimations of specific climate parameters, but is hampered by a species effect on the isotopic signal (van Geel & Middeldorp, 1988). Isotopic analysis was not attempted in this research owing to the unavailability of appropriate laboratory resources.

Elucidating periodicities within climate histories is another important objective for peat stratigraphic research. By necessity this requires fine-resolution palaeohydrological analysis and accurate ^{14}C dating to transform the sub-fossil profiles into time series. However, the investigations in this thesis and research elsewhere in the British Isles (Chambers *et al.*, 1997; Barber *et al.*, 1994b) are beginning to encounter similar periodicities within palaeohydrological signals, and a synchrony between solar fluctuations and the peat stratigraphic signal (Blackford & Chambers, 1995). Chambers *et al.* (in press) express concern that solar forcing is acknowledged in IPCC reports (Intergovernmental Panel on Climate Change) as a comparatively minor component affecting global climate (Houghton *et al.* 1990; 1995). If the association between late-Holocene climate changes recorded in a considerable number of palaeoclimate proxies and solar forcing is real, then there maybe substantial errors within predictions of future climate change (Chambers *et al.*, in press).

In conclusion there is a clear need for future research elucidating fine-resolution multi-proxy palaeoclimate histories from across the British Isles. Spectral analysis of these palaeohydrological data should identify whether there are dominant periodicities within the peat-based palaeoclimate signal, which may shed further light upon the agents forcing Holocene climate. Furthermore there is an onus upon those engaged in future climate research to uncover a plausible mechanism for amplifying the minor direct impact of fluctuations in solar activity upon global climate. The nature and magnitude of potential indirect effects of solar fluctuations upon the Earth's climate system have considerable implications for accuracy in predicting future climate change.

8.5 Moorland management

Mire conservation is an issue of paramount importance at a national level, and should be a major concern on the North York Moors. The status of the North York Moors as the driest upland area in the British Isles sustaining blanket mires, places peat accumulation under threat at the outset because the climate is so dry. The threat to mires on the North York Moors is amplified by the potential for anthropogenically induced climatic warming and by drying in response to land-use changes. Of the sites selected in this research, May Moss and Yarlsey Moss are the only areas of deep (>2 metres) actively accumulating blanket mire that are not affected by peat extraction. The sites are still under threat, with Yarlsey Moss currently managed as grouse moorland. In addition to the cyclical burning of the moor to maintain a monoculture of younger *Calluna vulgaris* plants, certain areas of the mire have been drained to assist construction of grouse butts. This interference is unfortunate because the Yarlsey Moss to Pike Hill Moss expanse of blanket moor is the largest unprotected area of blanket mire on the North York Moors.

May Moss is protected by both its status as a SSSI and by being surrounded by conifer plantations and RAF Fylingdales Early Warning Station. The site currently is not grazed by sheep and is not managed for grouse, and is the only area of unmodified blanket mire on the North York Moors. Lowering of the water table particularly from the edges of the mire near the conifer plantations and associated drainage schemes is the only real threat to May Moss. Levels of evapotranspiration will be higher around May Moss because of the quantities of trees, which will affect the mire water balance (Heathwaite *et al.*, 1993b).

Both Harwood Dale Bog and Bluewath Beck have been severely damaged by peat cutting and land-use changes. The situation at Harwood Dale Bog is irreversible, with much of the peat cut and the remaining moorland covered by conifer plantations. The situation at Bluewath Beck is equally bad; however, beyond the peat cutting there is a large expanse of moorland stretching from Bluewath Beck to North Gill. If peat cutting in this area was abandoned and the moorland was not subjected to further inference in terms of drainage and cyclical burning, ecologically it may eventually recover. Fen Bogs is in the best condition of the sites utilised in this research, mainly because it is protected as a SSSI and Yorkshire Wildlife Trust nature reserve. The site is not under threat from land-use change and its importance ecologically renders future interference unlikely.

Palaeoenvironmental research at these sites has implications for future moorland management at these and other sites across the North York Moors. All the sites have been through pronounced environmental changes in the past, which have largely been attributed to climate for example the ecological changes at May Moss and Yarlsey Moss in response to an cal. AD 700-800 drier climatic period. The ecological changes in these cases involved a radical alteration to the flora, with *Sphagnum* species declining. There were also significant changes in the testate amoebae communities and almost certainly with equivalent changes in communities not assessed in this research, for example other micro-organisms, insects and macro-fauna.

The most important implication of the palaeoenvironmental research in terms of mire conservation and management is the apparently ubiquitous capacity for mires to recover from ecological changes during adverse conditions. The high-diversity valley mire flora currently extant at Fen Bogs exemplifies this and represents a considerable recovery from the damage incurred during the construction of the Whitby-Pickering railway in 1836. However, this potential for recovery should not be used as a justification for taking no immediate action regarding mire conservation for two reasons. Firstly, the recovery of a mire after environmental damage or adverse climatic conditions takes time. Secondly, the situation at Harwood Dale Bog indicates there are thresholds beyond which conservation is impossible, rendering mire restoration the only alternative. The expense in terms of finance and man-power required for mire restoration means once these thresholds are crossed the mire is irrevocably damaged.

The environmental and ecological histories developed at the five sites demonstrate the condition of the mires in an unmodified state, which provides a target ecology for restoration and conservation projects. Future research investigating the nature of severe environmental change and the subsequent recovery period may shed further light on the process of mire restoration. Fine-resolution testate amoebae and plant macrofossil analyses at *circa* 1-5mm intervals across the environmental changes signified in this research, may also allow these techniques to be used as tools for monitoring the success of future attempts at mire conservation or restoration. Using uniformitarianist principles, a detailed understanding of the response and recovery of the mire ecosystem from severe dry events may also provide an analogue for future environmental changes in the response to either anthropogenically induced climate change or future land-use changes and mire drainage. The potential threat posed by future "global warming" is particularly important in an already dry upland area like the North York Moors. Mires in this comparatively arid part of Britain are perhaps already close to the precipitation threshold for the accumulation of blanket peat. Clearly understanding ecological changes during previous dry climatic periods will stand conservationists in good stead, providing an analogue for mire ecology during future climate changes (*sensu* Houghton *et al.*, 1990; 1996).

Directions for future research on moorland management include a need for future fine-resolution palaeoecological investigation of the changes identified in this research. In particular, investigating the response and recovery of plant macrofossil and testate amoebae communities to dry climatic periods *circa* cal. AD 700-800, and the complex suite of changes *circa* cal. AD 1000-1500. In addition there are several ecological projects for which monitoring extant testate amoebae and plant communities would be invaluable. May Moss is adjacent to Fylingdales meteorological recording station; consequently there is considerable potential for investigating long-term ecological response to climatic variations, particularly if coupled with monitoring of the water table. Research of this type achieves further significance in the light of proposed clearance of forestry around May Moss and the willingness of Forest Enterprise to see the cleared land return to moorland. Coupling the proposed land-use changes with long-term water table and ecological monitoring offers not only the chance for assessing the impact of future climate change upon the mire ecosystem, but offers a rare opportunity to assess the success of a mire restoration scheme scientifically.

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