HIGH-RESOLUTION PALAEOENVIRONMENTAL INVESTIGATIONS ON HOLOCENE MIRES IN THE BALTIC REGION

GARRY BOSWORTH

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Abstract

The principal aim of this research project was to generate proxy datasets from four sites in the Baltic region. In order to achieve this, a core of peat was taken from four ombrotrophic mires, and high-resolution multi-proxy analyses of contiguous 1 cm peat samples were undertaken. Proxy-climate curves were generated for each site using colorimetric humification analysis and plant macrofossil analysis as the primary proxies. At a slightly coarser resolution, testate amoebae analysis was carried out to provide an independent source of palaeohydrological data. Detrended Correspondence Analysis (DCA) and Weighted Averages Ordination (WAO) were applied to the raw macrofossil data in order to generate proxy-climate datasets that can be directly compared with the humification record. A series of wiggle-matched AMS ^{14}C dates enabled an effective chronological framework to be produced for each site and allowed inter-site comparison of the datasets. Results indicate that changes in peat stratigraphy may in fact be driven by additional internal factors, notably autogenic succession and that climate appears to have played a secondary role. This supports the established view of many Baltic researchers and indicates that changes on Baltic mires are driven by the interplay of a range of internal and external factors.

Additionally, critical evaluation of the methodologies and proxy indicators was also undertaken in order to ascertain whether they were able to record proposed episodes of climate change.

Acknowledgements

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Chapter 1 Introduction

1.1 Background and Context of Research

Increased concern about changes in twentieth and predicted twenty-first century climate has resulted in a rapid rise in the amount of research evaluating both anthropogenic and natural causes of climate change. In particular, the causes of sub-Milankovitch scale (mainly centennial/millennial) climate change have been the focus of palaeoclimatological research over the last two decades (Rind & Overpeck, 1993; Blackford & Chambers, 1995; Karlen & Kuylenstierna, 1996; Bond *et al.* 1997, 2001; Stuiver *et al.*, 1997; Chambers, *et al.*, 1999; Leftus, 2000; Crowley, 2000; Chambers & Blackford, 2001; Mauquoy *et al.*, 2002). The term 'enhanced greenhouse effect' has been widely used by governments and environmental pressure groups to draw attention to postulated anthropogenic climate change.

However, it is still unclear what proportion, if any, of observed 21st century climate change may be attributed to human activity. Until recently, palaeoclimatological research has mainly focused on the causes of long-term climate change and decadal and centennial climate research has been rather neglected. Indeed, climate within the Holocene has been considered rather uniform and unremarkable when placed in context with the glacial and earlier interglacial stages. Nevertheless, evidence from ice cores and other proxy data archives has demonstrated that this is not the case and the Holocene has been marked by oscillating climate that has fluctuated at a rate and magnitude not explicable by existing theories (Morgan & van Ommen, 1997). Recent high-resolution and multi-proxy investigations over much shorter time scales have identified episodes of rapid and/or short-lived climate change during the Late Holocene.

In particular, Mayewski *et al.* (1993) suggest that the warm conditions associated with the Medieval Warm Period (MWP) and the colder conditions of the subsequent Little Ice Age (LIA) may serve as our most recent analogues of climate change. Whilst the magnitude of these events may be relatively small they still represent the limits of natural climate variability within the Late Holocene.

It is against this backdrop of Late Holocene climate change that recent research has attempted to ascertain and evaluate the mechanisms of sub-Milankovitch climate forcing. Research has concentrated on the sun-climate relationship, most notably on establishing a connection between short-term fluctuations in solar output and episodes of corresponding climate change (van Geel *et al.*, 1998, 1999, 2000). In the northern hemisphere, ocean research has also identified a temporal link between changes in the North Atlantic Oscillation (NAO) and climate. However, whilst documented and proxy evidence suggests that events such as the MWP and LIA were recorded throughout much of northwest Europe the magnitude and timing of these episodes is variable.

Therefore, a principal aim of this research project has been to reconstruct a high-resolution record of climate change that encompasses the Medieval Warm Period and Little Ice Age. It is anticipated that this will provide additional proxy data for the Baltic region and will enable climatic teleconnections to be made with episodes of climate change elsewhere. A series of high-precision AMS ^{14}C wiggle-matched dates enables cross-correlation of data and aids the identification of known fluctuations in solar activity. A postulated link between solar activity and Late Holocene climate is then evaluated.

1.2 Peat bogs as archives of palaeoclimatic data

The effectiveness of ombrotrophic peat bogs in providing a high-resolution and replicable record of Late Holocene climate change is evidenced by research in the UK and north-west Europe (Chambers *et al.*, 1997; Barber *et al.*, 1994b, 2000; Blackford, 2000; Mauquoy *et al.*, 2002; Blaauw *et al.*, 2003).

Peat bogs are an ideal repository for reconstructing and investigating the causes of climate change. The distinctive dome shape of ombrotrophic peat bogs limits the influence of the surrounding catchment and effectively isolates them from external inputs from the regional groundwater table. Ombrotrophic mires, it is claimed, receive their nutrient supply solely from atmospheric precipitation and therefore act as a close-coupled atmosphere/biosphere system. The dynamic relationship between raised mires and climate is a consequence of the sensitive balance between the growth of the mire's plant community, decomposition of peat, water table height and the corresponding thickness of the aerobic acrotelm. Clymo (1984) notes that all biological production and the majority of peat decomposition takes place in the acrotelm. As the depth of this layer is determined by the water table position, which in turn is controlled by effective precipitation, any stratigraphical changes in the mire can be attributed to climate. Clymo also suggests that even minor fluctuations of several centimetres in the thickness of the acrotelm can result in marked changes in the rate of peat decomposition. Peat production is therefore especially sensitive to changes in effective humidity that is influenced by variations in temperature, precipitation or both.

Ombrotrophic peat bogs are unique plant communities. Typically composed of *Sphagnum* species these ecosystems are able to respond to short-term or low-magnitude changes in climate. In northwest Europe, ombrotrophic peat formation began at approximately the time of the Boreal-Atlantic Transition (*c*.5000 BC). The continuous vertical growth of peat means that at undisturbed sites a sequential record of past climate can be retrieved and compared with similar sites and documented episodes of climate change.

The pioneering work of Blytt (1876) on raised bogs in Scandinavia resulted in peat stratigraphy becoming a major source of evidence for climate change in northern Europe (Birks & Birks, 1980). Additional studies by Sernander (1908), Weber (1910) and observations by Lewis (1905 -1911) in Scotland resulted in a fivefold division of the Post-glacial. Despite some early opposition the Blytt-Sernander scheme was generally adopted and extensively used as a temporal framework for climatically driven changes in peat stratigraphy of northern Europe. However, in the last two decades high-resolution studies incorporating radiocarbon dates have demonstrated that this subdivision is much too simplistic and this concept has since been rejected.

Early mire research in Scandinavia identified alternating bands of light and dark peat termed ‘recurrence surfaces’ (Granlund, 1932). These recurrence surfaces were evident over wide areas of the bog and were initially thought to reflect large-scale changes in precipitation. However, further investigation at Gifhorner Moor, Germany showed that an age variation of up to 1100 years was evident for what appeared to be the same recurrence surface (Schneekloth, 1965). This was supported by the research of

Lundqvist (1962) and it was these difficulties concerning the asynchroneity of recurrence surfaces that led to the eventual abandonment of the Blytt-Sernander scheme.

Following these pioneering studies there was a period of *c.* 50 years between the 1920s and 1970s when much of this research was in abeyance owing to a misconception about how peat bogs grow (Backeus, 1990). Since then, proxy-climate records have been generated from ombrotrophic mires using a range of palaeoecological techniques. Early research commonly used the degree of peat humification as a means of identifying climate shifts. Highly humified peat was considered indicative of warmer and/or drier conditions whilst conversely less humified peat was used to indicate a shift to relatively wetter conditions. However, many of the proxy-climate datasets generated from these mires were at a coarse resolution and often comprised only one principal palaeoecological technique (Casparie, 1972; Aaby, 1976).

More recently, research has demonstrated that ombrotrophic mires can yield detailed, high-precision proxy records (Blackford, 1998; Langdon *et al.*, 2003; Barber *et al.*, 2003a). The UK and Ireland have been at the forefront of recent palaeoclimatic research. Raised and blanket mires in Cumbria, Scotland and Ireland have been extensively cored and proxy climate records have been generated for much of the Holocene from these sites. Hughes *et al.* (2000) retrieved a full Holocene record from Walton Moss, Cumbria. Using plant macrofossil data they were able to identify 10 episodes of increased mire surface wetness commencing at *c.*7800 cal. BP and the most recent wet shift dated at *c.*100 cal. BP. This record was then compared with the proxy record generated from nearby Bolton Fell Moss. Results support the hypothesis that mires record changes in regional/hemispherical climate and that the plant assemblage on ombrotrophic mires is sensitive enough to respond to changes in climate.

The need for increased precision in palaeoclimatic research has resulted in multi-proxy, high-resolution (0.5-1cm contiguous sampling) studies. Hong *et al.* (2000; 2001) used the ratios of $^{16}O/^{18}O$ and $^{12}C/^{13}C$ isotope in peat cellulose to generate a record of climate change over the last 6000 years from China. In the UK, pioneering research at Bristol University has attempted to use lipid biomarkers as an additional proxy data source (Baas *et al.*, 2000; Xie *et al.*, 2001). Nott *et al.* (2000) successfully showed that a varying abundance of the alkane C_{23} could be correlated with vegetation changes in a 40 cm peat profile from Bolton Fell Moss. However, recent studies have mainly used peat humification in conjunction with plant macrofossils and/or testate amoebae to infer episodes of climate change (Charman *et al.*, 1999; Hughes *et al.*, 2000; Mauquoy *et al.*, 2002; Blaauw *et al.*, 2003).

1.2.1 The influence of non-climatic factors on mire dynamics

The growth pattern and microtopography of mires has been the subject of considerable debate and research since the nineteenth century. As yet there is no universal agreement as to the relative importance of allogenic and autogenic factors in determining stratigraphic changes within the mire. A model of peat bog regeneration pioneered by von Post & Sernander (1910) and subsequently developed by Osvald (1923) proposed that the hummock/hollow complex characteristic of ombrotrophic mires would typically be unstable. In this model peat accumulation was faster in the hollows resulting in the formation of a hummock over time.

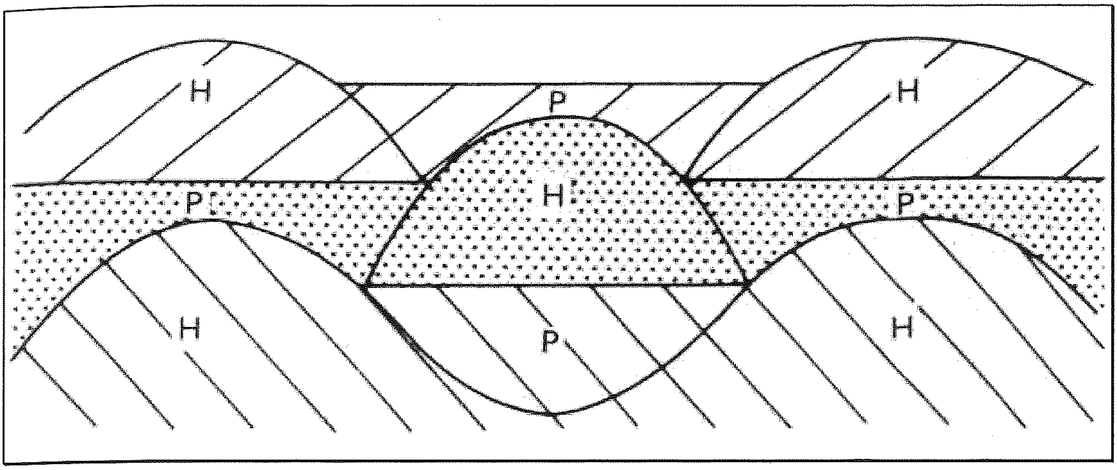

Figure 1.1 Theoretical stratigraphic section through a pool and hummock complex on a raised bog, showing how each generation originates from pools of the previous generation.
Taken from Birks & Birks (1980).

This would appear to be supported by Lindholm & Vasander (1991) who observed the growth dynamics of *Sphagnum* species in the hummock and hollow habitat. Hollow species were found to grow faster than their hummock counterparts and annual increments in the thickness of living *Sphanum* cover were also greater in the hollow. However, research by Walker & Walker (1961) on raised bogs in Ireland showed that these features are mainly stable landforms. This view is supported by research in Finland by Aartolahti (1965, 1967) and more recently Korhola & Tolonen (1998, p24) stated "There is a large consensus, however, that hummocks and hollows are quite permanent features; there is little evidence for cyclic succession, except for the small-scale "*Sphagnum* regeneration" observed in many peat sections in southern Finland".

Nungesser (2003) has recently developed a model HOHUM (HOllow-HUMmock) to replicate microtopographical growth patterns on boreal peatlands. HOHUM is a dynamic, process-based simulation model reproducing biological and physical processes leading to hummock, hollows and pools. The model yielded excellent results with a high degree of precision (less than 2 cm) between predicted and measured heights of hummocks, hollows and water table depths for North American and European sites. Nungesser concludes that hummocks and hollows arise primarily from the variation in growth rate of different peat forming taxa. Interactions between moisture, *Sphagnum* characteristics and decomposition rates are responsible for the maintenance and resilience of hummock and hollows (Belyea & Clymo, 2001). Feedback between *Sphagnum* growth, decay and moisture restricts peat accumulation, creating a stable equilibrium with local climate within decades. This supports the claim of Walker & Walker (1961) that microtopographical features are relatively stable over time. However, results also indicate that climate alone is not responsible for microtopographical change but rather it is the interplay between a range of internal and external dynamics.

Several theories have been proposed for the origin of pool formation (Tallis, 1973; Boatman & Tomlinson, 1973, 1977; Karofeld, 1998). Karofeld (1998) investigated the dynamics of pool development and formation from raised bogs in Estonia. Results showed that no correlation was evident between the temporal distribution of hollows either within the mire or when compared with nearby sites. Therefore, hollow formation is likely to be initiated by extra-local factors that differ from site to site and may even differ within one bog. Hulme (1986) also suggests that it is the interplay between climate and the developmental stage of the bog, and the physical and hydrological characteristics of the peat that initiate pool formation. However, whilst no temporal link can be established for pool formation a clear relationship is evident for episodes of pool enlargement and contraction. Simultaneous increases in pool size occurred at 1600-

1400, 1100-900 and 600-400 yrs BP whilst the contraction of pools is dated to 1700-1500, *c.*1200 and 400-200 yrs BP. The changes in shape and areas of hollows are therefore likely to reflect changes in mire hydrology. Korhola (1995) concludes that if the form and development of mires is consistent within a region then the temporal pattern can only be interpreted as a response to regional climate change.

One of the most intensively studied peat stratigraphical changes is the Swarztorf/Weisstorf Kontakt or Grenzhorizont that is usually associated with the climatic cooling of *c.* 3000-250BP when the rejuvenation of many mires occurred (Svensson, 1988). Despite intensive peat stratigraphical studies the Grenzhorizont in many Finnish mires remains at best indistinct and at some sites is completely absent (Tolonen, 1967, 1973, 1987). In addition, where this boundary has been identified radiocarbon dates indicate that this is a 'time transgressive' event, with dates varying up to 2500 ^{14}C years even in relatively small geographical areas (Tolonen, 1987). The diachroneity of the Grenzhorizont in Finnish mires suggests that a range of autogenic factors including hydrology, morphology and vegetation influences the individual peat bogs' response to climate. Frenzel (1979) notes that as early as 1904 research suggested that autogenic processes played a significant role in the formation of strongly and less well humified peat strata. The reluctance of Finnish and many Scandinavian researchers to ascribe mire growth or expansion to climate is demonstrated by Seppä (2002). In a review of the regional and local controls of vegetation, landforms and long-term dynamics of mires in Finland, the emphasis is firmly placed on mires responding to autogenic hydroseral succession rather than a climatically driven growth pattern. In particular Seppä suggests that stratigraphical changes may be due to the natural growth dynamics of the mire, including long-term developments towards drier conditions on the bog surface, the rhythmic growth pattern of the low hummocks and the local changes in water table resulting from growth of hummocks and hollows. Whilst not excluding the effects of climate on mire growth and dynamics, it is often considered of secondary importance in contrast to UK studies where it is usually considered to be the primary factor.

At a smaller scale and perhaps more pertinently to this project, Barber *et al.* (2003b) found that the response of different *Sphagnum* species to hydrological change varied quite markedly. The sensitivity of the macrofossil assemblage on peat bogs is determined by the interaction and local presence of species that can respond to climatically forced changes in the mire water table. Barber *et al.* suggest that where one species is dominant, such as the *Sphagnum fuscum* bogs of Finland, then the *Sphagnum* assemblage is unable to respond to changes in climate. This view is also held by many Scandinavian researchers who express doubts as to the extent of climatically driven changes in mire plant composition (Korhola, pers com). Nevertheless, a synthesis of palaeoclimatic data derived from lakes and peat bogs in Scandinavia showed that broadly synchronous changes in climate had been recorded at numerous sites including lakes and bogs. In particular, increased bog formation in southern Scandinavia seems to be coincident with raised mean water levels in lakes at *c.*5000 BP (Berglund, 1983).

1.2.2 Anthropogenic Influences

Berglund (1983) suggests that deforestation caused by prehistoric man may have favoured bog formation in oceanic parts of Norway as early as *c.*2000 BP. In Finland, paludification is considered an important peat-forming process accounting for between 35 – 50% of the present peatland area prior to drainage. Korhola & Tolonen (1998) indicate that up to two-thirds of ancient paludification events occurred after fire. This is in agreement with research from Scandinavia, where fire is thought to have been an important factor in mire initiation, especially by paludification (Berglund, 1983).

Historically, mires have been used extensively as a source of fuel. Gottlich *et al.* (1993) record that peat was used in the middle of the first century AD and it is likely that peat has been used for fuel during the last two millennia throughout much of Europe. Asplund (1996) notes that peat is still used in many countries to provide energy for power generation. The exploitation of peat is therefore still commercially viable in many countries. Furthermore, peat has been used in pastoral agriculture and in more recent times as a fertilizer in horticulture (Charman, 2002).

Increased human settlement during the Late Iron Age and Early Christian Era often resulted in the drainage of peatlands. In order to use peatlands for fuel, agriculture or forestry it is often necessary to change the hydrological regime of the mire. This usually involves drainage at the periphery of the bog to lower the water table artificially and aerate the surface layers. Charman (2002) notes that drainage can result in mire dehydration by various mechanisms. Direct drainage from peat cutting increases the hydraulic gradient between cut and uncut areas and may increase seepage down to the substrate. Abstraction of water for agricultural use may also artificially lower surrounding water tables, which can result in the growth of 'atypical' mire species that in turn may change the balance of effective precipitation (the balance of precipitation remaining after evapo-transpiration processes). This is exemplified in Figure 1.2 below:

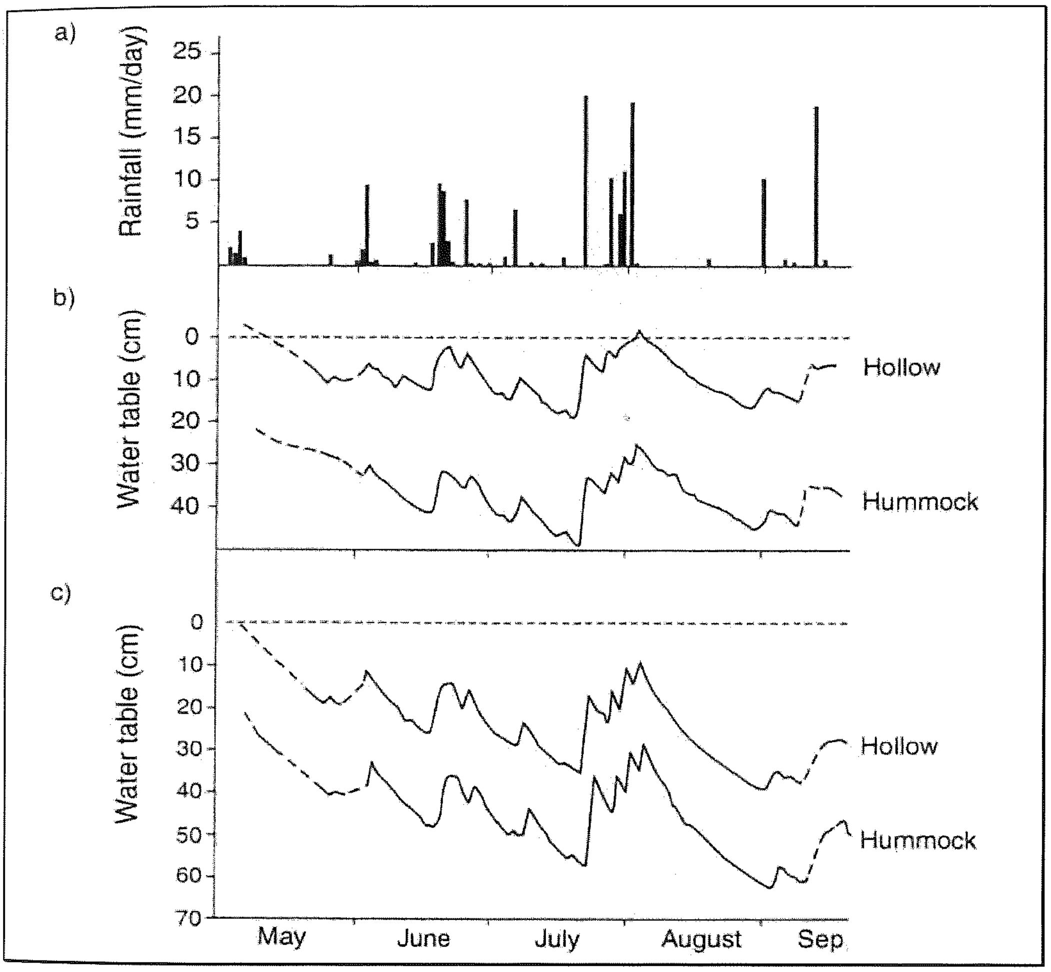

Figure 1.2 Shows the changes in water table over the period May to September 1976 on drained and undrained areas of a raised bog in Finland. (a) Daily rainfall, and water table changes in (b) undrained hummocks and hollows, (c) drained hummocks and hollows.

Taken from Charman (2002)

In the context of palaeoclimatic research any disturbance to the mire may cause significant problems. Peat cutting will obviously result in a hiatus in the normally continuous palaeo-proxy record, whilst grazing will cause similar difficulties. Furthermore, any drainage of the mire may result in compaction of the peat and therefore a loss in resolution or blurring of the palaeohydrological record.

1.3 Medieval Warm Period

The term Medieval Warm Period was used by Lamb (1977) to denote a period of proposed continuous warmth from *c.* AD 1000-1300. High-resolution palaeoclimatic data from a variety of sources have since indicated that the magnitude and timing of this event may have been geographically variable. A considerable body of research has also refuted the idea of a prolonged period of relatively homogenous warmth as initially proposed by Lamb (e.g. Briffa *et al.*, 1992; Hughs & Diaz, 1994; Crowley & Lowery, 2000; Hiller *et al.*, 2001). In a review of data for this period Hughs & Diaz (1994) found that temperatures, particularly in summer, appear to have been higher at certain times than those of the late twentieth century. However, this was not universal and whilst regions including Scandinavia, China, Tasmania and the Canadian Rockies recorded warm conditions there is little or no evidence elsewhere (for example, the Southeast USA, southern Europe along the Mediterranean, and parts of South America). Nevertheless, in 1989 the US Department of Energy released the following statement:

> "A thousand years ago, climate in the North Atlantic regions was perhaps 1°C warmer than now..."

A brief review of the evidence for this event is detailed below. Whilst the discussion focuses on Scandinavia and Europe, research from elsewhere is also considered.

Dendroclimatological data have been widely used as a means of reconstructing past environments and deriving palaeo-temperature records. These data include tree-line fluctuations and also tree-ring analysis. Hiller *et al.* (2001) found that during the period *c.* cal. AD 1000-1300 pine forests grew at least 100-140 m above the modern tree-line in the Khibiny Mountains, Russia. Based on an assumed lapse rate of 0.6°C per 100 m (e.g. Kullman, 1998) this advance could correspond to a mean summer temperature increase of *c*.0.8°C compared to present-day summer temperatures. Hiller *et al.* (2001, p495) claim:

"the Khibiny data set actually represents the strongest evidence for the Medieval warm epoch for mountainous regions of Fennoscandia".

This is exemplified in Figure 1.3 which shows a sustained increase in the frequency distribution of pine wood from the Khibiny Mountains in the 800 – 1000 ^{14}C age group.

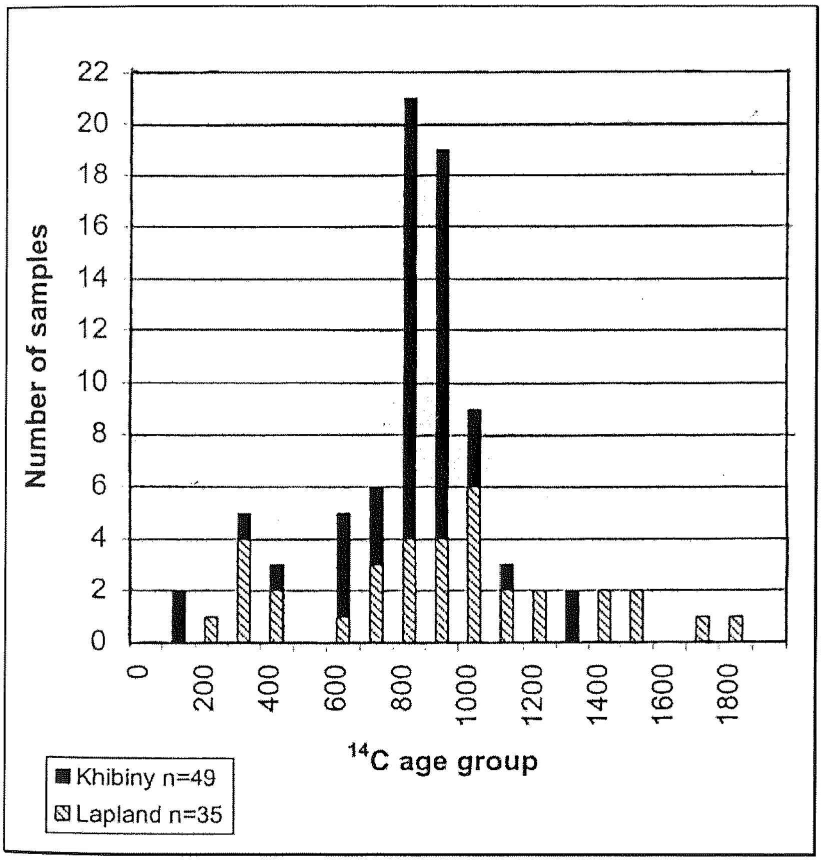

Figure 1.3 Frequency distribution of radiocarbon dated pine wood from Khibiny mountains and its correlation with ^{14}C dates from mountainous areas in Finnish and Swedish Lapland. (Taken from Hiller *et al.*, 2001).

These data concur with studies in Finnish Lapland and the Scandes Mountains, Sweden where comprehensive records of tree-line fluctuations also indicate that during the MWP the tree-line height was *c.*100 m above the modern day limit (Kullman, 1995, 1998; Karlen, 1979).

Using spectral analyses of summer temperature data derived from continuous tree-ring records in northern Sweden, Briffa *et al.* (1992) identified only two short episodes of warming that correlated with the MWP. These dates were AD 870 - 1110 and 1360 - 1510 and notably identified a significant cold trough at *c.* AD 1140 with generally cooler conditions centred around AD 1110 - 1150 and AD 1190 - 1360. The rapid oscillations of climate during this period suggest that rather than the proposed period of homogenous warmth, climatic conditions may have fluctuated quite markedly. This is supported by multi-proxy reconstruction of northwest European annual temperature records (Guiot *et al.*, 1992). Whilst recording an episode of persistent warmth that appears to be broadly coeval (AD 1190 – 1350) with that identified by Briffa *et al*, the Fennoscandian data also indicate a negative temporal correlation with warm episodes centred around AD 971-100 and AD 1350-1540. The asynchroneity of these episodes lends credence to the suggestion that climate varied both spatially and temporally within the epoch known as the Medieval Warm Period.

As with any biological proxy record, it is necessary to differentiate between climatic factors and other environmental variables that may complicate any linear relationship between climate and the proxy. For example, in tree-line research, factors including soil quality, aspect, catchment size, species composition and succession stage may confuse a simple climatic explanation. Hughs & Diaz (1994) similarly note that the statistical manipulation of the raw tree-ring data may result in a loss or diminution of the signal.

Documentary evidence also supports the idea of warmer conditions from *c*. AD 900. In particular, the settlement of the northern North Atlantic region from Greenland to Newfoundland by Norse seafarers was considered indicative of more clement conditions (Lamb, 1977). This is also supported by limnological data from lake sediments in southern Greenland. Kaplan *et al.* (2002) found that intervals of ameliorated limnological conditions occurred between 1300-900 cal yr BP possibly in response to a temperature rise of approximately 1.5°C from 2000 to 1100 cal yr BP (Dahl-Jensen *et al.*, 1998). Grove & Switsur (1994) suggest that the Medieval Warm Period can be dated using moraine deposits. They note that this period was preceded and followed by periods of glacier expansion, enabling the MWP to be bracketed between the dates of these moraines. Glacial geological evidence was taken from numerous sources including the European Alps, Scandinavia, The Himalayas, North America, tropical South America and New Zealand. Analysis of these data led Grove & Switsur to conclude that the MWP was global in extent but not climatically uniform. They suggest that this episode occurred between AD 900 and 1250 and was possibly interrupted by a minor readvance of ice between about AD 1050-1150.

Keigwin (1996) examined a range of proxy data from Bermuda Rise in the northern Sargasso Sea. Analysis of $CaCO_3$ and $^{18}O/^{16}O$ isotope ratios found in the planktonic foraminiferid *Globigerinoides ruber* enabled palaeo sea-surface temperatures (SST) to be reconstructed, whilst an increasing influx of terrigenous material was used to denote episodes of climatic deterioration. Abrupt decadal-to-century scale oscillations in sea-surface temperature were identified in the record, with a maximum inferred SST at *c.*900 - 1000 years ago. This was immediately followed by several rapid episodes of climatic instability that imply much colder conditions that can be positively correlated with terrestrial conditions for much of Fennoscandia.

A comprehensive synthesis of data from fifteen sites located in both the northern and southern hemisphere was recently undertaken by Crowley and Lowery (2000). Reconstruction of temperatures during the Medieval Warm Period was achieved by analyzing a range of proxy data including tree-ring records, pollen, oxygen isotope records from both ocean and ice cores, the historical sea ice/temperature record, the central England temperature record and a phenological temperature record. These are detailed in Figure 1.4.

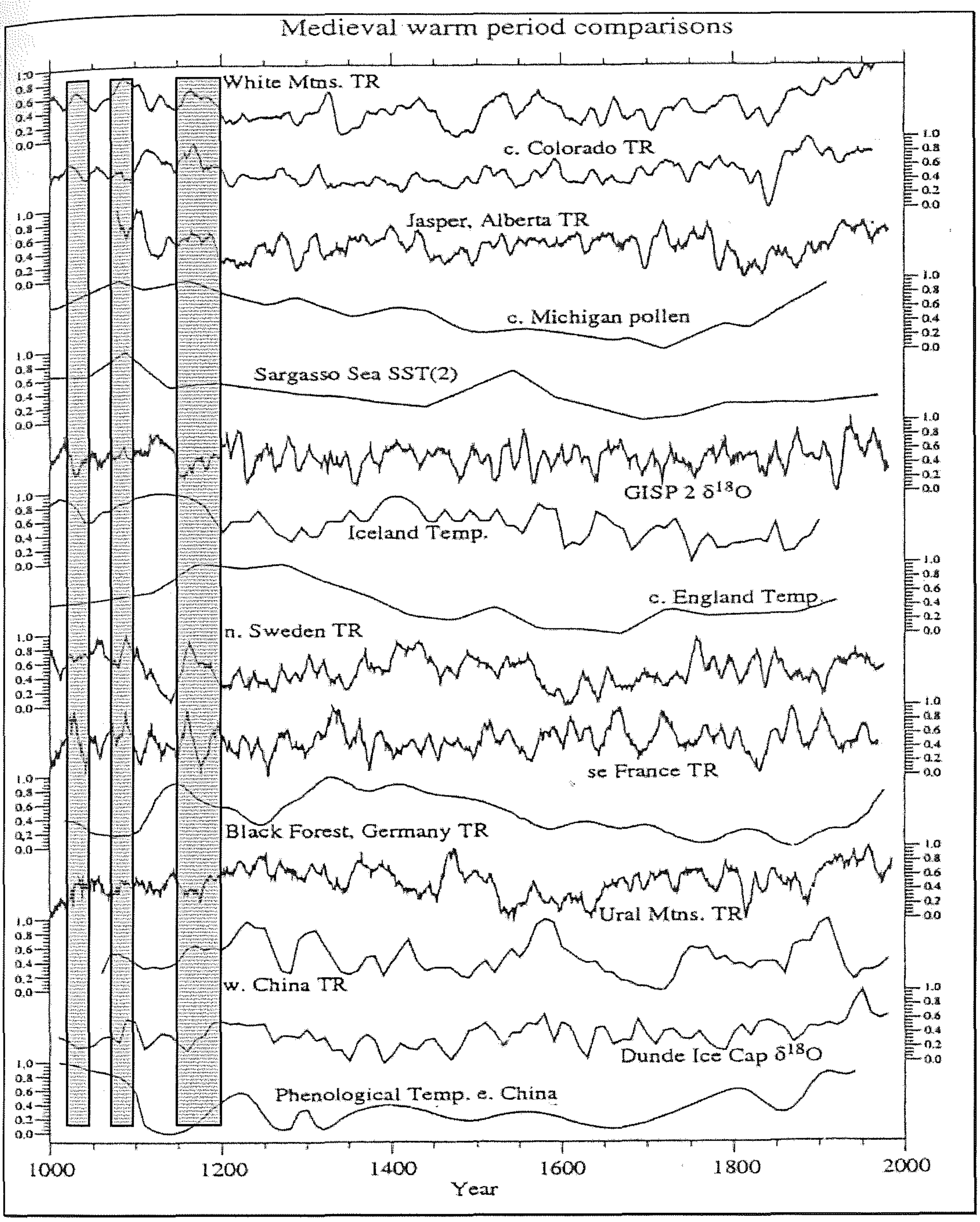

Figure 1.4 Scaled record of climate change based on 15 sites. Vertical grey bars indicate intervals of maximum hemispheric warmth. Taken from Crowley & Lowery (2000)

Crowley and Lowery conclude that from the compilation of these data, three relatively short-lived episodes of Medieval warmth are evident at *c.* AD 1010 - 1040, 1070 - 1105 and 1155 - 1190 and that climate during these periods was comparable to mid-20th century warming. Temperatures between AD 1000 - 1200 were calculated to be only about 0.2°C warmer than during the Little Ice Age period and if their analysis is correct it would therefore invalidate any attempts to suggest recent warming of 0.7°C may be attributable to the same natural mechanisms, such as the Medieval Solar Maximum, that induced the Medieval Warm Period.

Mire research has also yielded valuable data about the timing and the geographical extent of the Medieval Warm Period. In the UK, peat records from Temple Hill Moss, Raeburn and Bells Flow in Scotland and Coom Rigg Moss, Felecia Moss and Bolton Fell Moss in England have all provided evidence of a broadly synchronous change to drier conditions during the Medieval Warm Period (Barber *et al.*, 1994; Mauquoy & Barber, 1999; Langdon *et al.*, 2003). In Ireland, research on Abbeyknockmoy Bog and Mongan Bog has provided supporting data of increased dryness recorded in the mire stratigraphy (Barber *et al.*, 2003a). Blackford & Chambers (1995) provided a high-resolution (0.5 cm contiguous sampling) record of climate change of the last 1000 years from a blanket peat near Letterfrack, County Galway, western Ireland. In that study two parallel cores were extracted and then peat humification data were produced using a colorimetric method. Results showed that a broadly coherent and replicable record was produced from each core. Evidence of a shift to drier conditions was evident in both cores at *c.* AD 1230-1380. Comparison with historical documentary evidence and other proxy data show that this is consistent with the period known as the 'Medieval Optimum'.

A 7500-year peat based palaeoclimatic reconstruction from Temple Hill Moss demonstrated the sensitivity of peat bogs and the different palaeoecological proxies in recording episodes of inferred climate change (Langdon *et al*., 2003). In that study colorimetric humification, plant macrofossil and testate amoebae analyses were undertaken to identify changes in the hydrological regime of the mire. The MWP is recorded by all three proxies and dated to between *c*. cal.1000-800 BP. During this period high amounts of unidentified organic matter (UOM) and *Eriophorum vaginatum* (>20% of the total macrofossil assemblage) are recorded. *Sphagnum* is almost totally absent from the mire at this time. This corresponds with a testate amoebae assemblage that records a high percentage of xerophilous species comprising *Assulina muscorum, Euglypha rotunda, Hyalosphenia subflava,* and *Nebela militaris.* These taxa are all considered indicative of a lowered water table and relatively dry conditions. A notable phase of increased humification absorbance values indicating a shift to drier conditions coincided with the macrofossil and testate amoebae data at between 1000-800 BP. In addition to providing a record of the MWP the study helps justify the choice of proxies adopted for this research project and confirms their ability to adapt to and therefore record changes in climate.

A dearth of peat-based palaeoclimatic studies from Baltic sites has impeded the identification of this period in many raised mires. However, in a peat macrofossil investigation at Dosenmoor, Schleswig-Holstein, Germany and Svanemose, Jutland, Denmark a period of dominance by *Sphagnum* section *Acutifolia* suggests a phase of drier conditions. The ascendancy of these species occurs between cal. AD 600-1300 before it ends abruptly and is replaced by *Sphagnum* section *Cuspidata* indicating a deterioration in climate with the onset of the Little Ice Age (Barber *et al*. 2003b).

1.4 Little Ice Age

The term 'Little Ice Age' (LIA) is used to denote the last period of neoglaciation. The timing, geographical extent, magnitude and cause of this interval have been the subject of considerable research (e.g. Fischer *et al.*, 1998; Broecker, 2000; Jones & Briffa, 2001; Mauquoy *et al.*, 2002; Cronin *et al.*, 2003). Documentary and proxy records suggest that the timing of this event is geographically variable. For example, Porter (1986) suggests that the LIA began towards the end of the Middle Ages *c.* AD 1250 and lasted until approximately 1920, whereas Lamb (1977) confines it to AD 1550 – 1850, with its main phase from 1550 – 1700. A synthesis of climate data since AD 1500 led Jones & Bradley (1995, p659) to state:

> "there is no evidence for a worldwide synchronous and prolonged cold interval to which we can ascribe the term 'Little Ice Age'."

Nevertheless, there is a substantial body of both historical documented and proxy data that provides strong evidence for an episode of considerably colder climate for much of Europe and the North Atlantic region (Mikalsen *et al.*, 2001).

Syntheses of data from a variety of sources demonstrate the ephemeral and spatially diachronous nature of the climate of this period. Studies by Jones *et al.* (1998), Mann *et al.* (1999) and Briffa (2000) have used an extensive range of palaeoclimatic data to reconstruct conditions for the LIA period. From these data Jones and Briffa (2001) suggest that rather than a homogenous cold period the LIA is temporally and spatially variable with the seventeenth century being the coldest experienced in Europe over the last 1000 years, whilst in North America the coldest period was confined to the nineteenth century. Furthermore, decadal-to-century scale climate oscillations are also evident in the records with an initial cold phase during the seventeenth century giving way to much warmer conditions during the following century, before returning to cooler conditions during the nineteenth century.

Instrumental temperature data for the period AD 1659 – 1973 can be derived from the 'Central England' temperature series compiled by Manley (1953,1974). This is shown in Figure 1.5 below.

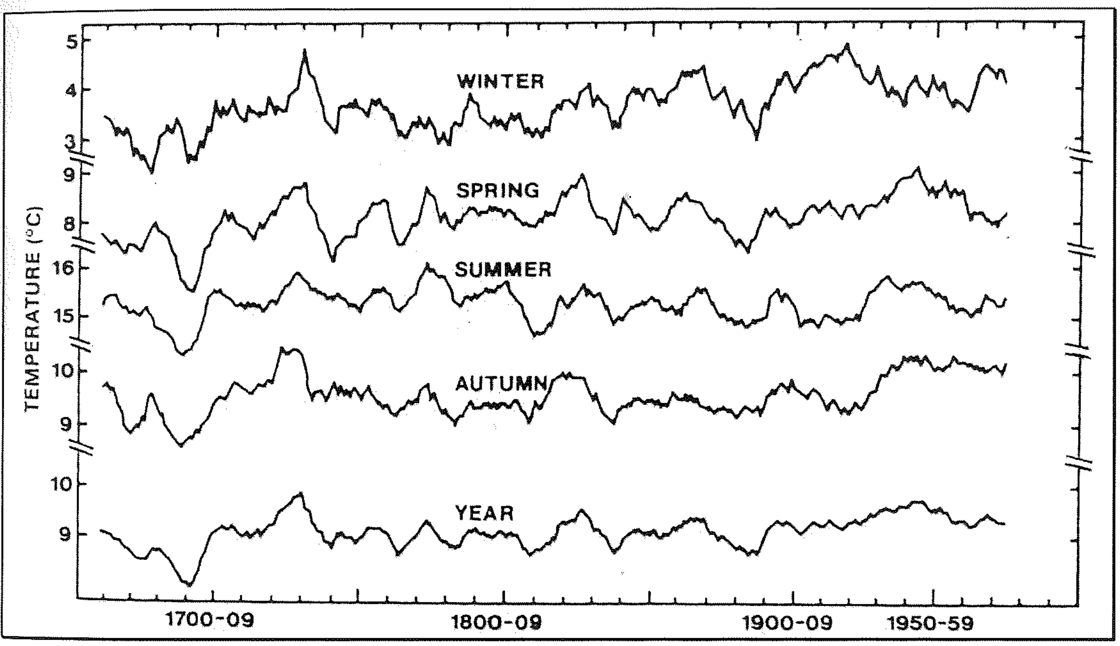

Figure 1.5 Seasonal and overall average temperatures in Central England from 1659 to 1982: 10 year running means.

The series shows a markedly fluctuating record of temperature change. A significant trough indicating colder conditions is apparent in the annual record between *c.* AD 1680 and 1700. This is particularly evident in the spring seasonal record and possibly suggests prolonged winter conditions. A shift to warmer conditions is also evident for the decade 1720-1730 and this concurs with the research of Pfister (1981) who notes that warmer conditions are prevalent from the mid 1700s.

The research of Kaplan *et al.* (2002) also provides supporting evidence of fluctuating climatological conditions during this period. Using % Loss on Ignition (LOI) and % Biogenic Silica and Organic matter ($BSiO_2$) as a proxy for lake palaeoproductivity they were able to demonstrate that changes in the proportion of these proxies in the sediment corresponded with the MWP and succeeding LIA.

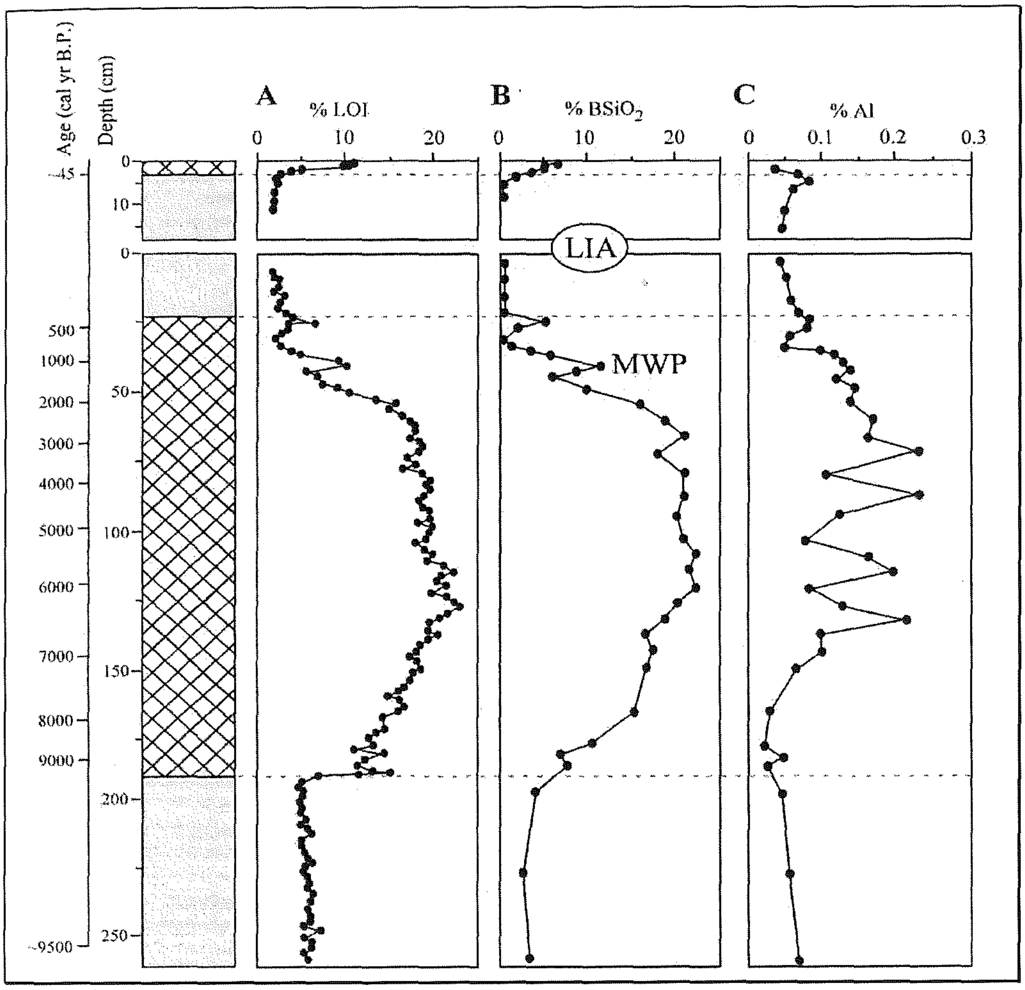

Figure 1.6 Lake sediment data taken from Lake Qipisarqo, Southern Greenland encompassing MWP & LIA. **(Kaplan *et al.* 2002)**

As can be seen from Figure 1.6, both the % LOI and % $BSiO_2$ values record an increase around the MWP (*c.* 1000 yrs BP) and then decrease markedly during the LIA. . The onset of the LIA occurs at *c.* AD 1400 and extends up to the nineteenth century. However, closely paralleling other proxy and historical records, the data indicate that this period was marked by two cold phases. The first of these started in the seventeenth century with the coldest decades confined to the mid to late 1600s. The second phase occurred in the nineteenth century and lasted for approximately one hundred years with particularly cold conditions centred around the early 1800s and late 1800s. Three phases of increased temperature are also evident in the record. Peak temperatures of ~0.9°C above the mean occur in AD 1375, 1425 and then again around AD 1650 – 1700. Notably, for the LIA period as a whole, data indicate that the average temperature is in broad agreement with the temperatures from central England, which drop only marginally below the mean between AD 1550 – 1700.

In much of northern Scandinavia glacier advance is well documented, with farm abandonment common during the late sixteenth and seventeenth centuries (Grove, 1988). An excellent example of this is the farm abandonment associated with the LIA advance of the Jostedalsbreen glacier in Norway. In a thorough review of both farm abandonment and tax concessions for this period Grove (1988) shows that the enlargement of glaciers occurred broadly simultaneously in north and south Scandinavia during the eighteenth century. Figure 1.7 shows the number of farms in Norway that suffered ‘serious physical damage’ during the LIA as recorded in *avtak* records.

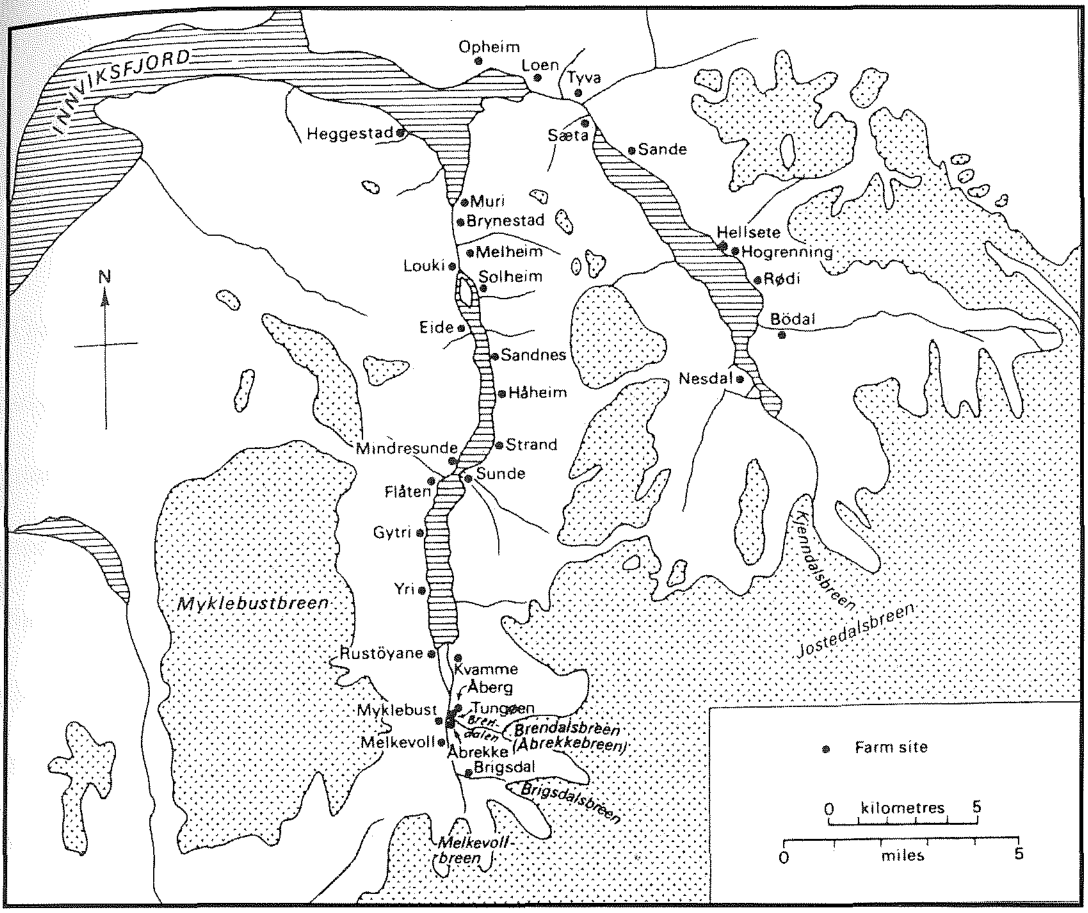

Figure 1.7 Map of valleys at the northern margin of Jostedalsbreen showing farms, which were severely damaged by floods or mass movements once or more at dates between 1667 and the late 18th century. The dot shading shows the extent of the ice cap & the horizontal shading the extent of water (Taken from Grove, 1985).

Typical of this period is the following statement made by a farmer in 1693 to the Norwegian local government (Grove 1988, p76)

> "This farm, Boedahl, has suffered much damage this year to its hayfields outside the fenced lands by a landslide, called the glacier landslide, and last year ... another landslide called Espe... Immediately inside the fenced land the river has broken out and made a new course across the farm's best meadows and fields, damaging up to five maeler of seed

> ground and the closer the river approaches the great freshwater lake, the more it spreads out on each side, causing great damage to their meadows and ploughland."

The damage to Bodal in upper Lodalen in 1693 was explicitly attributed to glacier advance and exemplifies historical documentary records for the eighteenth century in much of Scandinavia. Karlen (1979) used lichenometric analysis of 125 moraines in northern Norway to reconstruct glacier movements. Glacier advances coincident with the LIA epoch occurred at AD 1780, *c.*1800, 1810-1820, 1860, *c.*1880, 1900-1910 and then *c.*1930. These dates also concur with dates for glacier advances in the Sarek and Kebnekaise mountains of Sweden where LIA advances culminated at AD *c.* 1590-1620, 1650, 1680, 1700 -1720, 1780, 1800 -1810, 1850 -1860, 1880 -1890 and 1916 -1920 (Denton & Karlen, 1973).

A degree of agreement can also be established between reconstructed summer temperatures and episodes of glacier advance. From analyses of tree-ring records in northern Fennoscandia, Briffa *et al.* (1992) indicate that LIA cold episodes occur between AD 1570 -1750 with particular cold troughs at AD 1580 -1620 and AD 1640 which closely parallels the glacier advances. Interestingly Briffa *et al.* record two episodes of increased warmth that are within the LIA epoch, dated at AD 1760 and AD 1820. This also concurs with tree-ring data from Norway. Kirchhefer (2001) used tree-ring data from Scots Pine (*Pinus sylvestris L.*) to reconstruct summer temperatures for northern Norway. From these data he concluded that the coldest phase of the LIA occurred during the seventeenth century, and three cycles of summer temperature minima were identified at AD 1605, 1640 and 1680. Temperature reconstructions

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1.7 Thesis Structure

The thesis is organised into six chapters. Chapter 1 provides the background and context to the project. Evidence for known episodes of late Holocene climate change, namely the Little Ice Age and the preceding Medieval Warm Period, are also examined in this chapter. Previous peat-based palaeoclimatic research is also discussed in this section and some of the limitations and problems are considered. Chapter 2 provides a comprehensive review of the methodologies adopted in this project. Additional information is provided on the components of both the macrofossil and testate amoebae assemblage and their hydrological preference. This chapter ends with a review of wiggle-matched radiocarbon dating - the procedure used in this study. Chapter 3 provides a comprehensive site-by-site description and initial palaeohydrological interpretation of all three datasets. The final section of this chapter tabulates the calibrated radiocarbon determinations for each core and then the additional precision obtained for each suite of dates after the wiggle-matched dating procedure. Chapter 4 then provides a detailed account of both the DCA (Detrended Correspondence Analysis) and WAO (Weighted Average Ordination Analysis) multivariate statistical procedures. Proxy-climate curves have been generated from the raw macrofossil data for each of the sites and these have then been directly compared with the humification data. Chapter 5 begins with an overview of the data and tabulates shifts to either relatively wetter or drier conditions. The timing of these shifts is compared between sites to establish whether changes are as a result of regional climate or whether they simply reflect internal mire processes. Following this, the effectiveness of each of the proxies is evaluated in order to determine its ability to record hydrological changes on the mire which may possibly be associated with climate. Finally, the chapter closes with a

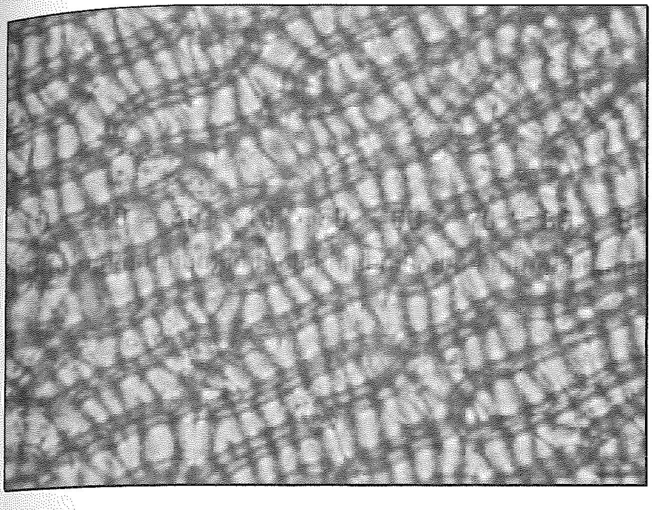


Plate 2.4 *Sphagnum riparium* (x400)

Under the microscope this species can be identified by its large apical resorption gap in branch leaves and a distinctive pore morphology. Additionally, the large size of the branch leaves (2 – 2.6 x 0.8 – 1.2 mm) helps to distinguish it from other species (Daniels & Eddy, 1990).

2.5.2.3 Sphagnum angustifolium

This species is able to tolerate a wide range of ecological conditions and therefore is of limited use in palaeoclimatological research. Typically found on the lawn microform of bogs it can also tolerate partially submerged conditions where it can be found with *S. riparium* or on low hummocks in association with *S. fuscum* or *S. magellanicum* (Daniels & Eddy, 1990). Several distinguishing features can identify *Sphagnum angustifolium*. Firstly the branch leaf size is comparatively small usually measuring 0.7 – 0.9 mm long. Additionally, this species has distinctive hyaline cell morphology with large abaxial and apical pores.

2.5.2.4 *Sphagnum cuspidatum*

A good indicator of increased wetness this species typically inhabits pool margins, wet hollows and can even be found floating or submerged in pools.

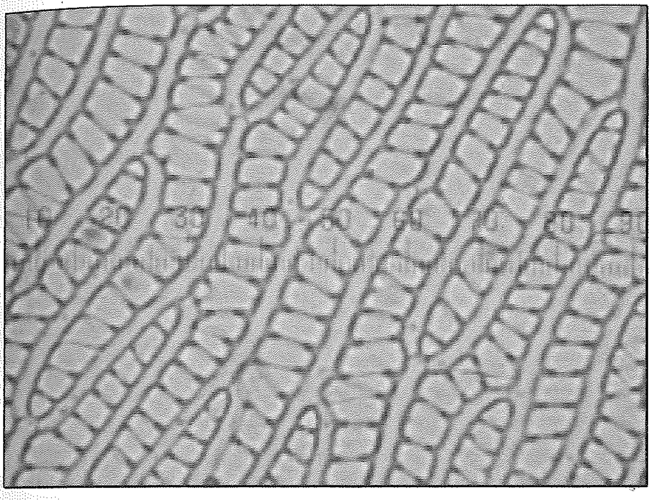


Plate 2.5 *Sphagnum cuspidatum* (x400)

This species is readily identifiable by the branch leaf size and shape. Narrowly lanceolate to linear leaves are usually between 3-6 times as long as they are wide and measure between 1.7 – 5 mm in length.

2.5.2.5 *Sphagnum balticum*

This taxon was only found at the Männikjärve site and only then in relatively small proportions. *Sphagnum balticum* is tolerant of diverse conditions. Usually found in ombrotrophic mires it can also occur in association with *S. majus* or *S. cuspidatum* in the wetter part of the bog or with *S. papillosum* or *S. magellanicum* in the drier parts (Daniels & Eddy, 1990). Consequently it is of limited use in reconstructing palaeohydrological mire conditions. The branch leaves of this species are again relatively small *c.*1.2 – 1.6 x 0.4 mm. A distinguishing characteristic of this species is a small resorption gap visible on the adaxial surface.

2.5.2.6 *Sphagnum lindbergii*

This is a hydrophilous species usually found beside lakes and streams and in montane flushes. Preferring oligotrophic conditions this species is often found in association with *S. riparium*. This taxon is a good indicator of increased wetness on ombrotrophic mires, particularly when it is found in conjunction with *S. riparium* or *S. cuspidatum*.

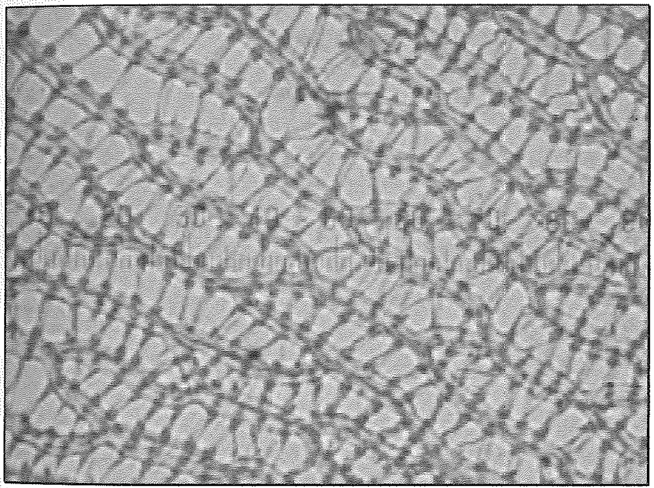


Plate 2.6 *Sphagnum lindbergii* (x400)

Again, leaf size and shape help to identify this species. Leaves mostly measure between 1.6 – 2 mm in length and *c.*0.7mm width and are mainly lanceolate or occasionally linear-lanceolate in shape. Additionally, the abaxial surface of the leaf is often without pores, with the exception of a small resorption gap in the apical angle (Daniels & Eddy, 1990).

2.5.2.7 *Sphagnum magellanicum*

This is generally a poor indicator species. Daniels & Eddy (1990) note that whilst normally found forming broad carpets or low hummocks in wet oligotrophic bogs, *S. magellanicum* is also able to tolerate drier wooded sites in north and east Europe. Usually found in association with *S. papillosum* or *S. capillifolium*, Li *et al.* (1992) note that this species is an 'effective drought avoider' and is a valuable indicator of low hummock microforms.

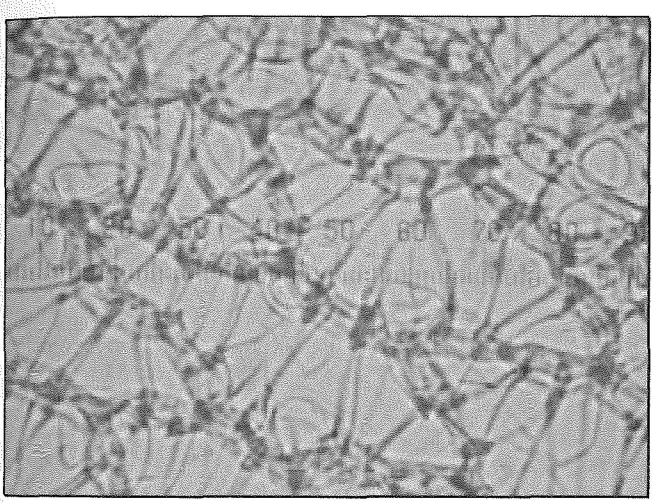


Plate 2.7 *S. magellanicum* (x400)

This species is readily identifiable under the microscope. Branch leaves are uniform in size, typically *c.*1.5 – 2.4 mm and broadly ovate in shape. Variable magnification of the photosynthetic cells that are mainly enclosed by the hyaline cells also aids identification.

2.5.2.8 Sphagnum tenellum

Barber (1981) states that this species is a good indicator of elevated local water tables. More recently, in studies of climate change in north-west European ombrotrophic bogs *S. tenellum* was considered indicative of increased wetness on the mire surface (Mauquoy *et al.*, 2002). Daniels & Eddy (1990) note that this taxon is common in open, damp, oligotrophic habitats where it is often found in association with other 'unaggressive' *Sphagnum* species.

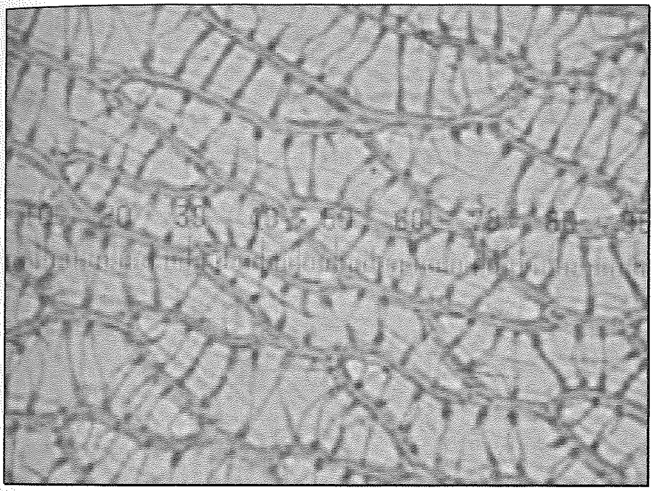


Plate 2.8 *Sphagnum tenellum* (x400)

S. tenellum has several diagnostic features. Daniels & Eddy (1990, p226) state, "no other European species has the combination of short, broad branch leaves with large pores and markedly abaxially displaced photosynthetic cells".

2.5.3 Monocotyledonous remains

This group includes a variety of species including *Eriophorum vaginatum*, *Eriophorum angustifolium, Rynchospora alba* and *Scheuchzeria palustris*. Identification of specific monocotyledonous remains can yield important hydro-climatic data, particularly where

Sphagnum may be absent from the bog. However, in order to identify monocots to species level it is essential that the morphological structure of the epidermal tissue has remained relatively intact. Owing to these problems, where it has not been possible to identify monocotyledonous remains to species level the remains have been split into two categories, namely monocotyledonous root (undifferentiated) and monocotyledonous cells (undifferentiated).

As is evident from the ecological descriptions detailed below the species within this category have widely differing water table positions. Hence monocotyledonous remains (undifferentiated) as a proxy in their own right are of limited use in reconstructing mire water table fluctuations. A comprehensive reference collection and detailed morphological drawings and diagrams in Grosse-Brauckmann (1972) and Smith (1980) aided identification of the following species.

2.5.3.1 ***Eriophorum vaginatum***

This species is often considered indicative of drier mire conditions and is typical of a hummock forming species (Wein, 1973). Research conducted by van der Molen *et al.* (1994) on Clara Bog, Ireland assigned a height above the water table for plant species occupying the hummock/hollow microform. *Eriophorum vaginatum* was found to be most abundant at 25-35 cm above the water table. However, care needs to be taken when using this taxon as a sole indicator of drier conditions. Barber (1981) concluded from studies on Bolton Fell Moss that this species was capable of invading pools; similarly Gore & Urquhart (1966) note that *Eriophorum vaginatum* can cope with waterlogged conditions. Research by Casparie (1972) also supports these findings, with remains of *E. vaginatum* present in both highly and less humified peat strata.

Tansley (1939) suggests that conditions particularly favourable to *E. vaginatum* are a surface water table during spring followed by a drying out of the mire and subsequent lowering of water table during summer. This would be consistent with conditions in the Baltic region where spring snow melt causes a rapid rise in water tables followed by relatively hot and dry summer. Nevertheless, when found growing in conjunction with *Calluna vulgaris* it is confirmed as an indicator of drier conditions (Walker & Walker, 1961; Barber, 1981).

Plate 2.9 *Erioiphorum vaginatum* epidermis (x400)

This species is readily identifiable by its distinctive epidermal structure. The cells are arranged in an orderly fashion and are typically transparent in appearance. Additionally, the cells are characteristically many times longer in length than width and have a 'crinkled' texture.

2.5.3.2 *Eriophorum angustifolium*

The ecology and hydrological parameters of this species are well defined. Rodwell *et al.* (1991) note that *E. angustifolium* often dominates in shallow pools and can be an important coloniser in dried-up hollow bottoms. This supports the earlier research of Philips (1954) who also found this species present in bog pools. van der Molen & Hoekstra (1988) investigated the hummock-hollow microtopography of Engbertsdijksveen mire and found that this species was often present with *S. cuspidatum* in the hollow environment. This is also corroborated by the research of Barber (1981) who records its presence with *S. cuspidatum*. Haslam (1987) found that *E. angustifolium* consistently indicated high mire surface wetness, confirmed by low colorimetric humification absorbance values and the presence of hygrophilous rhizopods. From research in Ireland, van der Molen *et al.* (1994) assigns this taxon a mean height above the water table of 8-10 cm. The presence of this species in the sub-fossil matrix can therefore be used to infer relatively wet conditions.

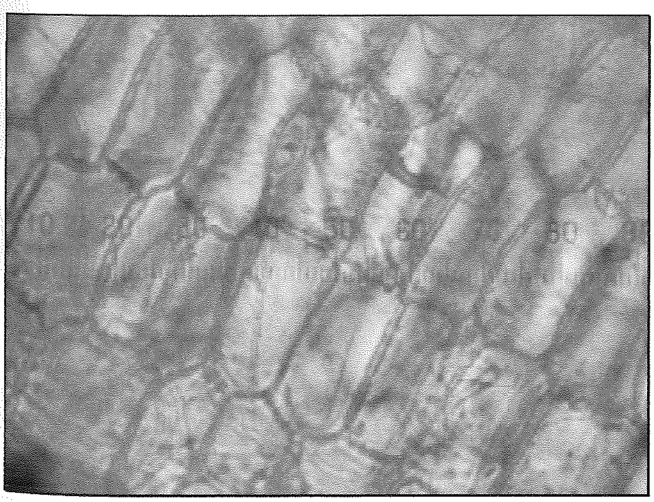


Plate 2.10 *Eriophorum angustifolium* epidermis (x400)

This sedge can be identified by its distinctive cell morphology. Cells have a 'crinkled' appearance and are typically short and wide resembling a rectangle in appearance. The red-stained colour of the rhizomes is also characteristic of this species.

2.5.3.3 Rynchospora alba

This species is usually found inhabiting shallow pools and along the margins of hollows in the hollow/hummock complex (Tansley, 1939; Godwin & Conway, 1939). It is often found growing in association with other 'wet loving' taxa including *S. cuspidatum*, *Scheuchzeria palustris* and *Eriophorum angustifolium*. Blaauw *et al.* (2003) record the presence of *Rynchospora alba* during 'wet phases' from two raised mires in the Netherlands. Ratcliffe & Walker (1958) assigned a hydrological range of 3 – 5 cm above the water table for this species from research on Silver Flowe Bog in Scotland. The presence of *Rynchospora alba* in the sub-fossil matrix is therefore a good indicator of raised water tables.

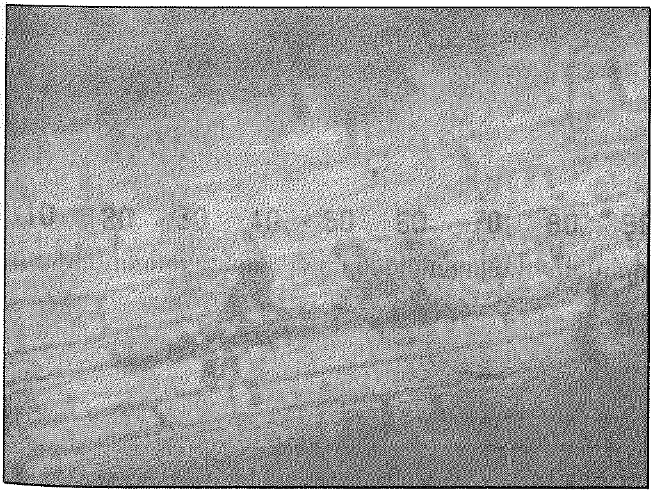


Plate 2.11 *Rynchospora alba* epidermis (x400)

This species is readily identified by the very distinctive arrangement of the stem sheath. The cells are longer than they are broad at the edge, whilst at the centre of the stem sheath this pattern is reversed.

2.5.3.4 *Scheuchzeria palustris*

This taxon is an excellent indicator of elevated water tables. Ordination analysis by Økland (1990) demonstrated that the occurrence of *Scheuchzeria palustris* indicated very wet conditions. Similarly Tallis & Birks (1965) note that this species is found where the ground water table is very high or where there is permanent standing water. Additionally, Casparie (1972) notes that *Scheuchzeria* appears to have a preference for minerotrophic conditions. This is also supported by the ordination analysis of Økland (1990) where *Scheuchzeria* is placed relatively high on the (second) axis of DCA that indicated a poor-rich gradient.

2.5.4 Ericaceous Remains

This group includes a number of species that have widely differing hydro-climatic parameters. At all four sites *Calluna vulgaris*, *Vaccinium oxycoccus* and *Andromeda polifolia* are the main components within this group although additional roots material that was unidentifiable has also been classified as Ericaceous remains.

2.5.4.1 *Calluna vulgaris*

Malmer *et al.* (1994) observe that this species is important in maintaining the distinctive hollow/hummock topography of mires. Wallèn (1987) found that *Calluna vulgaris* has a distinct hydrological distribution on mires primarily favouring hummock tops and drier microhabitats. Nordbakken (2001) also notes that the roots of *Calluna* require an aerated layer implying that water table levels are lower and mire conditions drier. Similarly, Malmer (1986) notes that on northwestern European mires the lower limit for a dense covering of *Calluna vulgaris* is closely linked to the maximum water table height during the year. Du Rietz (1949) demarcates the boundary between a hummock and hollow environment as the '*Calluna*' limit where the lower limit of dominance exists. However, Ratcliffe & Walker (1958) found that stunted forms of *Calluna vulgaris* were present on the flat lawn area of mires. Casparie (1972) also states that the presence of *Calluna* alone should not be considered as evidence of a shift to drier conditions.

2.5.4.2 *Vaccinium oxycoccus*

This species is characteristic of and often an important constituent of ombrogenous peat. Jacquemart (1997) records that optimal growth conditions for this species occur in moist hollow bottoms. Lindsay *et al.* (1988) note that this species is often associated with wet *Sphagnum*-rich margins around deep, watershed pools. DCA results placed this species at intermediate levels on the moisture gradient axis (Økland, 1990). Rodwell (1991) notes that whilst *Vaccinium oxycoccus* is often found on the 'lawn' microhabitat of mires it is also able to withstand much wetter conditions. The ability of this species to occupy a broad range of hydrological conditions limits its usefulness as a palaeoclimatological indicator.

2.5.4.3 Andromeda polifolia

This species is typically found on low hummocks and the lawn area of ombrotrophic mires (Jacquemart, 1998). Overbeck (1975) noted that it usually grows slightly higher on the lawn-hummock microform than *Vaccinium oxycoccus*. Nevertheless, the DCA results of Økland (1990) place the species at an intermediate level on the moisture gradient axis. *Andromeda polifolia* is therefore again of limited use as a palaeohydrological indicator.

2.6 Testate Amoebae Analysis

Testate amoebae (Protozoa, Rhizopoda) are unicellular organisms typically measuring between 20 – 250 microns, with a test that covers the cytoplasm. In peatlands these organisms inhabit the thin film of water around plants or soil particles. Tolonen (1986) notes that the principal control of these organisms is moisture content and water table position. Therefore, on ombrotrophic peat bogs, changes in the composition of the fossil assemblage are likely to reflect fluctuations in the water table position that is in turn a function of climate change. The identification and quantification of testate amoebae can therefore provide an additional and possibly independent source of information on a mire's palaeohydrology (e.g. Tolonen, 1986; Woodland *et al.,* 1998; Charman *et al.*, 1999; Schoning *et al.*, 2003).

Testate amoebae can be classified on the basis of the small-scale moisture requirements of certain species (Tolonen, 1986). Species can generally be placed in one of three categories, namely:

1. Hydrophiles – these species inhabit plants that are constantly submerged in water. Consequently they are not restricted to the film of water surrounding soil particles or *Sphagnum* leaves.
2. Hygrophiles – these testate amoebae are found in moist plants often in the thin water film.
3. Xerophiles – species that typically occupy relatively dry conditions and are able to withstand desiccation, often by encysting.

Numerous studies have confirmed that hydrology is the single most important parameter influencing testate amoebae assemblage (Tolonen *et al.*, 1992; Woodland *et al.*, 1998; Mitchell *et al.*, 1999; Bobrov *et al.*, 1999; Charman & Warner, 1997). Research has also shown that pH (e.g. Heal, 1961) and nutrient status (e.g. Gilbert *et al.*, 1998a,b) affects the testate amoebae assemblage. A further more detailed classification of the habitats of peatland testate amoebae is given in the table below.

Table 2.1: Classification of wetness values for habitats of peatland-dwelling testate amoebae according to Jung (1936) and Meisterfeld (1977) and compiled by Tolonen (1986). Taken from Charman *et al.* (2000).

Testate amoebae group (de Graff, 1956)	**Moisture class (Jung, 1936)**	**Relative water content (Jung, 1936)**	**Moisture content Meisterfeld, 1977)**
	I	Open or submerged vegetation	>95%
Hygrophilous	**II**	Floating vegetation, partly submerged, partly at the surface	>95%
	III	Emerged vegetation, very wet water drops out without pressure	>95%
χ- hydrophilous	**IV**	Wet, water drops out with moderate pressure.	~95%
	V	Half-wet, water drops out with moderate pressure	85-95%
β-hydrophilous	**VI**	Moist, water drops out with strong pressure	85-90%
Xerophilous	**VII**	Half-dry, a few drops with strong pressure	<80%
	VIII	Dry, no water drops with strong pressure	<50%

Whilst recent research has confirmed the usefulness of testate amoebae as a palaeohydrological proxy, the technique is not without certain limitations and problems. For example, a fundamental assumption of this technique is that the hydrological parameters of each species is geographically consistent and has remained constant over time. From research carried out on two ombrotrophic peat bogs in Sweden, Schoning *et al.* (2003) conclude that this is not always the case. Furthermore, the co-existence of both 'dry' and 'wet' indicator species may reflect different seasonal assemblages. The hydrophilic taxa may reflect spring conditions when the bog surface is saturated and water tables are high owing to snowmelt. In contrast an increase in xerophilous taxa may simply reflect a drying out of the mire during the summer months (Schoning *et al.*, 2003). These factors may blur or complicate any strictly palaeoclimatological interpretation of the fossil assemblage.

An additional complicating factor can be the decay rate and subsequent preservation of empty tests from particular species. Lousier & Parkinson (1981) note that tests constructed of chitin were far more resistant to decay than those composed of secretion. However, this is refuted by research conducted by Charman (2002) who states that there is no clear and consistent evidence of whether test composition has a differential effect on preservation. Similar problems exist with the morphological variability within species. Medoli & Scott (1983) found that in many instances morphological variation is actually a continuum of change. Schonborn (1992a) and Wanner & Meisterfeld (1994) similarly note that morphological plasticity can occur depending on environmental conditions.

2.6.1 Preparation and Identification

Several different preparation techniques have been used in the analysis of testate amoebae often depending upon the environment being investigated (e.g. Grospietsch, 1958; Moore *et al.*, 1991; Reinhardt *et al.*, 1998). In a comparison of different methodologies, Hendon & Charman (1997) found that preferential preservation of certain tests occurred particularly when a relatively harsh chemical-based preparation technique had been used (e.g. pollen preparation procedures). This project used a slight variation of the water-based methodology developed and recommended by Hendon & Charman (1997). This was to ensure potential problems of species loss, reduction in concentration or species over-representation could be largely avoided.

In this study, analysis of testate amoebae was included as a means of corroborating existing datasets generated through the primary techniques of humification and macrofossil analyses. Owing to time constraints and the lack of a modern data set for Estonia, analysis was restricted to the identification of specific indicator-species and carried out at a slightly coarser resolution, relative to the primary analysis techniques. Four indicator species were chosen on the basis of their hydrological parameters and their abundant distribution throughout the Baltic. These species are *Amphitrema flavum*, *Amphitrema wrightianum*, *Assulina muscorum* and *Trigonopyxix arcula*.

Sampling for testate amoebae was carried out at 3 cm intervals throughout all cores. Sub-samples of *c.*2 cm^3 were extracted and then placed in a 250 ml beaker and topped up with 100 ml of distilled water. These were then placed on a hot plate and boiled for 10 minutes in order to disaggregate the peat. Samples were then sieved through a coarse

300 micron mesh in order to remove the coarse detritus and back sieved through a 15 micron mesh in order to remove any remaining fine material. Each sample was then washed into a tube and centrifuged at 3000 rpm for five minutes. Each slide preparation was mounted in water and then scanned using a Nikon Optiphot-2 microscope at x 400 magnification. A minimum of 150 tests per sample was then counted and the number of each indicator species recorded. The proportions of each species were then calculated and expressed as a percentage of the entire fossil assemblage.

Detailed below is a morphological description and the hydrological parameters of each indicator species.

2.6.1.1 *Amphitrema flavum*

This species is readily identifiable. It has a smooth, round to elongate test typically measuring between 45 – 77 microns in length with a distinctive brown colouring. Additionally, Charman (2002) notes that *Amphitrema* is the only taxon with two pseudostomes, symmetrically positioned at either end of the test. The test is composed of proteinaceous material, sometimes with agglutinated particles.

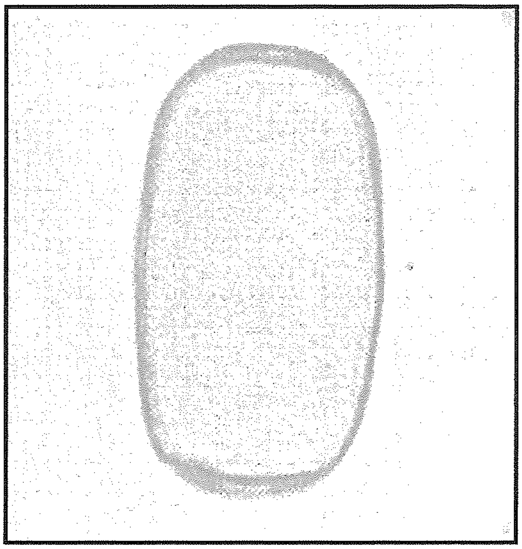


Plate 2.12 *Amphitrema flavum* (x400)

The hydrological parameters of this species are well known. It is one of the commonest species of testate amoebae inhabiting ombrotrophic peat bogs in northwest Europe (Charman, 2002). Numerous studies have shown that this species is indicative of relatively wet or sometimes standing water conditions (e.g Tolonen, 1966; Meisterfield, 1977; Warner, 1987). From peat-based studies worldwide, hydrological indicator values have been assigned to testate amoebae based on the depth to the water table (cm) inhabited by each species. From research in Finland, Tolonen *et al.* (1994) assigned an optimal water table depth of 2.8 cm for *A. flavum*, indicating its preference for wet conditions and a near surface water table. This is in broad agreement with the research of Woodland *et al.* (1998) in the UK and Bobrov *et al.* (1999) in western Russia, where values of 4.60 cm and 6.6 cm were attributed to this species. The slight variation in water table depth is perhaps supported by the earlier research of Heal (1964) who found that whilst preferring pool conditions *A. flavum* could inhabit hummock tops in oceanic areas. However, recent palaeoclimatological research has used this taxon exclusively as an indicator of wet conditions (e.g. Charman *et al.*, 2000; Speranza *et al.*, 2002).

2.6.1.2 *Amphitrema wrightianum*

Charman (2002) notes that this species can be difficult to distinguish from *A. stenostoma*. However, *A. wrightianum* has distinctive collars at both poles, extending the pseudostomes. In fossil form, it is typically yellow to amber brown with a proteinaceous test that can be obscured by a mixture of siliceous particles. This species can be almost spherical to elongate with parallel sides in broad lateral view and measures between 50 – 95 microns.

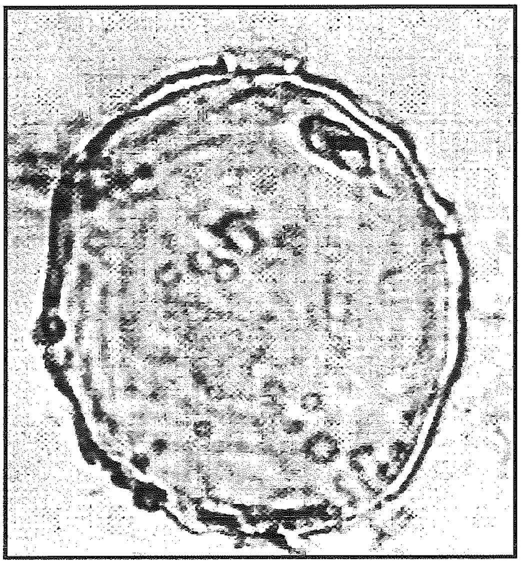


Plate 2.13 *Amphitrema wrightianum* (x400)

This is an excellent indicator of elevated water tables. Tolonen *et al.* (1994) assign an optimal water table position of only 0.8 cm for this species. van der Molen & Hoekstra (1988) observed that this species was mainly found inhabiting the pool microform on peat bogs. Additional research by Woodland *et al.* (1998) in the UK, Charman & Warner (1997) in Newfoundland and Mitchell *et al.* (2001) in the Jura mountains support the use of *A. wrightianum* as a hydrophilous indicator.

section investigating internal or external processes are the primary control in determining stratigraphic changes in the peat profile. The final chapter details the main findings of the project and suggests further research options and extensions to the project.

Chapter 2 Field and Laboratory Methodology

2.1 Introduction and Background to Methods

Palaeoclimatological research is based on the premise that the fossil assemblage can be meaningfully interpreted to provide information on past environments (e.g. Mitchell, 2005). A prerequisite for this is therefore that the ecological requirements of species have remained constant in time and space. A fundamental assumption is that the relationship between environmental variables and the proxy observed today also occurred in the past (Roberts, 1998). Birks and Birks (1980) suggest that because of processes of transportation, diagenesis and redeposition great care needs to be taken when basing palaeoclimatic reconstructions on fossil assemblages. These complicating factors can be further exacerbated where certain species are either now extinct or absent from the 'modern day' assemblage.

Recent palaeoecological research has adopted a high-resolution, multi-proxy methodological approach. This has enabled short-lived and/or low-amplitude climate fluctuations to be identified (e.g. Mauquoy & Barber, 1999a; Mauquoy *et al.*, 2002). Additionally, this approach is advantageous in providing a more secure 'climatic reconstruction' based on multiple proxy indicators that can be compared within the core as well as to other sites.

The methodology used in this study is that of peat humification, plant macrofossil and testate amoebae analyses as an aid to test multiple working hypotheses. Chamberlain (1890, p.94) states that "a special merit of the method is, that by its very nature it promotes thoroughness". Similarly Birks (1988) suggests that the approach of multiple working hypotheses is an attractive and desirable goal in palaeoecological research. However, the method is not without drawbacks and Chamberlain notes the difficulty in fully understanding the simultaneous workings of more than one influencing factor. He states "there is therefore a certain predisposition on the part of the practitioner of this method to taciturnity" (Chamberlain, 1890, p94). Nonetheless it remains that the method of multiple working hypotheses is the most important and practical approach to palaeoecology. In order to avoid predetermined or biased results, surmising of causal mechanisms of change was not undertaken until all of the datasets had been generated.

This project adopts a range of established and relatively new palaeoecological techniques. High-resolution peat humification and plant macrofossil analyses have been carried out at 1cm contiguous intervals throughout the core. Additionally, testate amoebae analysis has been conducted at a slightly coarser resolution to provide an independent source of local palaeohydrological data. In order to develop an effective chronological framework for each site, high-resolution ^{14}C wiggle-matched dates have been applied to each core.

2.2 Site Selection

Sites in Finland and Estonia were chosen in order to test whether high-resolution palaeoclimatic records could be obtained from Baltic mires. Whilst frequently utilised in the British Isles and Europe (e.g. Blackford & Chambers, 1995; Anderson, 1998; Chambers & Blackford, 2001; Mitchell *et al.*, 1996), the use of raised mires as an archive of palaeohydrological and hence past climate data has been largely unexplored in the Baltic region. Therefore working in collaboration with Prof. A. Korhola of the University of Helsinki, Finland and Dr. E. Karofeld of the Tallinn Institute, Estonia, four sites were identified (Figure 2.1). The choice of each site was governed by a number of criteria: firstly that each mire was ombrotrophic in character, secondly that the sites had been subject to minimal human disturbance and thirdly that plant species at each site were climatically sensitive enough to be responsive to climate change.

A particular problem in high-resolution late Holocene peat-based palaeoclimatic studies is the integrity of the mire. Natural and anthropogenic activities on the mire can result in modification of the mire landscape and/or hydrology resulting in a blurring or possible concealment of any climate signal. This is especially problematical in the UK and throughout NW Europe where draining of peatland for agriculture and extensive grazing during the Medieval Period has resulted in considerable ecological background noise that can cause gaps in the normally continuous palaeohydrological record as well as a loss in resolution.

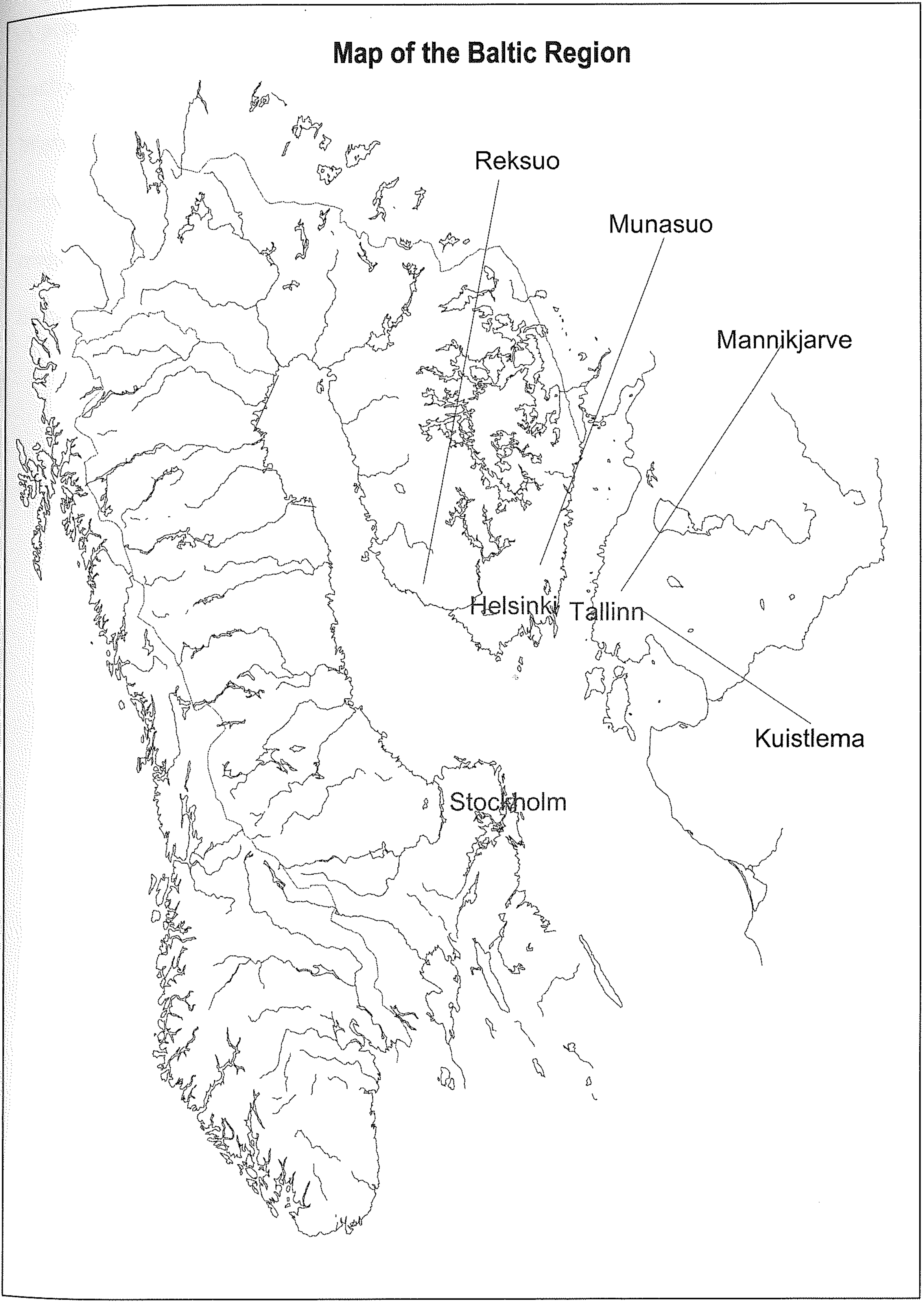


Figure 2.1 Site map showing the location of all four sites and their proximity to each other.

A prerequisite for this study was that the sites were within a close enough proximity of each other to record regional/hemispherical changes in climate, namely the Medieval Warm Period and the succeeding Little Ice Age. As can be seen from Figure 2.1, the sites meet this criteria and therefore it is reasonable to expect that episodes of high-magnitude and sustained climate change would be recorded at all four sites. A detailed description is provided on a site-by-site basis in chapter 3.

2.3 Coring Strategy

Careful site selection is of paramount importance in any palaeoecological study. In order to recover a continuous, high-resolution record of hydrological change, cores were extracted from the deeper central area of the mire. Peripheral areas that would have been more likely to suffer from disturbance by either natural (bog bursts) or anthropogenic activities (grazing, burning etc) were avoided (Barber *et al.*, 1994a). Similarly hummock and pool microforms were avoided and the cores were extracted from the more sensitive lawn area, typically displaying a dominance of *Sphagnum fuscum*. Every care has therefore been taken in ensuring that a complete palaeo-record has been retrieved from each site.

Plate 2.1 An example of the lawn microform that cores were taken from at each site.

Profiles were extracted using a wide bore (30 x 9 cm diameter) Russian-type corer. See plate (2.2). Additionally at Munasuo an open-faced corer was used to retrieve the first metre owing to compaction and a loss of material whilst using the Russian corer. At both of the Finnish sites additional material was collected from the top 25 cm by using a piece of open-faced plastic guttering pushed into the peat and then cut free using a scalpel. Cores were extracted to a minimum depth of 1.8 m after advice from local researchers.

Plate 2.2 Peat core retrieved using a wide bore (30x90 cm) diameter Russian-type corer.

Single cores were extracted from each site owing to time constraints in laboratory analyses and limitations of transport. A justification of single core palaeoclimatic research on ombrotrophic peat bogs is given by Barber *et al.* (1998). Using ten short cores taken from two adjacent bogs, macrofossil analysis was carried out to determine whether a coherent and replicable palaeo-record could be obtained from each site. Barber *et al.* (1998 p515) concludes, "variation between profiles is slight and less than observations of present vegetation mosaics might suggest".

The cores were transported from each site in 4x50 cm plastic guttering. The cores were carefully placed in the guttering and tightly wrapped in polythene tubing to ensure that the peat was not subject to drying out or shrinkage. The guttering was clearly labelled with the site name, depth and which end was uppermost in the stratigraphic sequence. Samples were stored in refrigerated conditions until sub-sampled.

2.4 Colorimetric Humification Analysis

Since the pioneering research of Blytt (1876), changes in peat stratigraphy have been extensively used as a source of evidence for climate change in northern Europe (Birks & Birks, 1980). Consequently, several different methods have been developed. These include measurement of chemical and physical peat properties, visual measurement and classification and laboratory chemical extraction procedures.

Schnitzer and Levesque (1979) define the humification of peats as the transformation of organic material within the aerobic acrotelm to chemically complex substances, such as humic and fulvic acids. The degree of humification is therefore directly related to the position of the water table, which in turn controls the rate/degree of near-surface material decomposition. Hydrological conditions on ombrotrophic mires are therefore closely linked to fluctuations in effective precipitation (the balance of precipitation remaining after evapo-transpiration processes).

Early research attempted to provide a standard scale that could be used in the field to provide data on changes in humification. The first of these was developed by von Post (1924) and provided a 10-point scale using variables including colour, texture and deterioration. Although arguably a rather subjective measurement, this scale has been used frequently in palaeoclimatic research. Haslam (1987) used this scale in conjunction with macrofossil analysis, whilst Tolonen (1985) used it in addition to rhizopod analysis in S.W Finland. More recently Troels-Smith (1955) has produced six classifications for determining the degree of humification based on water colour. Whilst useful in the context of fieldwork or as an initial determinant of stratigraphical change a lack of quantitative data severely limits these techniques.

Measurement of the physical and chemical components of peat has also been extensively used (Levesque and Mathur, 1979; Levesque *et al.*, 1980). In particular, fibre content determination was used as a measurement of humification. However, problems with differential decay rates and preservation between species can skew results. Additionally, difficulties in interpreting the data resulted in Mathur and Farnham (1985) stating that no single method of measuring the extent of humification to the exclusion of all others should be used.

The methodological approach adopted for this study is that of colorimetric humification analysis as outlined in Blackford and Chambers (1993). This procedure involves the alkali extraction of humic and fulvic acids from peat. Numerous studies have attested to the ability of this technique to yield replicable and semi-quantitative data from ombrotrophic peat bogs (Barber *et al.*, 1998; Hughes *et al.*, 2000; Mauquoy and Barber, 2002). Nevertheless, this technique is not without certain problems and limitations. Firstly, it is known that differential decay rates occur within a mire's plant community. Heal *et al.* (1978) note that *Calluna* stems contain high levels of resistant lignin and hence decay more slowly in the acrotelm than species containing high levels of carbohydrates - more readily degradable compounds. Similarly Johnson & Damman (1991) established that differential decay rates were apparent within two *Sphagna* species. Analyses of *S. cuspidatum* and *S. fuscum* over a 10-and 22-month period enabled decay rates to be measured on both hummock and hollow microforms. Johnson & Damman concluded that *S. cuspidatum* decayed 1.5 times faster in the hollows than *S. fuscum* decayed in the more favourable oxic part of the hummock. Therefore decay rates appear to be species dependent and generally overrule the effects of micro-habitat.

More recently Caseldine *et al.* (2000) used luminescence spectroscopy to assess the chemical composition of these extracts. Whilst results indicated that in some instances different plant species may be affected to different degrees by the NaOH extraction procedure, the overall findings supported the use of colorimetric humification as a palaeohydrological proxy data. Whilst botanical composition of peat may need to be taken into account when either choosing a coring site or when interpreting results, the use of peat humification in palaeoclimatic studies remains one of the primary palaeoecological techniques. The close correspondence between changes in the humification curve and changes in other proxy records such as pollen, plant macrofossils, testate amoebae and stable isotopes, confirm its effectiveness as a tool for palaeoclimatic reconstruction (Aaby, 1976; Hughes *et al.*, 2000; Nott *et al.*, 2000; Hong *et al.*, 2000).

2.4.1 Preparation and Analysis

All peat cores were sampled contiguously at 1 cm intervals and then weighed to 0.2 g (ground, dry weight) and digested in 8% NaOH to extract what has been assumed to be humic and fulvic acids in solution. Colorimetric determinations were made on a Cecil CE-303 Grating Spectrophotometer at a wavelength of 540nm for three of the cores, whilst Mannikjarve samples were measured at the same wavelength using a Cecil CE 2011 spectrophotometer.

Results are expressed as percentage light transmission relative to a standard of distilled water. Blackford and Chambers (1993) suggest that this is preferable to the measurement of absorbance values as percentage transmission is on a linear scale. Determinations were replicated three times per sample in order to obtain a mean value. Higher transmission values are therefore indicative of and proportional to, but not an absolute measure of, lower degrees of humification. (See Appendix 1 for a Humification Schedule).

2.5 Plant Macrofossil Analysis

The stratigraphic analysis of plant macrofossils enables reconstruction of the plant community of a bog over time. Macrofossils in peat deposits are usually derived from plants growing at or very close to the sampling site, and therefore reflect changes in local hydrological conditions. Barber *et al.*, 1998 claim that on ombrotrophic mires this is a function of effective precipitation. The macrofossil assemblage can include a diverse range of material ranging from microscopic fragments of leaf tissue to much larger fossilized pieces of wood or roots. Owing to the acidic nature and relatively slow decay rate of ombrotrophic peat bogs, fruits, leaves, seeds, stamens, megaspores, buds, cuticle fragments and flowers are preserved in the mire. This results in macrofossils that can usually be identified to genus or often species level.

Plant macrofossil analysis was one of the pioneering techniques used in Quaternary palaeoclimatic studies. In Scandinavia it has been used extensively in studies of bog microform, particularly the interplay between the development of hummock and hollow topography (Lindholm & Vasander, 1991). In the UK plant macrofossils have been used extensively in palaeoclimatological and palaeoenvironmental research. For example Tallis (1995) investigated the significance of *Racomitrium lanuginosum* remains in blanket peat profiles from the Southern Pennines and Berwyn Mountains. From detailed stratigraphical analyses, Tallis concluded that the presence of *Racomitrium* remains in the profile indicated phases of drier conditions succeeded by a return to wetter more humid conditions. More recently, plant macrofossils have been used in conjunction with additional proxies to enable high-resolution palaeoclimatic reconstructions to be made (e.g. Mauquoy & Barber, 2002; Mauquoy *et al.*, 2002; Langdon *et al.*, 2003).

However, the plant macrofossil technique is not without limitations and some of the inherent assumptions can be problematical. One of these is that the decay rate for different species is constant both spatially and temporally and therefore preferential preservation of certain species does not occur. As mentioned above the research of Johnson & Damman (1991) and Heal *et al.* (1978) showed that this is not always the case. Whilst in no way invalidating the technique this issue demonstrates that care needs to be taken when attempting to interpret fossil macrofossil assemblages. Earlier research conducted by Coulson & Butterfield (1978) showed that on blanket mires the rate of plant decomposition was affected by several biotic factors. Most important of these was the chemical composition of plant species and the underlying substrate. Furthermore, substrates with high concentrations of nitrogen relative to the surrounding catchment resulted in increased local microbial activity with enhanced decomposition rates as a consequence. The role of soil animals in decay rates was also investigated. Again the soil type and plant species of the substrate markedly affected decomposition rates. For example Coulson & Butterfield (1978) showed that whilst little of the decay of *Eriophorum vaginatum* was attributable to animal activity *Calluna vulgaris* owed an appreciable part of its decomposition to the activity of soil animals.

In the UK stratigraphic changes in ombrotrophic mires are almost wholly ascribed to water table fluctuations as a function of variation in regional climate. Backeus (1988) indicates that *Sphagnum* growth is dependent upon the distribution of precipitation throughout the year and especially in August of the preceding year. Additionally, factors of mire shape, size and hydrology may mask or result in the bog displaying an inertia to short-lived or low-magnitude climate change. Haslam (1987) demonstrated that sites with a limited ability to absorb increases in effective precipitation are more sensitive and respond rapidly to deteriorations in climate. Fluctuations in regional/hemispheric climate (particularly temperature and effective precipitation) are therefore accepted as the driving mechanism for changes in peat stratigraphy and by association the plant macrofossil assemblage.

An alternative explanation that is accepted throughout much of the Baltic region and parts of Scandinavia is that autogenic processes operating within the mire predominate and are generally assigned greater significance in causing changes in mire stratigraphy. In particular autogenic plant succession is generally considered the primary cause of botanical changes on the mire surface. Korhola (1995) accepts that climate may act as a driver for mire initiation but after this initial phase allogenic factors are effectively replaced by autogenic factors (Karofeld, 1998; Seppä, 2002).

2.5.1 Preparation and Identification

The identification and quantification of plant macrofossils forms a key part of this research project. *Sphagnum* leaves form the majority of the subfossil peat matrix of ombrogenous mires and after microscopic examination can usually be identified to species level. In order to generate quantitative data that can be compared meaningfully with other sites a variation of the Quadrat and Leaf Count Macrofossil technique (QLMCA) developed by Haslam (1987) has been employed for this project.

Although time consuming, this enables accurate reconstruction of the vegetation component and the data can then be subject to multivariate analyses including Detrended Correspondence Analysis (DCA) and Weighted-averages Ordination (WAO). Whilst not as complex as the 10-point reliability index developed by Janssen (1983) it is an advance on the earlier 5-point scale developed by Walker & Walker (1961). The QLMCA technique has been widely utilised in palaeoclimatological research (Barber *et al.*, 1998; Mauquoy & Barber, 1999; Mauquoy *et al.*, 2002) therefore enabling direct comparison and correlation with datasets generated from this project.

Each peat monolith was sampled contiguously at 1cm intervals to a depth of 180 cm. Samples measuring *c.*4 cm^3 were extracted, placed in a 125 micron sieve and washed thoroughly using a strong jet of water in order to remove fine detritus and disaggregate the sample. The macrofossils remaining were then placed in a trough and distilled water was added to produce a monolayer of remains suitable for analysis. Proportions of each of the major peat components such as unidentified organic matter (UOM), Dicot leaves, *Vaccinium oxycoccus*, monocotyledons, identifiable *Sphagnum* and other bryophytes were then estimated from 10 averaged quadrat counts at 10 x magnification using a 10 square grid graticule in the eyepiece of a Nikon stereozoom microscope. A minimum of 100 *Sphagnum* leaves per sample was randomly extracted. The leaves were identified down to their lowest taxonomic level using a Nikon Optiphot compound microscope at x100-400 magnification. Macrofossils were identified using a reference collection obtained in the field and identified by Prof. A. Korhola of the University of Helsinki and Dr. E. Karofeld of the Tallinn Institute. Dr P. Hughes of Southampton University and Dr D. Mauquoy of the University of Amsterdam provided additional aid. Detailed descriptions and drawings in Grosse-Braukman (1972), Smith (1980), Daniels & Eddy (1990) and Vanner (1995) also proved extremely useful in the identification of macrofossil components and *Sphagnum* leaves.

Detailed below are a morphological description and the ecological requirements/constraints of the major components of the macrofossil diagrams. Additional ecological information on the remaining species will be provided in the results chapter.

2.5.2 *Sphagnum* Species

Sphagnum forms the bulk of the peat matrix in ombrogenuous mires. Identification to species level although generally possible can be hampered by a certain degree of within-taxon variability. However, Daniels & Eddy (1990) note that the majority of species have several distinctive characteristics that can aid identification. In particular an increase in size of the hyaline cells in hummock-forming species is apparent in contrast to pool-forming species. Photosynthetic cell morphology and the size, number and arrangement of hyaline cell pores yield valuable taxanomic information. Additional, diagnostic features including fibrils, the resorption furrow and papillae are peculiar to specific species.

2.5.2.1 *Sphagnum* section Acutifolia

Sphagnum fuscum

This species was by far the most dominant at all four sites and often comprised in excess of 90% of the total *Sphagnum* assemblage. The importance of *S. fuscum* is emphasised by Eurola *et al.* (1984). Eurola *et al.* note from study sites in Finland that only *S. fuscum* is capable of tolerating very slow thawing. This may offer a partial explanation as to why *S. fuscum* appears to form the majority of the *Sphagnum* assemblage and seems able to tolerate a broad range of climatic and ecological conditions. Daniels & Eddy (1990) note that whilst occurring as pure stands in hummocks, *S. fuscum* also has a high degree of association with other species including *S. angustifolium*, *S. papillosum* and *S. magellanicum* in open mires. Typically it is an ombrotrophic species forming dense, usually low and wide hummocks in oligotrophic and mesotrophic mires.

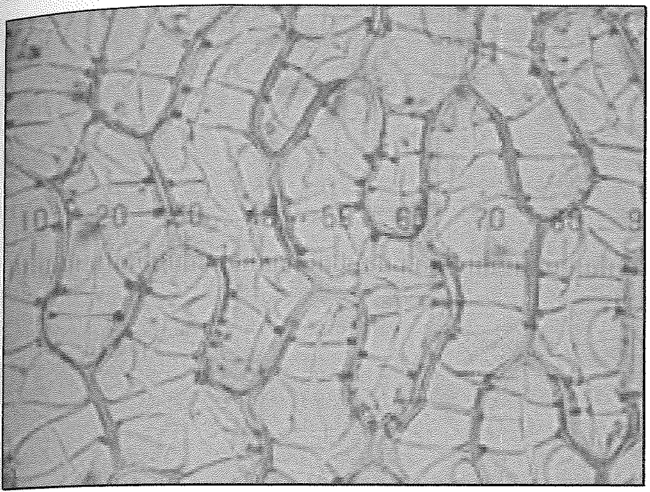


Plate 2.3 *Sphagnum fuscum* (x400)

Morphologically the leaves of section Acutifolia are especially difficult to differentiate. All species in this section possess small to medium sized leaves typically 1.2 – 1.9 mm long and the photosynthetic cells are triangular to trapezoid in shape with the widest exposure on the adaxial leaf surface (Daniels & Eddy, 1990). Nevertheless, a comprehensive field collection of branch and stem leaves was invaluable in the identification and quantification of this species.

2.5.2.2 *Sphagnum* section Cuspidata

Sphagnum riparium

This species is an excellent indicator of elevated water table as it is typically confined to very wet areas, often being found in shallow water (Daniels & Eddy, 1990). It is often found in conjunction with *S. lindbergii* or raised tufts of *S. angustifolium.*

showed secular trends comparable to those observed east of the Scandes although the magnitude and timing of the extremes differed. Using 'partial least squares regression' (PLS) analysis of tree-ring data from Norway, Kalela-Brundin (1999) supports these findings with cool summers around AD 1600, 1710 and 1800. However, a study of tree-ring widths from a master ring-width chronology of Scots pine (*Pinus sylvestris L.*) in northern Scandinavia led Lindholm and Eronen (2000) to conclude that only limited evidence of a 'Little Ice Age' was recorded in the chronology.

Data from viticulture have also provided complementary information on sub-decadal climate oscillations. Le Roy Ladurie & Baudant (1980) combined a series of data relating to the timing of grape harvests from areas of France and Switzerland encompassing the period AD 1400s – 1900. From these data they suggest that late harvests are generally indicative of cooler temperatures throughout the growing season. They conclude that the viticulture record does not show any sustained episodes of late harvests; rather, the record shows pronounced and rapid fluctuations between relatively warmer and cooler conditions.

Tarand & Nordlli (2001) used a combination of instrumental information and proxy data to generate a palaeotemperature record for Estonia. Proxy data were derived from three sources. These were the first day of ice break-up in Tallinn port, a proxy for the mean winter air temperature (December to March); the first day of ice break-up on the rivers in northern Estonia, a proxy for the beginning of spring; and the first day of the rye harvest, a proxy for the mean air temperature in spring and summer (April to July). On the basis of these data the mean winter temperature record has been extended back to AD 1500 and the spring/summer record to 1731. In areas without glaciers, like

Estonia, the LIA has been defined by the presence of cold winters. Results from this study demonstrate both the variation in magnitude and the asynchroneity of this event. A cluster of severe winters occurs in the first three decades of the nineteenth century in AD 1800, 1803, 1809, 1820, and 1829. However, during the entire 500yr record only four winters had mean temperatures estimated at below –10°C. Tarand & Nordlli suggest that the term 'Little Ice Age' may be applied to the entire period AD 1500 to the mid nineteenth century. In general, this period is characterised by moderately cold conditions with the exception of a phase of warming during the first half of the eighteenth century.

In Iceland, historical and documentary evidence demonstrate that climatic oscillations occurred regularly and started and terminated abruptly. Ogilvie (1995) examined historical records from 33 annals of Icelandic farmers and settlers. Evidence from these annals indicates that in Iceland cooler conditions were prevalent during the latter part of the sixteenth century, which were then interrupted by a much milder decade in the AD 1610s before climate deteriorated again during the next two decades. This cold episode was then terminated abruptly at AD ~1641 with much more clement conditions prevailing until the AD 1680s. The AD 1690s saw a return to very cold conditions in Iceland although during the first decade of the eighteenth century milder conditions were again recorded and remained until AD ~1730. Following this milder period a return to intense cold conditions occurred up until AD 1760. Whilst conditions generally improved during this decade the AD 1770s were colder and the AD 1780s stand out as being the coldest decade in Iceland with maximum levels of sea-ice also recorded during this period. Interestingly, historical documents also record particularly mild decades during the AD 1640s, 1650s, 1660s and early 1700s. The high frequency and rapidity of climate change recorded during what is recognized as the LIA interval further reinforces that rather than a prolonged episode of intense cold, the period was regularly punctuated by much warmer conditions.

The cause of the Little Ice Age cooling has been thoroughly debated particularly in view of its recent history and its relevance to possible future climate change. Numerous studies have demonstrated that the LIA is coincident with a period of reduced solar activity known as the 'Maunder Minimum'. The role of solar forcing in global climate change is still poorly understood with complex interaction between atmosphere-biosphere and oceanic processes complicating any simple linear interpretation of the solar-climate relationship.

Recent use of Global Circulation Models (GCMs) has enabled some conclusions to be made about the effect of reduced solar activity for the 'Maunder Minimum' period of the LIA. Proxy and historical records indicate that the most significant cold episode corresponds exactly with this period of reduced solar activity. Equilibrium simulations of climate response to changing solar radiation using the Laboratoire de Meteorologie Dynamique (LMD) atmospheric GCM estimate that for the Maunder Minimum a 0.4% reduction in solar radiation accounts for a corresponding surface temperature decrease of 1.5°C. This contrasts with the Goddard Institute of Space Studies (GISS) circulation model that estimates a global temperature decrease of 0.47°C for a 0.25% solar irradiance decrease. Research suggests that effects of solar changes can either be amplified or modulated by up to 1°C by dynamic circulation patterns driven by the differential heating of the continents and oceans (Lean & Rind, 1998).

Mauquoy *et al.* (2002) used ^{14}C and ^{10}Be isotope analyses to investigate possible solar-driven climate changes during the Little Ice Age at Walton Moss, UK (WLM) and Lille Vildmose, Denmark (LVM). Contiguous 1cm sampling of plant macrofossils was also used to determine 'wet shifts' in each mire's hydrology and then closely spaced series of ^{14}C AMS dates immediately preceding and following each of the identified 'wet shifts' were obtained. Results showed that at LVM two wet shifts were identified, with the first of these occurring at AD 1449 and the second at AD 1604. At WLM three wet shifts were identified with the first at.AD 1224 and with the second and third episodes occurring at AD 1434 and 1605 respectively. The five wet shifts identified in the peat stratigraphy at the two sites all correlate with known periods of reduced solar activity. As can be seen from Figure 1.8 four episodes of solar minima are evident preceding, during and succeeding the LIA period.

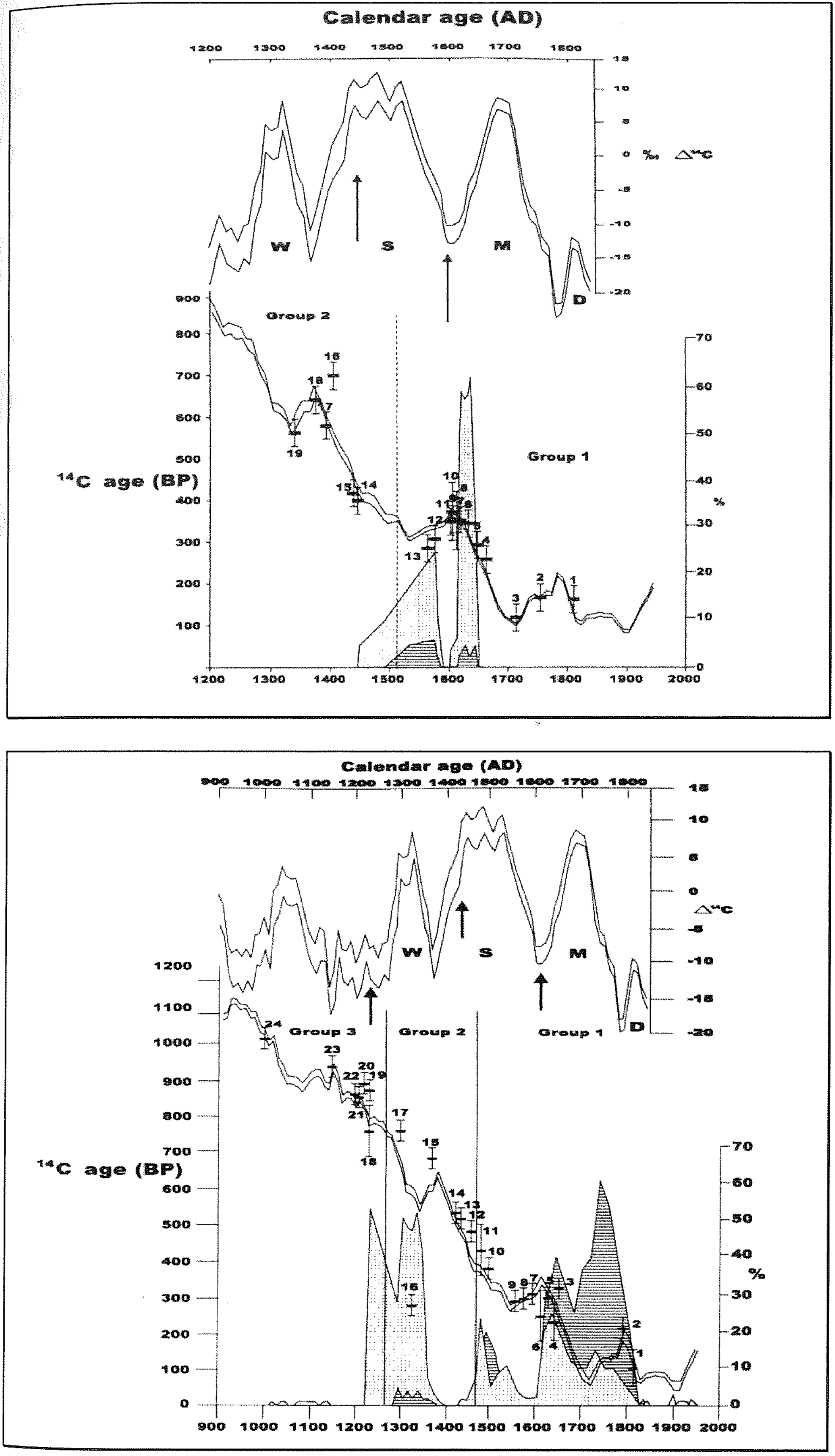


Figure 1.8 Episodes of solar minima that correspond with the LIA (Mauquoy *et al.*, 2002)

Mauquoy *et al*. (2002) state that at WLM the three wet shifts correspond to the Wolf (AD 1224), Sporer (AD 1434) and Maunder Minima (AD 1604) respectively. Notably no climatic deterioration is recorded at the time of the Dalton Minimum, during which solar changes may not have been so pronounced as the preceding minima periods. This is reinforced by examining the ^{14}C increases during the Dalton Minimum which were around 8.8 ‰ in contrast to the Wolf, Sporer and Maunder Minima with values typically of *c*. 20 ‰.

1.5 Natural causes of Late Holocene climate change

Several mechanisms have been postulated as plausible explanations for the fluctuations in Late Holocene climate. These include changes in ocean circulation (Broecker *et al.*, 1985; Bond *et al.*, 1993); volcanic eruptions (Lamb, 1977; Grove, 1988, Zielinski *et al.*, 1994) and perhaps most importantly for this period, changes in solar output (Hoyt & Schatten, 1993; Lassen & Friis-Christensen, 1995; Anderson, 1992; Cliver *et al.*, 1998; Damon & Peristykh 1999; Thejll & Lassen, 2000; Chambers & Blackford, 2001; Blaauw *et al.*, 2004).

Chambers *et al.* (1999) provide a comprehensive review of the palaeoenvironmental evidence for solar forcing of Holocene climate. Various changes in the characteristics of the sun over different timescales have been shown to affect global climate. These changes include sunspots that reflect convectional activity within the photosphere, solar flares, solar UV flux, solar radius variations, changes in the sun's magnetic field and the length of solar cycles. As yet, the importance of each factor is unquantified; however, as is evident from Figure 1.9 an apparent correspondence is evident between temperatures recorded in the last century and variations in the solar cycle length.

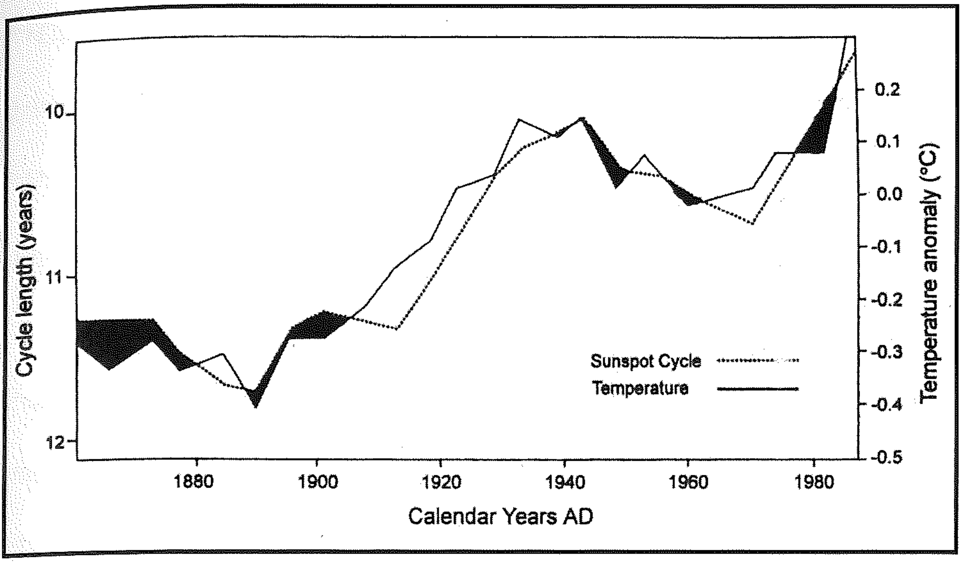


Figure 1.9 The apparent correspondence between solar cycle length and temperature observed by Friis-Christensen & Lassen (1991) (Taken from Chambers *et al.*, 1999)

Research into the causes of relatively short-term climate change (10^1 to 10^2 years) has focused on fluctuations in solar output. Several cycles with differing periodicities have been identified from historical observations and proxy data sets. These cycles are detailed in **Table 1.1** below:

Solar Cycle	**Evidence**
Schwabe – sunspot 10-11 yrs	Dust, Greenland ice core; meteorological records
Hale – double sunspot, 22 yrs	Storm tracks? Tree-rings?* Sediments
Gleissberg – 78 yrs (72-83 yrs)	Meteorological records; SSTs? Lake sediments; ocean sediments
Suess - 211 yrs (180-220 yrs)	Peat humification? Pollen data from peat bogs?
Hallstattzeit – 2200 yrs	Cosmogenic isotopes
Other allegded cycles	
1470 years**	Deep sea cores; ice cores
~2500***	Ice cores; tree-rings; varves; lake levels

Notes:

* May be confused with 18.6-year lunar cycle (see Hoyt & Schatten, 1997).

**Claimed to be pervasive in the late Quaternary (see Bond *et al.*, 1997); solar/ocean driven?

***Possibly confused with 2200 year Hallstattzeit cycle; or may be related to meteorite impacts. (Taken from Chambers *et al.*, 1999)

Peat bogs provide an ideal repository for investigating the links between solar variability and climate because the plant communities are very sensitive to changes in effective precipitation (the balance of precipitation remaining after evapotranspiration processes) (Mauquoy *et al.*, 2002). Chambers & Blackford (2001) investigated postulated solar forcing periodicities from four blanket mires in the UK. Although equivocal the results demonstrated that the mires studied do show a response to periodic forcing factors. In particular, the 80-and 200-yr. signals were replicated in two out of the four sites. Additionally, several other periodicities with solar correlatives were also identified (100, 72, 60 and 50-52 yr.). Evidence for solar forcing of Holocene climate has also been generated from raised bog deposits in The Netherlands. Fluctuations in solar activity can be reconstructed using the proxy $\delta^{14}C$ (Stuiver & Braziunas, 1993; Stuiver *et al.*, 1998; Beer, 2000; Bard *et al.*, 2000; Spernanza *et al.*, 2002). High-resolution (0.5-1 cm) analyses were undertaken on two peat cores retrieved from Engbertsdijksvenen and Meersstalblok mires in the eastern area of The Netherlands. 'Wet shifts' in the record were inferred from stratigraphic changes in the local macrofossil composition, and based on the ecological requirements of each species. The cores were dated at high precision using ^{14}C wiggle-match dating. Results showed that of the 17 'wet shifts' recorded from both sites nine of these coincided with major increases in residual $\delta^{14}C$. Blauuw *et al.* (2004) also note there is only one occasion when a peak in ^{14}C is not associated with a corresponding 'wet shift' in the mire. Indeed they note that even relatively small increases in ^{14}C are coeval with phases of increased mire wetness, although they suggest this may be coincidence.

Palaeoecological research on peat bogs throughout much of Europe has generated full or partial Holocene climate records. In particular, teleconnections have been suggested for a period of abrupt climate change at around 2650 BP (van Geel *et al.*, 1998). Speranza *et al.* (2002) also recorded this episode of climate change from a peat sequence in the Giant Mountains, Czech Republic. At both sites this period of abrupt and high magnitude climate change is coincident with a marked fluctuation in the $\delta^{14}C$. Both sets of authors suggest that the recorded climate change at cal.2650 BP may have been caused by a decline in solar activity. Speranza *et al.* suggests several possible explanations of how changes in solar activity/irradiance may have been amplified in terrestrial climate.

1. an increased cosmic ray flux in the high atmosphere would enhance ionization and the production of more aerosols, which would result in an increased global cloud cover, which would produce wetter and cooler climatic conditions. (e.g. Svensmark & Friis-Christensen, 1997; Raspopov *et al.*, 1997).

2. a decrease in solar UV radiation would cause a decrease in the ozone production in the high atmosphere; a lower ozone content would determine changes in the global atmospheric circulation, with equatorward displacement of the westerly jet streams and of the Hadley cells as proposed by Haigh (1994,1996,1999). This would imply a cooling in the middle and high latitudes and a change in precipitation patterns due to a southward displacement of storm tracks.

The influence of solar activity on climate is demonstrated by the study of Karlen & Kuylenstierna (1996) from a range of proxy sources in Scandinavia. ^{14}C isotope measurements were calculated by measuring the difference between dendro-age and the ^{14}C age of tree-rings and then used as a proxy for solar irradition. These variations were then correlated with Holocene glacier and tree-line fluctuations. Analysis of the results demonstrated that of the nineteen episodes of low solar activity observed, seventeen could be positively correlated with periods of cold climate in Scandinavia. As has been mentioned previously, both of the most recent climate excursions (MWP & LIA) correspond to changes in solar activity. This is shown in Figure 1.10

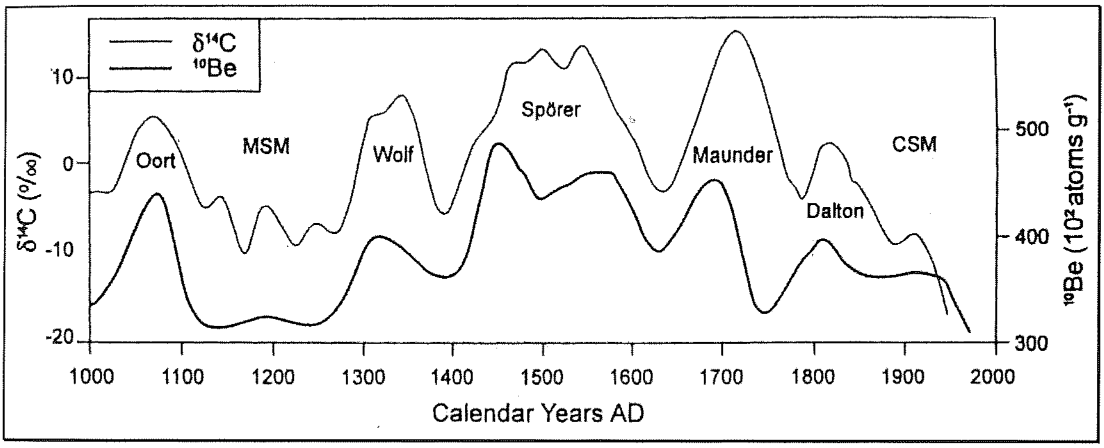


Fig 1.10 Trends in isotope ^{14}C AND ^{10}Be from AD 1000 to present, together with the solar minima and solar maxima (CSM – Contemporary Solar Maximum; MSM – Medieval Solar Maximum, showing that the concentrations of these cosmogenic isotopes in south polar ice apparently relate to historic solar activity. (Taken from Chambers *et al.*, 1999).

Numerous studies have identified or suggested a link between sunspot variations and climate change (Stuiver, 1980; Ribes & Nesme-Ribes, 1993; Hunt & Davies, 1997; Leftus, 2000; Rozelot, 2001). A recent paper by Lean & Rind (1998) noted that for the pre-industrial period 1610-1800 a correlation of 0.86 for reconstructed solar irradiance and Northern Hemisphere surface temperature anomalies could be established. Whilst concluding that during this period solar forcing was the predominant climatic influence, extrapolation of these data to the present indicates that solar forcing may only have contributed approximately half of the observed 0.55°C warming.

However, several other studies have sought to ascertain whether these relatively small-scale variations in solar output can be amplified or modulated by other atmosphere/biosphere processes and therefore account for a greater proportion of climatic change than is presently acknowledged (e.g. Lassen & Friis-Christensen, 1995; Pudovkin & Veretenenko, 1995; Svensmark & Fris-Christensen, 1997; Raspopov *et al.*, 1997). As mentioned previously several such mechanisms have been postulated, although at present there is little or no agreement as to the relative importance or contribution of individual processes. Chambers *et al.* (1999) draw attention to the possibility that climate change may follow a non-linear pattern such as that exhibited in the longer-term orbital forcing cycles that are thought to initiate or terminate glacial and interglacial episodes.

Evidence of short-term cycles is also recorded in the GISP2 ice core, oxygen isotope record from Greenland. Stuiver *et al.* (1997) investigated changes in the solar constant over the 11-year (Schwabe) solar cycle. Using atmospheric ^{14}C as a proxy for solar change, this was then compared with a high-resolution $^{18}O/^{16}O$ record from the same profile. Analyses of the isotope ratios again indicate that for the current millennium, solar activity may be the dominant forcing mechanism for initiating pre-industrial climate change. A fluctuation in the solar constant of ~0.3% is compatible with the magnitude of proposed temperature changes that are associated with both the 'Medieval

Warm Period' and the succeeding 'Little Ice Age'. Analyses of the GISP2 ice core found no evidence of a 'solar fingerprint' for earlier periods of the Holocene and this led the authors to conclude that prior to this millennium changes in the pattern of oceanic/atmospheric circulation may have been the dominant forcing mechanism in climate change. After examining background dust concentrations in the GISP2 record over the last 1000 years, Ram *et al.* (1997) found evidence of an eleven-year solar modulation of climate further reinforcing the importance of the sun-climate relationship for the last 1000 years.

The lack of scientific agreement demonstrates the complexity of sun-climate relationships and the current limited understanding of atmosphere/biosphere interaction. Whilst a clear relationship between solar activity and pre-industrial change can be demonstrated, evidence of more recent climate change being attributable to solar activity remains ambiguous.

Volcanic Activity

Research has indicated that short-term variations in climate have often been broadly coeval with volcanic activity and marked changes in regional climate can be positively correlated with a single volcanic eruption (Crowley & Kim., 1993; Crowley & Kwang Yul Kim, 1996; Zielinski *et al.*, 1994; McCormick *et al.*, 1995). Devine *et al.* (1984) note that a short-lived reduction in local/regional temperature often occurs as a result of fine ash and dust being injected into the atmosphere. Additionally, when large amounts of sulphur volatiles are contained in the eruption these are converted to sulphuric acid in the atmosphere and can remain in the atmosphere for up to five years (Schonweise, 1988). Atmospheric dissemination of these aerosols can then result in the back-scattering of incoming long-wave radiation and a further cooling of the lower-troposphere (Lowe & Walker, 1998). Research on the effects of the Mount Pinatubo eruption in 1991 showed that after this eruption radiation receipt in The Philippines and tropical regions declined by up to 10%, whilst in the Northern Hemisphere surface temperatures also fell by ~1.0°C (Handler & Andsager, 1994).

Whilst climate forcing of up to several years after a single volcanic eruption is generally accepted the evidence for longer-term (decadal/centennial) scale forcing is much weaker. Research on ice cores in Greenland led Fischer *et al.* (1998) to conclude that volcanic aerosols in the stratosphere are unlikely to have had an effect on Holocene climate at a century or millennial scale. Stuiver *et al.* (1997) reach a similar conclusion after high-resolution oxygen isotope analysis of the GISP2 ice core. They suggest that a relatively small volcanic influence on century-scale $\delta^{18}O$ is recorded in the ice core.

It is generally accepted that volcanism plays a relatively small part in causing late Holocene climate change and that the evidence for long-term climate change is weak.

Ocean Circulation changes

Recent research has shown that the oceans play a key role in regulating climate change (Lehman & Keigwin, 1992; Hurrell, 1995; Cubasch *et al.* 1997; Marchitto *et al.* 1998; Rodwell *et al.*, 1999). In fact for northern Europe, Thurman & Trujillo (1999) claim that North Atlantic currents (the Gulf Stream) in conjunction with heat transferred by the atmosphere results in a warming of as much as 9°C. The oceans also play a significant role in the transference of heat from the tropics to the polar-regions. Ocean measurements at 24°N have shown that heat transfer within the oceans is in the order of *c.*2 PW (1 PW $=10^{15}$W) (Summerhayes & Thorpe, 1996).

Evidence that late-Holocene climate changes are driven by changes in ocean circulation is again ambiguous. Several authors have suggested that temperature excursions associated with both the Little Ice Age (Broecker, 2000) and the Medieval Warm Period (Cronin *et al.*, 2003) may be related to fluctuations in the strength of North Atlantic thermohaline circulation. Additionally, several claimed periodicities have been identified from a variety of proxy records. Initially, longer-term periodicities were thought to be the major cyclic component of ocean circulation changes. Analysis of ice cores from Greenland has revealed a 2200yr cycle (Dansgaard-Oeschger). Other longer-term cycles include a 1500 yr cycle (Bianchi & McCave, 1999; Bond *et al.*, 2001) a proposed 800 yr cycle (Barber *et al.*, 1994a; Broecker, 2000) and from analysis of sedimentological data, Chapman & Shackleton (2000) found evidence of both 1000 yr and 550 yr periodicities in North Atlantic circulation patterns during the Holocene.

However, more recently research has indicated that shorter-term cycles may be superimposed upon the more established long-term fluctuations in ocean circulation. From research in Chesapeake Bay, Cronin *et al.* (2003) suggest that multi-decadal processes typical of the North Atlantic Oscillation (NAO) are an inherent feature of late Holocene climate. This is also supported from Greenland ice-core data that indicate decadal climate variations in the North Atlantic can be related to fluctuations in the North Atlantic Oscillation (Hurrell, 1995). Cook *et al.* (1998) reconstructed a high-resolution record of North Atlantic Oscillation using tree-ring chronologies from North America and Europe. The study covered the period AD 1701 – 1980 and by conducting spectral analyses on the reconstructed data, Cook *et al.* claim that oscillations with periodicities of 24, 8 and 2.1 years can be identified from the data. They suggest that these are long-term features of NAO and probably North Atlantic climate in general.

In a study based on faunal and $\delta^{18}O$ variations in a sediment core from the Norwegian Trench, Lehman & Keigwin (1992) suggest that a warming of ~7°C occurred within a 50-year period between the end of the Younger Dryas cold stage and the present interglacial. They conclude that these changes occur too frequently and abruptly to have been forced by long-term fluctuations in solar radiation and instead attribute them to rapid changes in the rate of thermohaline overturn in the North Atlantic. Additionally, their results showed that sudden changes in surface circulation during deglaciation often corresponded to variations in summer sea surface temperatures of $\geq$5°C over a few decades. Furthermore, these shifts are shown to parallel closely the $\delta^{18}O$ record in the Greenland ice cores. Lehman & Keigwin conclude that shifts in air temperature over the ice sheet were caused by changes in the poleward flux of ocean heat. Sea and air temperature fluctuations appear to be correlated with shifts in the production rate of Lower North Atlantic Deep Water.

The complex nature of ocean/atmosphere circulation complicates any simple or straightforward explanation of the cause or driving force of late-Holocene climate change. A considerable body of evidence indicates that both the Little Ice Age (LIA) and the Medieval Warm Period (MWP) may have been coincident with changes in ocean circulation patterns and particularly the rate of production of North Atlantic deep water (Fischer *et al.*, 1998; Bianchi & McCave, 1999; Broecker, 2000; Cronin *et al.*, 2003). However, some of the claimed periodicities found in ocean circulation patterns are also evident in solar cycles (e.g. the NAO 550 yr cycle identified by Chapman & Shackleton is similar to the 530 yr solar cycle noted by Stuiver *et al.*, 1995).

It is clear from the lack of scientific agreement that further research needs to be completed before it can be ascertained which, if either, of these mechanisms is the driver of late-Holocene climate change.

1.6 Aims and Objectives of Project

The principal aim of this research project is to provide a high-resolution record of Late Holocene climate change in the Baltic region. In order to achieve this, four ombrotrophic peat bogs were cored and subjected to multi-proxy, high-resolution 1 cm contiguous sampling. Specific objectives included the identification of known episodes of climate change, namely the Medieval Warm Period (MWP) and the succeeding Little Ice Age (LIA). Using a range of established and relatively new palaeoecological techniques it was anticipated that short-lived and/or low amplitude climate changes would be detected in the peat record. Accurate and high-precision dating of the cores was achieved by the application of a suite of AMS (^{C14} accelerator mass spectrotmetry) dates, which were then 'wiggle-matched' against known variations in the dendrochronological calibration curve. Effective dating of the cores has enabled inter- and intra-site comparison of and correlation of temporally and spatially synchronous climate oscillations. Detailed statistical analyses of these results have then been undertaken using Detrended Correspondence Analysis (DCA), and the Dupont Wetness Index (Weighted-averages Ordination-WAO) in order to identify any trends or 'climate cycles' apparent within the data. An integral part of the project is to assess critically the climatic record inferred from each proxy and to evaluate the reliability and accuracy of each palaeoecological technique used in this project.

Specific aims and objectives of this research project are detailed below:

- Generate high-resolution multi-proxy datasets from each site.
- Statistical analyses of proxy-data, using (DCA) Detrended Correspondence Analysis and Dupont Wetness Index (WAO).
- Inter-and-intra-site interpretation of datasets enabling mechanisms of stratigraphic change to be identified.
- Critical evaluation of palaeoecological techniques.
- To determine the extent to which internal or external factors control changes in the mire vegetation assemblage.

2.6.1.2 *Amphitrema wrightianum*

Charman (2002) notes that this species can be difficult to distinguish from *A. stenostoma*. However, *A. wrightianum* has distinctive collars at both poles, extending the pseudostomes. In fossil form, it is typically yellow to amber brown with a proteinaceous test that can be obscured by a mixture of siliceous particles. This species can be almost spherical to elongate with parallel sides in broad lateral view and measures between 50 – 95 microns.

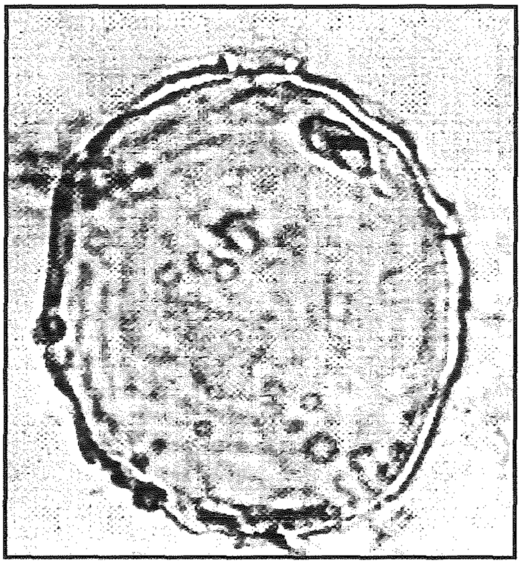


Plate 2.13 *Amphitrema wrightianum* (x400)

This is an excellent indicator of elevated water tables. Tolonen *et al.* (1994) assign an optimal water table position of only 0.8 cm for this species. van der Molen & Hoekstra (1988) observed that this species was mainly found inhabiting the pool microform on peat bogs. Additional research by Woodland *et al.* (1998) in the UK, Charman & Warner (1997) in Newfoundland and Mitchell *et al.* (2001) in the Jura mountains support the use of *A. wrightianum* as a hydrophilous indicator.

2.6.1.3 *Assulina muscorum*

The siliceous oval plates arranged in neat rows enable the test of *Assulina muscorum* to be identified easily (Charman, 2002). Although occasionally clear, this species is usually russet-brown or pale brown in colour and tests measure between 28 – 60 microns.

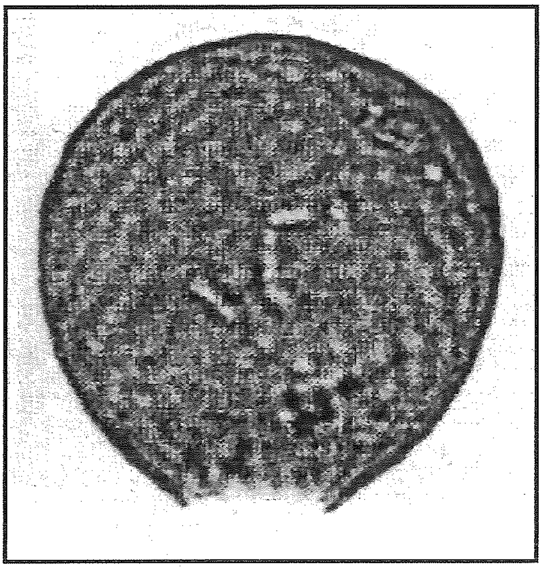


Plate 2.14 *Assulina muscorum* (x400)

In Finland, Tolonen *et al.* (1994) found that this species was a clear indicator of drier mire conditions. In contrast, studies in Canada have observed that *Assulina muscorum* can inhabit a relatively wide range of microenvironmental conditions and is therefore often described as a cosmopolitan species (Warner, 1990; Gent, 2000). The difference in 'optimal mean water table depths' assigned to this species from different study sites exemplifies this. In the UK, Woodland *et al.* (1998) assign a mean value of 6.82 cm for this species whilst from research in Finland Tolonen *et al* (1994) assign a value of 16.6 cm and the research of Charman & Warner (1997) in continental Canada and the USA assigns a value of 42.5 cm, clearly indicating drier conditions. In this study the water table value of 16.6 cm established by research in Finland has been adopted (Tolonen *et al.* 1994). The presence of *Assulina muscorum* in the fossil assemblage is therefore considered indicative of drier mire conditions.

2.6.1.4 Trigonopyxis arcula

This species has several morphological characteristics that aid identification. Bobrov *et al.* (1995) note that a large normally non-circular mouth, which often appears as a rough triangle but may also be four-sided or more irregular, is characteristic of this species. The test of *Trigonopyxis arcula* typically measures between 85 – 185 microns and is dark brown. It has a circular form in broad lateral view and is hemispherical in narrow lateral view (Charman, 2002).

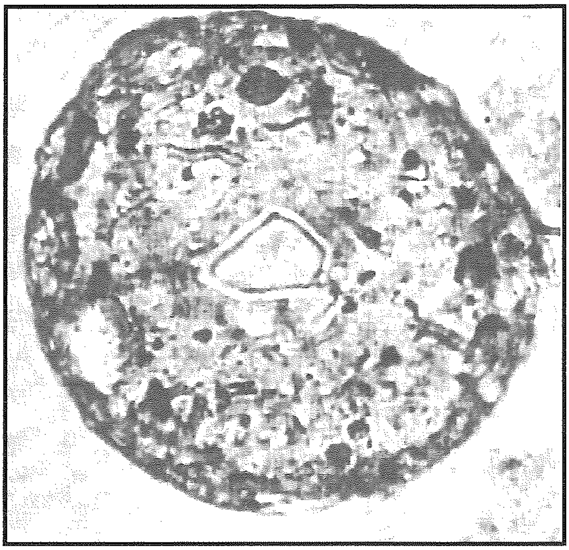


Plate 2.15 *Trigonopyxis arcula* (x400)

Tolonen (1986) states that *Trigonopyxis arcula* is universally regarded as a xerophilous taxon often occurring at the very driest end of the hydrological gradient in ombrotrophic mires. This is supported by the later research of Tolonen *et al.* (1994) and Bobrov *et al.* (1999) who assign hydrological values of 16.6 cm and 30.6 cm respectively for this taxon. The presence of this species in the sub-fossil matrix is therefore an excellent indicator of drier mire conditions.

Whilst no reference collection was available for identification purposes, Dr. D. Mauquoy provided initial help and advice. Additionally, the plates and identification key in Charman (2002) were invaluable in the identification process.

2.7 Chronology

2.7.1 Introduction

In order to ascertain possible causes of climate change and to verify additional external variables (e.g. fluctuations in solar output) it is essential that an effective chronology is established. Accurate and precise dating of peat sections also enables comparison with other sites and established changes in regional or hemispherical climate to be identified. Inter and intra-site comparison of data can also be undertaken to correlate synchronous changes within the mire and to test whether allogenic or autogenic processes are the dominant influence on peat stratigraphy.

Radiocarbon dating has been extensively utilised in palaeoclimatological research (e.g van Geel *et al.*, 1996; Mauquoy & Barber, 1999a; Barber *et al.*, 2000). Radiocarbon dating has several built-in assumptions: firstly that the production of ^{14}C is constant over time, secondly that the ^{14}C:^{12}C ratio in the biosphere and hydrosphere is in equilibrium with the atmospheric ratio, thirdly that the decay rate of ^{14}C can be established and fourthly that a closed system has existed since the death of the organism (Lowe & Walker, 1998). However, research over the last two decades has shown that these assumptions are not always correct.

Using high-precision ^{14}C measurements taken from an Irish Oaks series Pearson *et al.* (1986) demonstrated that ^{14}C activity had varied quite markedly over the period 5210 BC to AD 1840. Pearson & Stuiver (1986) suggest that this is primarily due to fluctuations in cosmic ray production. Factors influencing the cosmic ray flux include changes in the geomagnetic fields of the earth and the sun, sunspots and solar flares on the surface of the sun (Hoyt & Schatten, 1997). Instability in the North Atlantic thermohaline circulation may also have influenced ^{14}C:^{12}C ratios during the Holocene (Stuiver & Brazunias, 1993). Variations in the ^{14}C record appear to exhibit two main characteristics: a major long-term 'sine wave' and a series of middle and short-term high frequency components known as 'wiggles' (Taylor *et al.*, 1996). Radiocarbon dates therefore need to be either stretched or compressed to correct for the assumption of a constant ^{14}C production rate.

Research by Pilcher (1991) established that fractionation of carbon isotopes by plants resulted in a differential take-up of ^{14}C, thus contradicting the assumption that the ^{14}C:^{12}C ratio in living matter is in equilibrium with the atmospheric ratio. Olsson (1986) observed that where certain plants obtain their CO_2 from sediment, this can produce a reservoir effect with erroneous dates of between 300 – 400 years too old. Killian *et al.* (1995) investigated raised bog deposits at Engbertsdijksveneen, The Netherlands. They concluded that samples containing between 2-4% Ericaceae rootlets resulted in ^{14}C ages of between 100 – 150 years too old. This contradicts the established view that root material is comparatively younger than the surrounding plant remains. They postulated that the 'reservoir effect' may be caused by fungi inside the rootlets fixing CH_4-derived carbon and concluded that unless pure *Sphagnum* remains are used in conjunction with wiggle-matching, unrecognised errors of up to 500 years may occur.

2.7.2 Radiocarbon AMS wiggle-matched dating

The development of this technique has enabled much smaller fractions of the peat assemblage to be dated. Oldfield *et al.* (1997) note that AMS (Accelerator Mass Spectrometry) dating enables individual components of the macrofossil assemblage to be selected for dating. This helps to minimise problems of contamination and so avoids erroneous dates produced by either the 'reservoir effect' or the incorporation of modern ^{14}C. Furthermore, AMS dates can usually be determined quickly and typically require only 1-3 milligrams of carbon rather than the 5-10 grams required for conventional bulk dates.

Nilsson *et al.* (2001) investigated the variation in ^{14}C ages of macrofossils dated by AMS from raised mires in Sweden. Analysis of results showed that the average ^{14}C content of three living *Sphagnum* species representing the hummock, lawn and hollow bog microforms did not differ from each other or from the current ^{14}C content of the atmosphere. However, Jugner *et al.* (1995) found that 20% of the CO_2 assimilated by the hummock-growing species *Sphagnum fuscum* came from the decomposition of peat or peat litter. Jugner *et al.* nevertheless conclude that the CO_2 assimilated by the *Sphagnum* plants originated from the decomposition of relatively recent material, with a ^{14}C content that is broadly comparable to that of atmospheric CO_2. Therefore, results indicate that *Sphagnum* plants do not absorb 'old' $^{14}CO_2$ in sufficiently large quantities to produce a significant difference from atmospheric $^{14}CO_2$. These findings support the earlier research of Oldfield *et al.* (1997) and confirm the validity of using *Sphagnum* leaves in high-resolution AMS radiocarbon dating.

Recent studies have utilised wiggle-match dating as a means of improving the precision of AMS dates (see Speranza *et al.*, 2002; Mauquoy *et al.*, 2002; Blaauw *et al.*, 2003). This technique assumes that plants growing at the bog surface record the same variations in atmospheric ^{14}C recorded by trees in the dendrochronological calibration curve. It is therefore assumed that wiggles found in the dendrochronologically dated ^{14}C curve will also be evident in a series of ^{14}C peat deposits. Wiggle-match dating turns the non-linearity of the ^{14}C calibration curve in to an advantage.

Although assuming a perhaps overly simplistic linear accumulation rate, Blaauw *et al.* (2003) note that all other growth models have similarly built-in assumptions, many of which are more complex. Where stratigraphical changes within the peat core imply that this assumption is inaccurate then WMD sequences can be divided into subsets at the point of inferred change. Using this method also enables potential erroneous dates caused by the aforementioned 'reservoir effect' or by 'gaps' in the peat record to be identified. Blaauw *et al.* (2003) note that WMD (wiggle-match dating) is able to narrow down the confidence interval of dates significantly and the simple linear accumulation of a sequence over short intervals usually resulted in a highly satisfactory ^{14}C wiggle-match. This is particularly the case where dates occur within a period of major wiggles in the ^{14}C calibration curve. Therefore, provided that the suite of ^{14}C AMS dates falls within a period of 'wiggles' a 'best fit' scenario can be used, thereby improving the precision of dates.

Fluctuations in ^{14}C can also be used to provide a direct temporal link to variations in solar activity. Research has shown that reduced periods of solar activity have often been coincident with episodes of increased wetness as recorded on many ombrotrophic mires.

WMD can provide a secure and often precise chronology that can be calibrated into a series of calendrical dates. These can then be used to validate or corroborate the effects of solar forcing on known climate changes (see Mauquoy *et al.*, 2002).

2.7.2.1 Laboratory Procedures

Fifteen dates were allocated for each of the four cores. In accordance with the recommendations outlined in van Geel & Mook (1989) three groups of five 1 cm samples were taken from each core. In order to match each suite of AMS dates with separate Suess wiggles in the dendrochronological calibration curve, the time resolution of each sample should ideally represent no more than *c*.25 years (van Geel & Mook, 1989). Research in Finland by Korhola & Tolonen (1998) has established an average vertical growth rate *c*.0.5 mm/year. This is in agreement with the average growth rate of between *c*. 0.2 – 0.9 mm/year calculated for north-west European peat bogs by the earlier research of Aaby & Tauber (1975).

The depths at which samples were taken for AMS dating was determined by coeval changes in the humification and/or plant macrofossil data indicating a shift to either wetter or drier mire conditions. Dates where appropriate were spaced at *c*.4 cm intervals and typically covered a 20 cm section of the core.

Preparation of samples was carried out in accordance with the instructions contained in the NERC application forms. In brief, each sample was thoroughly washed using de-ionised water and where possible *Sphagnum* leaves, branches and stems were extracted for dating. Where *Sphagnum* was absent then *Dicranum scoparium* was substituted.

Samples containing >1 mg of carbon were oven dried overnight and then placed into glass vials, clearly labelled and sent to NERC Radiocarbon Laboratory, East Kilbride. Further chemical and/or physical pre-treatment of the samples was then undertaken before final ^{14}C analysis.

Chapter 3 Results

3.1 Introduction

This chapter is divided into two sections. The first of these provides a site-by-site proxy record and palaeohydrological interpretation of each of the datasets. Proxy data for each site are recorded and displayed as a TILIA plant macrofossil diagram. In order to improve the clarity of data and to enable intra-zone correlation between proxies more easily, the peat humification and testate amoebae results have been incorporated into the same diagram. The diagram has then been sub-divided into six zones (a-f) in order to facilitate interpretation of palaeohydrological conditions on the mire. The position of each zone was based on shifts in the humification data and where possible coeval changes in the macrofossil record. Humification data rather than macrofossil data were chosen as the primary palaeohydrological proxy owing to the lack of literature and research concerning climatically driven changes in plant macrofossils in Finland and Estonia. Furthermore, research in the Baltic region has generally supported the theory of 'autogenic succession' within the bog plant community and little support is evident for climatically driven changes in mire plant communities (e.g. Korhola, 1995; Seppä, 2002).

The second section provides a chronological framework within which the proxy datasets can be investigated. For each of the sites calibration of radiocarbon determinations has been undertaken. Additionally, where possible, wiggle-match dating has also been carried out in order to improve the precision of each suite of dates.

3.2 Munasuo – Core (MUN)

3.2.1 Site Description - Munasuo (MUN)

Situated in southeast Finland (60°34'N, 26°40'E), Munasuo is generally regarded as a prime example of a plateau raised bog (Tolonen, 1986). The mire is positioned in a broad, basin-like depression and has a maximum length of approximately 3.8 km and width of *c.*2.2 km and in the central plateau the peat extends to a depth of over 6 metres (Korhola, 1992).

Munasuo is included in the Finnish mire conservation programme. Since the mid-twentieth century a considerable amount of research has been carried out on the mire, including investigating shoreline displacement (Hyyppä, 1937), mire vegetation and stratigraphy (Tolonen, 1968, 1977, 1979; Seppä, 1991) and mire induction and ecosystem dynamics (Korhola, 1992). Clymo (1984) also used the mire as one of the reference sites when developing his hydrodynamic model.

The mire has a distinctive microtopography with wet hollows and low hummocks (See plate 3.1). Typically, the plant composition of the hollows includes *Rynchospora alba, Carex limosa* and *Scheuchzeria palustris*. *Sphagnum* species usually occupy hollows and include *S.majus, S.tenellum, S. lindbergii, S. riparium* and *S. cuspidatum* (Daniels & Eddy, 1990; Korhola, 1992). Hummock vegetation includes *Calluna vulgaris, Andromeda polifolia, Eriophorum vaginatum* and *Sphagnum fuscum*.

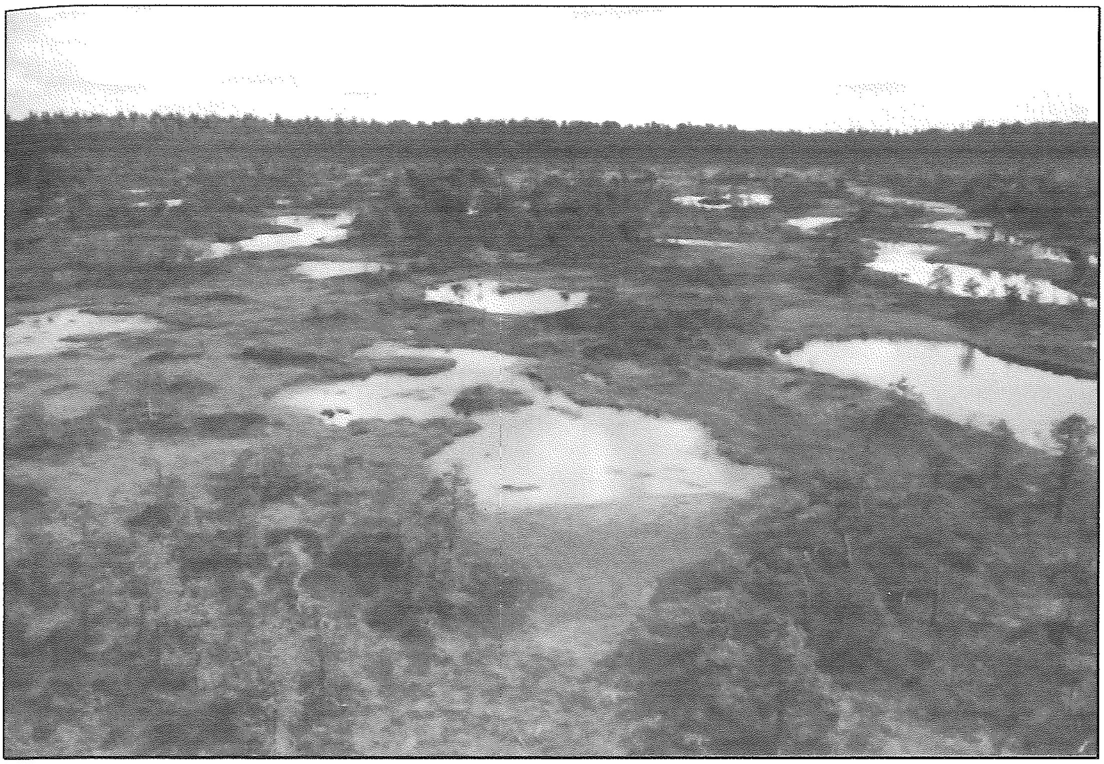


Plate 3.1 The distinctive hummock/hollow microtopography typical of Munasuo.

Plate 3.2 Typical lawn macrofossil mosaic comprising several *Sphagnum* species, *Vaccinium oxycoccus* and *Andromeda polifolia*.

3.2.2 Proxy Data Results – Munasuo – Core MUN.

Proxy data for Munasuo are shown in Figure 3.1. The diagram is divided into six zones (a-f), based on changes in the humification transmission data and where possible coincident changes in the mire plant assemblage composition.

Zone MUN - a (180 – 143 cm)

Peat Humification Data: This phase is characterised by fluctuating transmission values. Three inferred 'wet shifts' are recorded during this period. The first of these occurs at the base of the zone between 180 - 174 cm and is followed by a gradual and low magnitude decline in values. The data imply a second sustained but gradual shift to wetter mire conditions succeeded by a rapid return to drier hydrological conditions at *c.*153 cm. The final period of elevated water tables occurs at *c.*148 cm and is once again followed by a return to drier conditions at the transition with zone-b. In general the humification data for this zone imply oscillating hydrological conditions. It is notable that whilst transmission values vary they are still relatively low, typically ranging between 45 – 55%.

Plant Macrofossil Data: *Sphagnum* comprises the major peat component throughout this zone. However, at the base of the core between 180 – 175 cm *Eriophorum vaginatum* values increase sharply whilst Monocots undiff and *Calluna* are also present implying drier mire conditions. *Sphagnum fuscum*, a species typical of hummocks, comprises greater than 90% of the identifiable *Sphagnum* confirming evidence for lower water tables. Following this stage *Eriophorum vaginatum* is effectively replaced by *Dicranum scoparium*. Monocots undiff. and roots are again present whilst *Calluna* attains its highest value at the initiation of this phase. Increases in UOM (Unidentified Organic Matter) provide supporting evidence of drier conditions. *Sphagnum fuscum* is once again the dominant *Sphagnum* species with values typically between 80-95%. The remainder of zone-a is characterised by high proportions of Identifiable *Sphagnum* of which *S. fuscum* remains dominant. However, at *c.*165 cm *Sphagnum riparium*, a species normally associated with wetter conditions, comprises *c.*20% of the *Sphagnum* component. *Vaccinium oxycoccus* is also present although additional 'wet indicator' species are absent at this point.

Testate Amoebae Data: These data provide supporting evidence of fluctuating hydrological conditions during this zone. *Amphitrema flavum* is the dominant species throughout this phase although the relative abundance of this taxon does vary quite markedly. The base of zone-a is characterised by *A. flavum,* a hydrophilous species typically found in the wetter parts of hummocks (Corbet, 1973). However, values decrease and are replaced by increasing proportions of *Assulina muscorum,* which is often referred to as a hydro-xerophilous species occupying a mid-range position in relation to the water table. Following this period, values of *A. flavum* fluctuate, whilst *A. muscorum* values appear to remain relatively stable for the remainder of this zone. It is notable that *Trigonopyxis arcula*, a xerophilous species, is recorded at 163 cm.

Zone MUN – b (142 – 118 cm)

Peat Humification Data: Transmission values fall sharply throughout this zone implying a shift to drier mire conditions. Values fall to their lowest point within the core, typically between 30 – 40%, and are sustained throughout the zone.

Plant Macrofossil Data: The initial phase of this zone is characterised by a rapid rise in *Vaccinium oxycoccus*. Notably, this is also coeval with a small but sustained presence of *Scheuchzeria palustris* implying raised water tables. However, this episode appears to be very short-lived with UOM, *Calluna* roots, wood, Dicot leaves and an increase in *Dicranum scoparium* suggesting a return to drier mire conditions. High values of *Dicranum scoparium* are maintained throughout the remainder of this zone and a concurrent drop in *Sphagnum* is recorded with values typically falling to between 40 – 60% of the macrofossil assemblage. Whilst overall values of *Sphagnum* fall, *S. fuscum* remains the dominant taxon and represents in excess of 85% of the total identifiable *Sphagnum* leaf count.

Testate Amoebae Data: The testate amoebae data for this zone confirm drier mire conditions. Recorded values of *Amphitrema flavum* fall to their lowest level throughout the core during this zone. Conversely this is the only point in the profile where *Trigonopyxis arcula* is consistently recorded at relatively high levels. *Assulina muscorum* is also recorded throughout this zone implying a lower water table position.

Zone MUN – c (117 – 84 cm)

Peat Humification Data: Transmission values once again fluctuate quite markedly during this period. The start of the zone records a gradual rise in transmission values implying a shift to wetter conditions. However, values then decrease marginally before reaching *c*.70% at a depth of 94 cm. After this, values remain relatively stable for the remainder of the zone. In general the humification data for this zone imply a shift to wetter conditions relative to the preceding zone.

Plant Macrofossil Data: *Sphagnum* values rise sharply at the commencement of this zone. In conjunction with *Vaccinium oxycoccus* these taxa comprise the bulk of the peat assemblage. Five peaks in *Eriophorum vaginatum* are evident during this phase that may also indicate drier conditions. This is supported by a sustained presence of *Calluna* with high values broadly coeval with increases in *E. vaginatum*. Additional 'dry indicator' species including wood, Dicot leaves and small quantities of Ericales also suggest lower water tables. Roots and Monocots undiff. are represented throughout this zone and arguably when found in association with other 'dry indicators' reinforce the case for drier mire conditions. However, at *c.*98 cm *Sphagnum riparium*, a species typically associated with low lawn or pool conditions, briefly attains ascendancy with recorded values approaching 70% of the identifiable *Sphagnum* leaf count. Slightly higher up the core at *c.*94 cm *Scheuchzeria palustris* is evident in trace amounts implying wetter conditions. Nevertheless, an absence of additional 'wet indicator' species and the very low values of *Scheuchzeria* implies that this may have been a very short-lived and/or low magnitude change. *Sphagnum fuscum* remains the dominant species for the majority of this zone, with the exception of the short-lived incursion by *S. riparium*. In general the macrofossil assemblage for this zone implies a raised-lawn to low-hummock microenvironment.

Testate Amoebae Data: This zone is characterised by high levels of *Amphitrema flavum* indicating a return to wetter conditions. Small quantities of *Amphitrema wrightianum*, a particularly good hydrophilous indicator, also support this view.

Zone MUN – d (83 – 63 cm)

Peat Humification Data: This zone is characterised by an increase in transmission values implying elevated water tables. A sustained episode of high values is recorded for much of the zone with a short-lived and low-magnitude decline in values just before the transition with zone-e. In general the humification data for this zone imply stable conditions with elevated water tables.

Plant Macrofossil Data: The peat components within this zone appear to be relatively stable. However, this zone is marked by a rapid change in *Sphagnum* species. *S. fuscum* values fall to their lowest point throughout the core and a corresponding rise in *S. magellanicum* is recorded. Increases in *S. riparium*, *S. lindbergii* and particularly *S. cuspidatum* also imply elevated water tables. However, with the exception of the change in *Sphagnum* species the remainder of the macrofossil assemblage does not record an increase in 'wet indicator' species. Trace amounts of *Scheuchzeria palustris* are evident and *Vaccinium oxycoccus* is also present throughout the zone. Otherwise, roots, wood and *Sphagnum* stems make up the bulk of the remaining peat components. *Eriophorum vaginatum* is recorded at *c*.73 cm although additional 'dry indicator' species are absent and it is therefore unlikely that this represents a significant drier phase. However, just prior to the start of zone-e, *Sphagnum magellanicum* is replaced by *Sphagnum fuscum*, supporting the peat humification data in suggesting a shift to drier conditions. Nevertheless, the dominance of *S. magellanicum* and presence of *S. cuspidatum*, *S. lindbergii* and *S. riparium* indicate that this zone may be classified as a 'wet shift' and indicative of a low-lawn or shallow-pool microenvironment.

Testate Amoebae Data: Sustained and relatively high values of *Amphitrema wrightianum* support the macrofossil data in indicating that this zone is characterised by elevated water tables. *Amphitrema flavum* is the dominant taxon with values typically between 40-60%.

Zone MUN – e (62 – 38 cm)

Peat Humification Data: Transmission values fall at the start of this zone implying a shift to drier mire conditions. Values remain relatively stable throughout this period although a marked decline in values is evident at *c.*60 cm indicating lowered water tables. Towards the transition with zone-f, values increase suggesting a return to wetter mire conditions.

Plant Macrofossil Data: At the start of this zone *S. magellanicum* is again replaced by *S. fuscum* indicating a shift to drier conditions. This is also supported by an increase in *Eriophorum vaginatum* and the presence of *Calluna* rootlets. Roots and Monocots undiff. are also recorded throughout this zone. Approximately mid-way in this zone at *c.*48-49 cm a small increase in UOM is broadly coeval with an increase in recorded values of wood and Monocots undiff., possibly reflecting drier mire conditions. *Vaccinium oxycoccus* is again well represented throughout this zone and smaller values of *Andromeda polifolia* are also recorded. *Scheuchzeria palustris* is recorded sporadically and in small quantities during this phase although additional 'wet indicator' species are again absent. The bulk of identifiable *Sphagnum* comprises *S. fuscum,* but towards the top of the zone *S. angustifolium* values rise quite sharply.

Testate Amoebae Data: *Amphitrema flavum* is once again the dominant species during this zone. However, values of *A. wrightianum* decrease and are replaced by higher values of *Assulina muscorum*. This implies that this zone may be marginally drier than the preceding zone-d.

Zone MUN – f (37 – 0 cm)

Peat Humification Data: Although transmission values fluctuate during this zone, they remain relatively high implying raised water tables. Fluctuations are also relatively small, typically within the range of 10 – 12%, indicating relatively stable hydrological conditions for this zone.

Plant Macrofossil Data: *Sphagnum* again forms the major component of the peat matrix at the start of this zone. *Vaccinium oxycoccus* and Monocots undiff. comprise the bulk of the remaining peat matrix. *Eriophorum vaginatum* is also present and a peak in values is recorded at *c.*25 cm in conjunction with a sustained but small rise in the values of *Calluna*. Relatively small but sustained quantities of UOM, wood, Dicot leaves and *Andromeda polifolia* are also recorded at this stage implying drier mire conditions. However, from *c.*15 cm towards the top of the core a small presence of *Equisetum* and *Scheuchzeria palustris* implies a shift to wetter conditions. This is supported by sustained and relatively high levels of *Vaccinium oxycoccus,* and perhaps more significantly *Sphagnum cuspidatum* attains its highest recorded value, accounting for greater than 20% of the identifiable *Sphagnum* leaf count.

Testate Amoebae Data: The data for this zone support the macrofossil data indicating fluctuating hydrological conditions on the mire. *Amphitrema flavum* is dominant particularly towards the base of this zone. *A. wrightianum* is also recorded at the base of the zone in small quantities. *Assulina muscorum* is present throughout the zone although in relatively small proportions. It is notable that towards the top of the profile the testate amoebae and plant macrofossil record differ in their palaeohydrological indications. Whilst both *A. flavum* and *A. wrightianum* values decrease rapidly the *Sphagnum* data record the 'wet indicator' species *S. cuspidatum* as being present at this time. This may simply represent a 'time-lag' between the responsiveness of plant macrofossils and testate amoebae or possibly a low-magnitude and/or short-lived change that the plant assemblage was able to withstand.

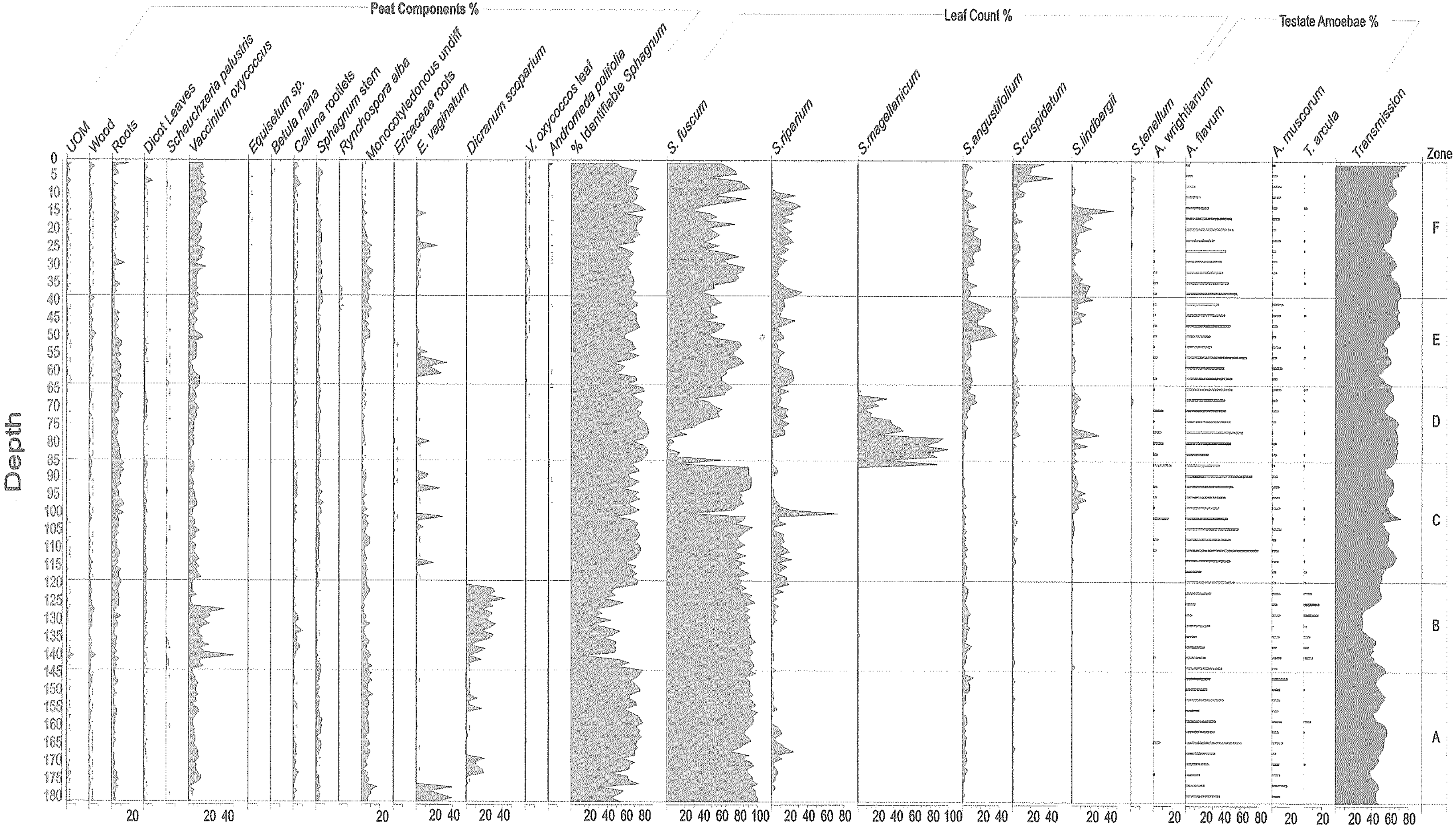


Figure 3.1 Macrofossil diagram for Munasuo

3.3 Reksuo – Core (REK)

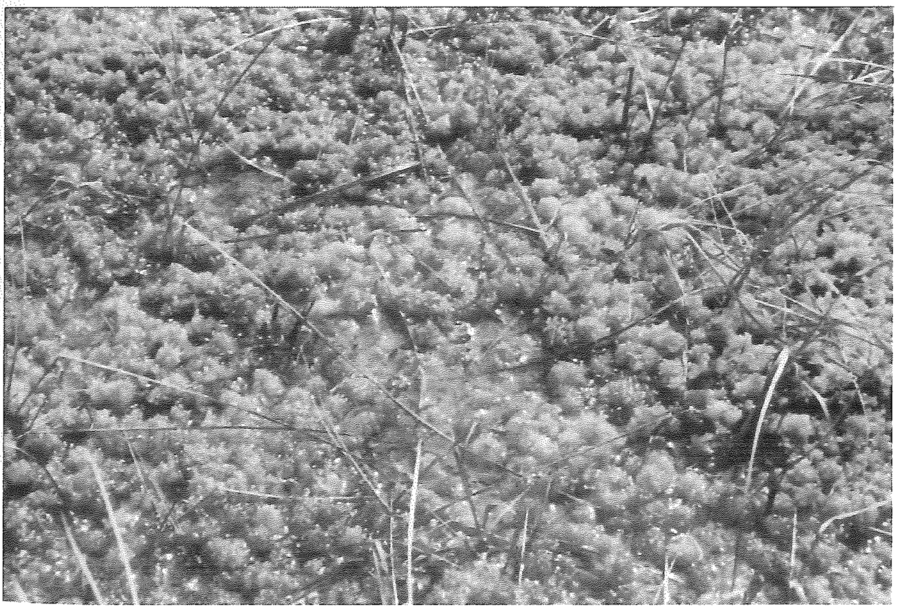
3.3.1 Reksuo Site Description

Reksuo is situated in between the Paimionjoki and Uskelanjoki river systems in southwest Finland (60°30'N,23°16'E). It is approximately 577 ha in area and is a good example of a raised bog, with its central plateau rising nearly 4 metres above the margins (Korhola, 1992). The mire itself is situated in a more or less symmetrical, NE-SW-oriented basin with a maximum length of 3.8 km and width of 2.4 km.

Paludification of mineral soils in a topographical depression towards the centre of the present-day mire is thought to have initiated mire development. A series of basal peat dates obtained by Korhola (1992) suggests that this process commenced at around 7880 BP or possibly slightly earlier. Previous research by Kujala (1924) describes the formation and development of mires from 'relict pools'. These pools are located in small depressions and only intermittently fill with water. Korhola (1992) suggests that Reksuo may be a good example of a mire that has been formed and developed in this way. Research on Reksuo has focussed primarily on the relationship between the assimilation and emissions of carbon and CH_4 from boreal mires (e.g. Crill *et al.*, 1992; Tolonen *et al.*, 1994; Korhola *et al.*, 1995; Korhola *et al.*, 1996). Research into mire initiation, lateral expansion rates and ecosystem dynamics has also been pursued (Korhola, 1992).

Several studies have examined the plant ecology of Reksuo (e.g. Ruuhijarvi, 1983; Korhola, 1992). The hollow vegetation of the central plateau includes *Scheuchzeria palustris, Rynchospora alba, Carex limosa* and *Sphagnum* species including *S. majus, S.*

cuspidatum, S.lindbergii, S. riparium and *S. tenellum*. According to Korhola (1992) hummocks are dominated by *Pinus sylvestris, Calluna vulgaris* and *Empetrum nigrum* with *S. fuscum* being the dominant *Sphagnum* species.



Plates 3.3 & 3.4

Sphagnum growing along the pool margins at Reksuo.

3.3.2 Proxy Data Results Reksuo – Core REK

Zone REK – a (180 – 163 cm)

Peat Humification Data: Transmission values rise sharply at the start of this zone indicating a shift to wetter mire conditions. Peak values of *c.*60% are attained towards the middle of the zone before declining gradually towards the transition with zone-b.

Plant Macrofossil Data: The start of this zone is characterised by a rise in 'dry indicator' species. Marked increases in *Dicranum scoparium, Eriophorum vaginatum,* UOM and Monocots undiff. coincide with a decline in *Sphagnum* values. Additional dry indicators including wood, Dicot leaves and roots are also recorded at this point. However, this episode appears to be short-lived and *Sphagnum* values increase at *c.*174 cm and form approximately 80% of the peat components for the remainder of the zone. A switch to wetter conditions is also supported by the presence of both *Scheuchzeria palustris* and *Rynchospora alba* between 175 – 173 cm. Increases in *Vaccinium oxycoccus, Andromeda polifolia* and *Sphagnum* stems also imply elevated water tables. *Sphagnum fuscum* is the principal species at the start of the zone and regains dominance towards the transition with zone-b. However, in between it is effectively replaced by 'wet indicators', primarily *S. riparium* with smaller quantities of *S. cuspidatum, S. lindbergii* and *S. tenellum.*

Testate Amoebae Data:

Testate amoebae are absent at this point in the profile.

Zone REK – b (162 – 133 cm)

Peat Humification Data: This zone is characterised by low transmission values indicating a shift to drier mire conditions. Relatively stable hydrological conditions are implied by these data with transmission values typically ranging between 35 – 45%.

Plant Macrofossil Data: This zone is characterised by a marked increase in 'dry indicator' species. *Sphagnum* values drop and a corresponding increase in *E. vaginatum, Calluna,* Monocots undiff. and Dicot leaves is recorded. A major change in the macrofossil assemblage is recorded at 138 cm when *Sphagnum* is effectively replaced by *Dicranum scoparium.* The sustained presence of 'dry indicator' species throughout this zone implies a period of relatively stable hydrological conditions with lowered water tables. This is also supported by the *Sphagnum* data. Where present, *S. fuscum* is the dominant taxon, often accounting for more than 90% of the total leaf count and indicating drier mire conditions.

Testate Amoebae Data: The data for this zone are equivocal. An absence of testate amoebae is noted at the start of the zone and it is not until 147 cm that these organisms are recorded in the peat profile. However, following this period similar quantities of *Assulina muscorum* and *Amphitrema flavum* are recorded for the remainder of the zone. Again, smaller but fluctuating quantities of *A. wrightianum* and *Trigonopyxis arcula* are also recorded. The ambiguity of these data complicates any strictly hydrological interpretation of the testate amoebae data for this zone.

Zone REK – c (132 – 111 cm)

Peat Humification Data: Transmission values during this period fluctuate markedly. Two peaks are recorded with values in excess of 60% implying a shift to wetter conditions. However, these are interrupted by a decline in values between *c.* 131–122 cm indicating a short-lived shift to drier mire conditions.

Plant Macrofossil Data: The start of this zone is characterised by a sharp increase in *Sphagnum* values. However, markedly fluctuating values of 'wet' and 'dry' indicator species within the peat components and also in the *Sphagnum* leaf count imply rapid changes and instability in the hydrological regime of the mire. Initially, a small peak in *E. vaginatum* and *Dicranum scoparium* is recorded with very small quantities of *Calluna* indicating drier conditions. In contrast the *Sphagnum* leaf count data record an increase in *S. riparium* at the expense of *S. fuscum* implying wetter mire conditions. This initial episode appears to be short-lived as a sharp rise in *Dicranum scoparium* is mirrored by a decline in *Sphagnum* values. A small peak in *E. vaginatum* is also recorded and most notably *S. riparium* is replaced by *S. magellanicum* as the principal *Sphagnum* species. Nevertheless, this episode is again relatively short-lived and *Sphagnum* values increase with *S. riparium* regaining dominance. Notably, at 119 cm a rapid and high-magnitude rise in *Eriophorum angustifolium* and *Rynchospora alba* imply elevated water tables. An increase in *Vaccinium oxycoccus* also supports these data.

Testate Amoebae Data: These data imply elevated water tables during this zone. High values of the hydrophilous taxa, *A. wrightianum* and *A. flavum* are recorded. Whilst *Assulina muscorum* is present throughout the zone, the shift to drier conditions identified in the other proxy data is not recorded by the testate amoebae data

Zone REK – d (110 – 68 cm)

Peat Humification Data: The start of this zone records a gradual decline in transmission values implying a shift to drier conditions. This episode is relatively short-lived and values increase and are sustained until 77 cm when they decline again before the transition with zone-e. In general, hydrological conditions appear to be relatively stable during this period. Wetter conditions are recorded for the bulk of the zone with two drier phases at the start and end of this period.

Plant Macrofossil Data: The start of this zone is characterised by a sharp and sustained increase in *E. vaginatum* values. A less pronounced increase in Monocots undiff. and roots is also recorded, whilst a corresponding decline in *Sphagnum* values is evident. Drier mire conditions are also implied by the dominance of *S. fuscum*. However, at *c.*103 cm *S. fuscum* is replaced by *S. riparium* although additional 'wet indicator' species are absent. This episode is relatively short-lived and *S. fuscum* regains dominance and apart from a peak in *S. magellanicum* at 93 cm remains the principal *Sphagnum* species for the remainder of the zone.

Testate Amoebae Data: These data imply a period of relatively stable hydrological conditions for this zone. *A. flavum* is the dominant taxon throughout this zone and recorded values remain fairly constant. Smaller quantities of *A. muscorum* are present, whilst minute amounts of *A. wrightianum* and *T. arcula* are recorded sporadically during this period.

Zone REK – e (67 – 47 cm)

Peat Humification Data: Transmission values remain stable during this zone, typically ranging between 55 – 65%. Slightly higher values than the previous zone imply marginally wetter hydrological conditions.

Plant Macrofossil Data: Whilst *Sphagnum fuscum* remains the dominant species, an increase in *S. angustifolium* and *S. riparium* is also evident. Two peaks in *E. vaginatum* are evident at the beginning of the zone in conjunction with small quantities of *Calluna*. A low but sustained presence of *Dicranum scoparium* is also recorded throughout much of the zone. The macrofossil record for this zone is representative of a lawn microform.

Testate Amoebae Data: These data are again rather ambiguous. High levels of *A. flavum* are sustained throughout the zone, whilst smaller quantities of *A. wrightianum* are also recorded intermittently. Two peaks in *A. muscorum* are evident at 56 and 63 cm although no additional 'dry indicator' taxa are recorded.

Zone REK – f (46 – 0)

Peat Humification Data: High transmission values are sustained throughout this zone, typically ranging between 60 – 70%. A nominal and very gradual decline is apparent towards the middle of the zone; however, in general stable but relatively wet conditions are inferred from these data.

Plant Macrofossil Data: The most prominent change in this zone is the replacement of *S. fuscum* by *S. magellanicum*. At the start of the zone a small peak in *Dicranum scoparium* is recorded, although additional 'dry indicator' taxa are absent. A sustained presence of roots and Monocots undiff. is recorded during the early stages of this zone. However, values for both taxa diminish towards the surface. In contrast values of *V. oxycoccus* increase markedly towards the surface. A peak in *E. vaginatum* is evident at *c.*15 cm and following this is a sustained peak in *Carex*. The macrofossil data for this zone are ambiguous with both 'wet' and 'dry' indicator species occurring together. The dominance of *S. magellanicum* may imply slightly wetter conditions than the previous zone, as this species is known to inhabit a 'low lawn' microenvironment in Baltic mires.

Testate Amoebae Data: These data are again equivocal. Low values of all the 'indicator species' are recorded during this zone. Initially *A. flavum* is the principal species, but mid-way through the zone, values diminish and are replaced by small but varying quantities of *A. muscorum* and *T. arcula*.

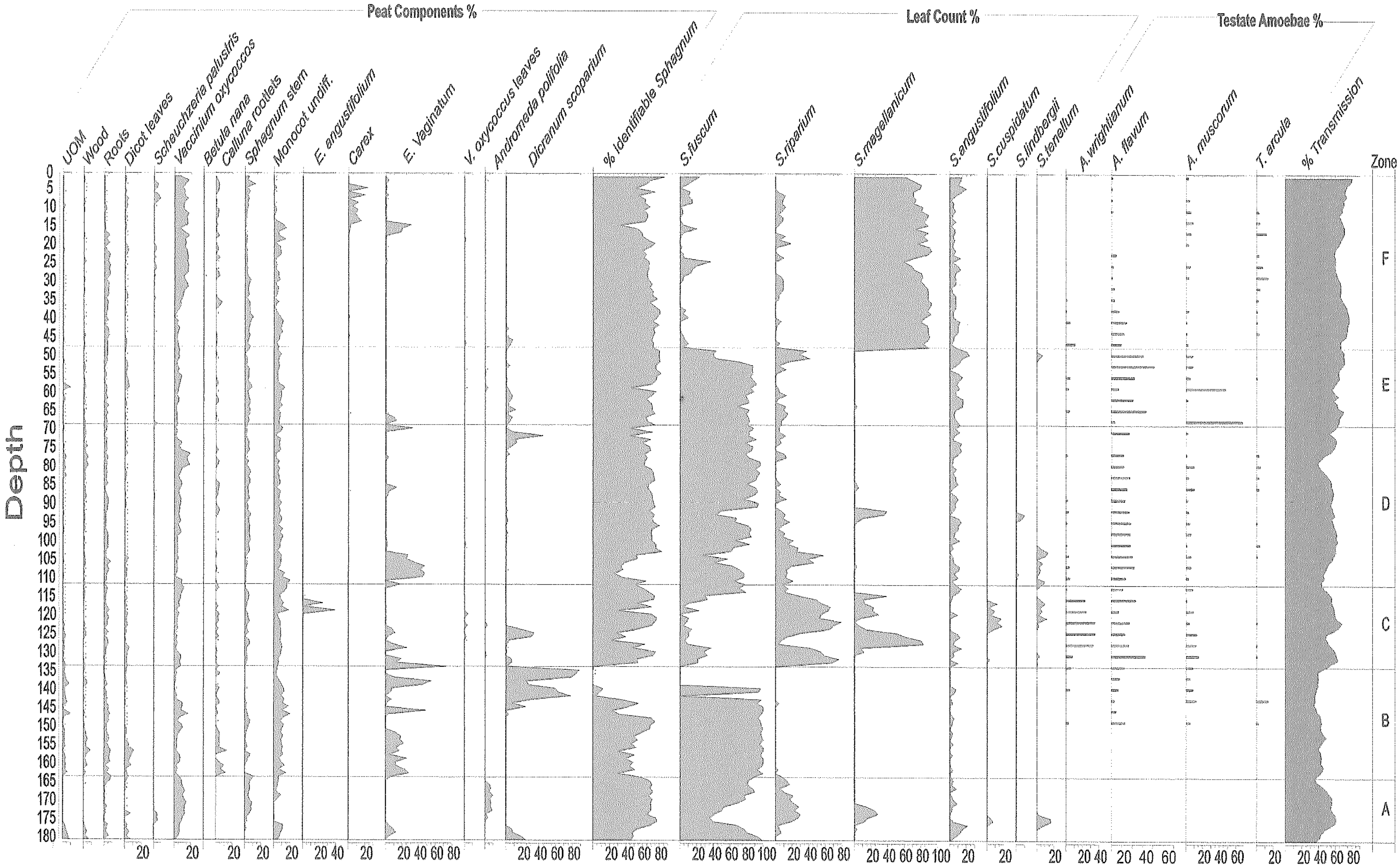


Figure 3.2 Macrofossil diagram Reksuo

3.4 Männikjärve – Core (MANN)

3.4.1 Männikjärve Site Description

Männikjärve bog is situated within the Endla Nature Reserve (see plate 3.5) located immediately south of the Pandivere Upland in east-central Estonia (N58°52', E16°15'). The Endla mire complex developed in the basin of the former Great Endla Lake, and the central part of the system contains seven raised bogs separated by narrow rivers and fens (Aaviksoo *et al.*, 1997; Kimmel, 2001). Peat formation started approximately 9000 years ago through the process of terrestrialization of Great Endla Lake and the paludification of the surrounding mineral soils (Kimmel, 2001).

Männikjärve is an ombrotrophic bog covering an area of approximately 178 ha (Masing, 1982a) and has a maximum peat depth of 7.5 m (Karofeld, 1998). Whilst the central area of the mire is intact and in a relatively natural state, some of the mire margins have been subject to drainage. Notably, in 1914 drainage ditches were dug along the NE edge of the mire and during 1963-64 these were deepened. However, since this period the ditches have become overgrown by *Sphagnum* and their influence on the bog water table has diminished (Kimmel, 2001).

Estonia can be divided into seven type regions based on geology, geomorphology and vegetation (Berglund *et al.*, 1996). The Endla mire system falls within the E-e type region (Peipsi and Vôrtsjärv Lowlands), characterised by extensive mires and forests and a moderately continental climate (Berglund *et al.*, 1996). The bogs are typical of the east-Estonian type with a convex form and systems of pools, hollows and long narrow *Sphagnum* hummocks that run parallel to the contours (Kimmel, 2001).

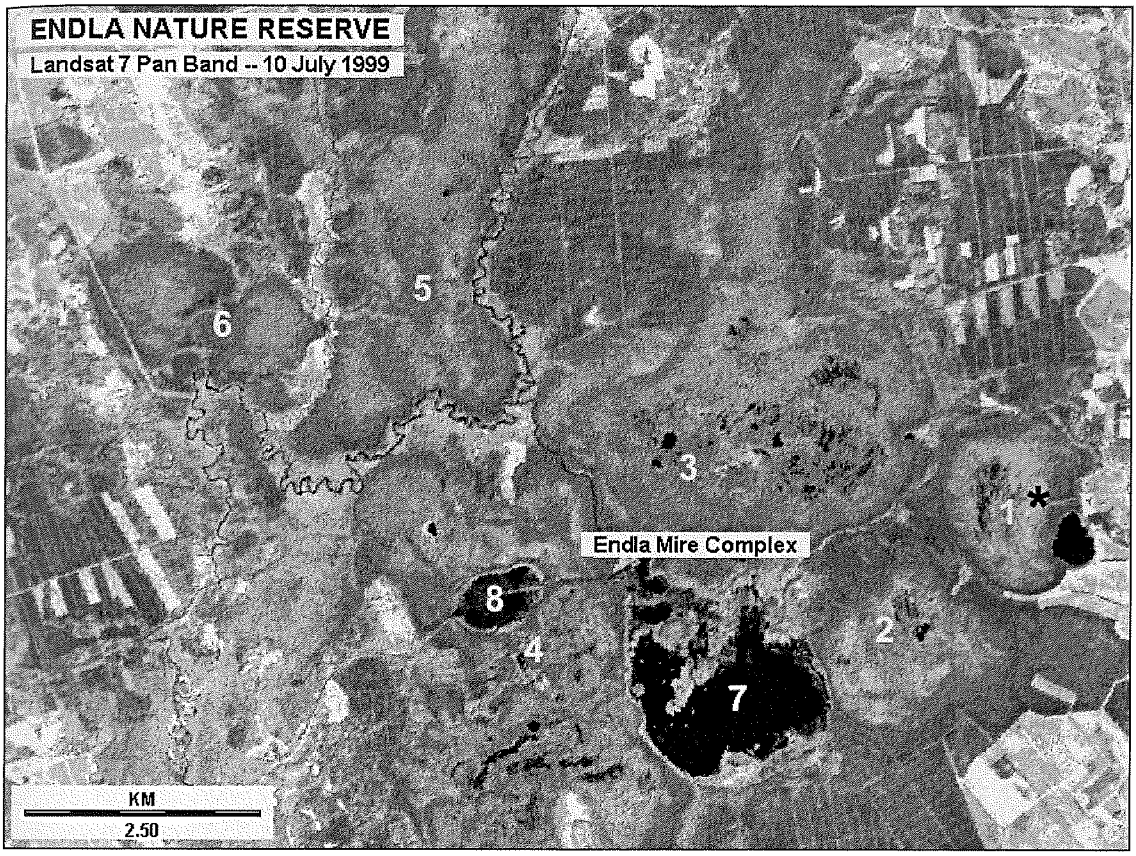


Plate 3.5 **Aber (1999)**

Landsat b/w image based on ETM+ pan band, 15 m resolution, 10 July 1999. Mires within the Endla Nature Reserve are numbered 1 – 8. 1 = Männikjärve bog, 2 = Kaasikjärve bog, 3 = Linnusaare bog, 4 = Endla bog, 5 = Kanamatsi bog, 6 = Rummallika bog, 7 = Endla Lake, 8 = Sinijärv (blue lake).

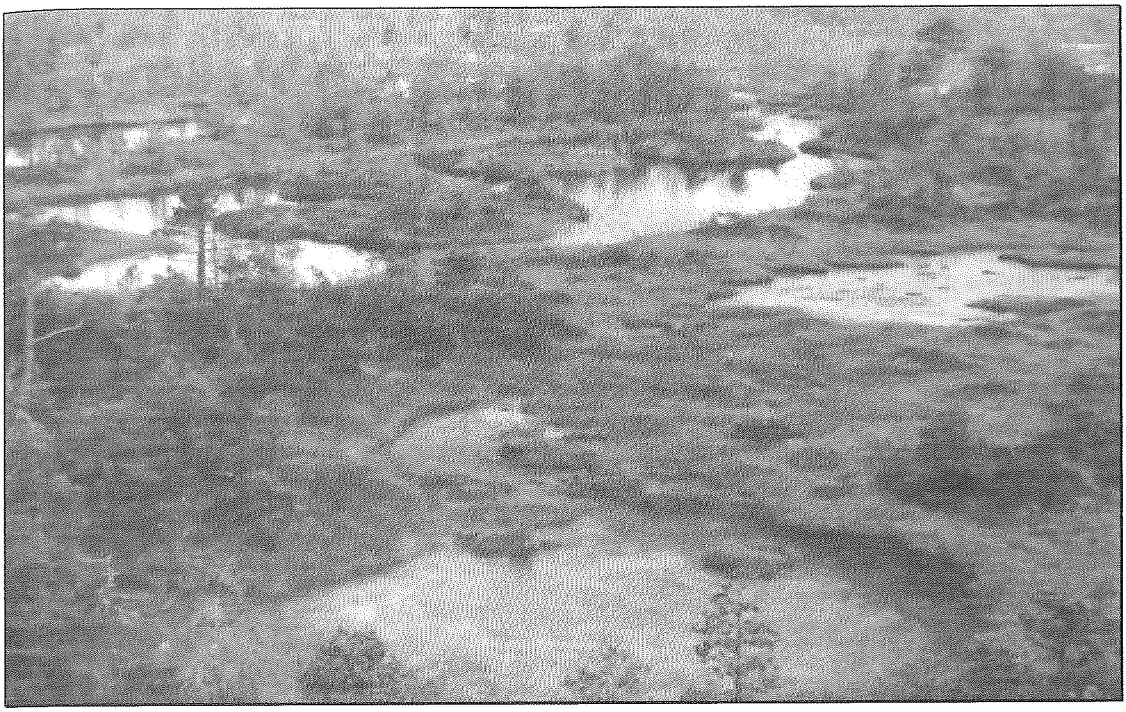


Plate 3.6 The view across Männikjärve bog showing hummock, lawn and pool microtopography

3.4 .2 Proxy Data Results Männikjärve — Core MANN

Proxy data for Männikjärve – Core MANN are shown in Figure (3.3). The diagram is divided into six zones (a-f), based on changes in the humification data and where possible coeval changes in the macrofossil assemblage.

Zone MANN – a (180 – 163 cm)

Peat Humification Data: Relatively stable conditions are implied by the humification data for this zone. Transmission values record limited variability and range between 45 – 60% implying generally wet mire conditions.

Plant Macrofossil Data: The base of this zone is characterised by high levels of *Sphagnum* of which *S. fuscum* is the dominant species with values in excess of 90% of the total leaf count. At between 175 – 172 cm, *Sphagnum* values decline and are replaced by a sharp rise in UOM (Unidentified Organic Matter) with simultaneous increases in wood, Dicot leaves, Monocots undiff. and a rapid rise in *Eriophorum vaginatum*. *Calluna* is also present in increasing amounts towards the top of this zone implying drier conditions. Additional peat components recorded in significant quantities during this phase include *Sphagnum* stems and *Vaccinium oxycoccus*.

Testate Amoebae Data: The data for this zone are ambiguous. *Amphitrema flavum* comprises the dominant species throughout the zone, whereas *A. wrightianum* is absent during this phase. *Assulina muscorum* values are relatively low although the highest values recorded coincide with a presence of *Trigonopyxis arcula* thereby implying much drier conditions. In general, the proxy data for this zone suggest relatively dry conditions possibly indicative of a high-lawn or low-hummock microenvironment.

Zone MANN – b (162 – 139 cm)

Peat Humification Data: According to the humification data, this zone represents a period of elevated water tables. Transmission data show a marked increase from the preceding zone and record values of 70 – 80%. However, an absence of testate amoebae and the macrofossil data indicate that this is a period of drier mire conditions. It is possible that owing to the high proportions of *Eriophorum vaginatum* in this zone, spurious humification data have been generated as was speculated for Mongan Bog in Ireland, for episodes of *E. vaginatum* dominance (Chambers, pers com).

Plant Macrofossil Data: The start of this zone is marked by a rapid and substantial decline in *Sphagnum*. UOM comprises the principal peat component whilst root material and varying amounts of *Eriophorum vaginatum* comprise the other major macrofossil taxa. Dicot leaves, wood and Monocots undiff. are also recorded in varying quantities during this zone. Additional macrofossil remains include *Calluna,* which is present towards the top of the zone, and *Vaccinium oxycoccus,* which is recorded sporadically and in relatively small quantities. This zone represents the driest phase within the Männikjärve profile.

Testate Amoebae Data: The absence of testate amoebae during this zone also supports the claim for significantly lowered water tables and a drying out of the mire surface.

Zone MANN – c (138 – 117 cm)

Peat Humification Data: Transmission data record a sharp and sustained fall in values during this zone. A shift to drier mire conditions is implied with transmission values recording minimal variability ranging between 35 – 45%.

Plant Macrofossil Data: The macrofossil record for this zone implies highly fluctuating hydrological conditions. The start of this zone is characterised by two large and rapid peaks in identifiable *Sphagnum*. However, these peaks are interrupted by a short-lived return to drier conditions as denoted by a steep rise in UOM and increasing proportions of roots, *Calluna* and Monocots undiff. *Vaccinium oxycoccus* is present throughout the zone, often comprising greater than 10% of the peat matrix. Two further peaks in UOM are identifiable and these can be correlated with increases in *Eriophorum vaginatum*. Additional increases in Monocots undiff. and *Calluna* may also indicate a shift to drier conditions. Proportions of identifiable *Sphagnum* continue to fluctuate, and where sharp increases in UOM and *Eriophorum vaginatum* occur this is reflected by an absence or rapid decline of *Sphagnum*. Nevertheless, where *Sphagnum* is recorded during this zone, it is again the hummock-forming species, *S. fuscum* that is dominant, accounting for between 60 – 80% of the *Sphagnum* leaf count.

Testate Amoebae Data: The data for this zone are again ambiguous. *Amphitrema wrightianum* is present in small quantities and can be correlated with small amounts of *Sphagnum tenellum*, a species indicative of wetter conditions. However, both taxa are recorded in relatively tiny amounts and it is therefore unlikely that they imply any significant shift to wetter conditions. *A. flavum* is the dominant species within this zone, although recorded values remain relatively low. Small quantities of *Assulina muscorum* and *Trigonopyxis arcula* are also present intermittently during this period.

Zone MANN – d (116 – 46 cm)

Peat Humification Data: Transmission data for much of this zone remains stable. However, several short-lived low magnitude episodes are apparent within the data. Transmission values typically range between 50 – 60% and again display limited variability. An exception to this is at *c.*68 cm when values fall rapidly to 30% implying a marked shift to drier conditions. Nevertheless, values then increase gradually and remain stable until zone-e.

Plant Macrofossil Data: This zone comprises a large part of the Männikjärve profile. The start of this phase records high values of identifiable *Sphagnum* of which *S. fuscum* is again dominant. *Vaccinium oxycoccus* is well represented and comprises between 10 – 20% of the peat matrix during the initial stage of the zone. Smaller quantities of roots and Monocots undiff. are present, whilst *Calluna* is consistently recorded until *c.*98 cm, after which point values become sporadic. Subsequently, *Eriophorum vaginatum* values increase and two peaks are recorded between *c.*88 – 93 cm accounting for nearly 20% of the peat components at its maximum. Values of Monocots undiff. also show a corresponding increase during this part of zone-d. Towards the top of this zone *Eriophorum vaginatum* again records two pronounced peaks, the larger of which accounts for between 40 – 50% of the macrofossil assemblage. Monocots undiff., wood and Dicot leaves also increase with a corresponding drop in identifiable *Sphagnum,* providing corroborative evidence of a shift to marginally drier conditions.

Throughout this zone *Sphagnum fuscum* remains the dominant species often comprising more than 80% of the identifiable *Sphagnum* leaf count. Smaller quantities of *S. angustifolium* and *S. tenellum* are also recorded intermittently during this period.

Testate Amoebae Data: *Amphitrema flavum* is the principal testate amoebae species throughout this zone. *A. wrightianum* is recorded sporadically and in small quantities. Similarly, *Assulina muscorum* values fluctuate at relatively low levels during this period. The exception to this is between 65 – 68 cm, when values increase fairly sharply and are coincident with very small quantities of *Trigonopyxis arcula* and a drop in *A. flavum* values. In general, the proxy data for this zone imply relatively stable conditions with a slight shift to marginally drier conditions towards the top of the zone.

Zone MANN – e (45 – 28 cm)

Peat Humification Data: This zone is characterised by a sustained period of high transmission values implying a shift to wetter mire conditions. Values record a step-wise increase during the majority of the zone and peak at *c.*80% before dipping slightly at the transition with zone-f.

Plant Macrofossil Data: This zone characterised by a return to high levels of identifiable *Sphagnum*. Notably, during this zone *S. fuscum* is effectively replaced by *S. magellanicum* with values fluctuating between *c.*40 – 80%. *S. angustifolium* is also present although in much smaller amounts. *Vaccinium oxycoccus* and *Sphagnum* stem are the two other main peat components recorded during this phase.

Testate Amoebae Data: Data for this zone support the macrofossil evidence and imply a shift to wetter conditions. *Amphitrema flavum* comprises the principal species and *A. wrigtianum* is also present confirming elevated water tables.

Zone MANN – f (27 – 0 cm)

Peat Humification Data: Transmission data record minimal variability and imply a period of stable hydrological condition during this zone. Values typically range around 68% implying a sustained episode of elevated water tables.

Plant Macrofossil Data: *Sphagnum* values again fluctuate during this zone. *S. magellanicum* is replaced by *S. riparium* at the beginning of this period. Succeeding this, *S. fuscum* again attains ascendancy although this is relatively short-lived. Towards the mire surface *S. riparium*, *S. magellanicum* and *S. balticum* comprise the principal *Sphagna* species. *Vaccinium oxycoccus* is again present during this zone whilst Monocots undiff., roots and *Sphagnum* stems are also recorded in small quantities. Two peaks in *Eriophorum vaginatum* are also evident at *c.*17 and 8 cm.

Testate Amoebae Data: These data imply relatively wet conditions. *Amphitrema flavum* is again dominant, whilst *A. wrightianum* is recorded sporadically and in small quantities. *Assulina muscorum* is also present in small amounts during this phase.

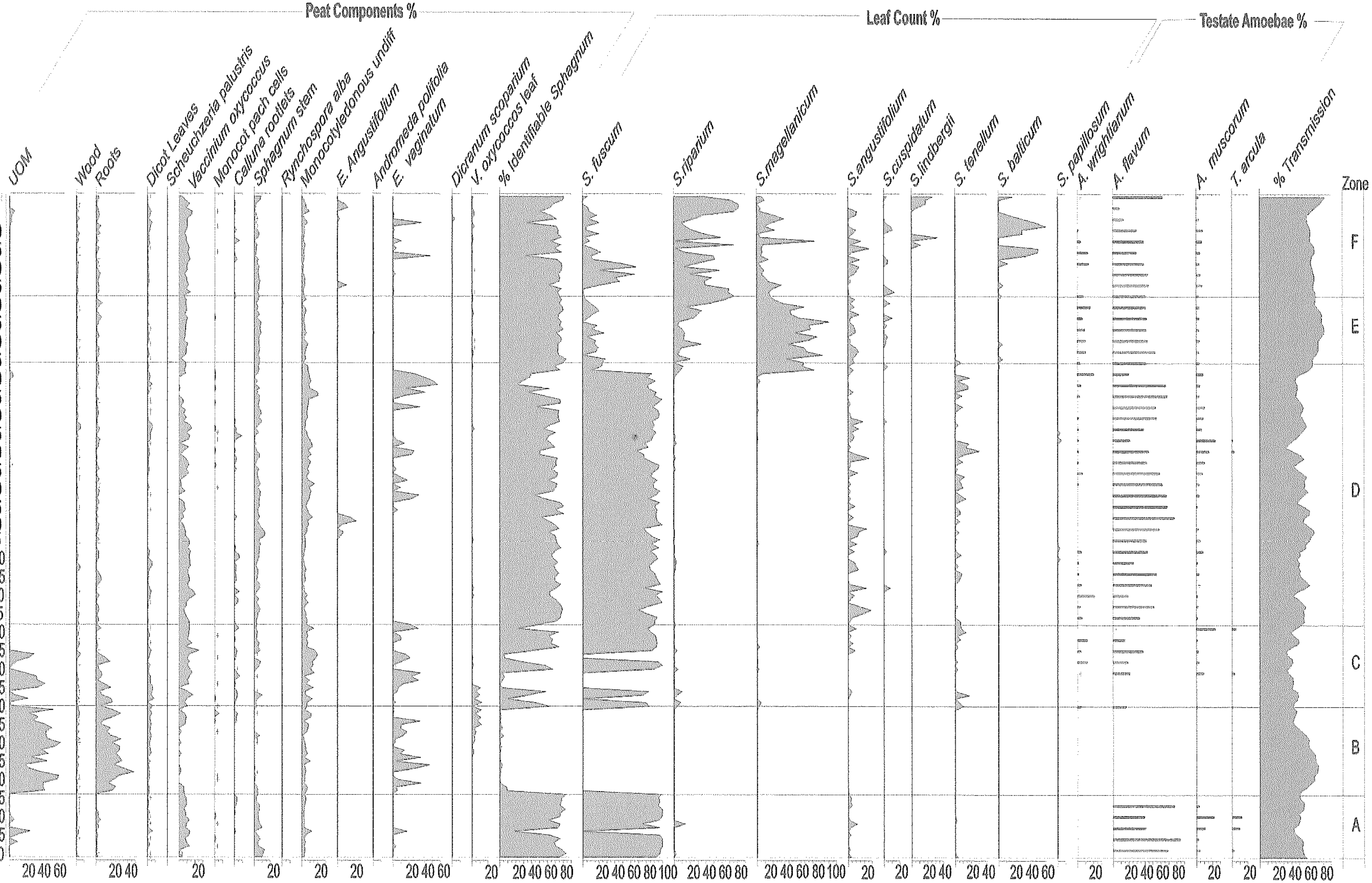


Figure 3.3 Macrofossil diagram for Männikjärve

3.5 Kuistlemma – Core (KUIS)

3.5.1 Site description

Kuistlemma bog is situated in west Estonia (Latitude 59.0077778: Longitude 24.1438889) and comprises an area of approximately 3735 hectares. The bulk of this area, circa 2251 ha. comprises peat bog, whilst the remaining 1484 ha is fen. Mire initiation started as the paludification of sandy-clay, and the maximum peat depth at the centre of the mire is *c*.7.2 metres. The bog is typical of the West-Estonian type and apart from general reconnaissance no detailed research has been conducted on this site prior to the present research project.

3.5.2 Proxy Data Results - Kuistlemma – Core KUIS

Zone KUIS – a (180 – 160 cm)

Peat Humification Data: Transmission data for this zone imply fluctuating hydrological conditions. Initially, values increase from *c.*65% up to a peak of 72% towards the middle of the zone. After this, a gradual and low magnitude shift to drier conditions is implied by declining values, falling to *c.*50% at the transition with zone-b.

Plant Macrofossil Data: *Sphagnum* is the principal peat component throughout this zone. Relatively high values of *Vaccinium oxycoccus*, Monocots undiff. and *Sphagnum* stems are also recorded during this period. UOM, wood, roots, Dicot leaves and *Calluna vulgaris* are present in smaller quantities and are recorded intermittently during this period. A peak in *Eriophorum vaginatum* is evident at *c.*173-174 cm, which is reflected by a fall in *Sphagnum* values. Throughout the zone *S. fuscum* remains the dominant species, typically accounting for greater than 70% of the identifiable leaf count. A smaller but sustained presence of *S. angustifolium* is also recorded, whilst a peak in *S. tenellum* is evident at 163 cm.

Testate Amoebae Data: The data for this zone imply relatively wet conditions. At the base of the zone *Amphitrema flavum* dominates and small quantities of *A. wrightianum* also indicate raised water tables. A sharp decline in *A. flavum* values is evident at *c.*173-174 cm and corresponds with a rise in *Assulina muscorum* and *Trigonopyxis arcula*. This also correlates with the aforementioned peak in *E. vaginatum* and provides supporting evidence of a short-lived episode of drier mire conditions. For the remainder of the zone testate amoebae data are rather ambiguous with values of *A.flavum* and *A. muscorum* fluctuating quite markedly.

Zone KUIS – b (159 – 118 cm)

Peat Humification Data: Transmission data rise sharply during the early stages of this zone. Values reach *c.*75% implying elevated water tables. Following this episode, a short-lived decline in values is recorded before the commencement of a sustained period of relatively high transmission data. At 126 cm values decline to *c.*55% just before the start of zone-c.

Plant Macrofossil Data: Mire conditions appear to be relatively stable during this zone. *Sphagnum* is again the principal peat component. Small quantities of UOM, wood, roots and Dicot leaves are also recorded. Marginally higher values of *Vaccinium oxycoccus*, *Sphagnum* stems and Monocots undiff. are sustained during this zone than during the preceding period. Sporadic and minor amounts of *Calluna* are also present. *S. fuscum* is once again the dominant *Sphagnum* species with a smaller but sustained presence of *S. angustifolium*. A small peak in *S.cuspidatum* implying wetter conditions is coeval with a presence of *Scheuchzeria palustris* at *c.*135 cm, although this is very short-lived and is unlikely to reflect major hydrological change. At the top of this zone *Sphagnum* values fall dramatically and are replaced by a coincident rise in UOM, Dicot leaves and Monocots undiff.

Testate Amoebae Data: The data for this zone are ambiguous. Initially, *Amphitrema flavum* values are relatively low, whilst increases in *Trigonopyxis arcula* imply drier conditions. However, at *c.*153 cm *A. flavum* values increase sharply indicating a 'wet shift'. This episode appears to be short-lived as at *c.*142 cm values again drop and a concurrent increase in *Assulina muscorum* and *T. arcula* imply a return to drier mire conditions. The remainder of the zone is characterised by high levels of *A. flavum* with values reaching 70% at their maximum point.

Zone KUIS – c (117 – 94 cm)

Peat Humification Data: Transmission data for this zone imply a period of hydrological instability with markedly fluctuating water tables. Initially, values are relatively high but this episode is short-lived and the data imply a brief shift to drier conditions before relatively high values are again recorded towards the middle of the zone. Following this period, a sustained shift to drier mire conditions is indicated by sharply declining transmission values that are constant for the remainder of the zone.

Plant Macrofossil Data: *Sphagnum* values increase sharply at the start of this zone and comprise the bulk of the macrofossil assemblage. *Vaccinium oxycoccus* values also increase and comprise the second most abundant taxon during this period. Smaller and sporadic quantities of UOM, wood, roots, Dicot leaves and *Calluna* are also recorded. A small peak in *Scheuchzeria palustris* is present at 112 cm although additional 'wet indicator' species are absent. *Sphagnum fuscum* is again dominant with a small but sustained presence of *S. angustifolium*.

Testate Amoebae Data: The data for this zone appear paradoxical. Relatively stable but wet conditions are implied by sustained and high values of *Amphitrema flavum*. However, a smaller but constant presence of *Trigonopyxis arcula* indicates drier conditions for much of this zone.

Zone KUIS – d (93 – 70 cm)

Peat Humification Data: Transmission data for this zone indicate a shift to wet mire conditions. Initially the transmission data rise sharply, reaching *c.*70%. A slight decline is then recorded before values once again increase markedly reaching 80%, the maximum recorded value throughout the profile. However, at the transition with zone-e, transmission values start to decline indicating a return to drier mire conditions.

Plant Macrofossil Data: This zone is characterised by high proportions of identifiable *Sphagnum*. Monocots undiff. and *Sphagnum* stems comprise the two other major peat-forming components. *Vaccinium oxycoccus* records sustained but relatively low values during this zone. Four peaks in *Eriophorum vaginatum* are recorded although values are relatively low and additional 'dry indicator' species are absent. Whilst *S. fuscum* remains the principal taxon it is notable that *S. angustifolium, S. lindbergii* and *S. cuspidatum* increase during this zone implying raised water tables.

Testate Amoebae Data: These data support the shift to wetter conditions indicated by the *Sphagnum* data. *Amphitrema flavum* is the dominant species with high values maintained throughout this zone. Small amounts of *Assulina muscorum* are also present whilst minute quantities of *T. arcula* are recorded intermittently.

Zone KUIS – e (69 – 31 cm)

Peat Humification Data: This zone is characterised by low transmission values implying a prolonged period of drier mire conditions. However, whilst values do fluctuate during this zone, they remain low, typically between 30 – 45%.

Plant Macrofossil Data: This zone records marked fluctuations in the macrofossil diagram. The start is characterised by high levels of identifiable *Sphagnum*. However, a sharp but short-lived decrease in *Sphagnum* values is recorded, coincident with a rise in 'dry indicator' species including UOM, Monocots undiff. and *Calluna*. Following this episode, *Sphagnum* again attains dominance and remains the principal peat component until *c.*51 cm. At this point a rapid decline in *Sphagnum* is mirrored by a pronounced increase in *Eriophorum vaginatum* and Monocots undiff. Smaller increases in UOM, roots and wood are also evident during this phase. For the remainder of the zone *Sphagnum* values continue to fluctuate quite markedly with corresponding changes in UOM, Monocots undiff., roots and *Eriophorum vaginatum*. *Sphagnum fuscum* is again dominant throughout this zone and where *Sphagnum* is present then *S. fuscum* comprises *c.*90% of the identifiable leaf count.

Testate Amoebae Data: These data record relatively high levels of *Amphitrema flavum* during the early stages of this zone. However, from *c.*58 cm testate amoebae are absent apart from a single recording at 47 cm. It may be significant that 'dry indicator' species are absent for much of this zone. This may imply either a rapid and significant drop in water table position or possibly a marked change in the surface ecology of the mire.

Zone KUIS – f (30 – 0)

Peat Humification Data: Transmission values rise sharply at the base of this zone reaching *c.*70%. Elevated water tables are indicated throughout this period with transmission values increasing marginally towards the surface.

Plant Macrofossil Data: The initial stage of this zone records falling levels of UOM and a coincident rise in identifiable *Sphagnum*. *Vaccinium oxycoccus* values also increase gradually towards the surface. Several peaks in *Eriophorum vaginatum* are recorded although additional 'dry indicator' species are absent. Most notable in this zone is the replacement of *S. fuscum* by *S. magellanicum*; a small increase in *S. tenellum* implies a shift to wetter mire conditions.

Testate Amoebae Data: These data also provide supporting evidence of elevated water tables compared to the previous zone. *Amphitrema flavum* is again the principal species and is recorded throughout this zone although in relatively low amounts. *Assulina muscorum* is also present. Proxy data for this zone are typical of a lawn/pool margin bog microform.

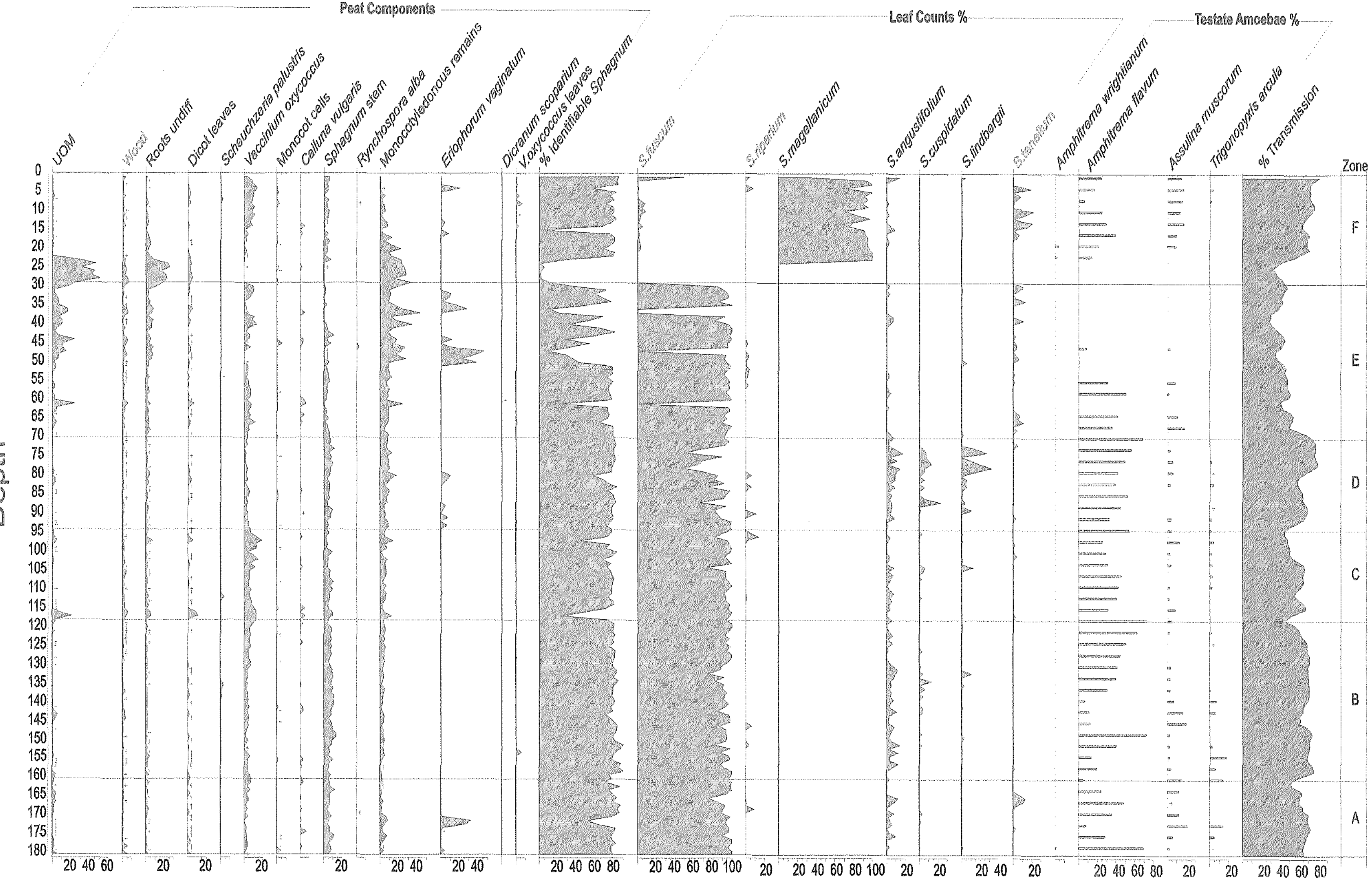


Figure 3.4 Macrofossil diagram for Kuistlema

3.6 Chronology

3.6.1 Radiocarbon Chronology

For this project 15 AMS ^{14}C dates were obtained for each site. From each site, 3 groups of 5 closely spaced samples (*c*.3 cm) were chosen from specific locations along the peat core. The position of these samples was based on major fluctuations in the peat humification record and where possible coincident changes in both the plant macrofossil and testate amoebae datasets. Therefore, where possible, three groups each containing five equally spaced dated horizons have been applied to Munasuo, Reksuo, Männikjärve and Kuistlemma.

In order to produce a series of calendar dates, each raw ^{14}C date was calibrated using Oxcal version 3.9 (Bronk & Ramsey, 2003) that incorporates the Intcal98 calibration programme (Stuiver *et al.* 1998). However, several problems can occur when transforming ^{14}C dates into 'real' calendar dates. Firstly, ^{14}C age has a non-linear relationship with calendar age. Secondly, owing to the irregular shape of the ^{14}C calibration curve, individual dates may be imprecise with wide error ranges (van der Plicht & Mook, 1987). This problem is particularly pronounced when individual ^{14}C dates fall either within 'wiggles' on the calibration curve or alternatively during a period when the slope of the ^{14}C slope is almost flat (plateaux). When ^{14}C dates fall within these sections of the calibration curve a wide range of probable calendar ages is produced (Blaauw *et al.* 2003).

Palaeoecological studies have often used the mid-point of the two dates that encompass the 95.4% confidence limits (2-sigma error range) to produce a single calendar date for each sample. However, recent research has demonstrated that greater accuracy and precision may be achieved by using a suite of ^{14}C wiggle-matched dates (Blaauw *et al.* 2003). This technique utilises the irregular shape of the calibration curve to enable a suite of stratigraphically consecutive samples to be matched against 'wiggles' in the dendrochronological calibration curve. In other words, this procedure narrows the probability range in calendar dates and a 'best fit' scenario can be applied to each suite of dates.

For this project, the radiocarbon dates have been wiggle-matched using the newly developed Bpeat program (Blaauw & Christen, in press). This program is based on Bayesian statistics and uses a series of pre-determined palaeoecological based assumptions and then combines these data with the ^{14}C data to produce an age/depth curve.

The program has a number of built in assumptions. Firstly, that the radiocarbon dates are in chronological order and therefore samples towards the top of the core are younger than those below it. Secondly, that there has been a linear accumulation rate, at least between the top and bottom section of the core being dated. Whilst acknowledging that this assumption is not always valid, particularly for the entire core, Blaauw & Christen suggest that a piece-wise linear accumulation model is both statistically simple and generally produces good results. Thirdly, the model also allows for the possibility that there may have been a hiatus in peat accumulation. Finally, the program assumes that whilst the majority of radiocarbon dates are accurate, statistically there will be some dates that are outliers.

Using the Bpeat program, an age/depth profile has been generated for each site based on the above parameters. It is clear from the results that whilst an acceptable 'best fit' and subsequent age/depth profile have been produced, the program has also made several assumptions that appear to be incorrect. This is exemplified in the numerical data generated by Bpeat, which appears to suggest several gaps in the record, particularly where the chronology has been interpolated between the actual dated horizons. A more detailed discussion is provided on a site-by-site basis in the following sections. As a precaution, an alternative interpolated chronology has been generated assuming a constant linnear accumulation rate between dated horizons. In order to do this, the actual dates generated by Bpeat and based on the calibrated radiocarbon dates have been accepted as correct and then a constant linear accumulation rate has been applied between these dated sections. As a result, the age/depth interpolated profile has been smoothed and the spurious hiatus generated by Bpeat have been removed. These data are shown next to the Bpeat data and a comparative age/depth curve has also been generated.

3.6.1.1 Munasuo – Core MUN – Calibration

Calibrated ^{14}C dates are presented below in Table 3.1. Each date has a 2-sigma age range and a mid-point value. (Dates are expressed as Cal. AD).

Table 3.1 Munasuo calibrated ^{14}C dates

Date N°	Depth (cm)	Radiocarbon age BP (incl. 1σ error)	2σ calibrated range 95.4% conf. level (cal. AD)	Mid-point of 2σ range (cal. AD)
1	46-47	196 +/- 26	1730 – 1810	1770
2	50-51	113 +/- 62	1660 – 1960	1810
3	53-54	136 +/- 26	1670 – 1780	1725
4	56-57	142 +/- 28	1670 – 1780	1725
5	59-60	110 +/- 28	1800 – 1960	1880*
6	132-133	823 +/- 31	1160 – 1280	1220
7	136-137	856 +/- 26	1150 – 1260	1205
8	138-139	869 +/- 62	1030 – 1270	1150
9	141-142	882 +/- 58	1020 – 1260	1140
10	145-146	970 +/- 33	1000 – 1160	1080
11	158-159	965 +/- 26	1010 – 1160	1085
12	161-162	1083 +/- 28	890 – 1020	955
13	164-165	1141 +/- 29	780 – 990	885
14	167-168	1199 +/- 26	770 – 900	835
15	171-172	805 +/- 24	1190 – 1280	1235*

***Date appears to be anomolous**

Figures 3.5 and 3.6 overleaf show the age/depth profile generated by Bpeat and the 'best-fit' scenario for the wiggle-matched dates as positioned on the Intcal 04 calibration curve. Using the model generated by Bpeat, average accumulation rates within the dated horizons vary between 0.18 mm yr^{-1} towards the top of the core, slowing to 0.13 mm yr^{-1} in the mid-section before returning to 0.18 mm yr^{-1} at the base of the core.

However, it is clear that when the dates have been interpolated between wiggle-matched horizons Bpeat appears to have artificially generated several hiatus in the peat record in order to produce an

acceptable 'best-fit'. This is highlighted in both the table below which shows the numerical data generated by Bpeat and also figure 3.5 that displays two alternative age/depth profiles. According to the Bpeat model there is a gap in the record indicated by a difference in age of 58 yrs between contiguous samples at 91.5 and 92.5 cm. Analysis of the datasets however does not support the claim for a gap in the peat record. A similar or though relatively smaller hiatus is indicated by Bpeat between 148.5 and 149.5 cm. According to the program there is an age difference of 27 years between contiguous samples. It is, in the author's opinion, unlikely that these represent actual gaps or hiatus in the peat record, and rather, that in order to produce an acceptable 'best-fit' the Bpeat program simply inserts these gaps where it is programmed to do so.

However, owing to the inaccuracies and relative imprecision of the original radiocarbon dates it is difficult to be certain whether these problems are a result of possible inadequacies of the Bpeat program or as a consequence of the inverted radiocarbon dates or as is most likely, a combination of the two factors.

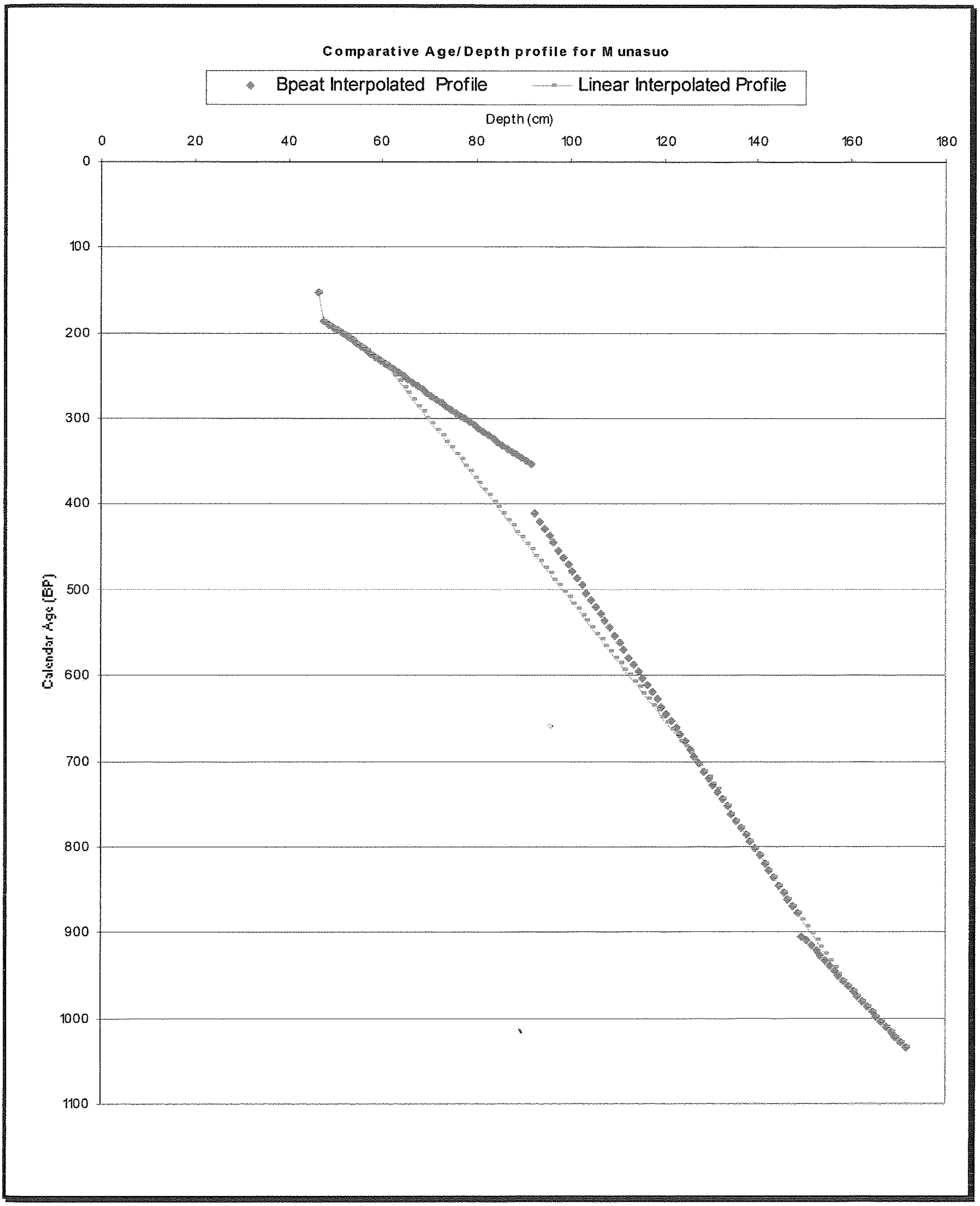


Figure 3.5 Age/depth profiles for Munasuo

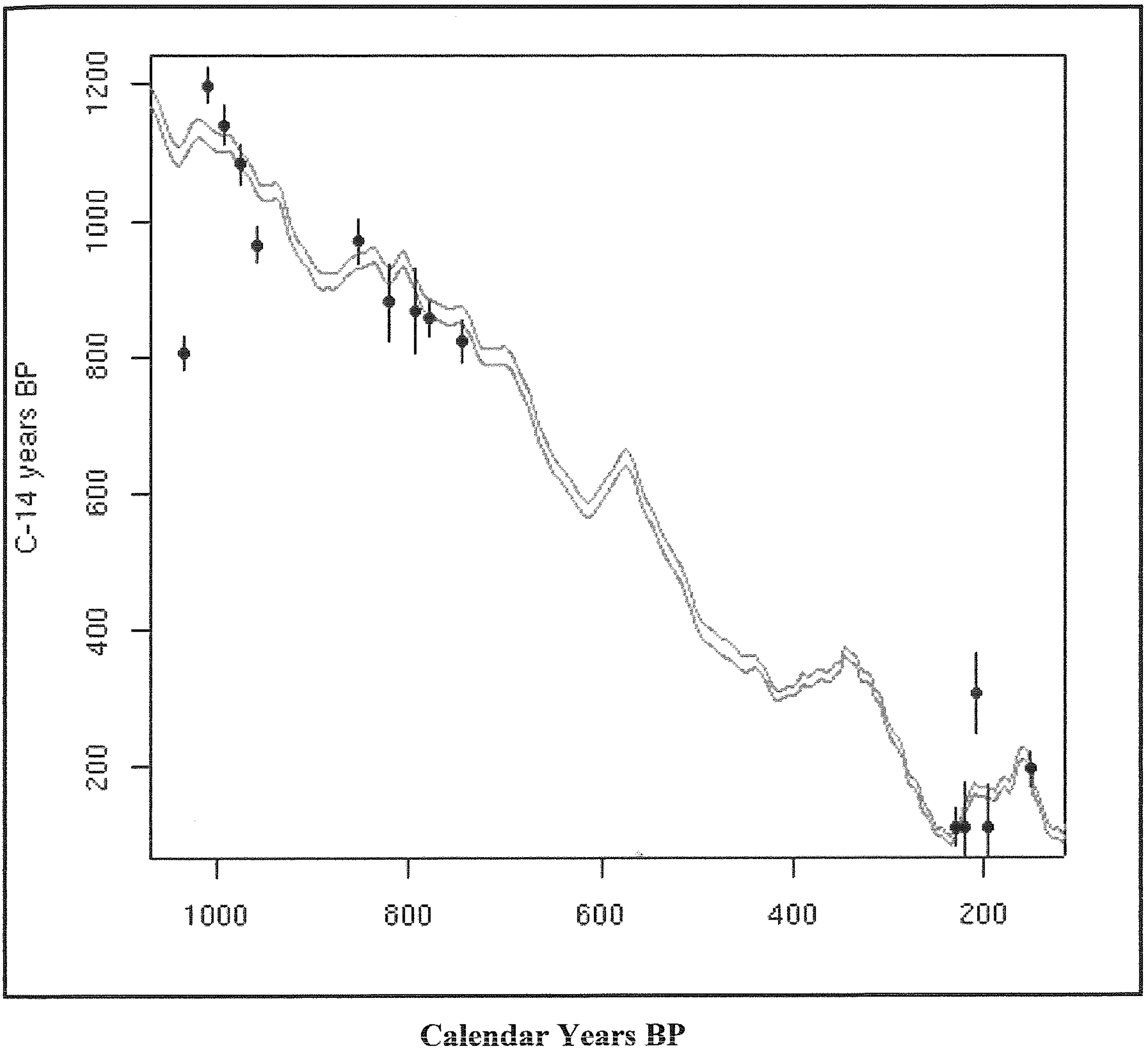


Figure 3.6 Best fit results for Munasuo

The table below details the numerical data generated by the Bpeat wiggle-match age/depth program. Hiatuses as indicated by the Bpeat program have been highlighted. An alternative age/depth profile is also presented assuming a constant accumulation rate between wiggle-matched horizons. Actual dated sections of the core are in bold whilst interpolated dates are italicized.

Table 3.2 Age/depth data for Munasuo

Depth (cm)	**Wiggle-matched Calendar Age (BP)**	**Alternative Age (BP)**
46.5	**153**	**153**
47.5	**186**	**186**
48.5	**190**	**190**
49.5	**194**	**194**
50.5	**197**	**197**
51.5	**201**	**201**
52.5	**205**	**205**
53.5	**209**	**209**
54.5	**213**	**213**
55.5	**216**	**216**
56.5	**220**	**220**
57.5	**224**	**224**
58.5	**228**	**228**
59.5	**232**	**232**
60.5	**236**	**236**
61.5	*239*	*243*
62.5	*243*	*250*
63.5	*247*	*257*
64.5	*251*	*264*
65.5	*255*	*271*
66.5	*258*	*278*
67.5	*262*	*285*
68.5	*266*	*292*
69.5	*270*	*299*
70.5	*274*	*306*
71.5	*278*	*313*
72.5	*281*	*320*
73.5	*285*	*327*
74.5	*289*	*334*
75.5	*293*	*341*
76.5	*297*	*348*
77.5	*300*	*355*
78.5	*304*	*362*
79.5	*308*	*369*
80.5	*312*	*376*

81.5	*316*	*383*
82.5	*319*	*390*
83.5	*323*	*397*
84.5	*327*	*404*
85.5	*331*	*411*
86.5	*335*	*418*
87.5	*339*	*425*
88.5	*342*	*432*
89.5	*346*	*439*
90.5	*350*	*446*
91.5	*354*	*453*
92.5	*412*	*460*
93.5	*420*	*467*
94.5	*429*	*474*
95.5	*437*	*481*
96.5	*445*	*488*
97.5	*454*	*495*
98.5	*462*	*502*
99.5	*470*	*509*
100.5	*479*	*516*
101.5	*487*	*523*
102.5	*495*	*530*
103.5	*504*	*537*
104.5	*512*	*544*
105.5	*520*	*551*
106.5	*529*	*558*
107.5	*537*	*565*
108.5	*545*	*572*
109.5	*554*	*579*
110.5	*562*	*586*
111.5	*570*	*593*
112.5	*579*	*600*
113.5	*587*	*607*
114.5	*595*	*614*
115.5	*603*	*621*
116.5	*612*	*628*
117.5	*620*	*635*
118.5	*628*	*642*
119.5	*637*	*649*
120.5	*645*	*656*
121.5	*653*	*663*
122.5	*662*	*670*
123.5	*670*	*677*
124.5	*678*	*684*
125.5	*687*	*691*
126.5	*695*	*698*

127.5	*703*	*705*
128.5	*712*	*712*
129.5	*720*	*719*
130.5	*728*	*726*
131.5	*737*	*733*
132.5	**745**	**745**
133.5	**753**	**753**
134.5	**762**	**762**
135.5	**770**	**770**
136.5	**778**	**778**
137.5	**787**	**787**
138.5	**795**	**795**
139.5	**803**	**803**
140.5	**811**	**811**
141.5	**820**	**820**
142.5	**828**	**828**
143.5	**836**	**836**
144.5	**845**	**845**
145.5	**853**	**853**
146.5	**861**	**861**
147.5	*870*	*870*
148.5	*878*	*878*
149.5	*905*	*886*
150.5	*910*	*894*
151.5	*916*	*902*
152.5	*922*	*910*
153.5	*928*	*918*
154.5	*934*	*926*
155.5	*940*	*934*
156.5	*946*	*942*
157.5	*952*	*950*
158.5	**957**	**957**
159.5	**963**	**963**
160.5	**969**	**969**
161.5	**975**	**975**
162.5	**981**	**981**
163.5	**987**	**987**
164.5	**993**	**993**
165.5	**999**	**999**
166.5	**1004**	**1004**
167.5	**1010**	**1010**
168.5	**1016**	**1016**
169.5	**1022**	**1022**
170.5	**1028**	**1028**
171.5	**1034**	**1034**

3.6.1.2 Reksuo – Core REK - Calibration

Calibrated ^{14}C dates are presented below in Table 3.3. Each date has a 2-sigma age range and a mid-point value. (Dates are expressed as Cal. AD).

Table 3.3 Reksuo calibrated ^{14}C dates.

Date N°	Depth (cm)	Radiocarbon age BP (incl. 1σ error)	2σ calibrated range 95.4% conf. level	Mid-point of 2σ range
1	71-72	696 +/- 42	1240 – 1330	1285
2	74-75	796 +/- 27	1210 – 1285	1247.5
3	76-77	821 +/-23	1160 – 1280	1220
4	81-82	672 +/-26	1340 – 1400	1370
5	83-84	823 +/- 24	1160 – 1280	1220
6	132-133	1489 +/- 29	530 – 650	590
7	135-136	1509 +/- 28	430 – 640	535
8	138-139	1564 +/- 28	420 – 570	495
9	141-142	1708 +/- 29	250 – 420	335
10	144-145	1708 +/- 29	250 – 420	335
11	167-168	2064 +/- 30	170BC – AD10	80BC
12	170-171	1839 +/- 69	20 – 390	AD205*
13	173-174	2042 +/- 27	120BC – AD30	45BC
14	176-177	2070 +/- 27	170BC – AD10	80BC
15	179-180	2024 +/- 32	120BC – AD70	25BC

***Date appears to be anomalous**

The interpolated chronology for this site again appears to have a major hiatus in the record as shown by the Bpeat program. This is evident in the age/depth profile and represents a supposed gap of 308 years between contiguous samples at a depth of 96.5-97.5cm. Once again corroborative evidence from either stratigraphic changes in the peat profile or changes in the datasets is absent. Owing to the problems with the interpolated chronology, accumulation rates have only been suggested for the sections of the core where actual dates have been obtained.

According to Bpeat, rates vary between 0.07mm yr^{-1} for the top section of the core and then increase to 0.13mm yr^{-1} for the two remaining dated horizons

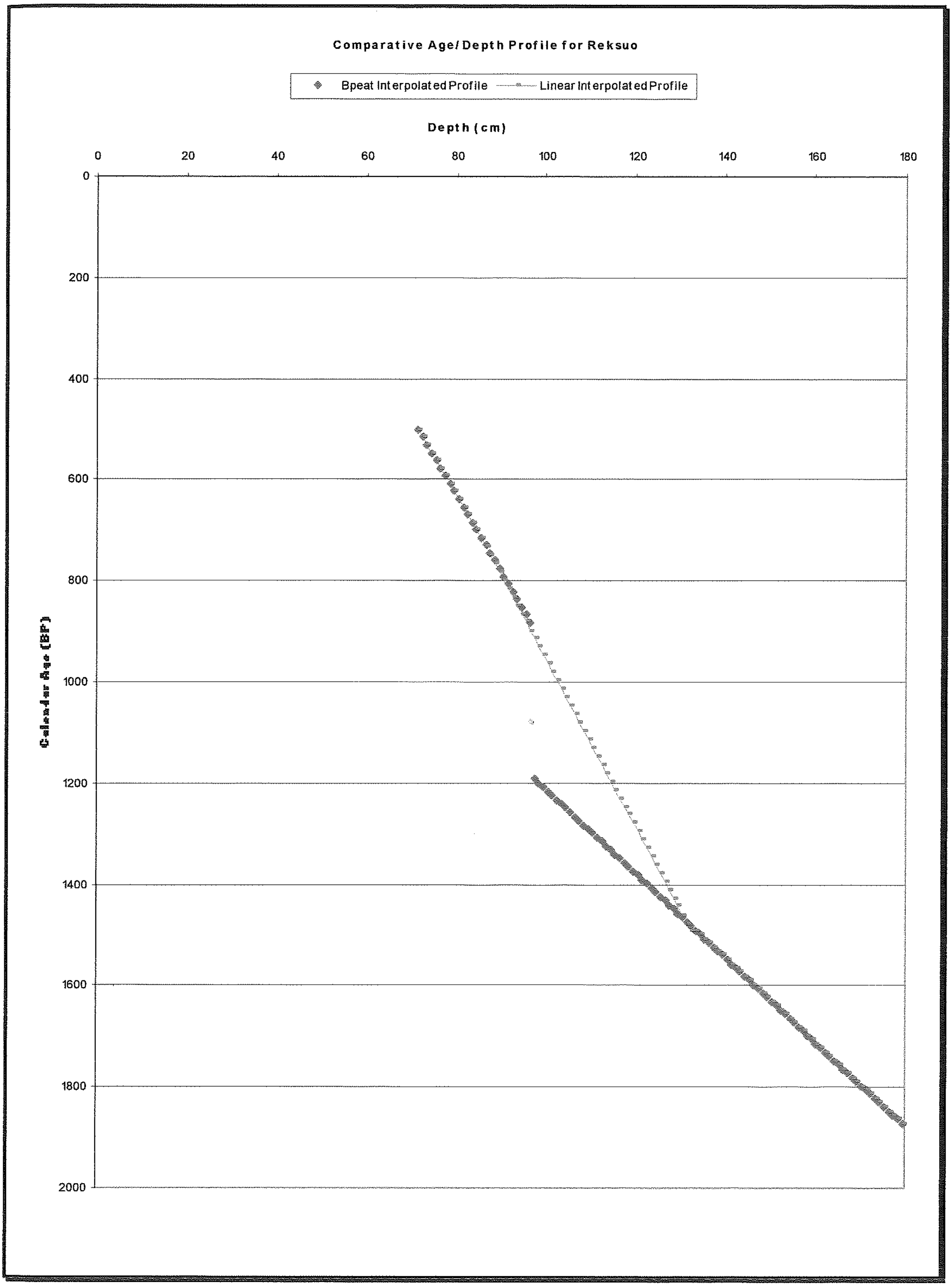


Figure 3.7 Age/depth profile generated for Reksuo.

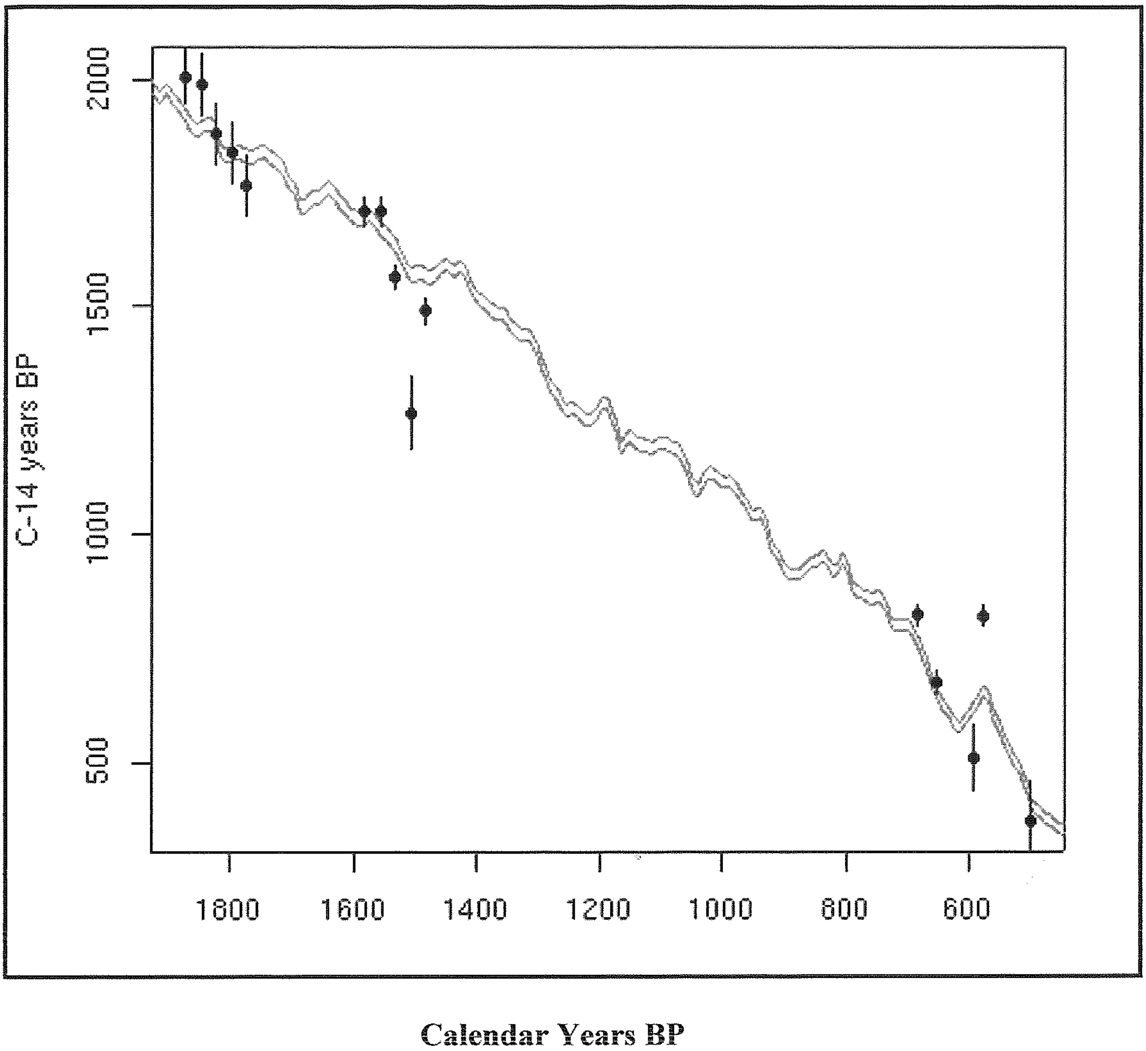


Figure 3.8 Best fit results for Reksuo

The table below again details the numerical data generated by the Bpeat wiggle-match age/depth program. Hiatus as indicated by the Bpeat program are again highlighted.

Table 3.4 Age/depth data for Reksuo

Depth (cm)	**Wiggle-matched Calendar Age (BP)**	**Alternative Age (BP)**
71.5	**501**	**501**
72.5	**516**	**516**
73.5	**531**	**531**
74.5	**547**	**547**
75.5	**562**	**562**
76.5	**577**	**577**
77.5	**592**	**592**
78.5	**608**	**608**
79.5	**623**	**623**
80.5	**638**	**638**
81.5	**654**	**654**
82.5	**669**	**669**
83.5	**684**	**684**
84.5	*699*	*700*
85.5	*715*	*717*
86.5	*730*	*733*
87.5	*745*	*750*
88.5	*760*	*766*
89.5	*776*	*783*
90.5	*791*	*799*
91.5	*806*	*815*
92.5	*822*	*832*
93.5	*837*	*848*
94.5	*852*	*865*
95.5	*867*	*881*
96.5	*883*	*898*
97.5	*1191*	*914*
98.5	*1199*	*931*
99.5	*1208*	*948*
100.5	*1216*	*964*
101.5	*1224*	*981*
102.5	*1233*	*998*
103.5	*1241*	*1014*
104.5	*1249*	*1031*
105.5	*1258*	*1047*
106.5	*1266*	*1064*
107.5	*1274*	*1081*
108.5	*1283*	*1097*
109.5	*1291*	*1114*

110.5	*1299*	*1130*
111.5	*1308*	*1147*
112.5	*1316*	*1163*
113.5	*1324*	*1180*
114.5	*1332*	*1196*
115.5	*1341*	*1213*
116.5	*1349*	*1230*
117.5	*1357*	*1246*
118.5	*1366*	*1262*
119.5	*1374*	*1279*
120.5	*1382*	*1295*
121.5	*1391*	*1312*
122.5	*1399*	*1328*
123.5	*1407*	*1344*
124.5	*1416*	*1361*
125.5	*1424*	*1377*
126.5	*1432*	*1394*
127.5	*1440*	*1410*
128.5	*1449*	*1427*
129.5	*1457*	*1443*
130.5	*1465*	*1460*
131.5	*1474*	*1477*
132.5	**1482**	**1482**
133.5	**1490**	**1490**
134.5	**1499**	**1499**
135.5	**1507**	**1507**
136.5	**1515**	**1515**
137.5	**1524**	**1524**
138.5	**1532**	**1532**
139.5	**1540**	**1540**
140.5	**1549**	**1549**
141.5	**1557**	**1557**
142.5	**1565**	**1565**
143.5	**1573**	**1573**
144.5	**1582**	**1582**
145.5	*1590*	*1590*
146.5	*1598*	*1598*
147.5	*1607*	*1607*
148.5	*1615*	*1615*
149.5	*1623*	*1623*
150.5	*1632*	*1632*
151.5	*1640*	*1640*
152.5	*1648*	*1648*
153.5	*1657*	*1657*
154.5	*1665*	*1665*
155.5	*1673*	*1673*
156.5	*1681*	*1681*

157.5	*1690*	*1690*
158.5	*1698*	*1698*
159.5	*1706*	*1706*
160.5	*1715*	*1715*
161.5	*1723*	*1723*
162.5	*1731*	*1731*
163.5	*1740*	*1740*
164.5	*1748*	*1748*
165.5	*1756*	*1756*
166.5	*1765*	*1765*
167.5	**1773**	**1773**
168.5	**1781**	**1781**
169.5	**1790**	**1790**
170.5	**1798**	**1798**
171.5	**1806**	**1806**
172.5	**1814**	**1814**
173.5	**1823**	**1823**
174.5	**1831**	**1831**
175.5	**1839**	**1839**
176.5	**1848**	**1848**
177.5	**1856**	**1856**
178.5	**1864**	**1864**
179.5	**1873**	**1873**

3.6.1.3 Männikjärve – Core MANN - Calibration

Calibrated ^{14}C dates are presented below in Table 3.5. Each date has a 2-sigma age range and a mid-point value. (Dates are expressed as Cal. AD).

Table 3.5 Männikjärve calibrated ^{14}C dates

Date N°	**Depth (cm)**	**Radiocarbon age BP (incl. 1σ error)**	**2σ calibrated range 95.4% conf. level**	**Mid-point of 2σ range**
1	36-37	139 +/- 32	1670 – 1960	1815
2	39-40	169 +/- 27	1720 – 1820	1770
3	42-43	150 +/- 23	1720 – 1890	1805
4	45-46	218 +/- 26	1730 – 1810	1770
5	48-49	223 +/- 30	1730 – 1810	1770
6	91-92	955 +/- 28	1020 – 1160	1090
7	93-94	990 +/-37	980 – 1160	1070
8	97-98	935 +/- 22	1020 – 1160	1090
9	100-101	976 +/- 25	1080 – 1160	1120
10	103-104	896 +/- 25	1030 – 1220	1125
11	161-162	1992 +/- 27	50 BC – AD 80	AD 15
12	164-165	2831 +/- 33	1130 BC – 890 BC	1010 BC *
13	167-168	1909 +/- 27	20 – 140	60
14	170-171	2058 +/- 20	120 BC – AD 10	55 BC
15	Missing data			

*** Date appears to be anomalous**

Männikjärve is again problematic. Bpeat has generated two gaps in the chronology; the first of these occurs at 104.5-105.5cm and covers a period of 463 years and the second at 163.5-164.5cm. The second of these proposed hiatuses is interesting because it occurs in a section of the chronology when actual wiggle-matched dates are available. As can be seen from Table 3.5 above, an apparently spurious date occurs at 164-165cm. Blaauw (pers com) states that it is not necessary to remove anomalous dates as to do so may adversely affect the integrity of the overall chronology. However, it is apparent from these data that Bpeat has itself generated spurious data – in this instance by assuming a gap of 219 years between contiguous samples. In the opinion of the author this is no more acceptable or parsimonious than removing obviously spurious dates at the beginning. It appears from these results that Bpeat is not able to deal with outlying dates particularly where they are significantly out of line with the dataset as a whole.

As a consequence of these problems, accumulation rates have only been generated for two of the three dated horizons. For both of these horizons the Bpeat data indicate an accumulation rate of 0.1mm yr^{-1}.

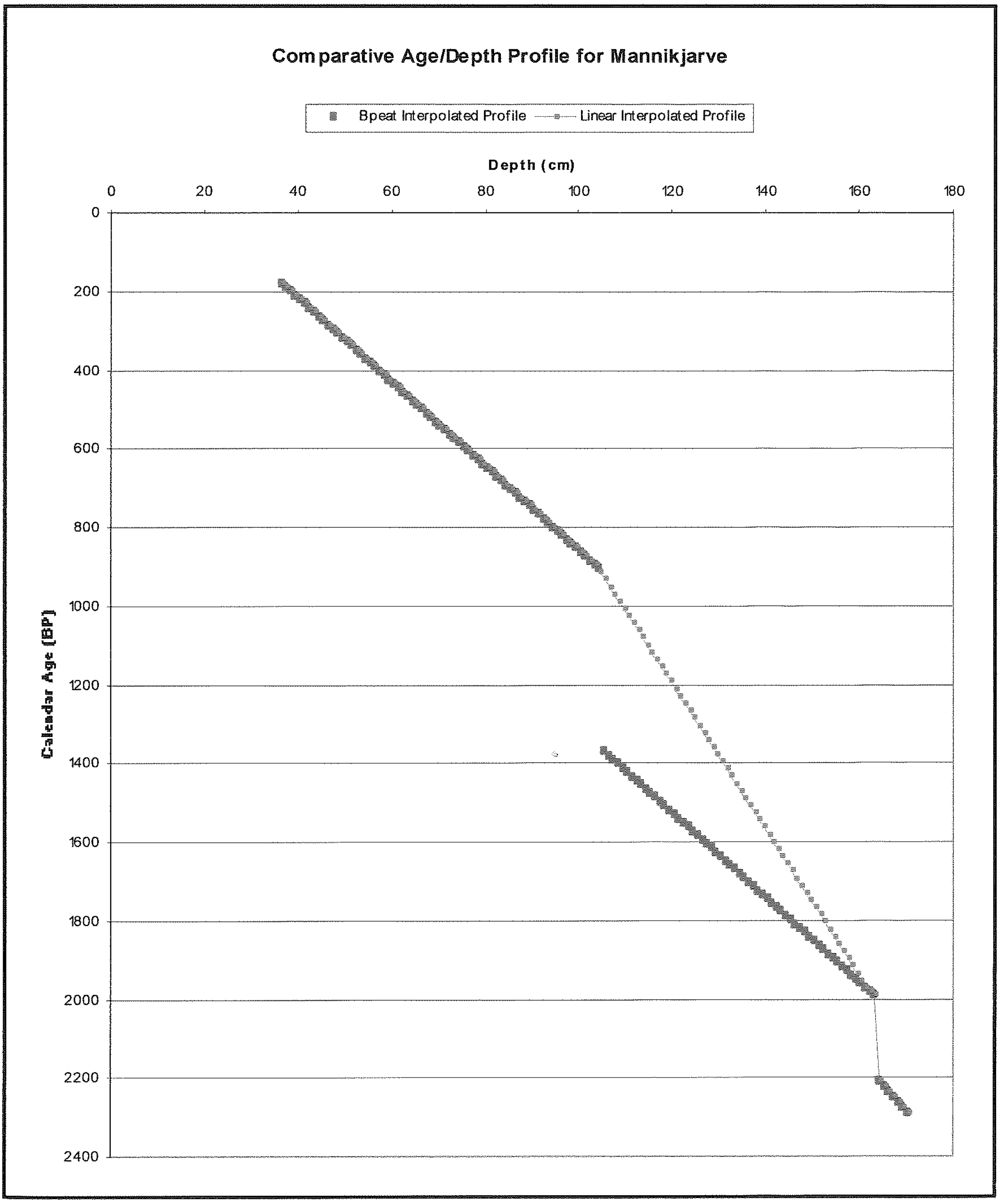


Figure 3.9 Age/depth profile for Männikjärve

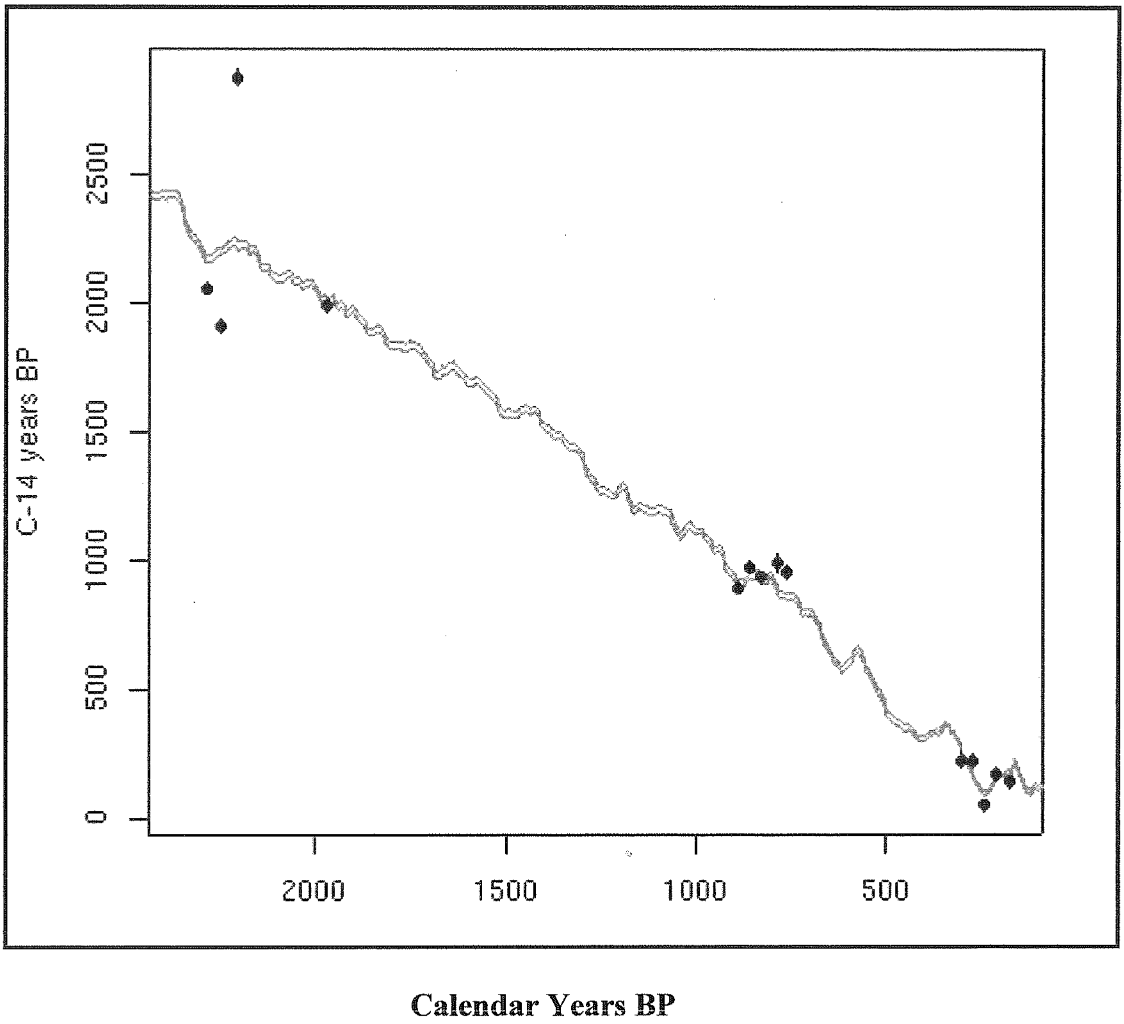


Figure 3.10 Best fit results for Männikjärve

The table below again details the numerical data generated by the Bpeat wiggle-match age/depth program. Hiatuses as indicated by the Bpeat program are again highlighted.

Table 3.6 Age/depth data for Männikjärve

Depth (cm)	**Wiggle-matched Calendar Age**	**Alternative Age (BP)**
36.5	**177**	**177**
37.5	**187**	**187**
38.5	**198**	**198**
39.5	**209**	**209**
40.5	**220**	**220**
41.5	**230**	**230**
42.5	**241**	**241**
43.5	**252**	**252**
44.5	**262**	**262**
45.5	**273**	**273**
46.5	**284**	**284**
47.5	**294**	**294**
48.5	**305**	**305**
49.5	*316*	*316*
50.5	*327*	*327*
51.5	*337*	*337*
52.5	*348*	*348*
53.5	*359*	*359*
54.5	*369*	*369*
55.5	*380*	*380*
56.5	*391*	*391*
57.5	*402*	*402*
58.5	*412*	*412*
59.5	*423*	*423*
60.5	*434*	*434*
61.5	*444*	*444*
62.5	*455*	*455*
63.5	*466*	*466*
64.5	*476*	*476*
65.5	*487*	*487*
66.5	*498*	*498*
67.5	*509*	*509*
68.5	*519*	*519*
69.5	*530*	*530*
70.5	*541*	*541*
71.5	*551*	*551*
72.5	*562*	*562*
73.5	*573*	*573*
74.5	*583*	*583*
75.5	*594*	*594*
76.5	*605*	*605*

77.5	*616*	*616*
78.5	*626*	*626*
79.5	*637*	*637*
80.5	*648*	*648*
81.5	*658*	*658*
82.5	*669*	*669*
83.5	*680*	*680*
84.5	*691*	*691*
85.5	*701*	*701*
86.5	*712*	*712*
87.5	*723*	*723*
88.5	*733*	*733*
89.5	*744*	*744*
90.5	*755*	*755*
91.5	**765**	**765**
92.5	**776**	**776**
93.5	**787**	**787**
94.5	**798**	**798**
95.5	**808**	**808**
96.5	**819**	**819**
97.5	**830**	**830**
98.5	**840**	**840**
99.5	**851**	**851**
100.5	**862**	**862**
101.5	**873**	**873**
102.5	**883**	**883**
103.5	**894**	**894**
104.5	*905*	*913*
105.5	*1368*	*931*
106.5	*1379*	*950*
107.5	*1390*	*968*
108.5	*1400*	*987*
109.5	*1411*	*1005*
110.5	*1422*	*1023*
111.5	*1433*	*1042*
112.5	*1443*	*1061*
113.5	*1454*	*1079*
114.5	*1465*	*1098*
115.5	*1476*	*1116*
116.5	*1486*	*1135*
117.5	*1497*	*1153*
118.5	*1508*	*1172*
119.5	*1519*	*1191*
120.5	*1529*	*1209*
121.5	*1540*	*1228*
122.5	*1551*	*1247*
123.5	*1562*	*1266*

124.5	*1572*	*1284*
125.5	*1583*	*1303*
126.5	*1594*	*1321*
127.5	*1605*	*1340*
128.5	*1615*	*1358*
129.5	*1626*	*1377*
130.5	*1637*	*1395*
131.5	*1648*	*1413*
132.5	*1658*	*1432*
133.5	*1669*	*1451*
134.5	*1680*	*1469*
135.5	*1691*	*1488*
136.5	*1701*	*1506*
137.5	*1712*	*1525*
138.5	*1723*	*1543*
139.5	*1734*	*1562*
140.5	*1744*	*1581*
141.5	*1755*	*1599*
142.5	*1766*	*1618*
143.5	*1776*	*1636*
144.5	*1787*	*1655*
145.5	*1798*	*1673*
146.5	*1809*	*1692*
147.5	*1819*	*1710*
148.5	*1830*	*1729*
149.5	*1841*	*1747*
150.5	*1852*	*1766*
151.5	*1862*	*1785*
152.5	*1873*	*1803*
153.5	*1884*	*1822*
154.5	*1895*	*1840*
155.5	*1905*	*1859*
156.5	*1916*	*1878*
157.5	*1927*	*1896*
158.5	*1938*	*1915*
159.5	*1948*	*1933*
160.5	*1959*	*1952*
161.5	**1970**	**1970**
162.5	**1981**	**1981**
163.5	**1991**	**1991**
164.5	**2210**	**2210**
165.5	**2223**	**2223**
166.5	**2236**	**2236**
167.5	**2249**	**2249**
168.5	**2262**	**2262**
169.5	**2275**	**2275**
170.5	**2288**	**2288**

3.6.1.4 Kuistlema – Core KUIS - Calibration

Calibrated ^{14}C dates are presented below in Table 3.7. Each date has a 2-sigma age range and a mid-point value. (Dates are expressed as Cal. AD).

Table 3.7 Kuistlemma calibrated ^{14}C dates

Date N°	Depth (cm)	Radiocarbon age BP (incl. 1σ error)	2σ calibrated range 95.4% conf. level	Mid-point of 2σ range
1	19-20	102 +/- 28	1800-1960	1880*
3	39-40	1091 +/- 24	890 – 1000	945
4	43-44	1296 +/- 33	660 – 780	720
5	52-53	1317 +/- 34	650 – 780	715
6	90-91	1457 +/- 58	430 – 670	550
7	93-94	1415 +/- 62	530 – 730	630
8	96-97	1468 +/- 57	430 – 670	550
9	99-100	1480 +/- 57	430 – 660	545
10	102-103	1483 +/- 28	530 – 650	590
11	161-162	1798 +/-29	130 – 330	230
12	164-165	1774 +/-29	130 – 350	240
13	167-168	1785 +/-29	130 – 340	235
14	170-171	1833 +/- 25	120 – 250	185
15	174-175	1832 +/- 32	120 – 260	190

*Hiatus in the peat record.

Bpeat has generated an acceptable interpolated chronology for this site. The hiatus between the first date at 19-20cm and then the next date at 39-40cm probably represents an episode of peat cutting. In contrast to the other sites this hiatus is also indicated by changes in the proxy datasets. The accumulation rate remains fairly constant throughout the dated horizons of the core. The rate initially starts at 0.18mm yr^{-1} before increasingly marginally to 0.19mm yr^{-1} towards the middle of the core and then returning to its former rate at the base of the core.

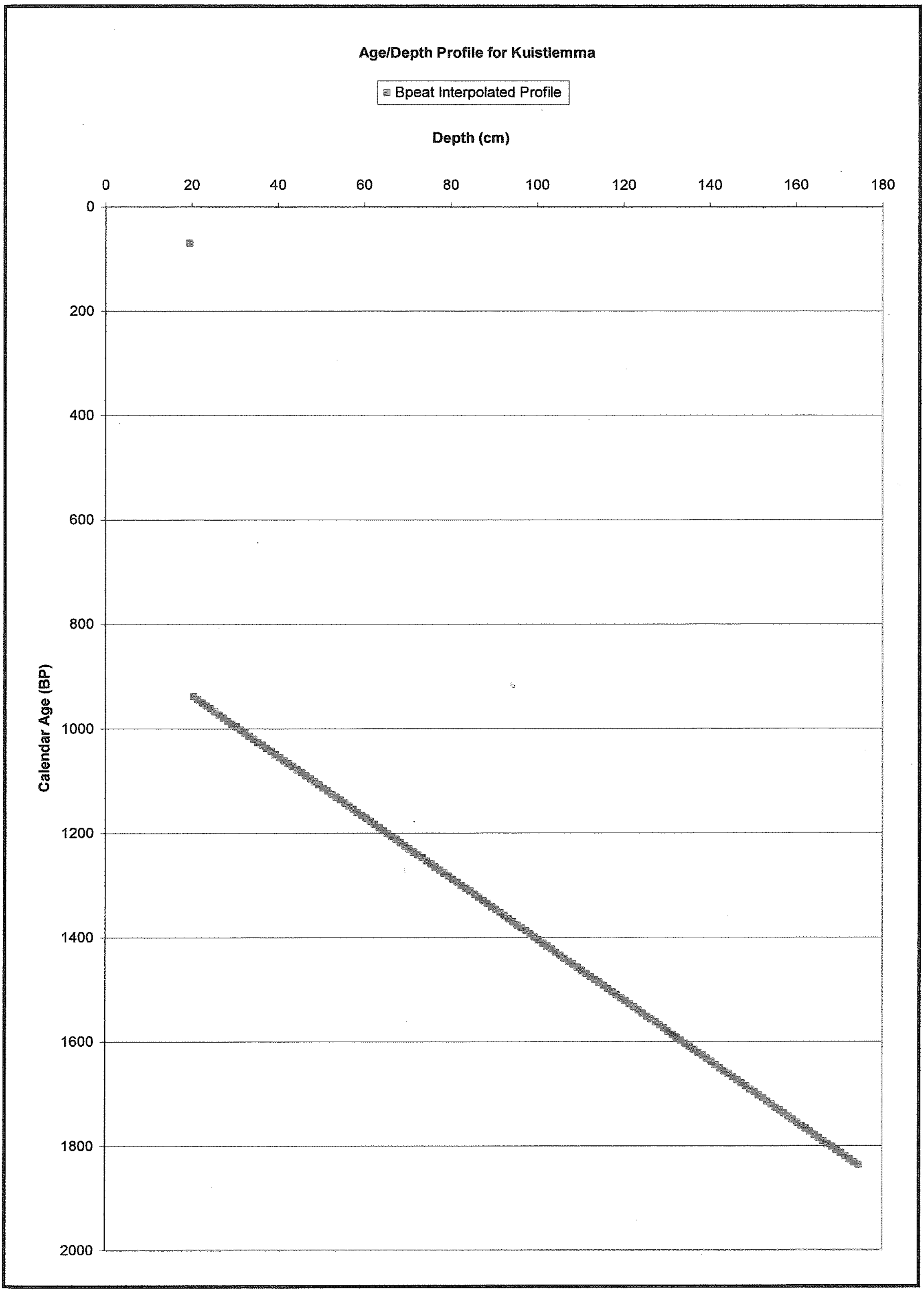


Figure 3.11 Age/depth profile for Kuistlemma

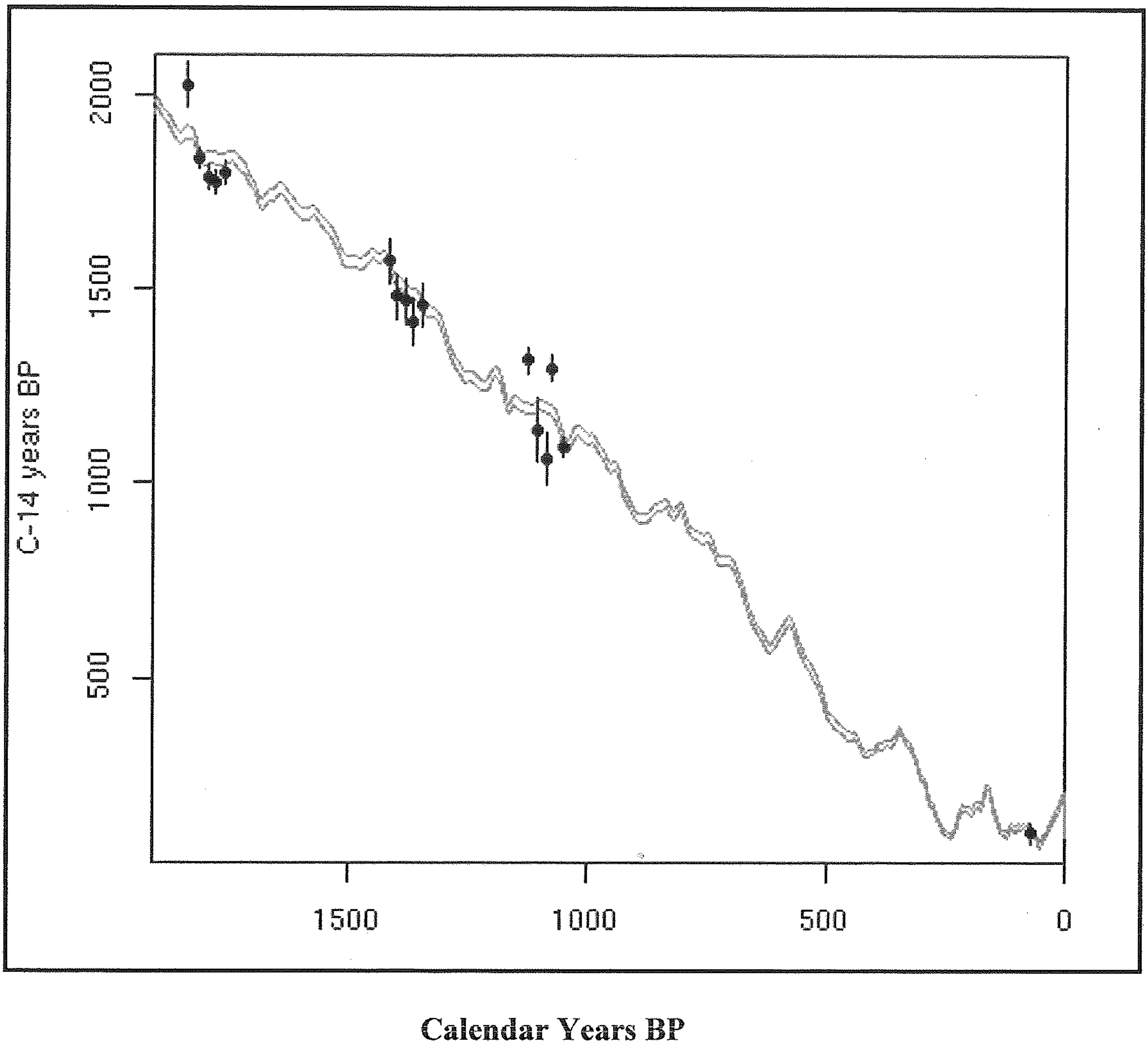


Figure 3.12 Best fit results for Kuistlemma

The table below again details the numerical data generated by the Bpeat wiggle-match age/depth program.

Table 3.8 Age/depth data for Kuistlemma

Depth (cm)	**Wiggle-matched Calendar Age (BP)**
19.5	**70**
20.5	*939*
21.5	*945*
22.5	*951*
23.5	*957*
24.5	*962*
25.5	*968*
26.5	*974*
27.5	*980*
28.5	*986*
29.5	*992*
30.5	*997*
31.5	*1003*
32.5	*1009*
33.5	*1015*
34.5	*1021*
35.5	*1027*
36.5	*1032*
37.5	*1038*
38.5	*1044*
39.5	**1050**
40.5	**1056**
41.5	**1062**
42.5	**1067**
43.5	**1073**
44.5	**1079**
45.5	**1085**
46.5	**1091**
47.5	**1097**
48.5	**1102**
49.5	**1108**
50.5	**1114**
51.5	**1120**
52.5	**1126**
53.5	*1132*
54.5	*1137*
55.5	*1143*
56.5	*1149*
57.5	*1155*

58.5	*1161*
59.5	*1167*
60.5	*1172*
61.5	*1178*
62.5	*1184*
63.5	*1190*
64.5	*1196*
65.5	*1202*
66.5	*1207*
67.5	*1213*
68.5	*1219*
69.5	*1225*
70.5	*1231*
71.5	*1237*
72.5	*1242*
73.5	*1248*
74.5	*1254*
75.5	*1260*
76.5	*1266*
77.5	*1272*
78.5	*1277*
79.5	*1283*
80.5	*1289*
81.5	*1295*
82.5	*1301*
83.5	*1307*
84.5	*1312*
85.5	*1318*
86.5	*1324*
87.5	*1330*
88.5	**1336**
89.5	**1342**
90.5	**1347**
91.5	**1353**
92.5	**1359**
93.5	**1365**
94.5	**1371**
95.5	**1377**
96.5	**1382**
97.5	**1388**
98.5	**1394**
99.5	**1400**
100.5	**1406**
101.5	**1412**
102.5	**1417**
103.5	*1423*
104.5	*1429*

105.5	*1435*
106.5	*1441*
107.5	*1447*
108.5	*1452*
109.5	*1458*
110.5	*1464*
111.5	*1470*
112.5	*1476*
113.5	*1482*
114.5	*1487*
115.5	*1493*
116.5	*1499*
117.5	*1505*
118.5	*1511*
119.5	*1517*
120.5	*1522*
121.5	*1528*
122.5	*1534*
123.5	*1540*
124.5	*1546*
125.5	*1552*
126.5	*1557*
127.5	*1563*
128.5	*1569*
129.5	*1575*
130.5	*1581*
131.5	*1587*
132.5	*1592*
133.5	*1598*
134.5	*1604*
135.5	*1610*
136.5	*1616*
137.5	*1622*
138.5	*1627*
139.5	*1633*
140.5	*1639*
141.5	*1645*
142.5	*1651*
143.5	*1657*
144.5	*1662*
145.5	*1668*
146.5	*1674*
147.5	*1680*
148.5	*1686*
149.5	*1692*
150.5	*1697*
151.5	*1703*

152.5	*1709*
153.5	*1715*
154.5	*1721*
155.5	*1727*
156.5	*1732*
157.5	*1738*
158.5	*1744*
159.5	*1750*
160.5	*1756*
161.5	**1762**
162.5	**1767**
163.5	**1773**
164.5	**1779**
165.5	**1785**
166.5	**1791**
167.5	**1797**
168.5	**1802**
169.5	**1808**
170.5	**1814**
171.5	**1820**
172.5	**1826**
173.5	**1832**
174.5	**1837**

3.6.1 Summary

It is clear from the macrofossil diagrams that marked shifts to wetter and drier conditions can be inferred from the proxy data. In general, there appears to be broad agreement between the proxies, although this does vary between sites and also the timing and magnitude of implied hydrological changes appears to differ between proxies. The dominance of *Sphagnum fuscum* at all four sites complicates a strictly hydrological interpretation of the *Sphagnum* assemblage and demonstrates the problems that can be encountered when a single species, with a wide tolerance of hydrological conditions, becomes dominant on the bog. Nevertheless, values of *S. riparium, S. cuspidatum, S. lindbergii* and particularly *S. magellanicum* often record an increase in conjunction with other wet indicators. The testate amoebae dataset also exhibits a similar problem, with *Amphitrema flavum* often dominant and seemingly able to withstand a broad range of hydrological conditions. In order to facilitate intra and inter-site comparisons, the raw macrofossil data have been subject to multivariate analysis, the results of which are detailed in the next chapter.

It is clear from the age/depth profiles generated by Bpeat that there are some problems and/or inconsistencies in the wiggle-matched radiocarbon chronology. Initially, the problems were thought to stem from the fact that the first batch of radiocarbon dates had produced some evidently spurious dates. However, Blauuw (pers. com.) confirmed that the Bpeat program statistically down-weighted spurious or outlying dates in order to minimise problems in the overall chronology. Nonetheless, it is clear from the Bpeat chronology generated for this project that several of these issues are still to be resolved. Of particular concern are the artificially generated gaps (hiatus) that Bpeat inserts into

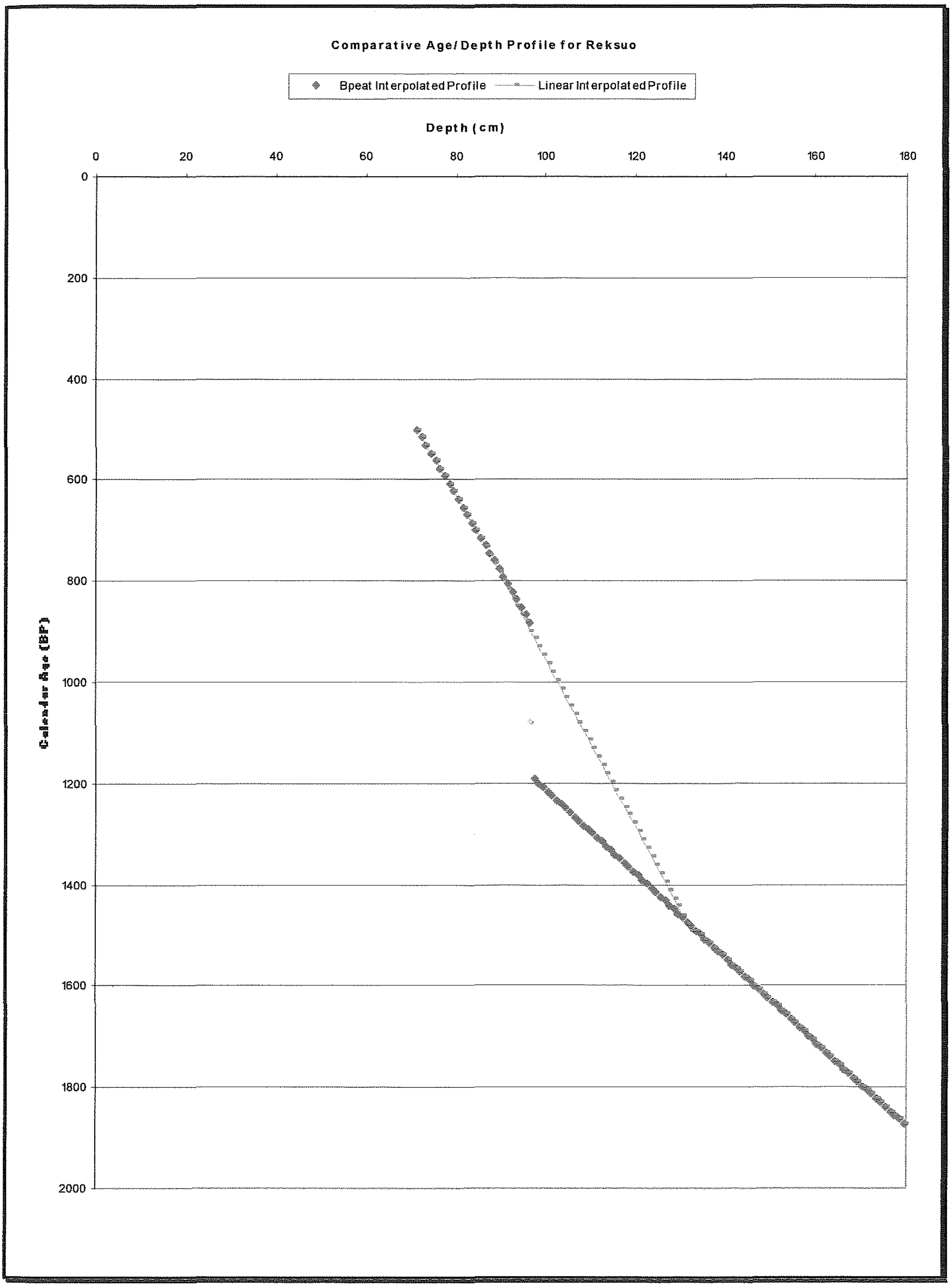
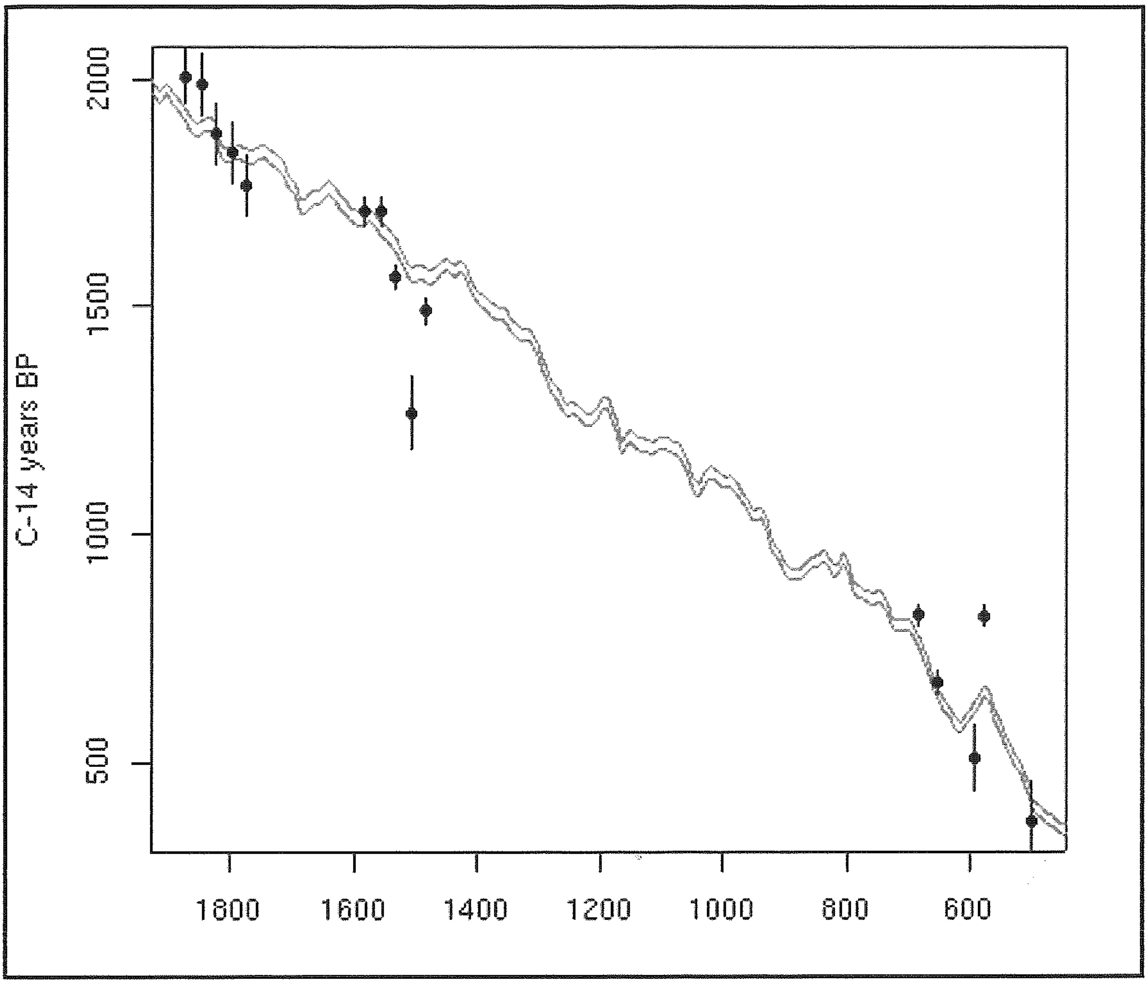


Figure 3.7 Age/depth profile generated for Reksuo.



Calendar Years BP

Figure 3.8 Best fit results for Reksuo

The table below again details the numerical data generated by the Bpeat wiggle-match age/depth program. Hiatus as indicated by the Bpeat program are again highlighted.

Table 3.4 Age/depth data for Reksuo

Depth (cm)	**Wiggle-matched Calendar Age (BP)**	**Alternative Age (BP)**
71.5	**501**	**501**
72.5	**516**	**516**
73.5	**531**	**531**
74.5	**547**	**547**
75.5	**562**	**562**
76.5	**577**	**577**
77.5	**592**	**592**
78.5	**608**	**608**
79.5	**623**	**623**
80.5	**638**	**638**
81.5	**654**	**654**
82.5	**669**	**669**
83.5	**684**	**684**
84.5	*699*	*700*
85.5	*715*	*717*
86.5	*730*	*733*
87.5	*745*	*750*
88.5	*760*	*766*
89.5	*776*	*783*
90.5	*791*	*799*
91.5	*806*	*815*
92.5	*822*	*832*
93.5	*837*	*848*
94.5	*852*	*865*
95.5	*867*	*881*
96.5	*883*	*898*
97.5	*1191*	*914*
98.5	*1199*	*931*
99.5	*1208*	*948*
100.5	*1216*	*964*
101.5	*1224*	*981*
102.5	*1233*	*998*
103.5	*1241*	*1014*
104.5	*1249*	*1031*
105.5	*1258*	*1047*
106.5	*1266*	*1064*
107.5	*1274*	*1081*
108.5	*1283*	*1097*
109.5	*1291*	*1114*

110.5	*1299*	*1130*
111.5	*1308*	*1147*
112.5	*1316*	*1163*
113.5	*1324*	*1180*
114.5	*1332*	*1196*
115.5	*1341*	*1213*
116.5	*1349*	*1230*
117.5	*1357*	*1246*
118.5	*1366*	*1262*
119.5	*1374*	*1279*
120.5	*1382*	*1295*
121.5	*1391*	*1312*
122.5	*1399*	*1328*
123.5	*1407*	*1344*
124.5	*1416*	*1361*
125.5	*1424*	*1377*
126.5	*1432*	*1394*
127.5	*1440*	*1410*
128.5	*1449*	*1427*
129.5	*1457*	*1443*
130.5	*1465*	*1460*
131.5	*1474*	*1477*
132.5	**1482**	**1482**
133.5	**1490**	**1490**
134.5	**1499**	**1499**
135.5	**1507**	**1507**
136.5	**1515**	**1515**
137.5	**1524**	**1524**
138.5	**1532**	**1532**
139.5	**1540**	**1540**
140.5	**1549**	**1549**
141.5	**1557**	**1557**
142.5	**1565**	**1565**
143.5	**1573**	**1573**
144.5	**1582**	**1582**
145.5	*1590*	*1590*
146.5	*1598*	*1598*
147.5	*1607*	*1607*
148.5	*1615*	*1615*
149.5	*1623*	*1623*
150.5	*1632*	*1632*
151.5	*1640*	*1640*
152.5	*1648*	*1648*
153.5	*1657*	*1657*
154.5	*1665*	*1665*
155.5	*1673*	*1673*
156.5	*1681*	*1681*

157.5	*1690*	*1690*
158.5	*1698*	*1698*
159.5	*1706*	*1706*
160.5	*1715*	*1715*
161.5	*1723*	*1723*
162.5	*1731*	*1731*
163.5	*1740*	*1740*
164.5	*1748*	*1748*
165.5	*1756*	*1756*
166.5	*1765*	*1765*
167.5	**1773**	**1773**
168.5	**1781**	**1781**
169.5	**1790**	**1790**
170.5	**1798**	**1798**
171.5	**1806**	**1806**
172.5	**1814**	**1814**
173.5	**1823**	**1823**
174.5	**1831**	**1831**
175.5	**1839**	**1839**
176.5	**1848**	**1848**
177.5	**1856**	**1856**
178.5	**1864**	**1864**
179.5	**1873**	**1873**

3.6.1.3 Männikjärve – Core MANN - Calibration

Calibrated ^{14}C dates are presented below in Table 3.5. Each date has a 2-sigma age range and a mid-point value. (Dates are expressed as Cal. AD).

Table 3.5 Männikjärve calibrated ^{14}C dates

Date N°	Depth (cm)	Radiocarbon age BP (incl. 1σ error)	2σ calibrated range 95.4% conf. level	Mid-point of 2σ range
1	36-37	139 +/- 32	1670 – 1960	1815
2	39-40	169 +/- 27	1720 – 1820	1770
3	42-43	150 +/- 23	1720 – 1890	1805
4	45-46	218 +/- 26	1730 – 1810	1770
5	48-49	223 +/- 30	1730 – 1810	1770
6	91-92	955 +/- 28	1020 – 1160	1090
7	93-94	990 +/-37	980 – 1160	1070
8	97-98	935 +/- 22	1020 – 1160	1090
9	100-101	976 +/- 25	1080 – 1160	1120
10	103-104	896 +/- 25	1030 – 1220	1125
11	161-162	1992 +/- 27	50 BC – AD 80	AD 15
12	164-165	2831 +/- 33	1130 BC – 890 BC	1010 BC *
13	167-168	1909 +/- 27	20 – 140	60
14	170-171	2058 +/- 20	120 BC – AD 10	55 BC
15	Missing data			

*** Date appears to be anomalous**

Männikjärve is again problematic. Bpeat has generated two gaps in the chronology; the first of these occurs at 104.5-105.5cm and covers a period of 463 years and the second at 163.5-164.5cm. The second of these proposed hiatuses is interesting because it occurs in a section of the chronology when actual wiggle-matched dates are available. As can be seen from Table 3.5 above, an apparently spurious date occurs at 164-165cm. Blaauw (pers com) states that it is not necessary to remove anomalous dates as to do so may adversely affect the integrity of the overall chronology. However, it is apparent from these data that Bpeat has itself generated spurious data – in this instance by assuming a gap of 219 years between contiguous samples. In the opinion of the author this is no more acceptable or parsimonious than removing obviously spurious dates at the beginning. It appears from these results that Bpeat is not able to deal with outlying dates particularly where they are significantly out of line with the dataset as a whole.

As a consequence of these problems, accumulation rates have only been generated for two of the three dated horizons. For both of these horizons the Bpeat data indicate an accumulation rate of 0.1mm yr^{-1}.

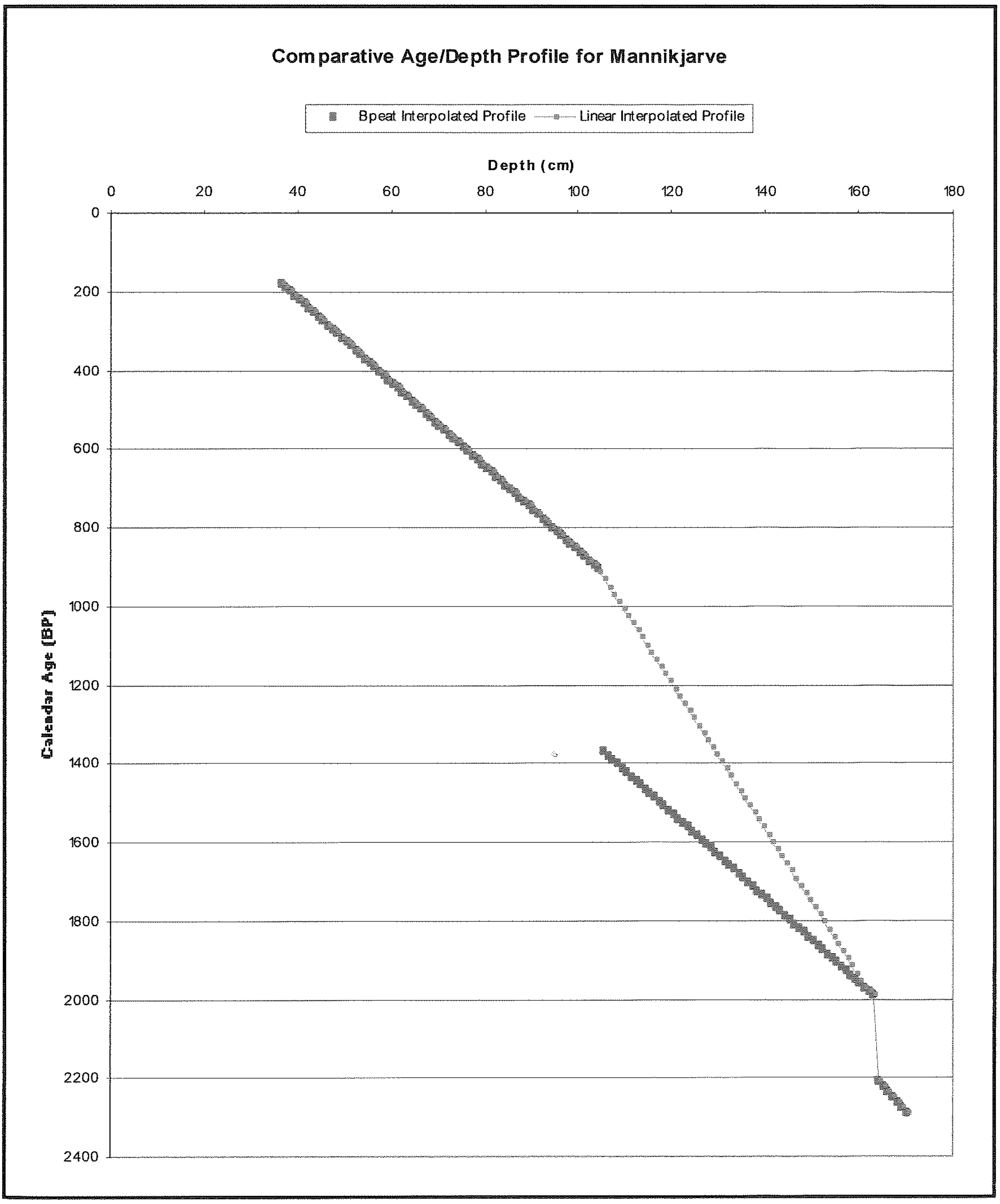


Figure 3.9 Age/depth profile for Männikjärve

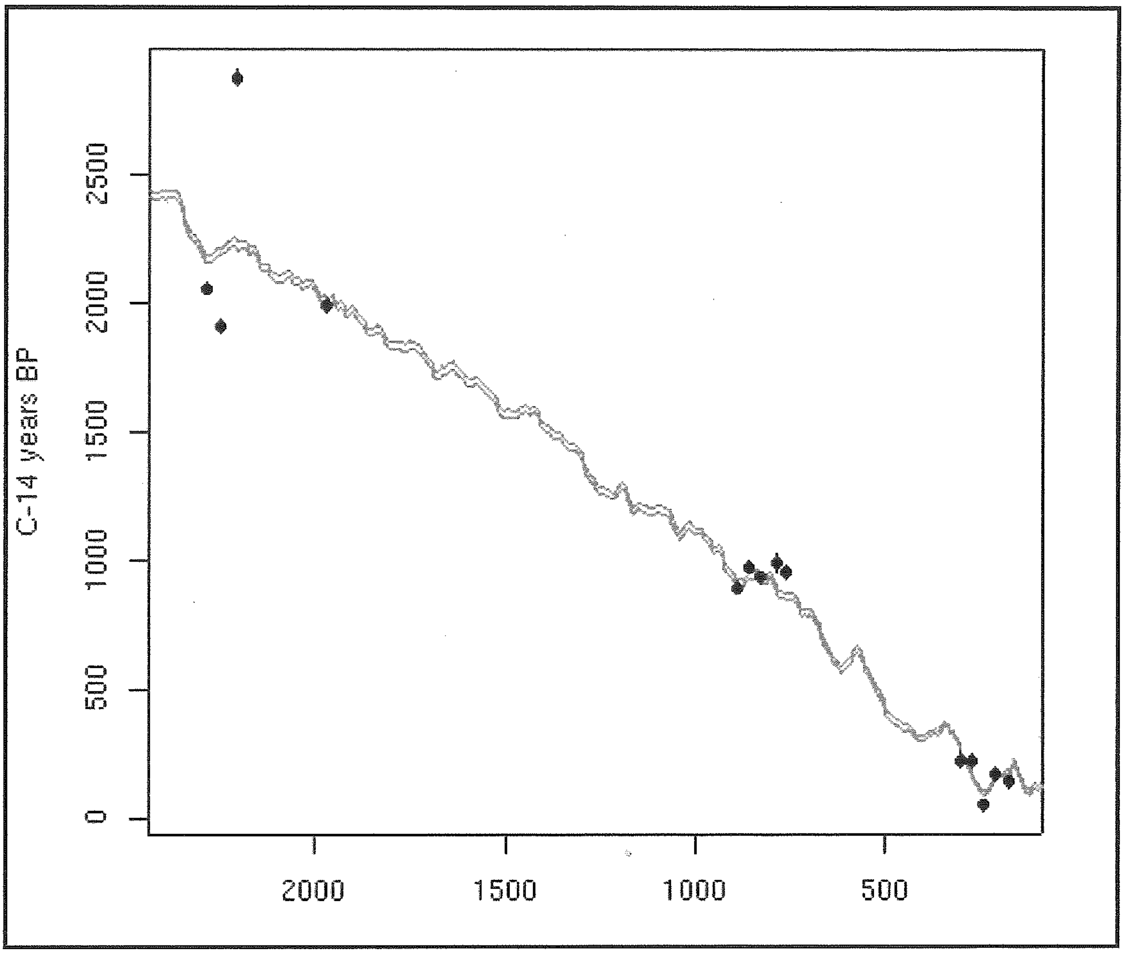


Figure 3.10 Best fit results for Männikjärve

The table below again details the numerical data generated by the Bpeat wiggle-match age/depth program. Hiatuses as indicated by the Bpeat program are again highlighted.

Table 3.6 Age/depth data for Männikjärve

Depth (cm)	**Wiggle-matched Calendar Age**	**Alternative Age (BP)**
36.5	**177**	**177**
37.5	**187**	**187**
38.5	**198**	**198**
39.5	**209**	**209**
40.5	**220**	**220**
41.5	**230**	**230**
42.5	**241**	**241**
43.5	**252**	**252**
44.5	**262**	**262**
45.5	**273**	**273**
46.5	**284**	**284**
47.5	**294**	**294**
48.5	**305**	**305**
49.5	*316*	*316*
50.5	*327*	*327*
51.5	*337*	*337*
52.5	*348*	*348*
53.5	*359*	*359*
54.5	*369*	*369*
55.5	*380*	*380*
56.5	*391*	*391*
57.5	*402*	*402*
58.5	*412*	*412*
59.5	*423*	*423*
60.5	*434*	*434*
61.5	*444*	*444*
62.5	*455*	*455*
63.5	*466*	*466*
64.5	*476*	*476*
65.5	*487*	*487*
66.5	*498*	*498*
67.5	*509*	*509*
68.5	*519*	*519*
69.5	*530*	*530*
70.5	*541*	*541*
71.5	*551*	*551*
72.5	*562*	*562*
73.5	*573*	*573*
74.5	*583*	*583*
75.5	*594*	*594*
76.5	*605*	*605*

77.5	*616*	*616*
78.5	*626*	*626*
79.5	*637*	*637*
80.5	*648*	*648*
81.5	*658*	*658*
82.5	*669*	*669*
83.5	*680*	*680*
84.5	*691*	*691*
85.5	*701*	*701*
86.5	*712*	*712*
87.5	*723*	*723*
88.5	*733*	*733*
89.5	*744*	*744*
90.5	*755*	*755*
91.5	**765**	**765**
92.5	**776**	**776**
93.5	**787**	**787**
94.5	**798**	**798**
95.5	**808**	**808**
96.5	**819**	**819**
97.5	**830**	**830**
98.5	**840**	**840**
99.5	**851**	**851**
100.5	**862**	**862**
101.5	**873**	**873**
102.5	**883**	**883**
103.5	**894**	**894**
104.5	*905*	*913*
105.5	*1368*	*931*
106.5	*1379*	*950*
107.5	*1390*	*968*
108.5	*1400*	*987*
109.5	*1411*	*1005*
110.5	*1422*	*1023*
111.5	*1433*	*1042*
112.5	*1443*	*1061*
113.5	*1454*	*1079*
114.5	*1465*	*1098*
115.5	*1476*	*1116*
116.5	*1486*	*1135*
117.5	*1497*	*1153*
118.5	*1508*	*1172*
119.5	*1519*	*1191*
120.5	*1529*	*1209*
121.5	*1540*	*1228*
122.5	*1551*	*1247*
123.5	*1562*	*1266*

124.5	*1572*	*1284*
125.5	*1583*	*1303*
126.5	*1594*	*1321*
127.5	*1605*	*1340*
128.5	*1615*	*1358*
129.5	*1626*	*1377*
130.5	*1637*	*1395*
131.5	*1648*	*1413*
132.5	*1658*	*1432*
133.5	*1669*	*1451*
134.5	*1680*	*1469*
135.5	*1691*	*1488*
136.5	*1701*	*1506*
137.5	*1712*	*1525*
138.5	*1723*	*1543*
139.5	*1734*	*1562*
140.5	*1744*	*1581*
141.5	*1755*	*1599*
142.5	*1766*	*1618*
143.5	*1776*	*1636*
144.5	*1787*	*1655*
145.5	*1798*	*1673*
146.5	*1809*	*1692*
147.5	*1819*	*1710*
148.5	*1830*	*1729*
149.5	*1841*	*1747*
150.5	*1852*	*1766*
151.5	*1862*	*1785*
152.5	*1873*	*1803*
153.5	*1884*	*1822*
154.5	*1895*	*1840*
155.5	*1905*	*1859*
156.5	*1916*	*1878*
157.5	*1927*	*1896*
158.5	*1938*	*1915*
159.5	*1948*	*1933*
160.5	*1959*	*1952*
161.5	**1970**	**1970**
162.5	**1981**	**1981**
163.5	**1991**	**1991**
164.5	**2210**	**2210**
165.5	**2223**	**2223**
166.5	**2236**	**2236**
167.5	**2249**	**2249**
168.5	**2262**	**2262**
169.5	**2275**	**2275**
170.5	**2288**	**2288**

3.6.1.4 Kuistlema – Core KUIS - Calibration

Calibrated ^{14}C dates are presented below in Table 3.7. Each date has a 2-sigma age range and a mid-point value. (Dates are expressed as Cal. AD).

Table 3.7 Kuistlemma calibrated ^{14}C dates

Date N°	Depth (cm)	Radiocarbon age BP (incl. 1σ error)	2σ calibrated range 95.4% conf. level	Mid-point of 2σ range
1	19-20	102 +/- 28	1800-1960	1880*
3	39-40	1091 +/- 24	890 – 1000	945
4	43-44	1296 +/- 33	660 – 780	720
5	52-53	1317 +/- 34	650 – 780	715
6	90-91	1457 +/- 58	430 – 670	550
7	93-94	1415 +/- 62	530 – 730	630
8	96-97	1468 +/- 57	430 – 670	550
9	99-100	1480 +/- 57	430 – 660	545
10	102-103	1483 +/- 28	530 – 650	590
11	161-162	1798 +/-29	130 – 330	230
12	164-165	1774 +/-29	130 – 350	240
13	167-168	1785 +/-29	130 – 340	235
14	170-171	1833 +/- 25	120 – 250	185
15	174-175	1832 +/- 32	120 – 260	190

*Hiatus in the peat record.

Bpeat has generated an acceptable interpolated chronology for this site. The hiatus between the first date at 19-20cm and then the next date at 39-40cm probably represents an episode of peat cutting. In contrast to the other sites this hiatus is also indicated by changes in the proxy datasets. The accumulation rate remains fairly constant throughout the dated horizons of the core. The rate initially starts at 0.18mm yr^{-1} before increasingly marginally to 0.19mm yr^{-1} towards the middle of the core and then returning to its former rate at the base of the core.

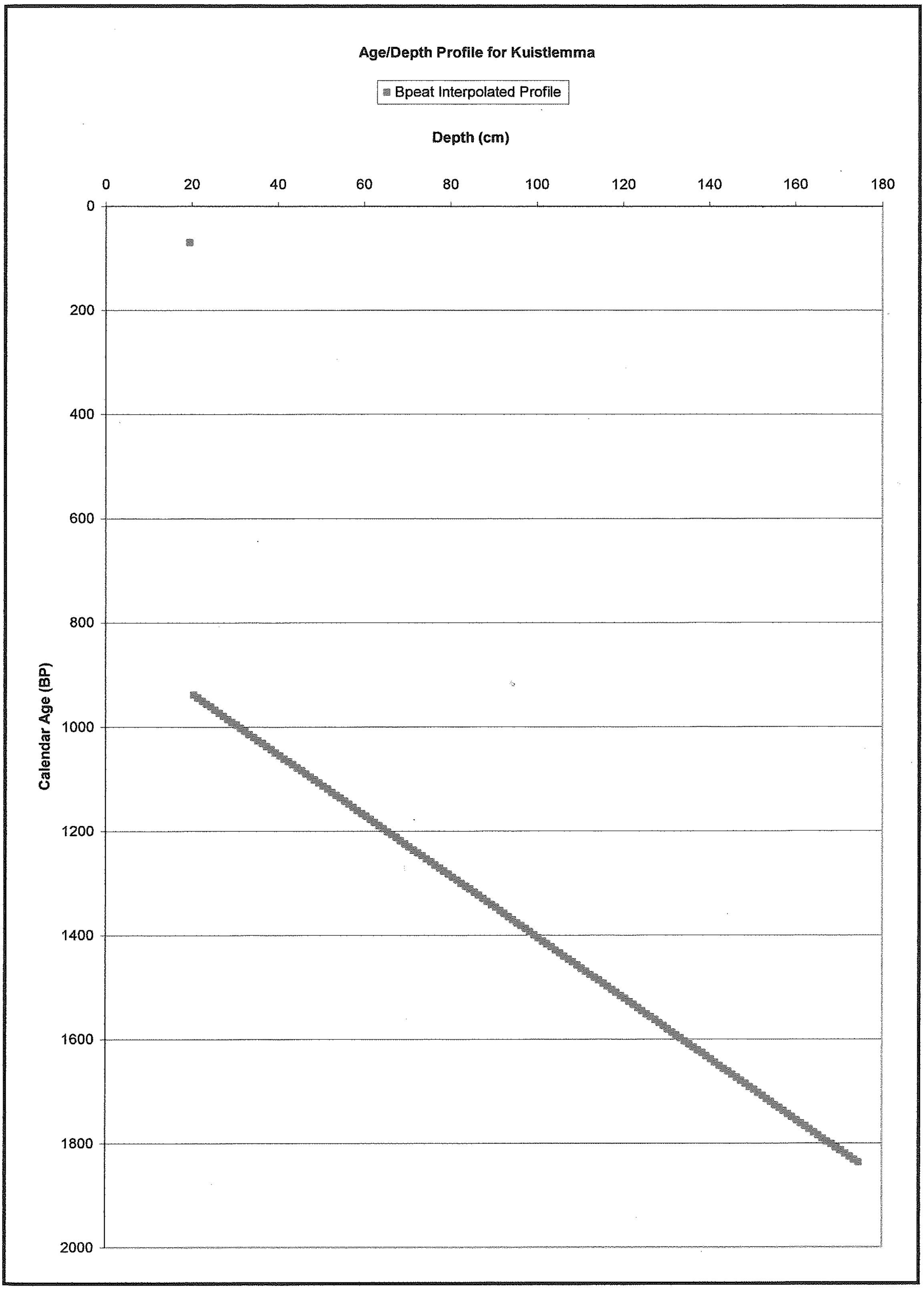
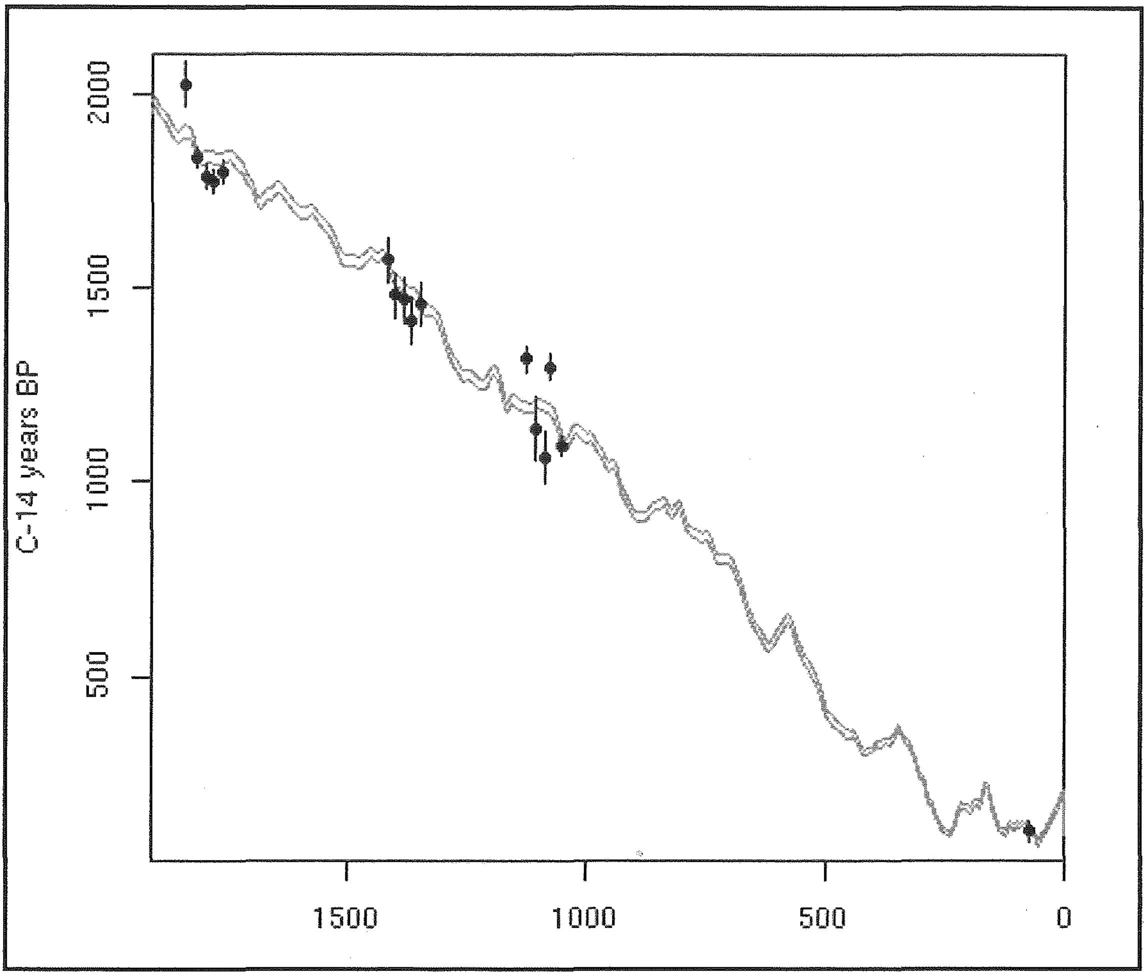


Figure 3.11 Age/depth profile for Kuistlemma



Calendar Years BP

Figure 3.12 Best fit results for Kuistlemma

The table below again details the numerical data generated by the Bpeat wiggle-match age/depth program.

Table 3.8 Age/depth data for Kuistlemma

Depth (cm)	**Wiggle-matched Calendar Age (BP)**
19.5	**70**
20.5	*939*
21.5	*945*
22.5	*951*
23.5	*957*
24.5	*962*
25.5	*968*
26.5	*974*
27.5	*980*
28.5	*986*
29.5	*992*
30.5	*997*
31.5	*1003*
32.5	*1009*
33.5	*1015*
34.5	*1021*
35.5	*1027*
36.5	*1032*
37.5	*1038*
38.5	*1044*
39.5	**1050**
40.5	**1056**
41.5	**1062**
42.5	**1067**
43.5	**1073**
44.5	**1079**
45.5	**1085**
46.5	**1091**
47.5	**1097**
48.5	**1102**
49.5	**1108**
50.5	**1114**
51.5	**1120**
52.5	**1126**
53.5	*1132*
54.5	*1137*
55.5	*1143*
56.5	*1149*
57.5	*1155*

58.5	*1161*
59.5	*1167*
60.5	*1172*
61.5	*1178*
62.5	*1184*
63.5	*1190*
64.5	*1196*
65.5	*1202*
66.5	*1207*
67.5	*1213*
68.5	*1219*
69.5	*1225*
70.5	*1231*
71.5	*1237*
72.5	*1242*
73.5	*1248*
74.5	*1254*
75.5	*1260*
76.5	*1266*
77.5	*1272*
78.5	*1277*
79.5	*1283*
80.5	*1289*
81.5	*1295*
82.5	*1301*
83.5	*1307*
84.5	*1312*
85.5	*1318*
86.5	*1324*
87.5	*1330*
88.5	**1336**
89.5	**1342**
90.5	**1347**
91.5	**1353**
92.5	**1359**
93.5	**1365**
94.5	**1371**
95.5	**1377**
96.5	**1382**
97.5	**1388**
98.5	**1394**
99.5	**1400**
100.5	**1406**
101.5	**1412**
102.5	**1417**
103.5	*1423*
104.5	*1429*

105.5	*1435*
106.5	*1441*
107.5	*1447*
108.5	*1452*
109.5	*1458*
110.5	*1464*
111.5	*1470*
112.5	*1476*
113.5	*1482*
114.5	*1487*
115.5	*1493*
116.5	*1499*
117.5	*1505*
118.5	*1511*
119.5	*1517*
120.5	*1522*
121.5	*1528*
122.5	*1534*
123.5	*1540*
124.5	*1546*
125.5	*1552*
126.5	*1557*
127.5	*1563*
128.5	*1569*
129.5	*1575*
130.5	*1581*
131.5	*1587*
132.5	*1592*
133.5	*1598*
134.5	*1604*
135.5	*1610*
136.5	*1616*
137.5	*1622*
138.5	*1627*
139.5	*1633*
140.5	*1639*
141.5	*1645*
142.5	*1651*
143.5	*1657*
144.5	*1662*
145.5	*1668*
146.5	*1674*
147.5	*1680*
148.5	*1686*
149.5	*1692*
150.5	*1697*
151.5	*1703*

152.5	*1709*
153.5	*1715*
154.5	*1721*
155.5	*1727*
156.5	*1732*
157.5	*1738*
158.5	*1744*
159.5	*1750*
160.5	*1756*
161.5	**1762**
162.5	**1767**
163.5	**1773**
164.5	**1779**
165.5	**1785**
166.5	**1791**
167.5	**1797**
168.5	**1802**
169.5	**1808**
170.5	**1814**
171.5	**1820**
172.5	**1826**
173.5	**1832**
174.5	**1837**

3.6.1 Summary

It is clear from the macrofossil diagrams that marked shifts to wetter and drier conditions can be inferred from the proxy data. In general, there appears to be broad agreement between the proxies, although this does vary between sites and also the timing and magnitude of implied hydrological changes appears to differ between proxies. The dominance of *Sphagnum fuscum* at all four sites complicates a strictly hydrological interpretation of the *Sphagnum* assemblage and demonstrates the problems that can be encountered when a single species, with a wide tolerance of hydrological conditions, becomes dominant on the bog. Nevertheless, values of *S. riparium, S. cuspidatum, S. lindbergii* and particularly *S. magellanicum* often record an increase in conjunction with other wet indicators. The testate amoebae dataset also exhibits a similar problem, with *Amphitrema flavum* often dominant and seemingly able to withstand a broad range of hydrological conditions. In order to facilitate intra and inter-site comparisons, the raw macrofossil data have been subject to multivariate analysis, the results of which are detailed in the next chapter.

It is clear from the age/depth profiles generated by Bpeat that there are some problems and/or inconsistencies in the wiggle-matched radiocarbon chronology. Initially, the problems were thought to stem from the fact that the first batch of radiocarbon dates had produced some evidently spurious dates. However, Blauuw (pers. com.) confirmed that the Bpeat program statistically down-weighted spurious or outlying dates in order to minimise problems in the overall chronology. Nonetheless, it is clear from the Bpeat chronology generated for this project that several of these issues are still to be resolved. Of particular concern are the artificially generated gaps (hiatus) that Bpeat inserts into

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the chronology in order to obtain an acceptable best-fit. As there was limited time and no easy way of re-visiting this problem it was decided that the most acceptable solution was to accept the actual Bpeat radiocarbon dated horizons but also to generate an alternative chronology based on linear interpolation between these horizons.

Chapter 4 – Proxy-Climate Reconstructions

4.1 Introduction

The aim of this chapter is to produce a palaeohydrological record for the Baltic region derived from proxy-data from the four sites investigated. In order to do this, statistical analysis of the plant macrofossil datasets has been carried out for each of the sites and then compared with the humification and testate amoebae data. Detrended Correspondence Analysis (DCA) and Weighted Averages Ordination (WAO) techniques have been applied to the data to generate proxy-climate curves that then were compared with the humification transmission curves. Synchronous changes to either wetter or drier conditions were then identified in the proxy record.

Proxy-climate curves have been plotted against both depth and an interpolated ^{14}C timescale. This has been developed through linear interpolation of the wiggle-matched ^{14}C chronologies and has enabled the dating of individual episodes of change of mire surface conditions.

4.2 Weighted Average Ordination of the plant macrofossil data

This technique was originally developed by Dupont (1986) and assigns a hydrological value to each component of the peat macrofossil assemblage based on its relative position on the hummock/hollow gradient (Figures 4.1 & 4.2). Consequently, a wetness index can be generated with each taxon assigned a weight, reflecting its inferred hydrological parameters.

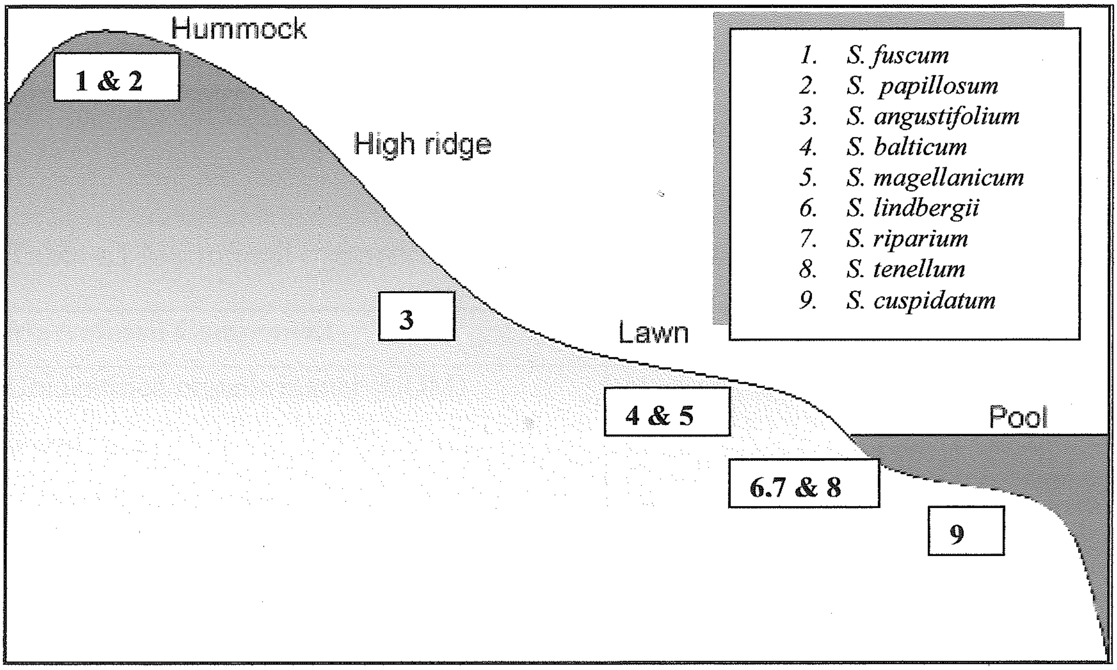

Figure 4.1 Generalised distribution of *Sphagnum* species across the hummock-pool bog microform (compiled from Daniels & Eddy, 1990).

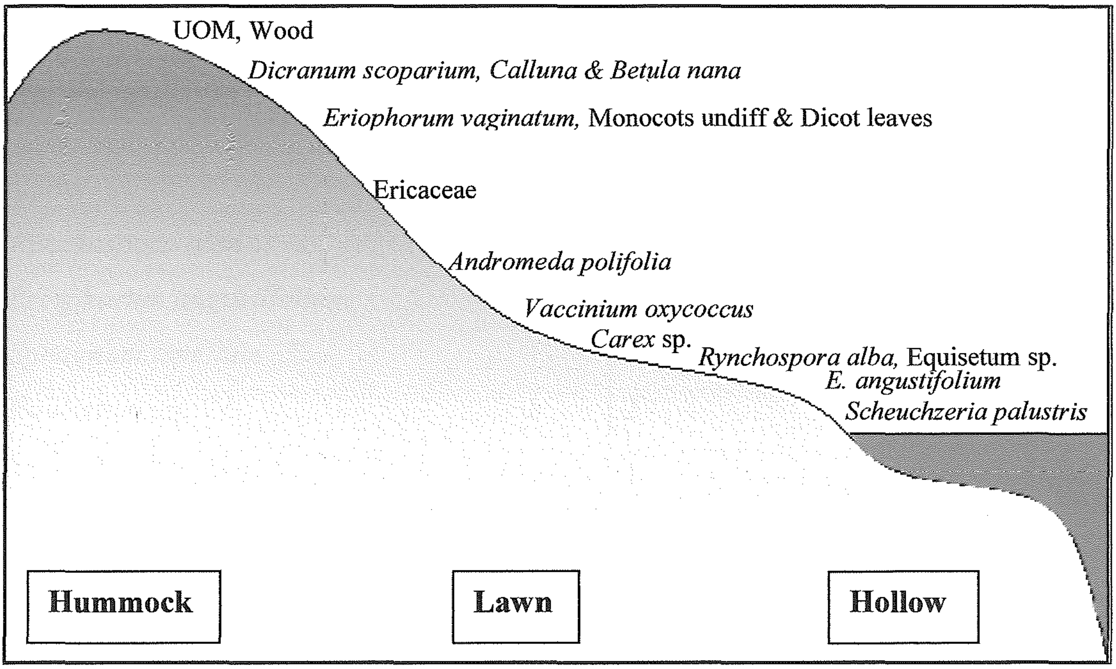

Figure 4.2 Interpreted range of generalised vegetational zonation through the hummock – hollow bog microform (Compiled from Birks & Birks, 1980; Blaauw *et al.* 2003).

Table 4.1 Macrofossil components and Dupont index values

Macrofossil Component	**Weight**
Unidentified organic matter (UOM)	15
Wood	15
Dicranum scoparium	13
Ericaceae	13
Calluna	13
Sphagnum fuscum	11
Sphagnum papillosum	11
Eriophorum vaginatum	11
Monocotyledons undifferentiated	9
Dicot leaves	9
Andromeda polifolia	9
Vaccinium oxycoccus	7
Sphagnum magellanicum	7
Sphagnum angustifolium	7

Sphagnum riparium	5
Sphagnum lindbergii	5
Sphagnum balticum	5
Carex	4
Rynchospora alba	3
Eriophorum angustifolium	3
Sphagnum tenellum	3
Equisetum sp.	2
Scheuchzeria palustris	1
Sphagnum cuspidatum	1

In order to derive a quantitative record of palaeohydrological conditions on the mire the abundance of each taxon is multiplied by its assigned wetness index value. This is repeated for each taxon at that level, and these values are then added together before being divided by the total abundance of macrofossil taxa in the sample. In this way an average mire wetness index value was determined sequentially at every centimetre along the core.

This technique has been used extensively in recent palaeoecological research. However, it is not without several problems and limitations. Most notably, the technique requires the rather subjective assignment of a hydrological value to a particular macrofossil component. The hydrological tolerance of many species is remarkably broad and this can be especially problematic in this instance. This is exemplified in this project by the dominance of *Sphagnum fuscum,* which in many cases appears to tolerate a wide range of hydrological conditions. Secondly, the ecological and hydrological parameters of a species may vary both temporally and geographically. Thirdly, the technique has a built-in assumption that any species change on the bog is related to climate change rather than additional environmental factors such as nutrient status, autogenic succession, pH or a symbiotic relationship with another taxon.

Recently, in order to improve the accuracy of mire surface reconstructions, several authors have added new components to this index whilst other have sought to adjust the weights assigned to particular taxa (Stoneman, 1993; Mauquoy, 1997).

In this study, where possible, the index developed by Mauquoy (1997) has been adopted. However, because this technique has not previously been applied to Baltic mires some of the components have not been given an index score. In order to overcome this problem an index value has been assigned, where necessary, based on the position of the taxon as denoted on the hollow-lawn-hummock bog microform in Figures 4.1 & 4.2 above. Following the procedure of Gent (2000), the distance between weight changes has been increased as a means of highlighting fluctuations in the reconstructed hydrological conditions of the mire.

4.2.1 Munasuo – Core MUN – Dupont Index Values

The Dupont index values for this site have been plotted against depth and are shown in Figure 4.3. The limits of the indices are 5 and 25 with higher values indicating drier mire conditions and conversely lower values implying an elevated water table. As can be seen from the graph the base of the core is characterised by oscillating but relatively high values implying drier conditions. However, this episode appears to be short-lived with a step-wise decline in values that then remain fairly stable. At *c.*142 cm values start to rise rapidly, again implying a shift to drier mire conditions. The generally high values are maintained until 119 cm when a rapid and steep fall in values is recorded. Following this period, fluctuating values are recorded with a particularly large shift in hydrological conditions implied at a depth of 101-99 cm. Immediately following this, a short-lived and low-magnitude shift to drier conditions is indicated by slightly higher values. However, at 88 cm a significant and rapid decrease in values is recorded implying a shift to wetter mire conditions. Values then remain relatively low until 61 cm when a two-stage but short-lived rise in values is evident before falling again at 56 cm. After this episode values remain relatively uniform.

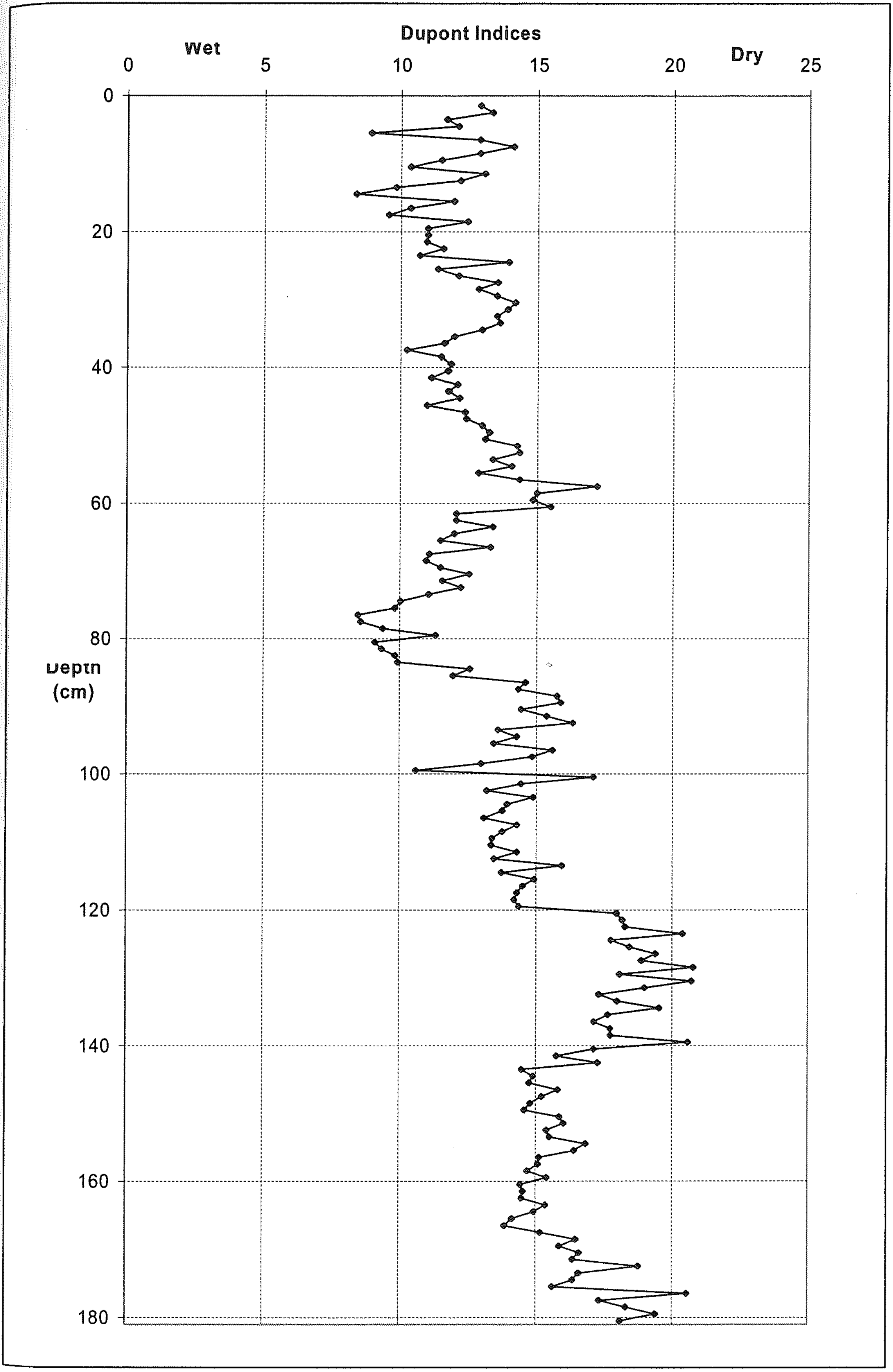

Figure 4.3 Dupont Index values for Munasuo

4.2.2 Reksuo – Core REK – Dupont Index Values

As can be seen from Figure 4.4, values drop steeply at the base of this core implying a rapid and high-magnitude shift to wetter mire conditions. However, this episode appears to be short-lived and values start to increase gradually from 174 cm. Drier mire conditions are indicated from 161 cm with values increasing rapidly and then remaining fairly uniform until 152 cm. Following this, values decline slightly before an episode of markedly oscillating hydrological conditions. Initially, values increase, rapidly reaching their maximum at 140 cm; however, this is short-lived and a steep and rapid decline in values is recorded at 138 cm. A relatively short episode of low values is then sustained until 130 cm indicating elevated water tables. Following this is a pronounced peak in values at 126 cm implying a shift to drier mire conditions. However, once again this period is short-lived and values decline to their lowest point throughout the core at 120 cm indicating a shift to wetter conditions. It is clear from Figure 4.4 that markedly fluctuating hydrological conditions are implied between 148 and 102 cm with short-lived and often high-magnitude shifts between wet and dry mire conditions recorded in the profile. After this period values record less variability and relatively stable conditions are maintained. It is noticeable that values decrease slightly at *c.*50 cm and this coincides with the replacement of *Sphagnum fuscum* by *S. magellanicum*.

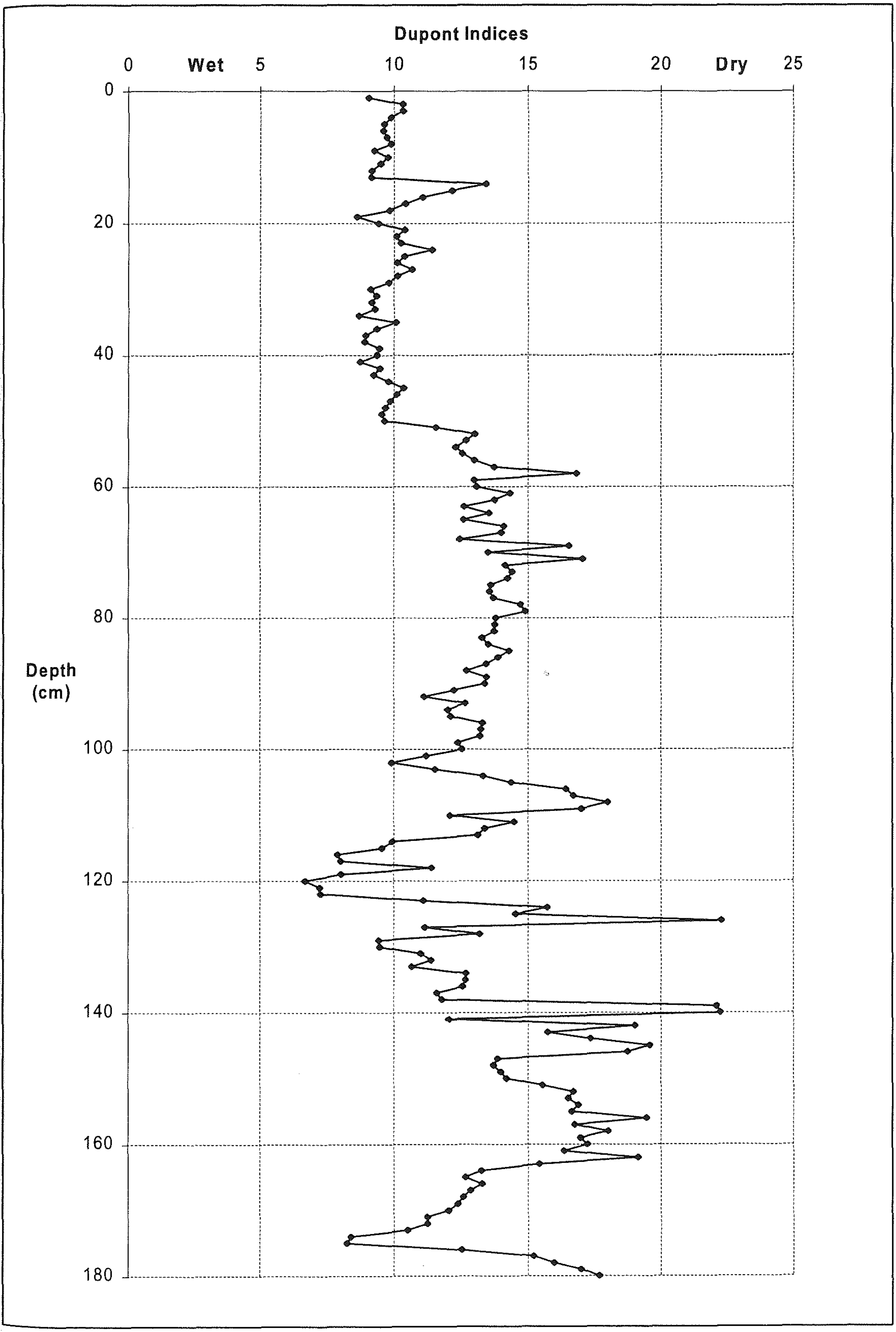

Figure 4.4 Dupont Index values for Reksuo

4.2.3 Männikjärve – Core MANN – Dupont Index Values

The start of this profile is marked by relatively uniform values from 180 cm to 141 cm. A single point at 173 cm may indicate a shift to wetter mire conditions although this is not a prolonged episode. Following this, a period of oscillating hydrological conditions is implied with an initial phase of drier mire conditions at 138 cm giving way to wetter conditions at 134 cm before a return to drier mire conditions at 127 cm. Values then continue to fluctuate until 115 cm. A period of relatively stable mire conditions is indicated between 114 cm and 85 cm before a gradual and low-magnitude shift to drier conditions at *c.*82 cm. Values then continue to rise gradually until 51 cm implying a prolonged period of lowered water tables. Once again the implied shift to wetter conditions at *c.*48 cm is coincident with the replacement of *Sphagnum fuscum* by *S. magellanicum* and it may be that this represents a vegetational change rather than a record of hydrological change.

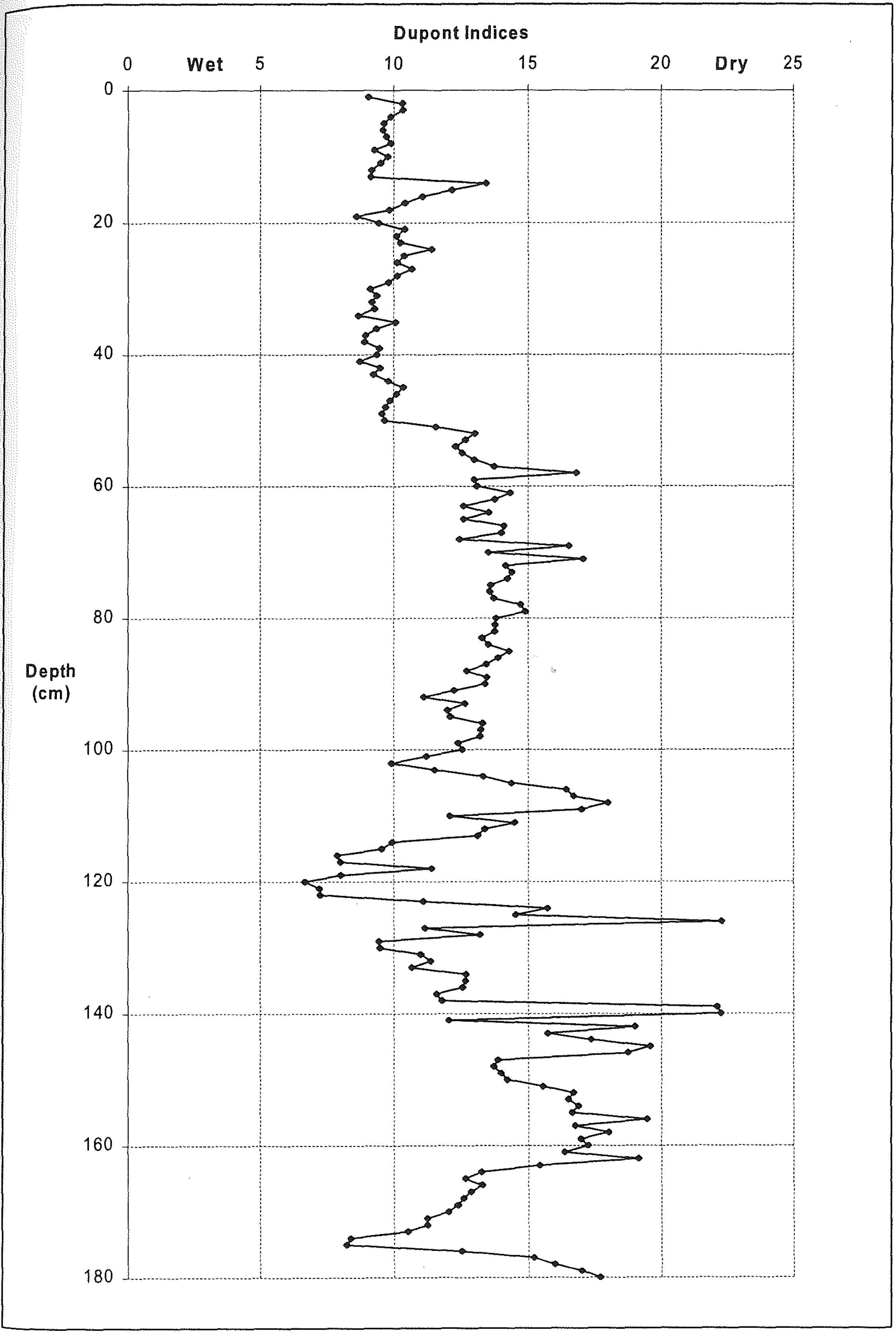

Figure 4.4 Dupont Index values for Reksuo

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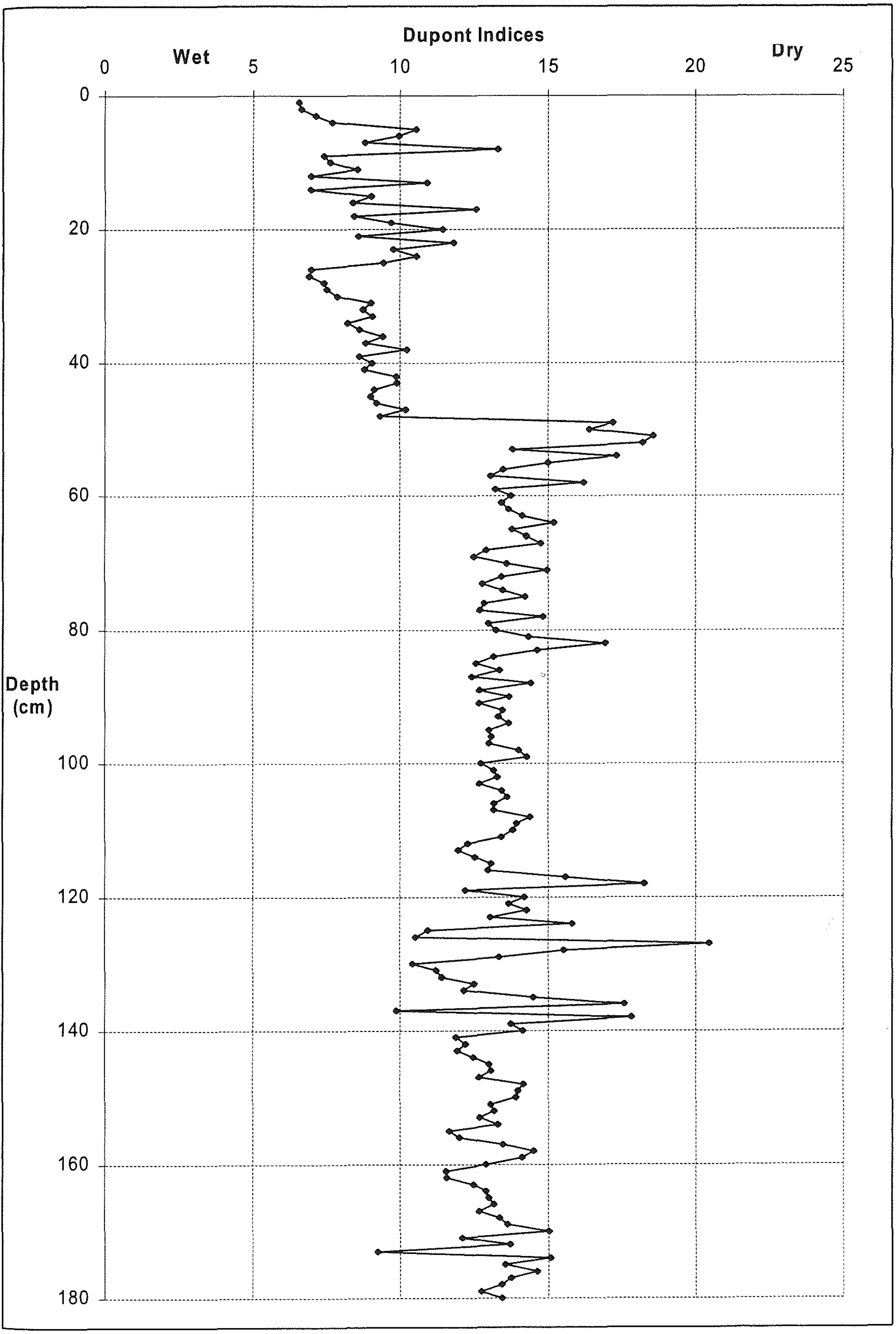


Figure 4.5 Dupont Index values for Männikjärve

4.2.4 Kuistlema – Core KUIS – Dupont Index Values

The base of this core is characterised by relatively uniform values with Dupont Index values ranging between 10 and 15. A possible low-magnitude shift to drier mire conditions is evident at 172 cm although this is once again a short-lived episode. The first significant peak in Dupont values occurs at 117 cm indicating a shift to drier mire conditions. However, values quickly return to their former levels and although there are several individual peaks and troughs in the data there is no sustained change in values that may imply a major shift in the mire's hydrology. At *c.*79 cm values decline marginally and a possible shift to wetter conditions may be implied. However, this episode is again short-lived and following this a period of relatively uniform values is evident until 51 cm. Succeeding this, a period of markedly fluctuating hydrological conditions is implied by the Dupont data. Initially, a period of drier mire conditions is indicated with higher values, but this appears to have been interrupted by a high-magnitude but short-lived shift to much wetter conditions at 47 cm. However, a rapid return to drier conditions is implied. This again appears to be short-lived and at *c.*38-39 cm a return to wetter conditions is implied by the data. Subsequently, the data imply oscillating hydrological conditions with higher values implying drier conditions at 30 cm and 23 cm interrupted by a return to slightly wetter conditions with values close to the core average.

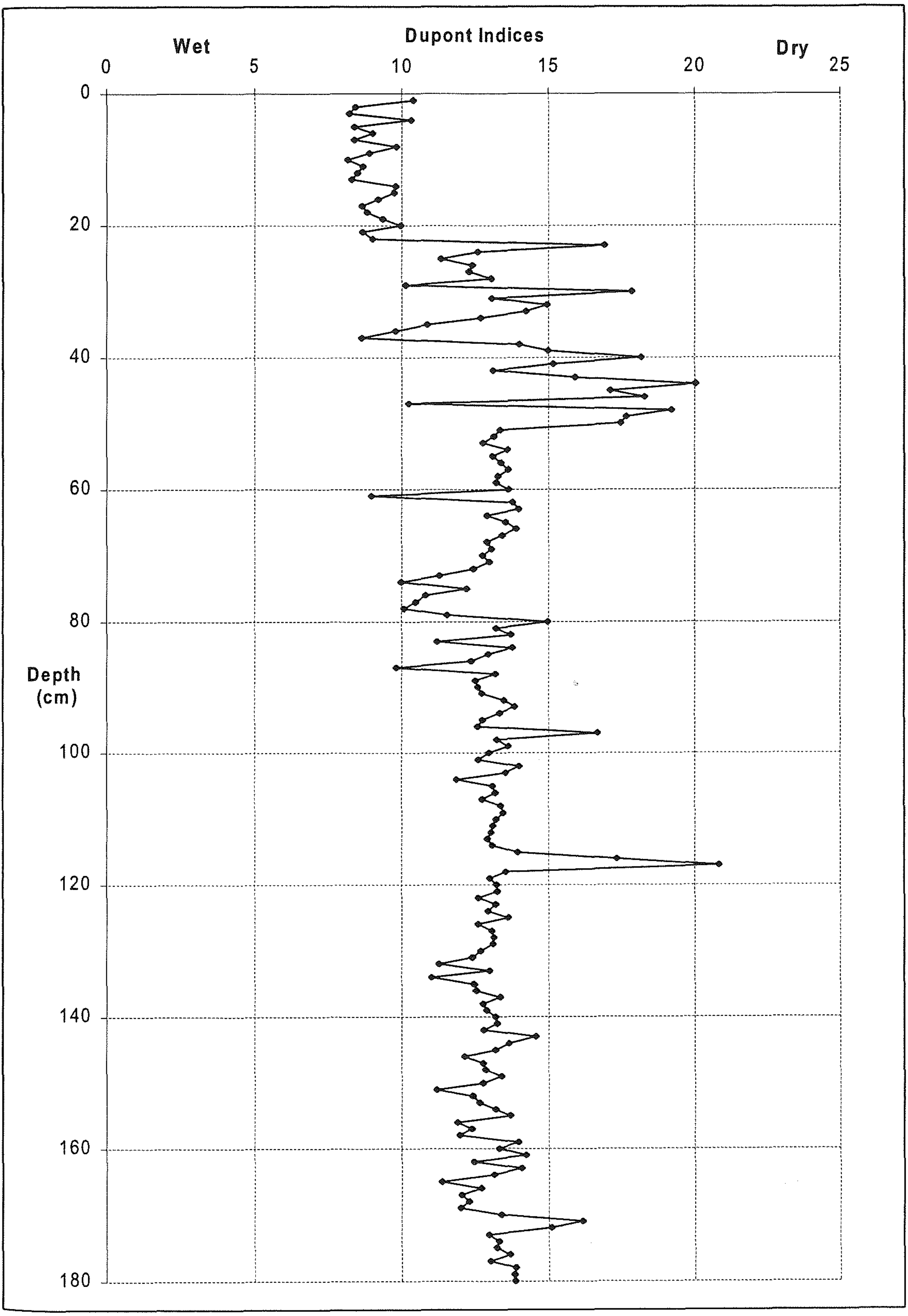


Figure 4.6 Dupont Index values for Kuistlema

4.3 Detrended Correspondence Analysis of plant macrofossil data

Detrended Correspondence Analysis (DCA) is an ordination technique designed to assess statistically the ecological niche (optima) of the components in the data being analysed. These components are then arranged so that the DCA axes maximise the separation of the 'ecological niche' or optima and hence explain the greatest possible amount of variation (Hill & Gauch, 1980; ter Braak, 1995). Axis 1 of the DCA is therefore a latent variable that explains the most variation in the data under the assumption of a unimodal species-response model. On ombrotrophic peat bogs the position of the water table is considered the primary control of species composition and it is therefore likely that the latent variable established by DCA reflects this niche separation (Kovach, 1995; Karadzic, 1999).

DCA was originally developed by Hill & Gauch (1980) as a means of eliminating some of the problems encountered using Correspondence Analysis (CA). In particular, DCA enables correction of what is known as the 'arch effect'. This occurs when the points are positioned in an arched pattern along the first two axes, rather than in a linear sequence as would be assumed. The arch is a result of the data reduction process and denotes a mathematical relationship between the first two axes, which are assumed to be independent (ter Braak, 1995; Kovach, 1995). This problem is especially pronounced when a long environmental gradient has been sampled. DCA overcomes this problem by applying a 'detrending procedure', whereby any polynomial relation between the first and higher ordination axes is removed (Karadzic, 1999). It is also worth noting that whilst this method is often able to provide clearer and more easily interpretable results it may also distort or cause instability of its own (Kovach, 1995). The second fault, which is a result of the first, is the compression of data points at the ends of the axes compared with the middle. This can result in taxa that are equally dissimilar appearing closer together when positioned at the end of the axes when compared to their position when placed toward the axes centre. Hill & Gauch (1980) note that this problem can be overcome by using non-linear rescaling to ensure the Gaussian response curve widths for all taxa are approximately equal.

DCA has been widely used in recent palaeoecological research and is arguably the most effective ordination procedure at interpreting taxon distribution in proxy datasets. Nevertheless, this technique is not without certain limitations and notable problems can occur when trying to analyse certain types of data (Hill & Gauch, 1980). The first of these is when outliers or rare taxa are apparent in the dataset. Hill & Gauch (1980) note that where these rare taxa are present, they may dominate the first axis, complicating the interpretation of underlying environmental gradients. Whilst it is possible to down-weight these extreme outliers in several statistical programmes, Hill & Gauch suggest that the most effective way of dealing with the problem is to remove them entirely. A further limitation of the DCA procedure is its inability to contend with datasets where a single taxon is dominant. Once again whilst several options are available to manipulate the dataset statistically or transform it into an unbiased format, Hill & Gauch advise against this and recommend that an ordination should at first be attempted on the untransformed dataset. A comprehensive review of the DCA technique is provided by ter Braak (1995) and Kovach (1995).

For this project DCA was applied to all four sites with the results presented here in the form of scattergrams. Initially, datasets were composed of all of the taxa that were regularly recorded in the macrofossil diagram. However, as results generally failed to show a clear hydrological gradient between taxa, several other options were tried. Firstly, outliers were down-weighted and then finally removed. Secondly, *Sphagnum fuscum* and *S. magellanicum* were removed, as both of these taxa are dominant at different sections of the core. Several other taxa were either selectively removed or combined to see whether a clearer hydrological gradient could be determined.

Unfortunately results remained ambiguous with only two of the sites displaying any kind of hydrological gradient for the data. Therefore, to avoid the unnecessary manipulation of data or the production of biased results the datasets used here remain unchanged. DCA results for each macrofossil dataset are presented as scattergrams with initially the macrofossil components displayed and then the spread of samples for each site. Therefore, where data points are clustered around a particular taxon, the greater the proportion that sample has of that taxon. DCA axis 1 scores have been plotted against depth in order to identify shifts in the mire's hydrology and enable intra-site comparison of the proxy datasets.

4.3.1 DCA Results – Munasuo – Core MUN

The DCA ordination for this dataset is presented in Figures 4.7 & 4.8. Initially, species only were plotted on the scattergram in order to determine whether a hydrological gradient could be established for each taxon. As is apparent from Figure 4.9, axis 1 of the DCA scattergram does not appear to be a hydrological gradient. This is exemplified by such species as *Scheuchzeria palustris* and *Sphagnum cuspidatum* positioned at the same point along the axis as *Calluna* and *Sphagnum fuscum*. It is clear from the scattergram that no hydrological separation of the species has occurred.

In Figure 4.7 the spread of data has been incorporated into the scattergram. The DCA results show that the taxon scores are well spread along Axis 1, accounting for 57% dispersion of the data points. As the positioning of particular taxa seems to rule out this axis being a hydrological gradient it is likely that the spread of taxon scores is representative of some other environmental factor or possibly the stratigraphical changes in species composition along the core.

Figure 4.8 shows the DCA axis 1 scores plotted against depth. It is clear from comparing this graph with the macrofossil diagram that the major fluctuation in axis 1 scores that occurs between *circa* 63-83 cm depth is a function of the replacement of *S. fuscum* by *S. magellanicum*. A comparison of the DCA results with the humification transmission graph (Figure 4.9) demonstrates that there is generally poor agreement between the two datasets.

It is clear that for this site DCA is unable to produce an effective hydrological ordination of the species. This may be because of the dominance of a particular taxon - in this instance *S. fuscum* - or possibly the number of rare taxa (i.e. outliers) contained within the dataset.

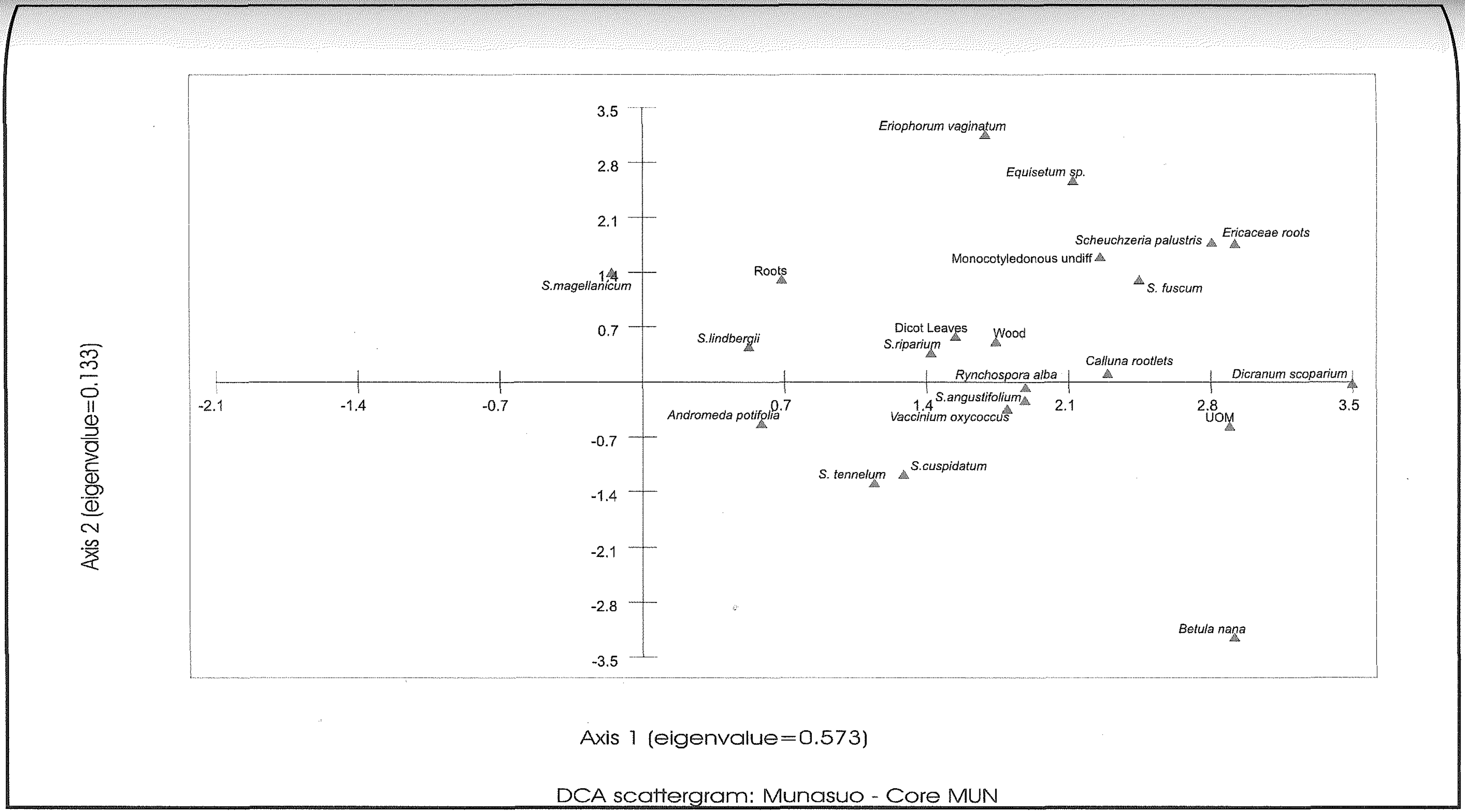
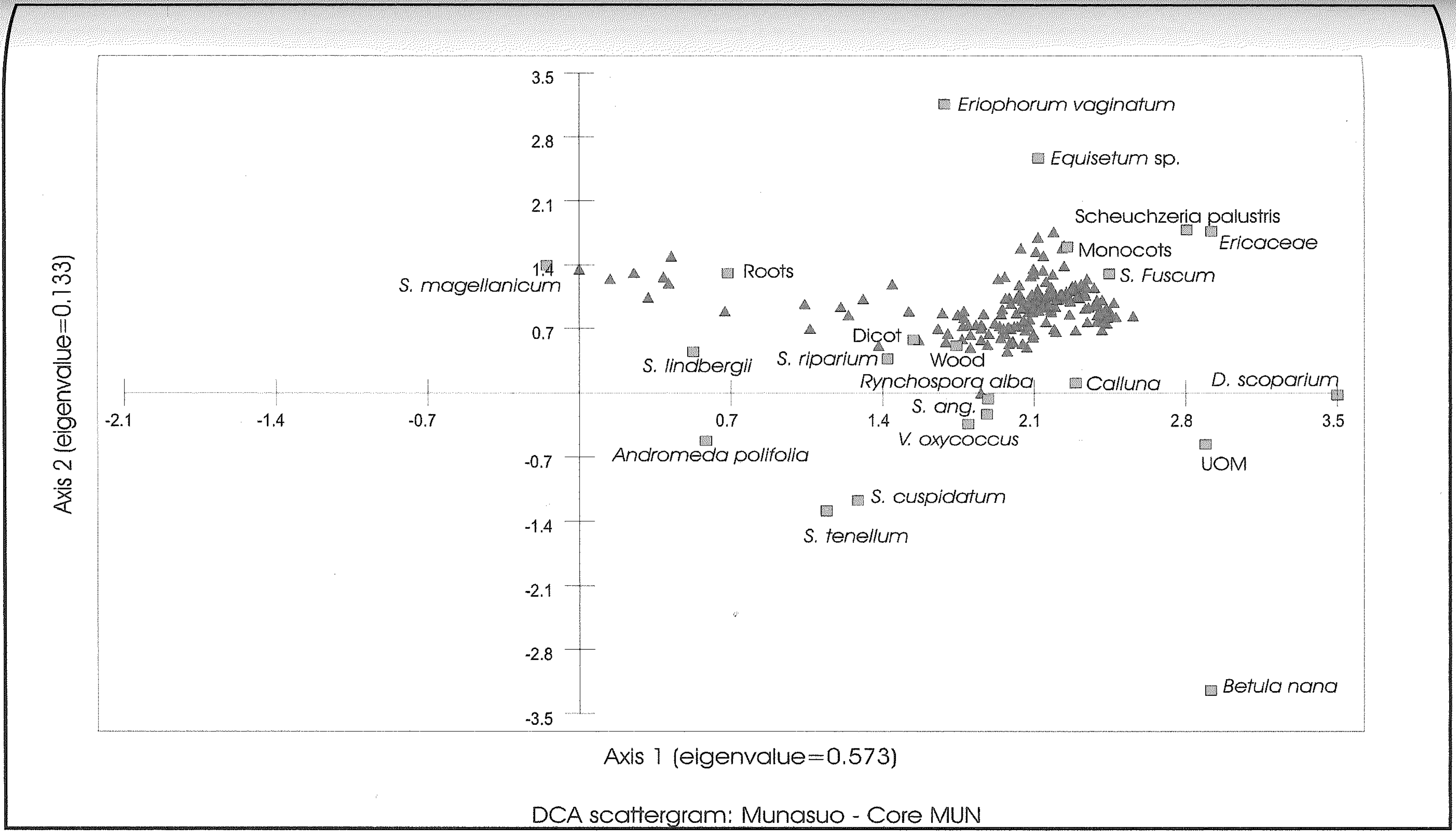

Eriophorum vaginatum
Equisetum sp.
Scheuchzeria palustris
Ericaceae roots
Monocotyledonous undiff
S.magellanicum
Roots
S. fuscum
Dicot Leaves
Wood
S.lindbergii
S.riparium
Calluna rootlets
Rynchospora alba
Dicranum scoparium
S.angustifolium
Andromeda potifolia
Vaccinium oxycoccus
UOM
S. tennelum
S.cuspidatum
Betula nana
3.5
2.8
2.1
1.4
0.7
-0.7
-1.4
-2.1
-2.8
-3.5
-2.1
-1.4
-0.7
0.7
1.4
2.1
2.8
3.5
Axis 2 (eigenvalue=0.133)
Axis 1 (eigenvalue=0.573)
DCA scattergram: Munasuo - Core MUN

Figure 4.7


Eriophorum vaginatum
Equisetum sp.
Scheuchzeria palustris
Ericaceae
Monocots
S. Fuscum
Roots
S. magellanicum
Dicot
Wood
S. lindbergii
S. riparium
Rynchospora alba
Calluna
D. scoparium
S. ang.
V. oxycoccus
Andromeda polifolia
UOM
S. cuspidatum
S. tenellum
Betula nana
3.5
2.8
2.1
1.4
0.7
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0.7
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3.5
Axis 2 (eigenvalue=0.133)
Axis 1 (eigenvalue=0.573)
DCA scattergram: Munasuo - Core MUN

Figure 4.8

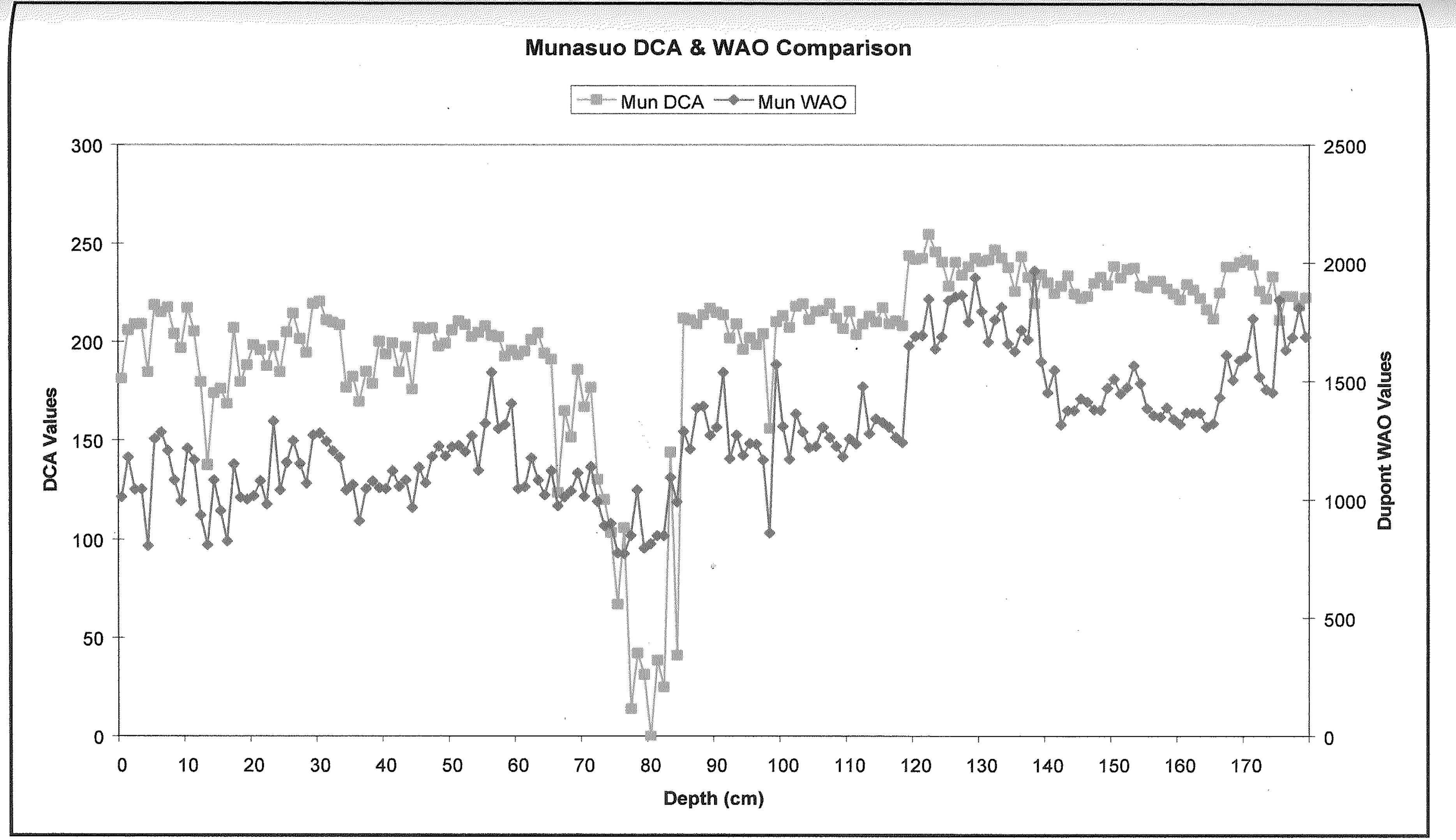


Figure 4.9 Comparison of DCA & WAO Data for Munasuo

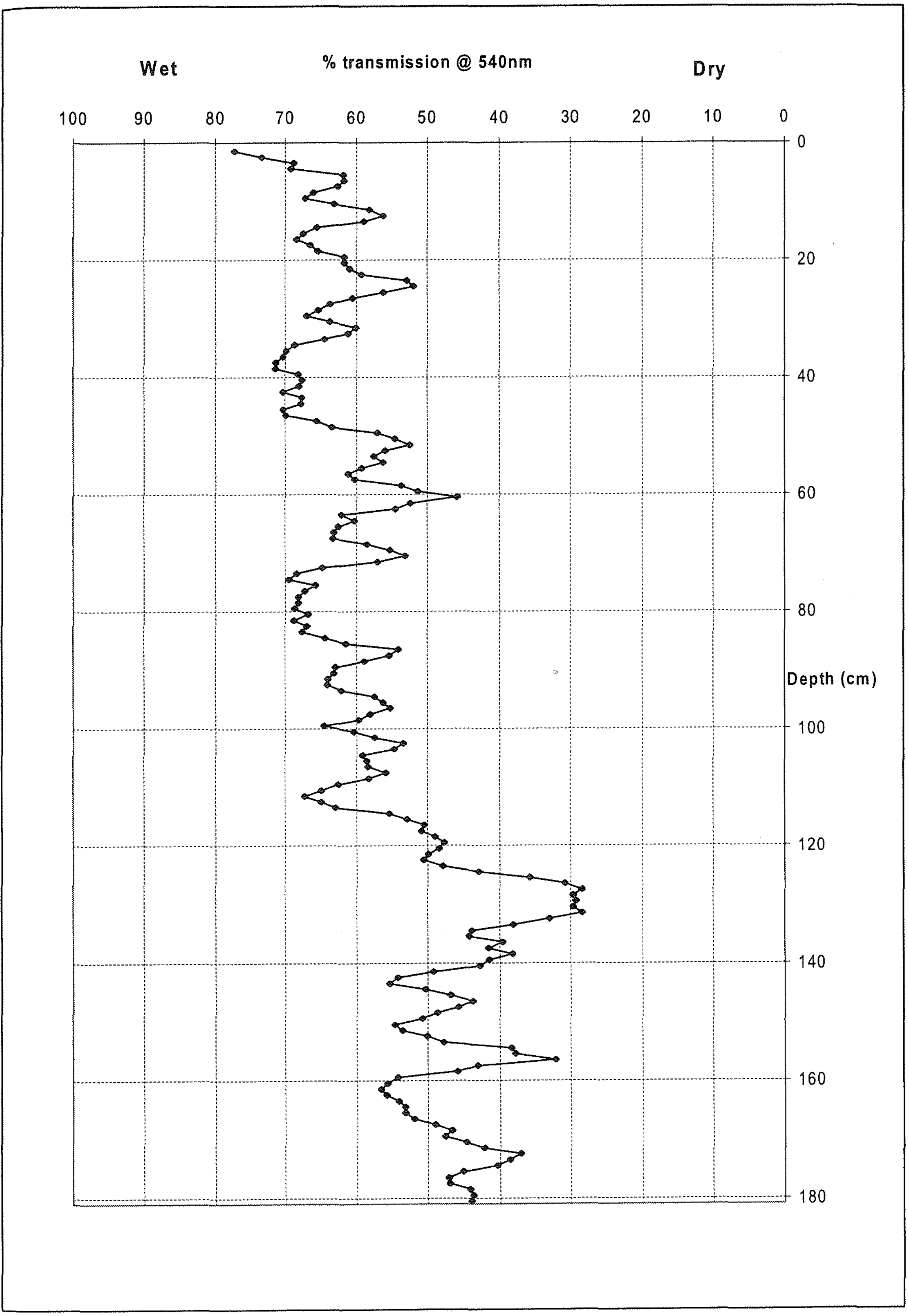


Figure 4.10 Peat Humification results for Munasuo (3 point running mean)

4.3.2 DCA results – Reksuo – Core REK.

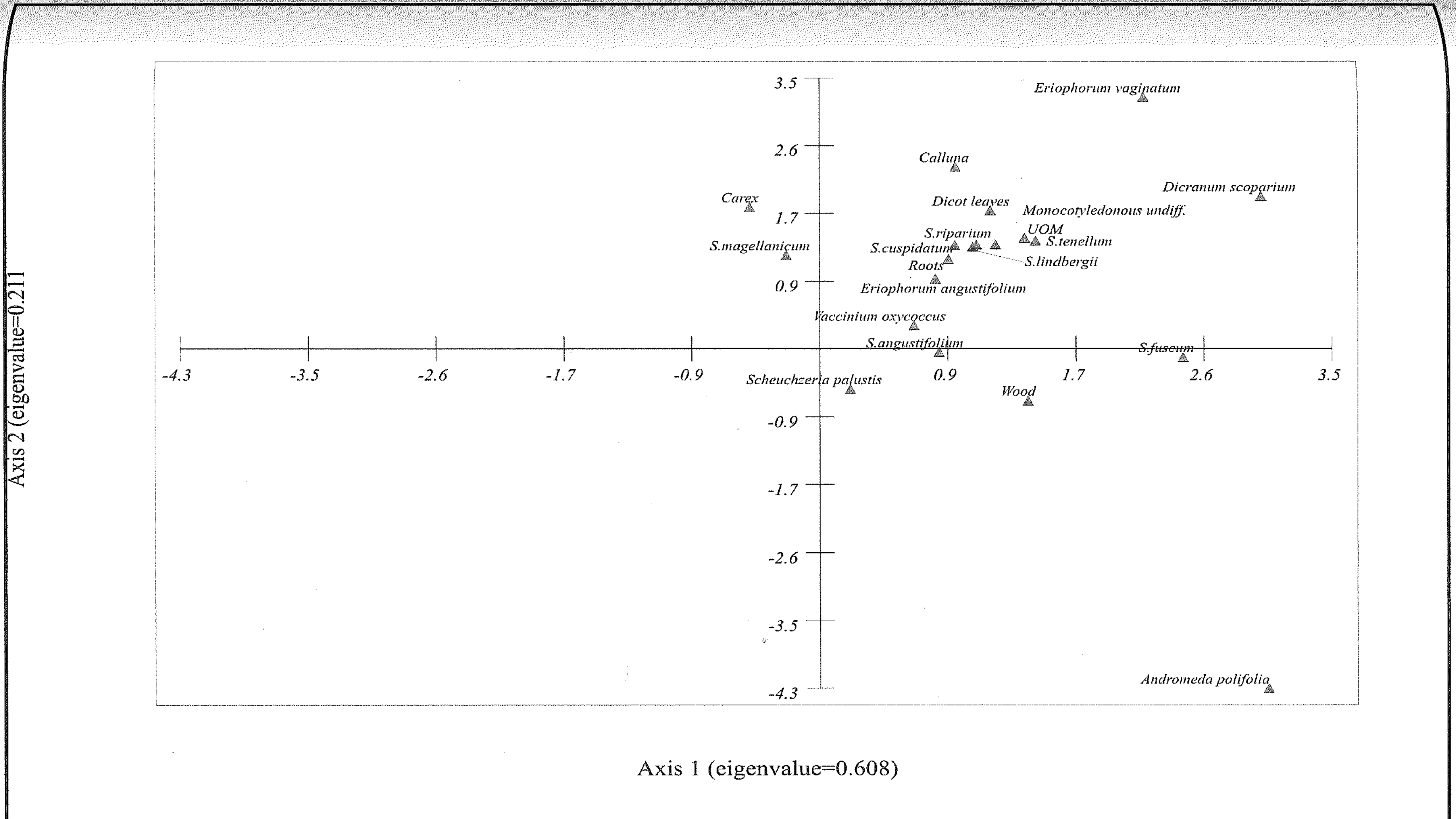
The DCA ordination results are again displayed on two scattergrams. The first of these (Figure 4.11) shows the spread and relative position of each of the taxa along axis 1 of the scattergram. The second (Figure 4.12) records the species score, the abundance and position of the data along the axis.

As can be seen from Figure 4.11 the taxa from this dataset have been plotted closely together, with the exception of *Andromeda polifolia*. The DCA taxon scores for this site are ambiguous. A weak hydrological gradient may be detected within the dataset although this is by no means certain. *Dicranum scoparium, E. vaginatum, wood* and *S. fuscum* are all positioned towards the right of axis 1 with relatively high eigenvalues. However, the position of *S. tenellum* appears anomolous, as it is similar to that of wood and in fact further along axis 1 than UOM. Similarly, the position of *Calluna* appears to be anomolous as it is positioned alongside *S. cuspidatum, S. riparium* and *E. angustifolium.* These anomalies in conjunction with the relatively small spread of data imply that the ordination of these species along axis 1 may again be representing another environmental variable, or stratigraphical changes.

Figure 4.13 shows the DCA axis 1 eigenvalues plotted against depth. It is clear that once again there is a clear stratigraphic change recorded at *c.*46 cm when *S. magellanicum* effectively replaces *S. fuscum* as the principal *Sphagnum* species. However, at several other points along the core there appears to be some correlation between the datasets that may imply hydrological change on the mire. Most notably the humification dataset (Figure 4.14) records a shift to wetter conditions at *c.*122 cm and then again at *c.*130 cm. The

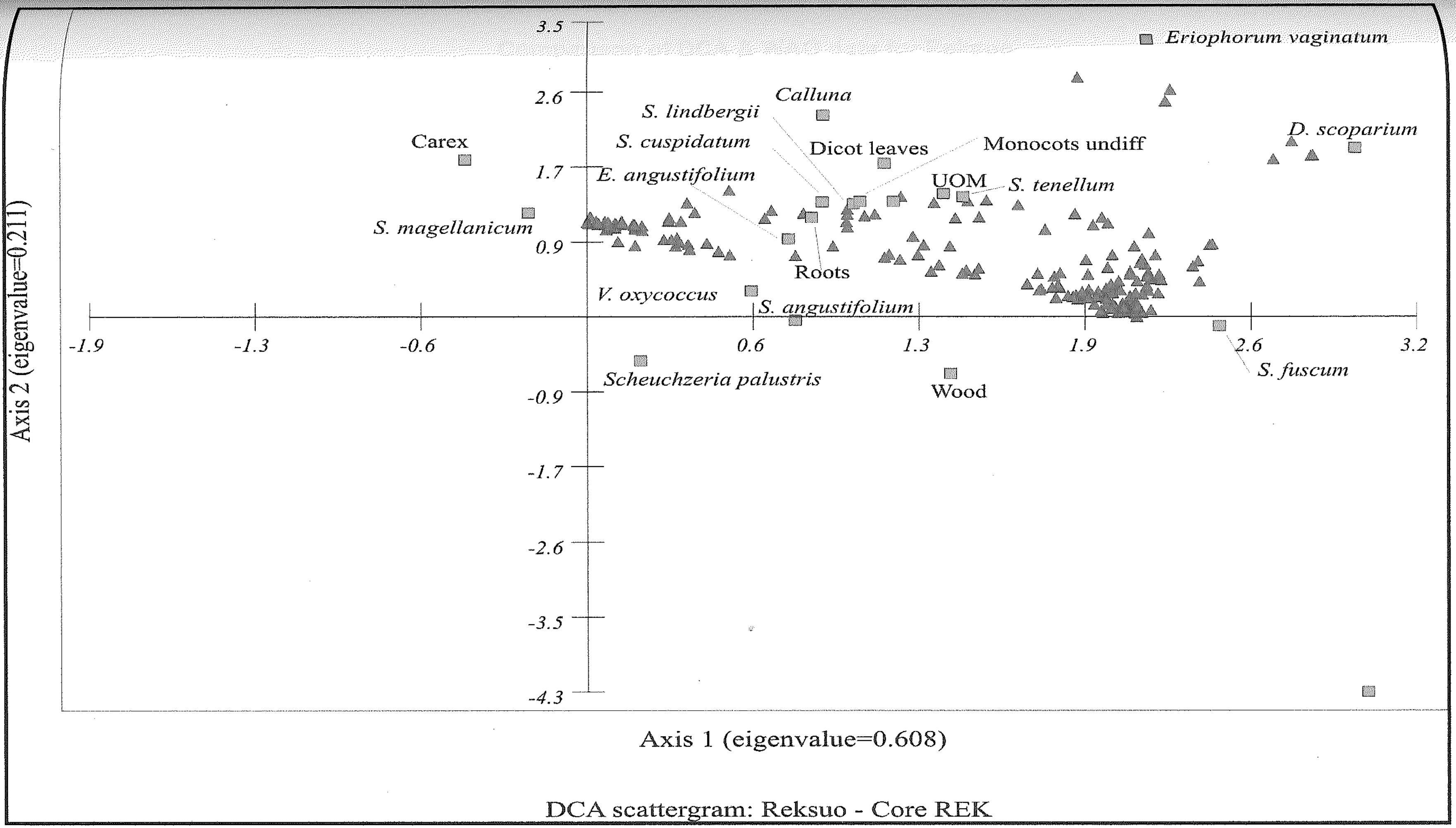
DCA results might also record this shift to wetter conditions with an episode of relatively low eigenvalues centred around 115 - 125 cm. Similarly, both datasets record a shift to drier conditions immediately after this episode. However, it is noticeable that this is much more pronounced in the DCA record with eigenvalues reaching their maximum point. Additionally, between approximately 170 – 175 cm both datasets record a shift to wetter conditions, although this is once again more pronounced in the DCA dataset.

Whilst by no means unequivocal there is some correspondence between the two datasets. It may be for this site that the two proxies are recording fluctuations in the mire's hydrology that is driven by climate change. The datasets record several other episodes of hydrological change although these do not appear to be synchronous or corroborated by the other dataset. Whether these fluctuations are indeed a function of hydrological change or are due to composition changes within the plant macrofossil assemblage is unclear. It may be that DCA in this instance has arranged the species in such a way that a hydrological gradient and possibly a stratigraphical change in species composition, is recorded along the same axis.



DCA scattergram: Reksuo - Core REK

Figure 4.11


Eriophorum vaginatum
Calluna
S. lindbergii
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Carex
Dicot leaves
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-0.9
-1.7
-2.6
-3.5
-4.3
-1.9
-1.3
-0.6
0.6
1.3
1.9
2.6
3.2
Axis 2 (eigenvalue=0.211)
Axis 1 (eigenvalue=0.608)
DCA scattergram: Reksuo - Core REK

Figure 4.12

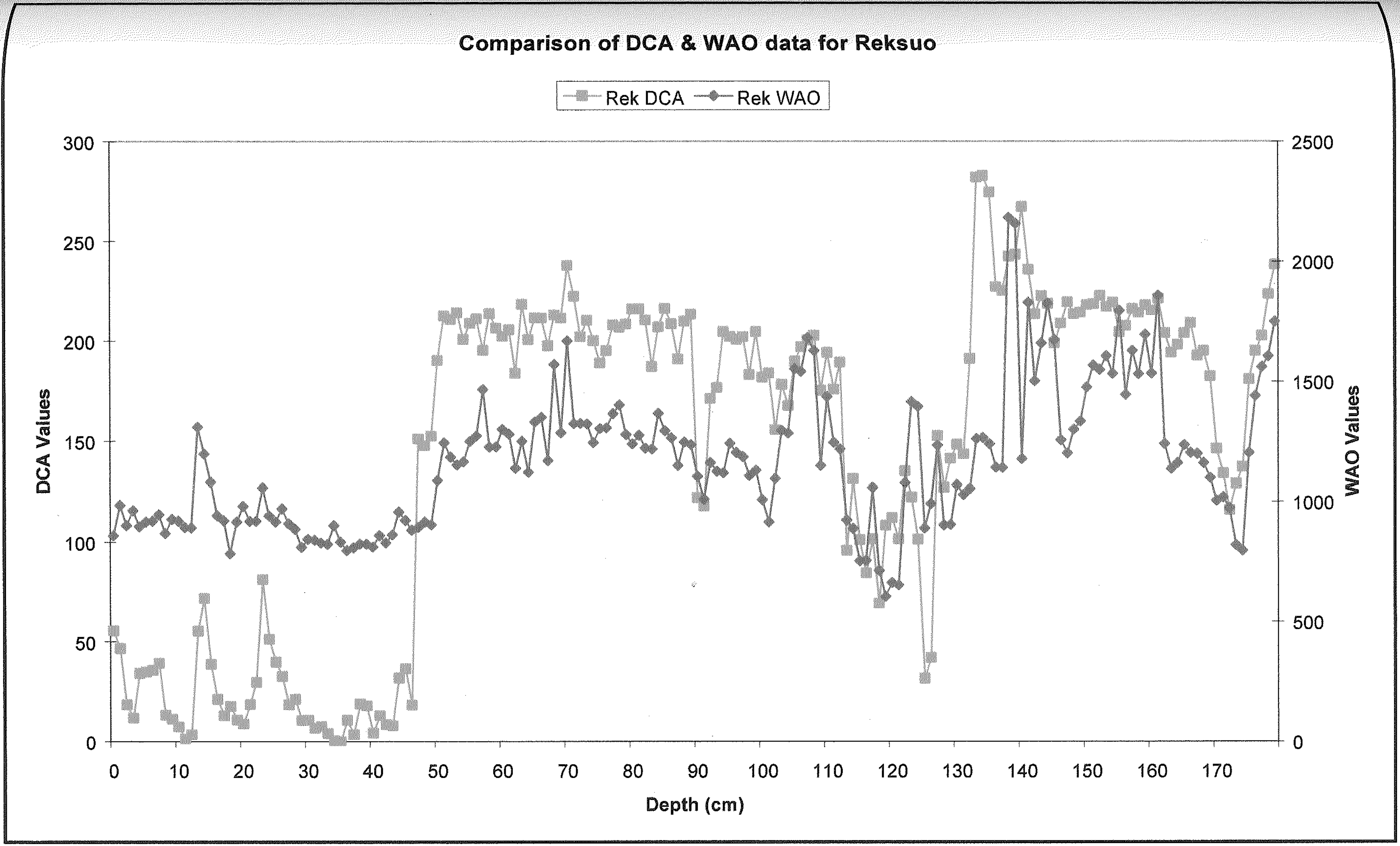

Figure 4.13 Comparison of DCA & WAO Data for Reksuo

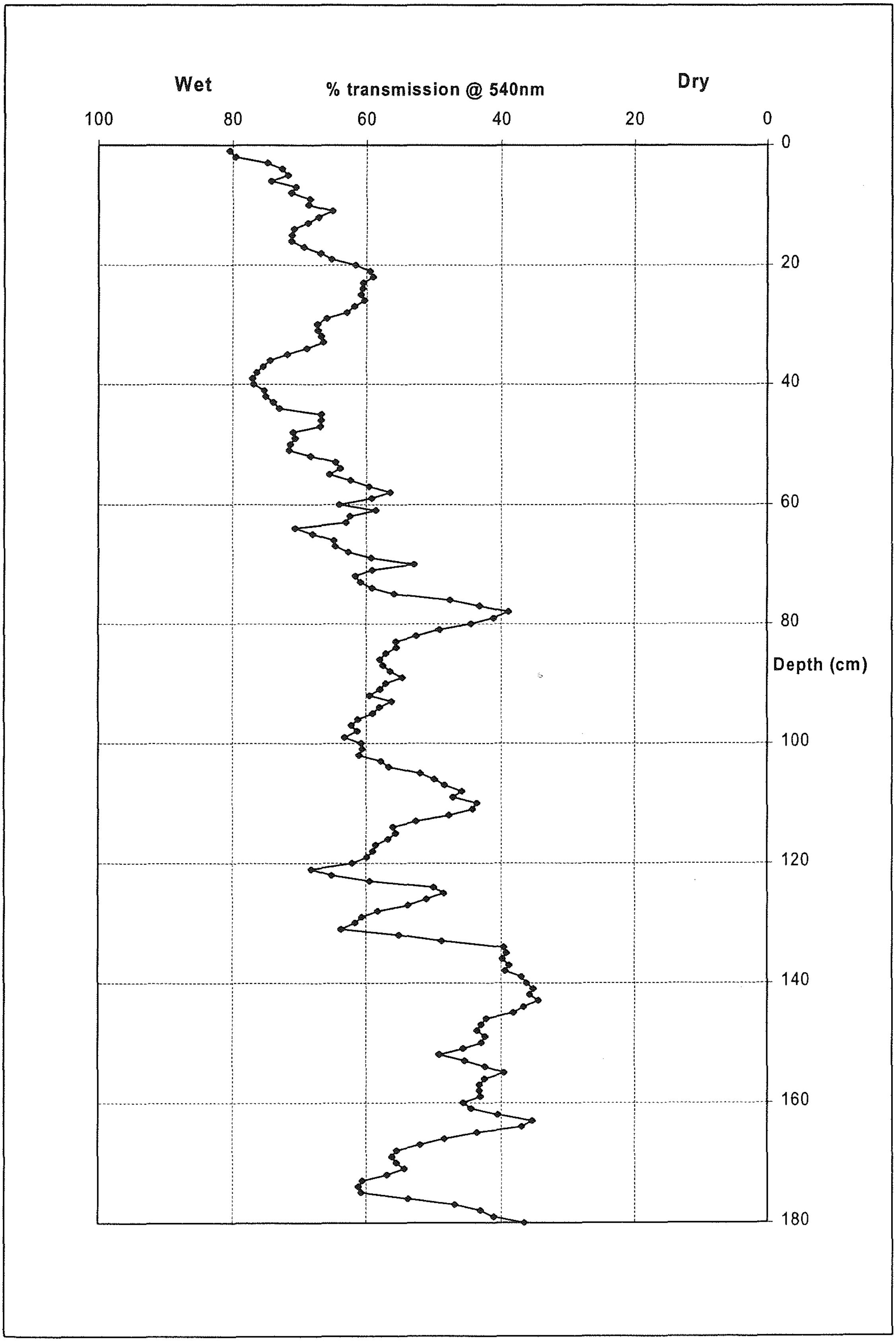

Figure 4.14 Peat Humification results for Reksuo (3 point running mean)

4.3.3 DCA results – Männikjärve – Core MANN

The DCA ordination results for Männikjärve are presented in Figures 4.15 & 4.16. As can be seen from Figure 4.17 the taxa are well spread along axis 1 with the majority of dry indicator taxa positioned towards the right of the scattergram. The spread of data therefore implies that axis 1 may be a hydrological gradient. However, as with Reksuo there are several exceptions to this. Most notably the position of *Sphagnum tenellum* implies drier conditions; interestingly an examination of the macrofossil diagram confirms this, with *S. tenellum* often found in association with *Eriophorum vaginatum* and *Calluna.*

As can be seen from Figure 4.16 the DCA results show that the taxon scores are well spread along axis 1, accounting for 62% dispersion of the data points. It is evident from the positioning of the samples that there are two fairly distinct clusters of data points. The first and most pronounced of these is centred on *Sphagnum fuscum* whilst the second cluster is more evenly spread around *S. magellanicum, S. riparium, S. cuspidatum* and *Vaccinium oxycoccus.* Once again it may be that this simply represents the stratigraphical change between *S. fuscum* and *S. magellanicum.*

Figure 4.17 shows the DCA axis 1 scores plotted against depth and it is evident that the major shift in eigenvalues at *c.*45-46 cm is coincident with the change in *Sphagnum* species. A comparison of the humification transmission dataset (Figure 4.18) and the DCA results indicate that the implied hydrological changes are sometimes contradictory. A shift to drier conditions at around a depth of 64 cm can be inferred from both proxies. The oscillating hydrological conditions evident between 81 – 101 cm are broadly supported by each dataset. However, whilst the humification data imply relatively drier conditions between depths of 121 to 141 cm the DCA results seem to imply fluctuating conditions with the exception of a single data point that indicates much drier mire conditions. Comparison of the datasets between *c.*141 and 161 cm suggest that an inverse correlation is apparent between each dataset. However, as explained in chapter 3, the high proportion of *E. vaginatum* may have resulted in spurious humification data. It is likely therefore that the shift to drier conditions implied by the DCA dataset is correct and the humification data simply reflect the technique's limitations when high proportions of *E. vaginatum* are present at the expense of *Sphagnum.*

In general the DCA results appear to show some evidence of hydrological change on the mire although once again the most prominent change appears to reflect a stratigraphic replacement of *S. fuscum* by *S. magellanicum.*

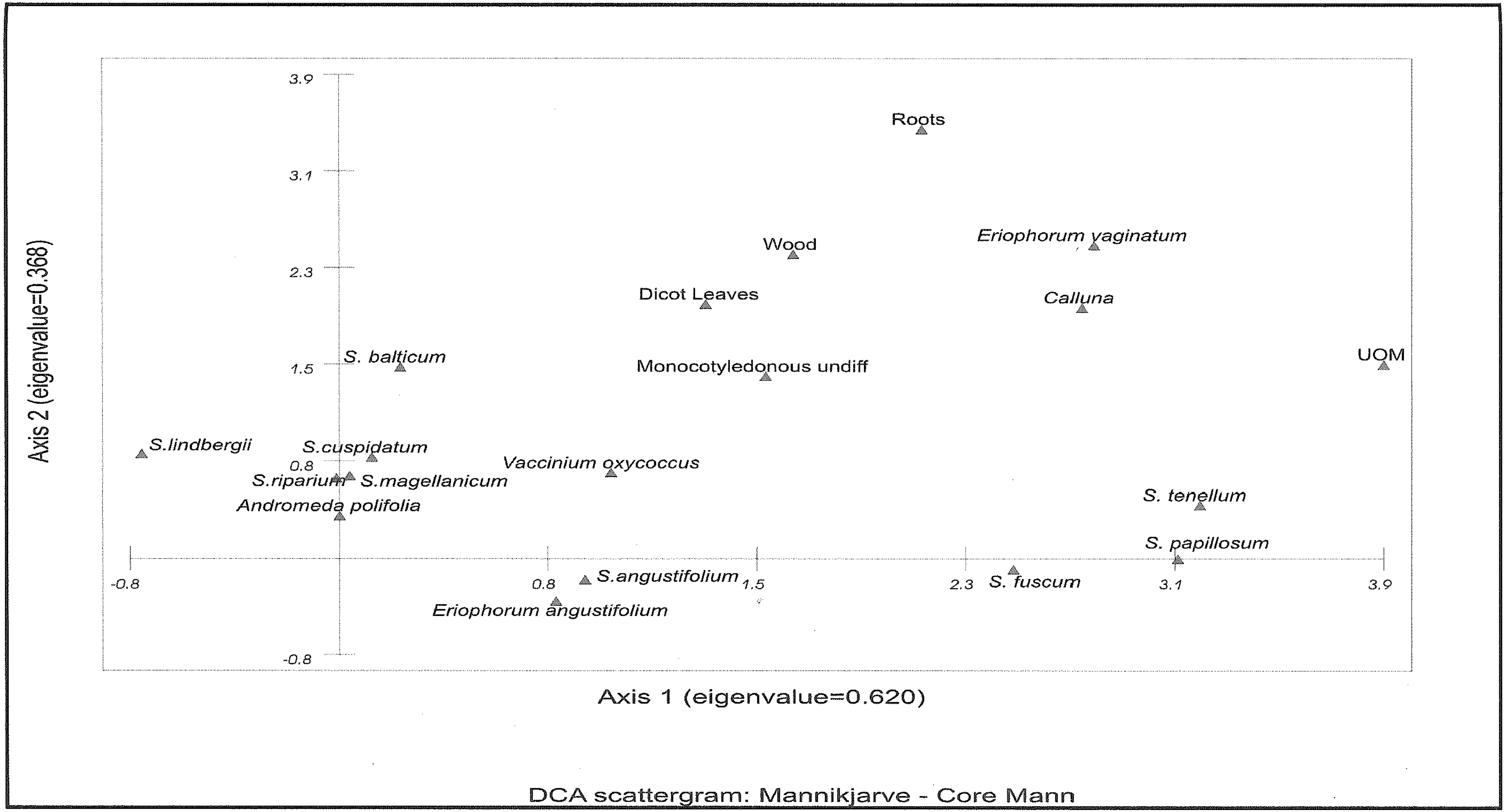
3.9
3.1
2.3
1.5
0.8
-0.8
-0.8
0.8
1.5
2.3
3.1
3.9
Roots
Wood
Eriophorum vaginatum
Dicot Leaves
Calluna
S. balticum
Monocotyledonous undiff
UOM
S.lindbergii
S.cuspidatum
Vaccinium oxycoccus
S.riparium
S.magellanicum
Andromeda polifolia
S. tenellum
S. papillosum
S.angustifolium
S. fuscum
Eriophorum angustifolium
Axis 2 (eigenvalue=0.368)
Axis 1 (eigenvalue=0.620)
DCA scattergram: Mannikjarve - Core Mann

Figure 4.15

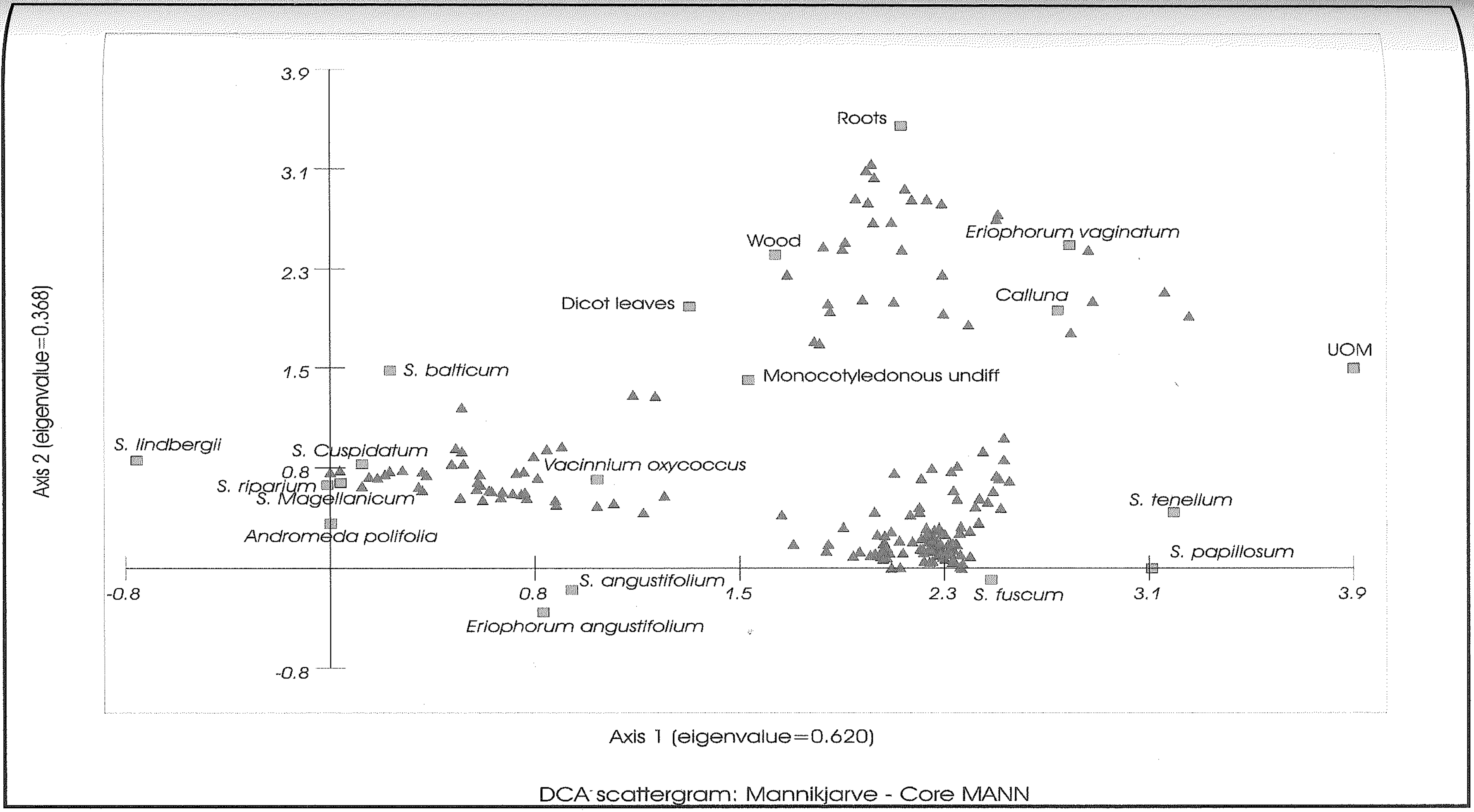
3.9
3.1
2.3
1.5
0.8
-0.8
Axis 2 (eigenvalue=0.368)
-0.8
0.8
1.5
2.3
3.1
3.9
Axis 1 (eigenvalue=0.620)
Roots
Wood
Eriophorum vaginatum
Dicot leaves
Calluna
UOM
S. balticum
Monocotyledonous undiff
S. lindbergii
S. Cuspidatum
Vacinnium oxycoccus
S. riparium
S. Magellanicum
Andromeda polifolia
S. tenellum
S. papillosum
S. angustifolium
S. fuscum
Eriophorum angustifolium
DCA scattergram: Mannikjarve - Core MANN

Figure 4.16

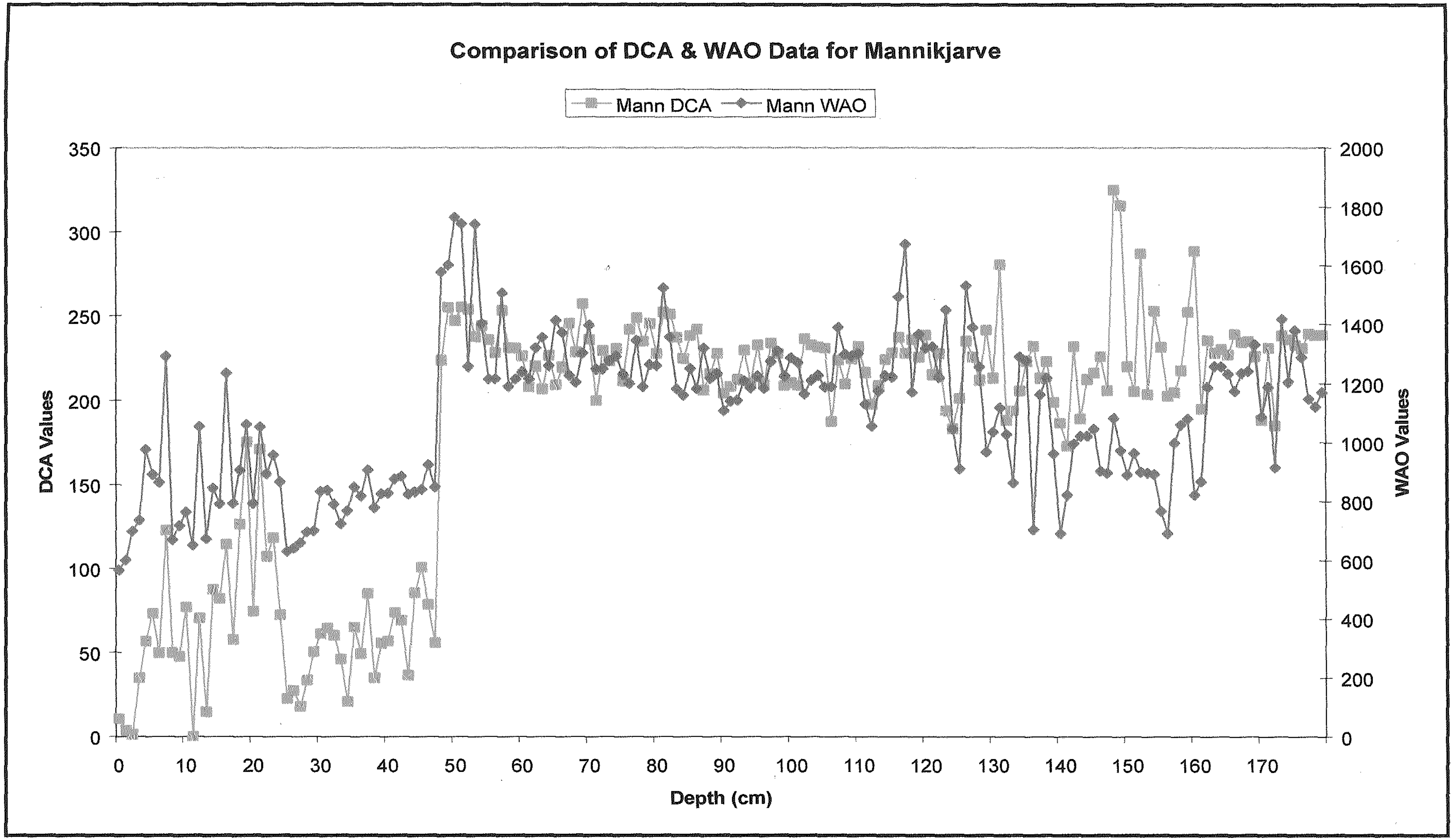

Figure 4.17 Comparison of DCA & WAO Data for Mannikjarve

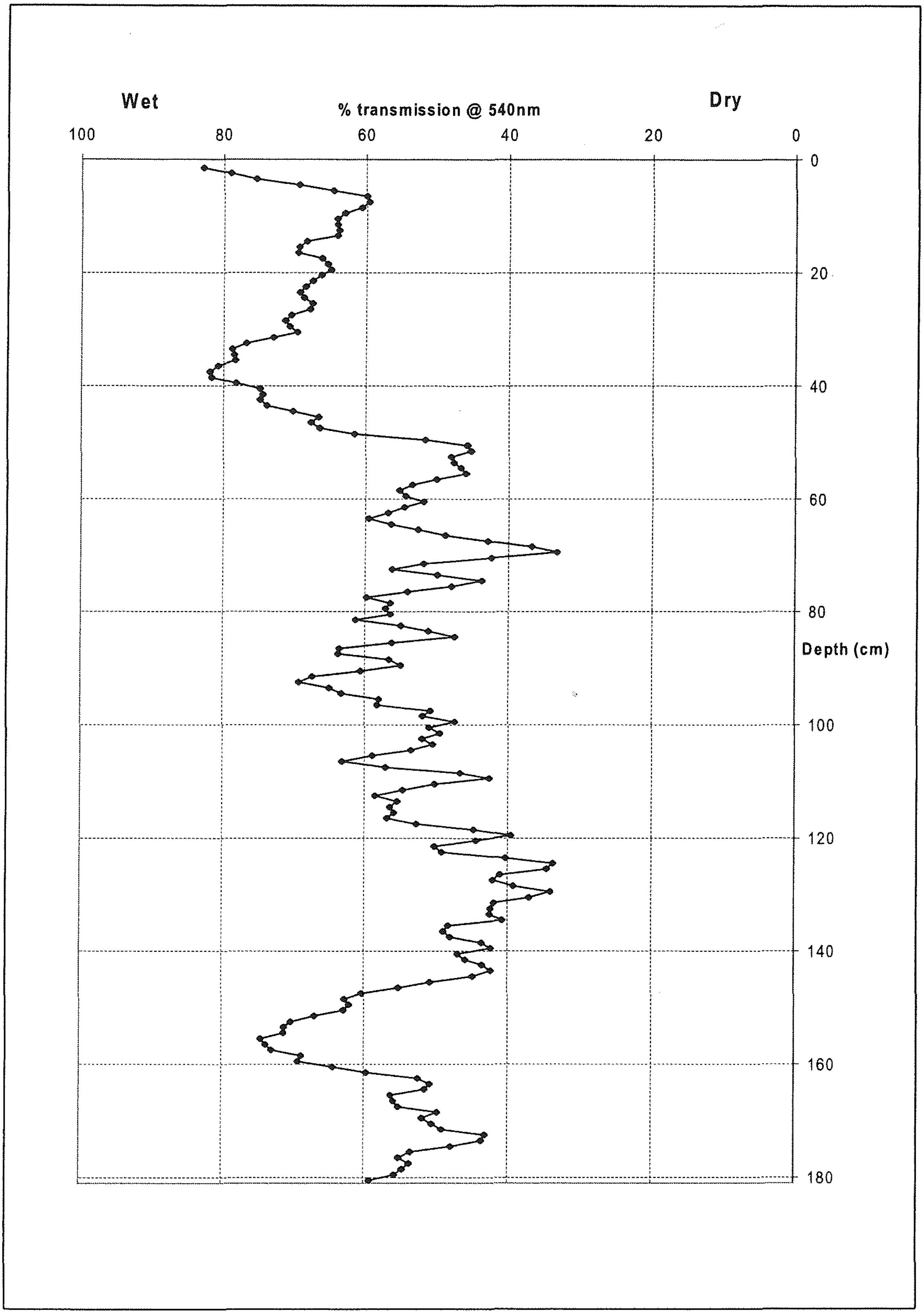

Figure 4.18 Peat humification results for Männikjärve (3 point running mean)

4.3.4 DCA results – Kuistlema – Core KUIS

The DCA ordinations for this dataset are presented in Figures 4.19 & 4.20. As can be seen from Figure 4.19, the taxa are positioned primarily to the right of the DCA scattergram. It is again clear that the relative position of taxa implies that axis 1 is not a hydrological gradient. *Sphagnum tenellum* and *S. cuspidatum* are again positioned to the far right of axis 1 whilst UOM, *Calluna*, wood and *Eriophorum vaginatum* are located more centrally.

The data points on Figure 4.20 are again clustered primarily around either *S. magellanicum* or *S. fuscum,* implying that the major difference in the DCA dataset is the stratigraphical replacement of *Sphagnum* species. However, unlike either Reksuo or Männikjärve there appears to be no hydrological ordering of the macrofossil assemblage.

A comparison of the humification dataset (Figure 4.22) and the DCA dataset (Figure 4.21) shows that there is once again minimal correspondence between the two proxy datasets. Between approximately 21 and 61 cm the humification data imply a shift to drier mire conditions with values typically between 30 – 50%. The DCA results indicate oscillating hydrological conditions for this period with limited evidence of a shift to drier conditions. It is notable that, apart from a single data point, values remain relatively constant, rarely exceeding 300 or dropping below 250.

N.B – For all of the above datasets, several attempts were made to manipulate the data to produce a hydrological gradient of the macrofossil species. Firstly, several attempts were made either to down-weight or to remove rare species (outliers). Secondly, *S. fuscum* and *S. magellanicum* were initially taken out of the dataset and then alternatively the values of these taxa were amalgamated. (See Barber *et al.* 1994 for a justification of this procedure.) Unfortunately, none of the above had the desired effect and no clear hydrological gradient could be derived from the datasets for all four sites. Therefore, the DCA datasets have been left without amendment or manipulation to demonstrate that every care and option was taken before concluding that the procedure did not yield a clear hydrological gradient.

Further investigation of this technique has shown that even on previously published sites in the UK, DCA does not always provide a clear hydrological ordination of species (e.g. Blundell, 2004). From DCA results on Cloonoolish Moss (Blundell, 2003 p203) states: "the axis 1 scores loosely resemble a gradient of tolerance to water table levels, although it is far from conclusive." As no other palaeoclimatic research has been carried out at the sites chosen for this project, it may be that changes in the plant macrofossil assemblage are indeed driven partly by autogenic succession as suggested by Seppä (2002) and many other Baltic researchers.

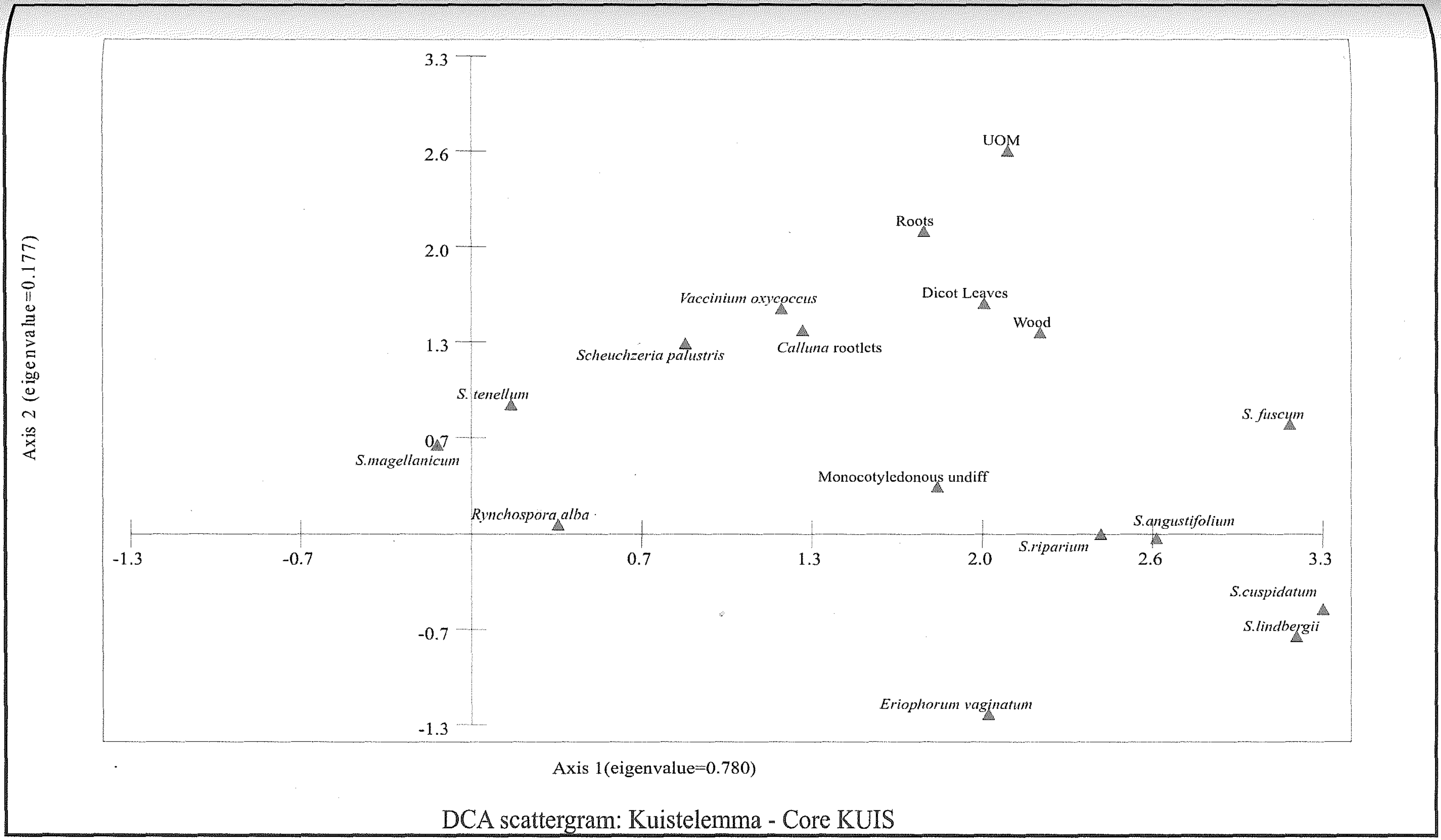
3.3
2.6
2.0
1.3
0.7
-0.7
-1.3
-1.3
-0.7
0.7
1.3
2.0
2.6
3.3
Axis 2 (eigenvalue=0.177)
Axis 1(eigenvalue=0.780)
UOM
Roots
Dicot Leaves
Wood
Vaccinium oxycoccus
Calluna rootlets
Scheuchzeria palustris
S. tenellum
S.magellanicum
S. fuscum
Monocotyledonous undiff
Rynchospora alba
S.angustifolium
S.riparium
S.cuspidatum
S.lindbergii
Eriophorum vaginatum
DCA scattergram: Kuistelemma - Core KUIS

Figure 4.19

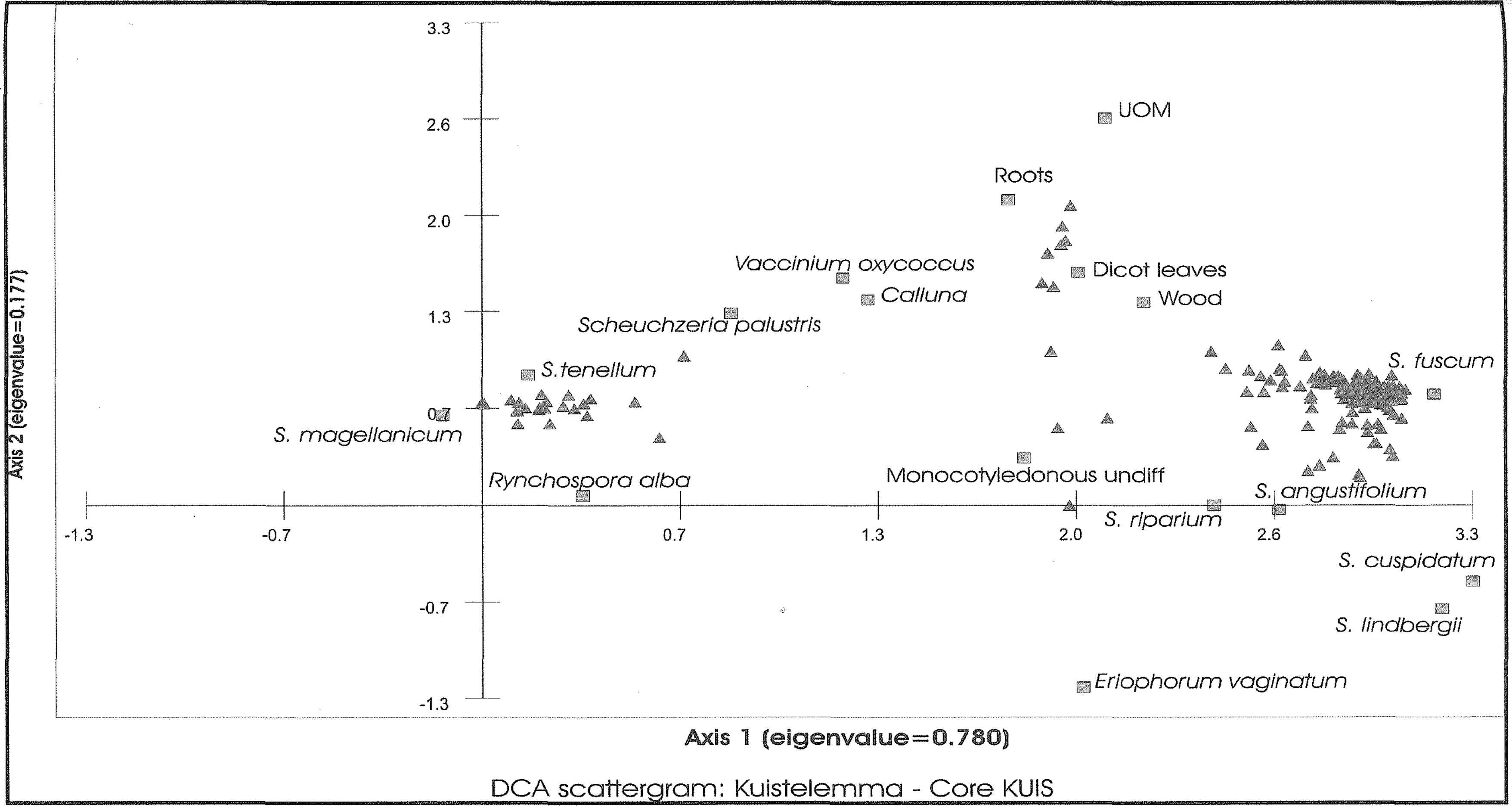
3.3
2.6
2.0
1.3
0.7
-0.7
-1.3
-1.3
-0.7
0.7
1.3
2.0
2.6
3.3
Axis 2 (eigenvalue=0.177)
Axis 1 (eigenvalue=0.780)
UOM
Roots
Vaccinium oxycoccus
Calluna
Dicot leaves
Wood
Scheuchzeria palustris
S.tenellum
S. magellanicum
Rynchospora alba
Monocotyledonous undiff
S. fuscum
S. angustifolium
S. riparium
S. cuspidatum
S. lindbergii
Eriophorum vaginatum
DCA scattergram: Kuistelemma - Core KUIS

Figure 4.20

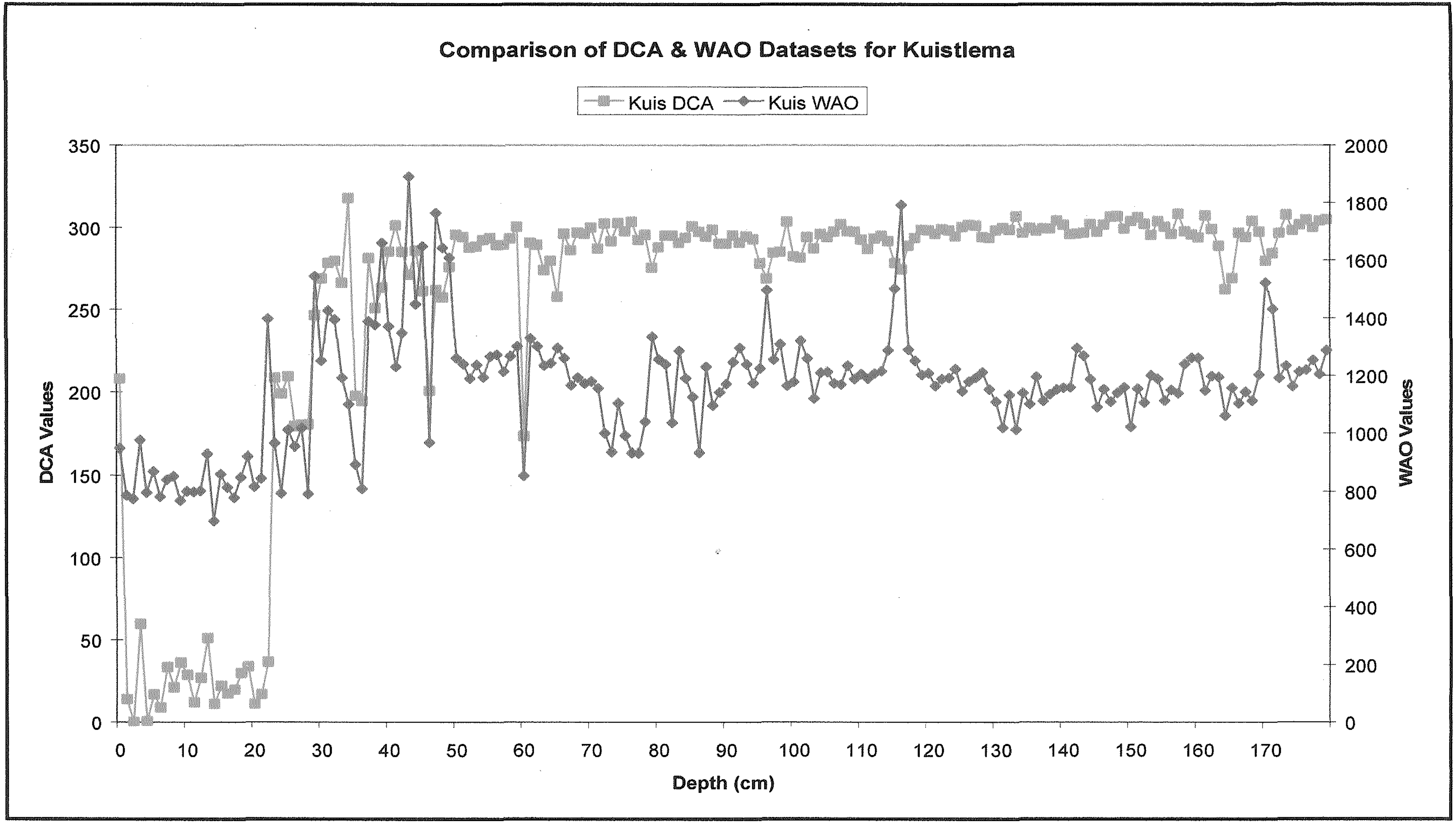

Figure 4.21 Comparison of DCA & WAO Data for Kuistlema.

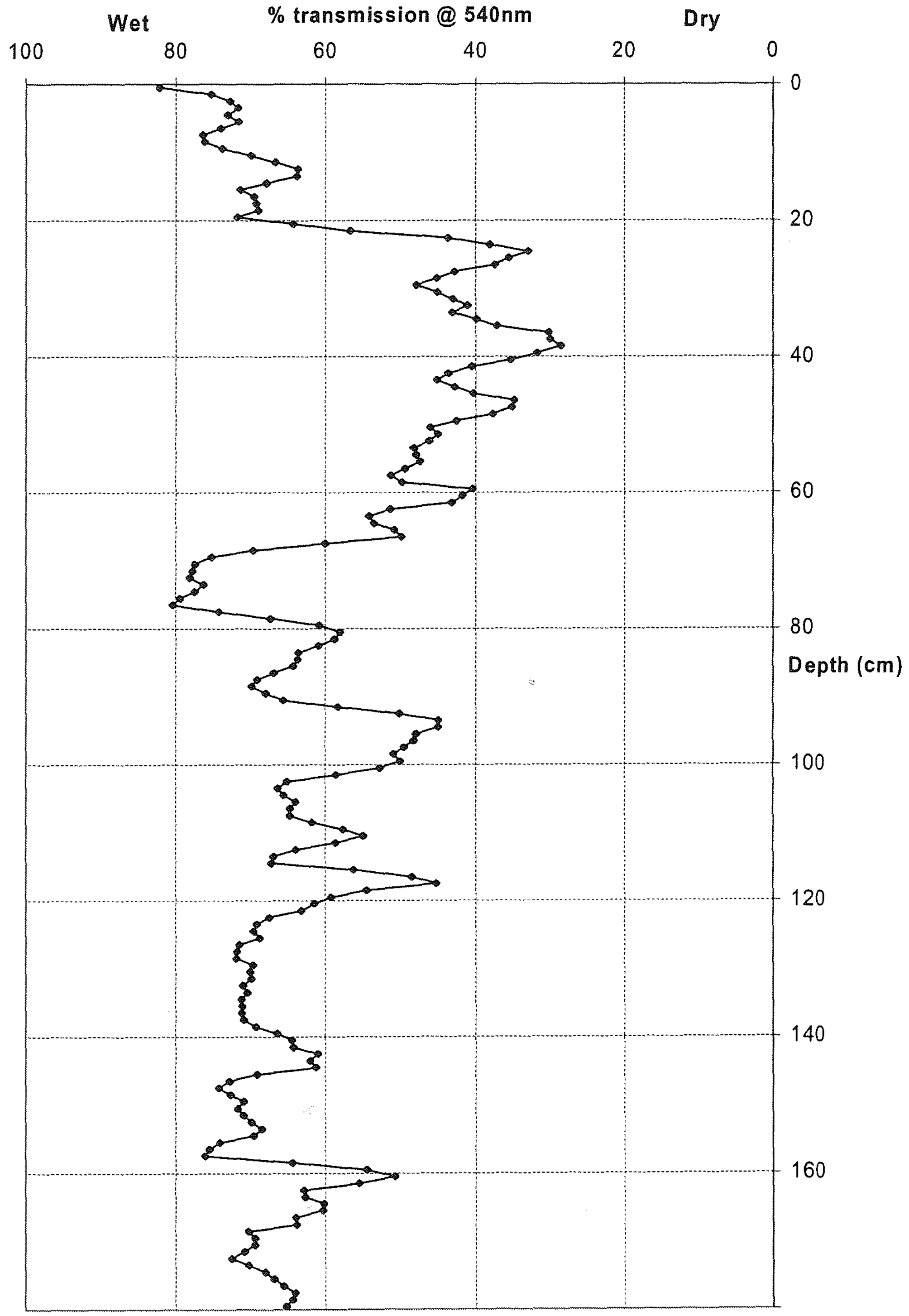

Figure 4.22 Humification results for Kuistlema (3 point running mean)

4.4 Synthesis and comparison of intra-site proxy data

4.4.1 Munasuo – Core MUN

Analyses of the datasets for this site show that there is generally a good correspondence between the peat humification and WAO (weighted-average ordination) plant macrofossil results. The testate amoebae results are equivocal with the dominance of *Amphitrema flavum* making it difficult to determine hydrological change. Nevertheless, there is some correspondence between all three proxies and high-magnitude and sustained shifts in the mire's hydrology appear to be recorded.

At the base of the core relatively dry conditions are implied by both the humification and WAO data. However, whilst the WAO data indicate a marginal shift to wetter conditions the peat humification data imply three discrete episodes of wetness interrupted by drier conditions between 158-154 cm and then a lower-magnitude shift at 147-146 cm. The testate amoebae data for this period are ambiguous. *Amphitrema flavum* is the dominant taxon during this period implying wet conditions; however, *Assulina muscorum* (a typically hydro-xerophilous species) is also well represented. Interestingly both proxies record a high-magnitude change between 127-131 cm indicating that this period was characterised by lowered water tables and drier mire surface conditions. The testate amoebae data also support a shift to drier conditions with *Trigonopyxis arcula* present in association with *Assulina muscorum*, implying lowered water tables. It is also notable that this is the only period when *Amphitrema flavum* is not the dominant taxon in the testate amoebae record.

Following this period all three proxies indicate a shift to wetter mire conditions. Single data points that may imply oscillating hydrological conditions appear not to be replicated between proxies. This is exemplified by the lack of correspondence between the two proxies at 99-100 cm. Whilst the WAO data imply a rapid and relatively high-magnitude shift to first drier and then wetter conditions this is not supported by the humification data. Nevertheless, at *c.*76-83 cm all of the proxy datasets indicate elevated mire water tables.

In general, good agreement is evident for the remainder of the core between the two primary proxy datasets. A shift to drier conditions is implied by the humification data at 62 cm whilst there is a slight time lag in the WAO data with drier conditions implied at *c.*60 cm. The testate amoebae data are ambiguous with *Amphitrema flavum* dominant although notably values of *Assulina muscorum* increase from the preceding period possibly implying a slight shift to drier conditions.

It is clear that there is generally good agreement between all of the proxies. High-magnitude and sustained shifts in the mire's hydrology appear to be recorded in all of the datasets. Shorter and/or low-magnitude hydrological fluctuations are however less clear, particularly when single data points imply shifts in the mire's hydrology. There appears to be good correspondence between the two primary proxy datasets with both the timing and magnitude of each shift in broad agreement. Unfortunately owing to the problems encountered when applying DCA (Detrended Correspondence Analysis) to the plant macrofossil data these results could not be compared with either of the primary datasets for this site.

4.4.2 Reksuo – Core REK

The base of this core shows good agreement between the proxy datasets. Both the humification data and the WAO plant macrofossil data imply relatively dry mire conditions giving way to a rapid and high-magnitude shift to wetter conditions. Once again there is good correspondence between the primary proxy datasets with data points implying much wetter mire conditions centred around 174-175 cm. Interestingly, for this site the DCA plant macrofossil dataset also imply a shift to wetter conditions between *c.*170-175 cm.

Immediately succeeding this episode, humification values decline, implying a shift to drier mire surface conditions. The WAO dataset also records this shift with values increasing markedly at *c.*162 cm. Both primary datasets record a sustained episode of drier mire conditions between *c.*162-136 cm. Notably, the WAO plant macrofossil data imply high-magnitude and rapidly fluctuating conditions whilst the humification data indicate relatively stable conditions. The humification data also indicate that this episode is slightly longer-lived than the WAO data. A return to wetter mire conditions is implied at *c.*138 cm in the WAO dataset whereas the humification data do not appear to record this shift until 133 cm. However, there is again good agreement between the primary proxy datasets and the testate amoebae data support this shift to wetter conditions with both *Amphitrema wrightianum* and *Amphitrema flavum* present. This episode appears to be short-lived and both primary datasets record a shift to drier conditions at *c.*128-130 cm.

Following this episode all three proxies indicate a shift to wetter conditions between *c.*123-115 cm. The DCA data also imply a shift to wetter conditions between 125-115 cm.

Although all of the proxies record similar hydrological changes there is some evidence of a slight time lag between proxies. An episode of lowered water tables is implied by all of the datasets (including DCA) between 110-105 cm. However, whilst the humification data imply a shift to drier mire conditions between *c*. 83-75 cm this is not supported by either the WAO data or the testate amoebae data. Nevertheless, from *c*.50 cm a gradual shift to relatively wet conditions is implied by the humification and WAO datasets. The testate amoebae results are equivocal with a lack of indicator species hampering a hydrological interpretation of the assemblage.

In general there appears to be a good correspondence between both the weighted-average ordination plant macrofossil and humification datasets. Notably, the DCA data also support several of the higher-magnitude and sustained hydrological changes. The testate amoebae data again tend to support significant and prolonged changes although results become more equivocal towards the mire surface.

4.4.3 Männikjärve – Core MANN

Comparisons of the two primary datasets for Männikjärve reveal that at the base of the core there is generally poor agreement between proxies. A clear shift to wetter conditions is implied by the humification data at *c.*159 cm. However, this is not supported by the plant macrofossil WAO data, which record a small peak in values but do not appear to be significantly higher than the preceding values. It is notable that testate amoebae are completely absent at this point in the core, possibly implying drier conditions. As discussed in section 3.4.1 it may be that high proportions of *Eriophorum vaginatum* have produced spurious humification results. Succeeding this period, humification values imply a prolonged shift to drier mire conditions. This is partially supported by the WAO dataset, which records an episode of high-magnitude but relatively short-lived shifts to drier conditions. Testate amoebae data are ambiguous for this period with both wet and dry indicator species present in varying quantities. At 121-117cm a shift to drier conditions is broadly replicated in both primary datasets.

However, following this episode correspondence between the primary proxies remains generally unconvincing. The humification data imply a shift to wetter conditions between 71-65 cm but this is not mirrored by changes in the WAO data. At *c.*55 cm both proxies imply a shift to wetter conditions and this episode is sustained in both datasets until approximately 30 cm. It is worth noting that this shift is coincident with the replacement of *Sphagnum fuscum* by *S. magellanicum*.

4.4.4 Kuistlema – Core KUIS

A comparison of Figures 4.21 & 4.22 shows that there is generally poor agreement between the macrofossil WAO and humification datasets. This is particularly pronounced at the base of the core where the humification data imply fluctuating hydrological conditions and both the WAO and DCA data imply relatively stable conditions. The testate amoebae data are ambiguous with both *Amphitrema flavum* and *Assulina muscorum* present. However, at *c.*173-172 cm an increase in *A. muscorum* and *Trigonopyxis arcula* is broadly coeval with a low-magnitude rise in WAO values. A distinct shift to drier mire conditions is implied by both the WAO and humification data at 117 cm.

Following this period the datasets again imply different hydrological conditions. Whilst the humification record implies markedly fluctuating hydrological conditions the plant macrofossil WAO data imply a prolonged period of relatively stable conditions. The marked shift to wetter conditions implied by the humification data between *c.*77-69 cm is partially replicated in the WAO data although these do not appear to imply the same magnitude of change. Nevertheless, a sustained episode of drier mire conditions is recorded by all three proxies between 70-23 cm, although the initiation, duration and magnitude of this phase do vary between the proxies. Whilst the humification data record a decrease in values from 70 cm the WAO data do not change significantly until 50 cm when a series of rapid and high-magnitude shifts to drier conditions is implied. Interestingly, for this period, testate amoebae are often absent from the record, possibly implying a rapid shift to drier mire conditions or a change in the mire surface ecology. Nonetheless, whilst the humification data imply relatively dry and stable conditions the

WAO data imply much more variable hydrological conditions. Several marked fluctuations are implied by the data at *c*.37 and 29 cm.

In general there is poor agreement between the WAO and humification data for this site. Whilst both proxies record several high-magnitude and sustained hydrological fluctuations there is minimal correspondence for large sections of the core. In particular, the humification data imply markedly fluctuating conditions whilst the plant macrofossil WAO and DCA data imply relatively uniform mire conditions.

Chapter 5 Discussion

5.1 Introduction

At the outset of this project it was anticipated that this section would provide a regional/hemispherical record of climate change extending back *c*.2000 years. However, as has been shown in the previous chapters, the sites chosen for this project do not appear to yield a replicable archive of hydrological change that can be attributed to past climate. The lack of agreement between sites probably indicates that changes in the mire's plant ecology are primarily being driven by internal factors rather than climate. This is further supported by the intra-site proxy datasets which often imply different hydrological conditions within the same profile. As has been discussed, Baltic researchers often ascribe changes in the mire plant assemblage to internal factors such as autogenic succession rather than as a response to climate. The syntheses of data detailed in Chapters 3 and 4 demonstrate that there is often a poor correspondence between intra-site proxies. This is particularly the case where short-lived and/or low-magnitude changes may be implied by the datasets. Factors such as bog inertia, species ecological tolerance and species time-lag may mask or complicate a simple climatic interpretation. As a result, only where two or more of the proxies imply a broadly coeval and sustained shift in the mire's hydrology has a climatic interpretation been applied. Furthermore, owing to the considerable distance between study sites, any broadly synchronous shifts to either wetter or drier mire conditions that are replicated at three or all of the sites, have, for the purpose of this project, been considered a function of regional climate change. The results from all four sites are detailed in the tables below.

Table 5.1 List of inferred wet shifts from all four sites. Actual dates are highlighted in bold whilst interpolated dates are italicised. Alternative interpolated dates are also in brackets by the side of the date derived from the Bpeat program. Dates are expressed as Cal BP. (bracket denotes a single episode or shift to wetter mire conditions).

Munasuo	**Reksuo**	**Männikjärve**	**Kuistlemma**
-	-	**198**	-
-	-	**209**	-
-	-	**220**	-
-	-	**230**	-
-	-	**242**	-
297 (348)	-	-	-
300 (355)	-	-	-
304 (362)	-	-	-
308 (369)	-	-	-
312 (376)	-	-	-
316 (383)	-	-	-
319 (390)	-	-	-
323 (397)	-	-	-
-	-	-	*1231*
-	-	-	*1237*
-	-	-	*1242*
-	-	-	*1248*
-	-	-	*1254*
-	-	-	*1260*
-	-	-	*1266*
-	*1374 (1279)*	-	-
-	*1382 (1295)*	-	-
-	*1391 (1312)*	-	-
-	*1399 (1328)*	-	-
-	-	-	-
-	**1806**	-	-
-	**1814**	-	-
-	**1823**	-	-
-	**1831**	-	-
-	**1839**	-	-
-	**1848**	-	-

Table 5.2 List of inferred dry shifts from all four sites. Actual dates are highlighted in bold whilst interpolated dates are italicised. Alternative interpolated dates are also in brackets by the side of the date derived from the Bpeat program. Dates are expressed as Cal BP. (bracket denotes a single episode or shift to wetter mire conditions).

Munasuo	Reksuo	Männikjärve	Kuistlemma
228	-	-	-
232	-	-	-
236	-	-	-
239 (243)	-	-	-
243 (250)	-	-	-
-	-	*316*	-
-	-	*327*	-
-	-	*337*	-
-	-	*348*	-
-	-	*359*	-
-	-	*369*	-
-	-	*380*	-
703 (705)	-	-	-
712	-	-	-
720 (719)	-	-	-
728 (726)	-	-	-
737 (733)	-	-	-
745	-	-	-
-	-	-	**957**
-	-	-	**962**
-	-	-	**968**
-	-	-	**974**
-	-	-	**980**
-	*1258 (1047)*	-	-
-	*1266 (1064)*	-	-
-	*1274 (1081)*	-	-
-	*1283 (1097)*	-	-
-	*1291 (1114)*	-	-
-	-	*1497 (1153)*	**1499**
-	-	*1508 (1172)*	**1505**
-	-	*1519 (1191)*	-
-	-	*1529 (1209)*	-
-	-	*1540 (1228)*	-
-	*1731*	-	-
-	*1740*	-	-
-	*1748*	-	-

It is clear from the data that synchronous change to either wetter or drier mire conditions are generally not replicated between sites. The only exception to this occurs at *c.*1499 cal years BP when a shift to drier mire conditions is implied by the datasets from Männikjärve and Kuistlemma (based on the Bpeat interpolated dates only). Therefore, using the criteria set out at the beginning of this section it is clear that episodes of synchronous climate change have not been recorded across the sites. However, problems with the wiggle-matched radiocarbon chronology make it difficult to be certain how accurate some of these recorded episodes of hydrological change are. It is evident from the tabulated data that several episodes of hydrological change appear to exhibit a slight time-lag between sites. This is demonstrated clearly in Table 5.1 where the initial 'wet shift' is recorded at Männikjärve between 198 – 242 cal years BP and this then appears to be almost immediately succeeded by a shift to wetter conditions at Munasuo between 297 – 323 Cal years BP.

Nevertheless, it is worth noting that at no time is a shift to either relatively wetter or drier mire conditions replicated at more than two sites. As the sites chosen for this project are close enough together to be affected by regional-scale climate events the results seem to indicate that the mires are primarily regulated by internal processes.

As has already been discussed in earlier chapters, changes in the macrofossil assemblage on mires in the Baltic region are generally thought to be driven by internal autogenic processes. The plant macrofossil datasets generated in this project also appear to support this theory. In view of this, it is possible that the macrofossil data may mask or blur hydrological fluctuations recorded by the other proxy indicators. It is clear from the tabulated data that when all three proxies are combined there is no clear and replicable palaeohydrological signal recorded between sites.

However, as mentioned in Section 4.4.4 (p.210) the humification data sometimes imply fluctuating hydrological conditions whilst the plant macrofossil datasets indicate a period of relative stability. The humification datasets are shown overleaf in figures 5.1, 5.2, 5.3 and 5.4 and the timing and duration of shifts to relatively wetter conditions are delineated by boxes which start at the point where values begin to decline and finish where the lowest values are recorded (i.e. the wettest point). The identification and delineation of wet shifts has been based on a visual and qualitative interpretation of the humification datasets. Wet shifts were identified when a sustained shift to wetter conditions, relative to the preceding period was implied by the humification data. The qualitative nature of humification data means that it is not possible to put an actual value on these data but rather that the wet shifts simply indicate a relative shift to wetter mire conditions. Furthermore, the author accepts that without supporting evidence from the other proxy datasets this is a somewhat weak and subjective interpretation of the humification results.

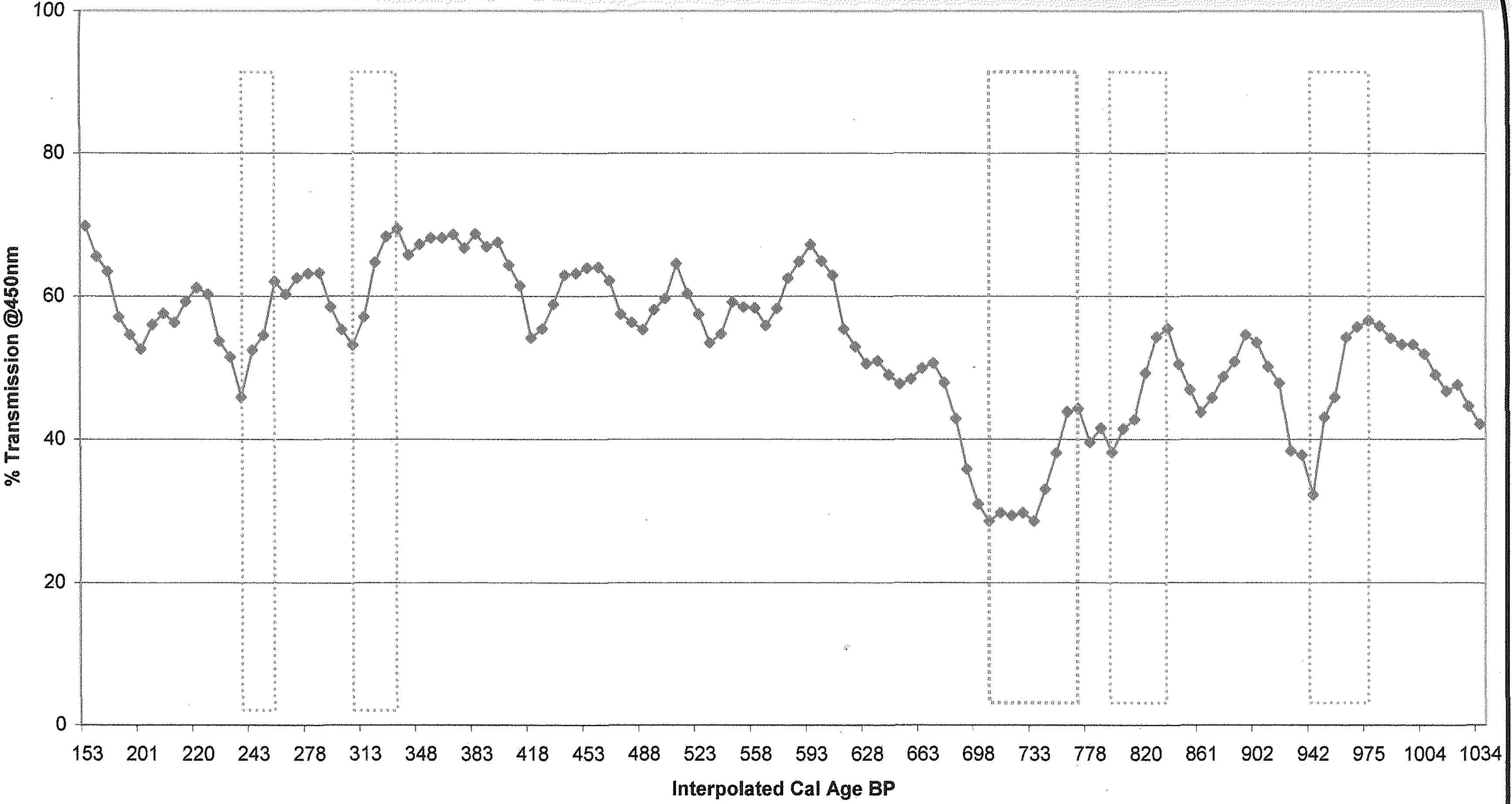

Figure 5.1 Timing and duration of wet shifts for Munasuo

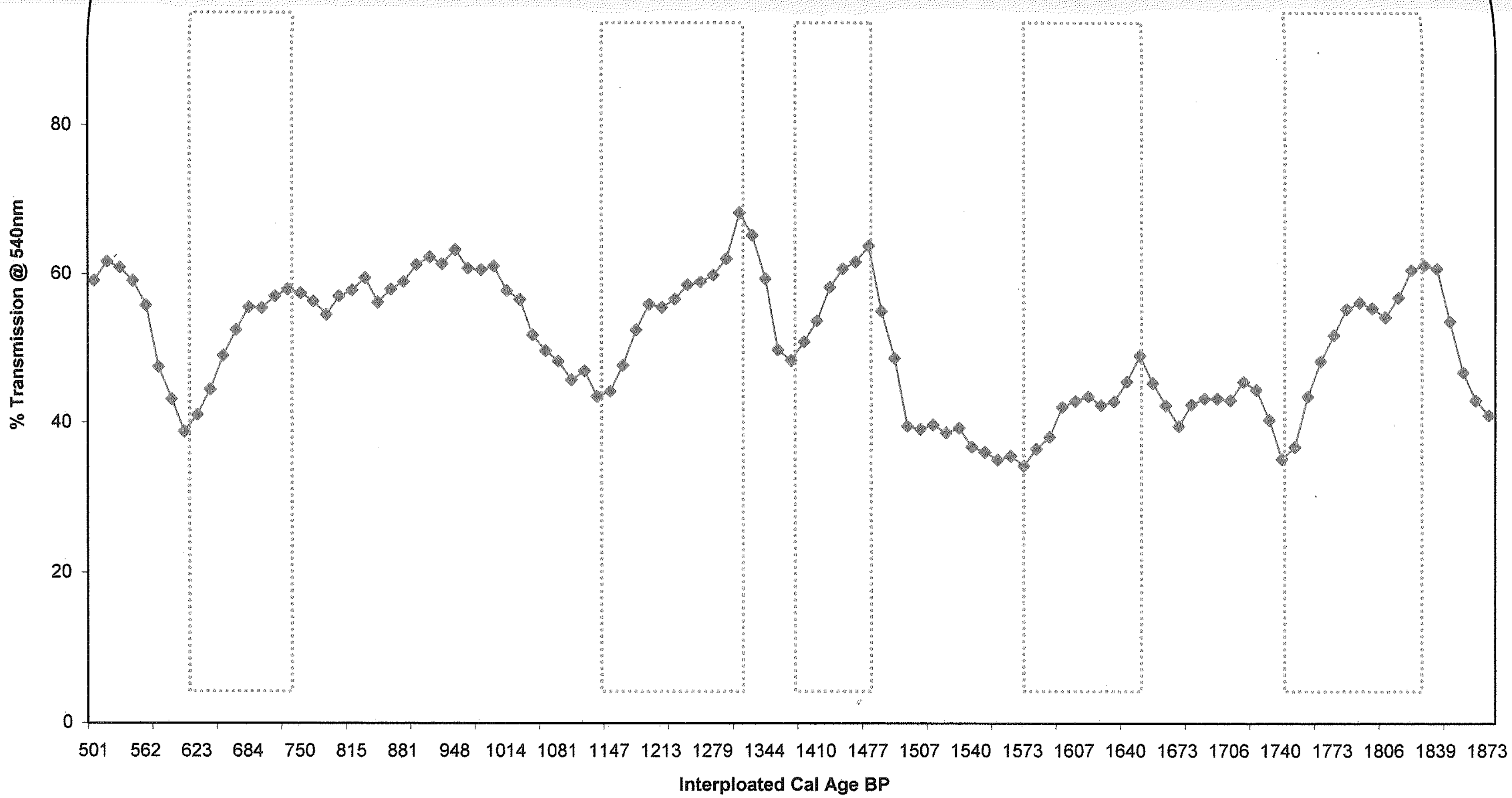

Figure 5.2 Timing and duration of wet shifts for Reksuo

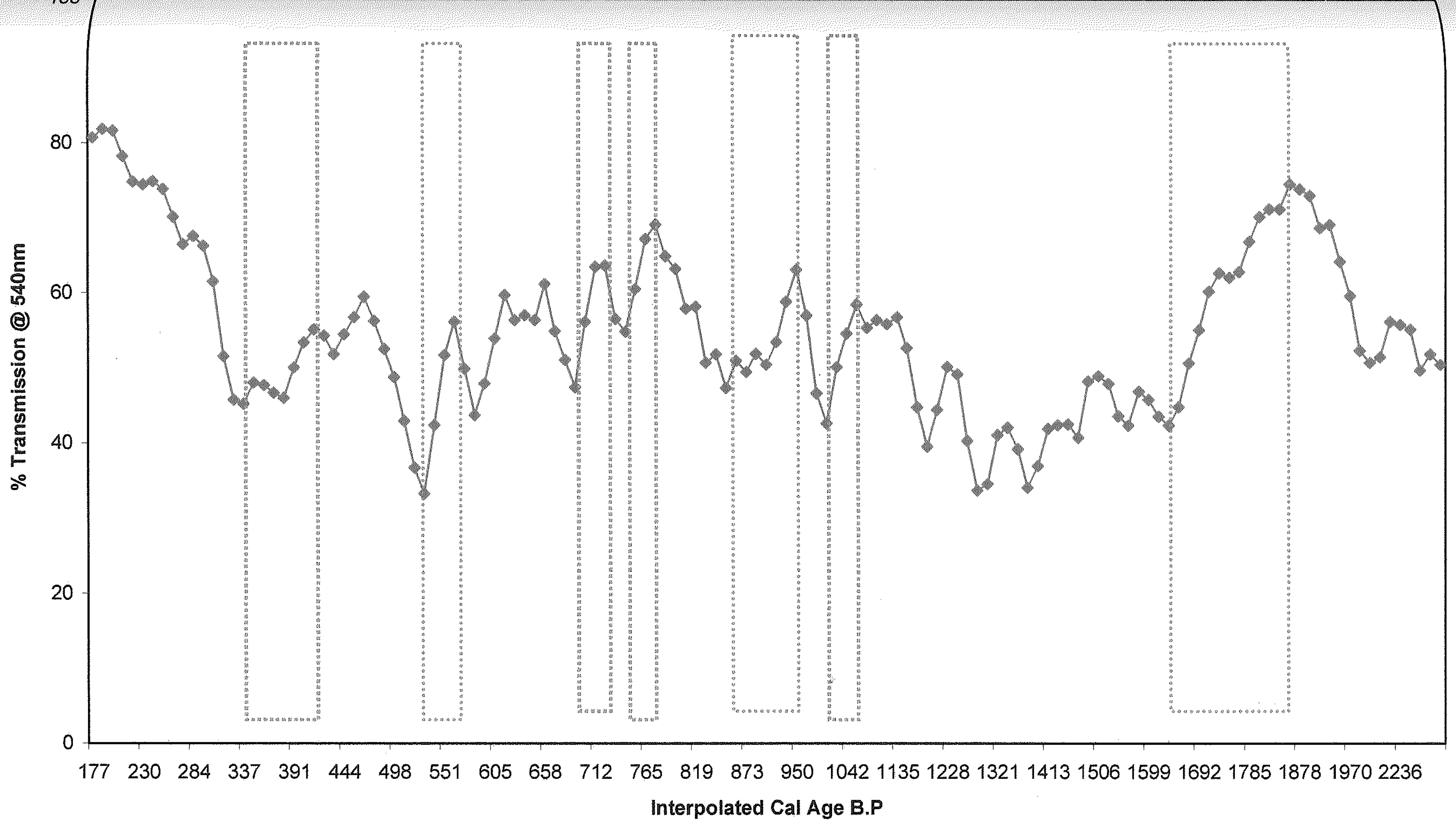

Figure 5.3 Timing and duration of wet shifts for Männikjarve

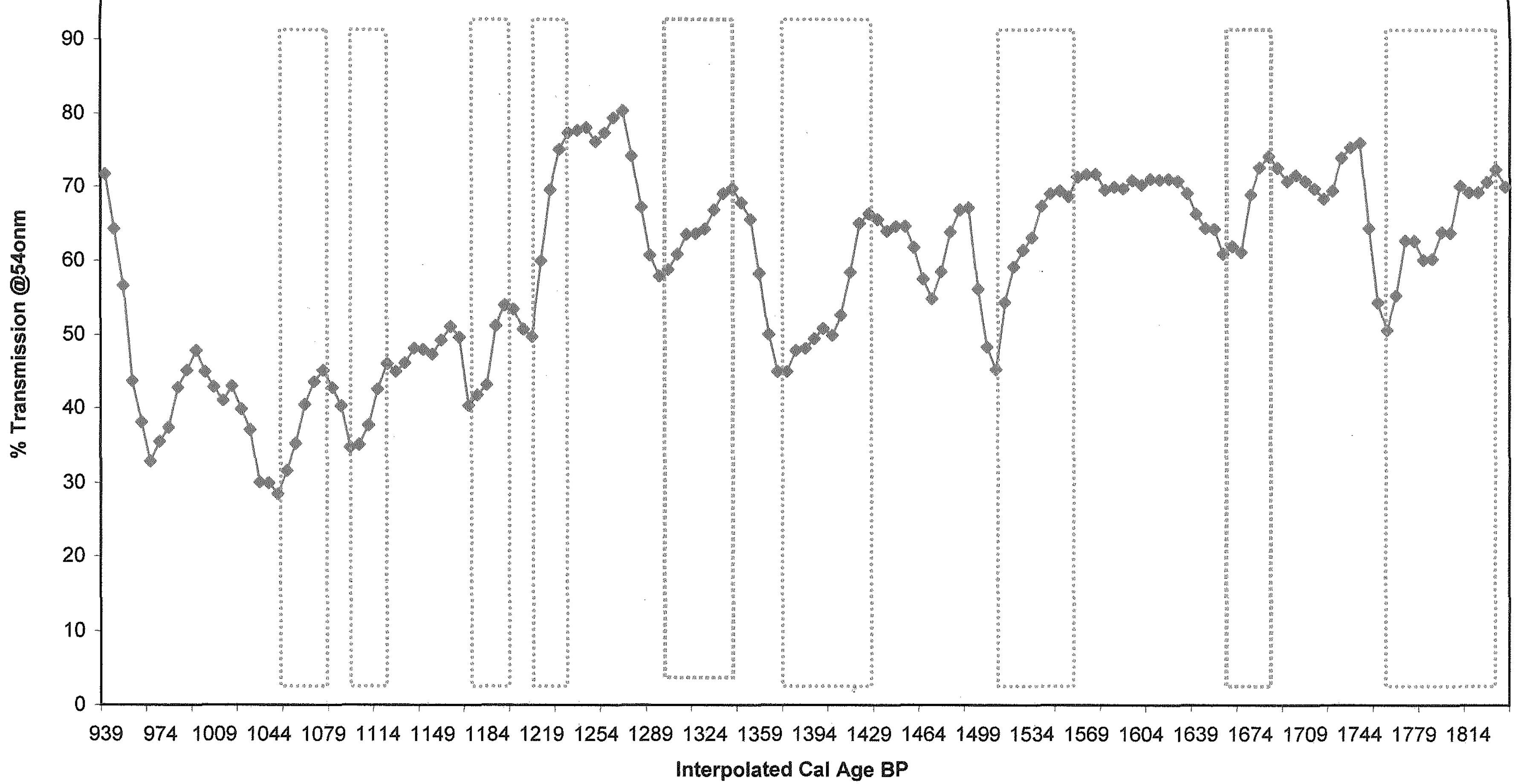

Figure 5.4 Timing and duration of wet shifts for Kuistlemma

Table 5.3 Replicated wet shifts in the humification record in years Cal. BP.

Munasuo	Reksuo	Männikjärve	Kuistlemma
236-257		337-412	1050-1079
306-334		530-562	1097-1120
705-770	608-733	691-723	1172-1196
795-836	1130-1312	744-776	1213-1237
942-975		851-950	1301-1342
	1344-1477		1371-1429
	1573-1648		1511-1563
			1662-1686
	1740-1831	1636-1859	1762-1832
	1864-1873		

As is evident from the tabulated data and from Figures 5.1, 5.2, 5.3 and 5.4 there is an improved correspondence between sites. However, the data still remain generally unconvincing and rather ambiguous. A shift to wetter conditions is recorded at Munasuo, Reksuo and Männikjärve between 770 and 608 Cal. BP. However, the start of this episode appears to be a time transgressive event covering a period of 97 years between the two Finnish sites. The duration of this shift also varies between sites: the Reksuo data imply a relatively prolonged period of raised water tables (*c*.125yrs) whilst at Männikjärve the data indicate that this was a relatively short-lived event covering only *c*.32 years. Unfortunately, owing to the hiatus in the peat record, at Kuistlemma there are no data available from this site to help determine whether this episode was driven by changes in regional/hemispherical climate. Nevertheless, the correspondence between the remaining sites seems to indicate that rates of decomposition within all of these mires slowed during this period and this is most likely to reflect a shift to wetter conditions probably driven by climate.

Following this episode the data are rather ambiguous; several shifts to wetter conditions are recorded at different sites although these are again not replicated at more than two sites. The timing and duration of these episodes is also diachronous, with several periods appearing to exhibit a time-lag between sites. However, between *c.*1636 and 1859 Cal. BP a shift to wetter conditions is again recorded at three of the sites. The timing and duration of this episode varies between sites; specifically, the Männikjärve and Reksuo datasets imply a relatively prolonged and sustained period of wetter conditions whilst the dataset from Kuistlemma implies oscillating hydrological mire conditions with relatively short-lived shifts to wetter conditions. Nevertheless, the broad agreement between sites may indicate that these changes are a response to elevated water tables, which in this instance is most likely to be driven by climate.

It is notable that many of the wet shifts identified in the humification datasets are not replicated when all of the proxies are used. It is possible that the relative dominance of species with a broad hydrological tolerance, such as *Sphagnum fuscum* and *Amphitrema flavum,* may mask or minimise the effects of hydrological changes in the palaeo-record. Similarly, when the macrofossil datasets are subject to further statistical analyses this also appears to lessen or effectively mask mire hydrological change.

5.2 Evaluation of palaeoecological techniques

High-resolution palaeoenvironmental research relies heavily on several built-in assumptions: firstly, that the fossil assemblage has remained relatively intact over time and can be meaningfully interpreted using modern-day datasets; secondly, that the ecological requirements of the proxy indicators are known and have not changed over time; and thirdly that the repository of palaeoclimatic information is able to respond to relatively short-lived and/or low-magnitude shifts in climate.

Numerous palaeoecological studies have demonstrated that ombrotrophic peat bogs can yield detailed and replicable records of past climate change (Haslam, 1987; Hughes *et al.*, 2000; Barber *et al.*, 2003). As can be seen from Table 5.4, several episodes of Late Holocene climate change have been identified in peat profiles from sites across the UK and much of Europe. However, the reluctance of many Baltic researchers to ascribe stratigraphic changes in the peat profile to changes in climate has resulted in a dearth of palaeoclimatic peat-based research in this region. Consequently, many of the techniques that have been successfully applied to UK and European peat bogs had not previously been tested in the Baltic.

Table 5.4 A compilation of inferred 'wet shifts' derived from peat-based research in the UK, Europe and Ireland.

Site	**Author/s**	**Dated 'wet shift' cal. years AD**
Store Mosse Sweden	Granlund (1932)	1200, 400.
Galway Ireland	Mitchell (1956)	500
Rusland Moss N. England	Dickinson (1975)	1145, 400
Draved Mose Denmark	Aaby (1976)	1500, 1050, 450, 250
White Moss (N) White Moss (S) Foulshaw Moss	Wimble (1986)	1350, 900, 250 1150, 450 600
Transect across NW Europe	Haslam (1987)	800, 100
Store Mosse Sweden	Svensson (1988b)	950-750
20 sites in Norway	Nilssen & Vorren (1991)	1530, 1230, 1100, 810, 550, 270, 20
Ireland, Galway	Blackford & Chambers (1995)	1720-1660, 1540-1410, 1050
Burnfoothill Moss Scotland	Tipping (1995a)	1550, 750
Talla Moss Scotland	Chambers *et al.* (1997)	1410, 855, 250, 20
Synthesis of 7 UK sites	Mauquoy (1997)	1800, 1530-1290, 1210-1010, 1060-760, 380-210
5 sites in NW Scotland	Anderson (1998)	1150-1010
Coom Rigg Moss Felicia Moss	Mauquoy & Barber (1999a)	1880-1770, 1260-1100, 1060-920, 670-550, 360-210, AD30-80BC 1470-1400
Coom Rigg M.oss	Charman *et al.* (1999)	1850, 1500, 1100, 950, 600, 400
Synthesis of 7 sites in	Langdon	1800-1700, 1100-900, 600-500

Scotland	(1999)	
Walton Moss N. England	Hughes *et al.* (2000)	1850, 1600, 500, 200
May Moss	Chiverrell (2001)	1800-1700, 1620-1400, 1450-1350, 980-670, 650-550, 540-260
Lille Vildmose Demark	Mauquoy *et al.* (2002)	1604, 1449
Walton Moss UK		1601, 1464, 1215
Bolton Fell Moss	Barber *et al.* (2003)	1400, 1000, 720, 620
Mongan Bog		1800, 850, 600
Abbeyknockmoy		1750, 1400, 1050, 700

Adapted from Hughes *et al.* (2000)

result from changes in temperature and/or precipitation. However, whilst it is recognised that changes in effective precipitation control the depth of the aerobic acrotelm there are additional considerations that need to be taken in to account before accepting a strictly palaeohydrological interpretation of the humification record.

The variability of decay rates within different plant species has been highlighted as a possible cause of fluctuations in the humification record. Field experiments conducted by Coulson & Butterfield (1978) revealed that *Sphagnum Juscum* and *Racomitrium lanuginosum* have relatively slow decay rates. Conducting litter bag studies of *Eriophorum vaginatum, Sphagnum recurvum, Calluna vulgaris* and *Rubus chamaemorus,* Coulson & Butterfield also established that plant chemistry, specifically the nitrate and phosphate content, could be positively correlated with the varying decay rates of different species. During laboratory analyses in a controlled environment, Johnson *et al.* (1990) found that when placed in the same microhabitat, *Sphagum cuspidatum* was susceptible to an accelerated rate of breakdown which resulted in a loss of dry mass at twice the rate, relative to that of *Sphagnum Juscum.*

These findings may go some way to explain why the macrofossil and/or humification datasets fail to record a clear hydrological record for the research sites in this project. As has already been discussed, *Sphagnum Juscum* is the principal species at all four sites and often comprises the bulk of the entire plant macrofossil assemblage. It may be that the relatively slow decay rate of this species results in its over representation in the fossil assemblage. In this instance, the macrofossil assemblage may not accurately reflect the hydrological conditions on the mire. This may be particularly pronounced when shifts to wetter conditions are effectively masked or the magnitude of such events lessened by the presence of large quantities of *Sphagnum fuscum.* The high proportions of this species together with root material, Monocots and *Eriophorum vaginatum* may have resulted in an artificial species effect in the humification datasets.

Earlier research by Clymo (1965) found that (under similar environmental conditions) it was possible to establish an order of decomposition from the greatest to the least for *Sphagnum cuspidatum, Sphagnum capillifolium* and *Sphagnum papillosum.* Clymo noted that the degree of decomposition was due both to the composition of the plant and its depth relative to the water table. Similarly, when root material such as that of *Eriophorum vaginatum* is located either wholly or mainly within the anaerobic catotelm, preferential preservation may occur, which in some instances can result in its over representation in the peat profile. There is evidence of this at Mannikj arve, where towards the base of the core c.159 em there is a negative correlation between the humification and plant macrofossil datasets. Examination of the peat matrix showed that at this depth, the bulk of the peat assemblage comprised *Eriophorum vaginatum* root material. As discussed, because this material is deposited at depth and mainly in anoxic conditions it has a relatively slow decay rate and therefore may in this instance have produced spurious humification results.

Aartolahti (1965) investigated the origin of so called 'humification streaks' often found on raised bogs in Finland. Initially it was thought that these streaks represented episodes of an abrupt and high magnitude shift to drier conditions. However, investigations at a number of sites across Finland revealed that these were essentially diachronous in nature and therefore unlikely to .be a result of large-scale climate change. Further research by Tolonen (1977) demonstrated that these streaks were in fact fragmentary

and asynchronous even within one mire. An alternative theory that has been widely accepted by Baltic researchers suggests that these were local features related to natural growth rhythms within the bog. If this theory is correct, then it may fundamentally change the way in which peat humification and/or other proxy data are related to hydrology and by association climate for mire research in the Baltic.

An additional factor in determining the decomposition rate of bog plant species is the length of time the mire is snow covered. In effect, for this period the water table is at the mire surface and it is likely that there are only nominal or minor differences in the decay rate between hummock and hollow species. Furthermore, as the snow melts, the water table would become artificially raised relative to the prevailing climate, and this would again affect the decomposition rate and humification signal. It is difficult to know what effect, if any, these issues have had on the humification datasets generated in this project.

More recently several researchers have questioned some of the assumptions inherent within the technique. Yeloff & Mauquoy (unpub.) suggest that the botanical composition of peat may be equally as important as climate in determining the degree of humification. After analysing two cores, one of which contained only *Sphagnum magellanicum* and the other comprised several *Sphagnum* species, Yeloff & Mauquoy concluded that there was indeed a significant botanical effect. They went further by concluding that the peat humification technique is essentially flawed unless it is used on a single species.

Notwithstanding the problems and issues outlined above, the results generated in this project demonstrate that the peat humification technique is a sensitive palaeo tool and is able to identify ecological and/or hydrological changes on the mire. However, owing to a lack of both intra- and inter-site proxy dataset agreement, it remains uncertain whether these changes are as a result of climate forcing or whether they may simply reflect changes in the peat composition or possibly an interplay between the two factors.

5.2.2 Plant macrofossil analysis

Plant macrofossil analysis is another primary technique that has been used extensively in palaeoclimatic research and has been effective at producing replicable climate records from peat bogs in the UK and Denmark (Blackford, 1998; Barber *et al.,* 2000; Mauquoy *et al.,* 2002).

In all of the cores analysed, large quantities of *Sphagnum* were present and often formed the bulk of the peat matrix. However, unlike on many European mires where a greater degree of species interaction and replacement occurs, the *Sphagnum* datasets generated here indicate that *Sphagnum fuscum* was typically the dominant species and in most samples represented the major *Sphagnum* and/or macrofossil component. This evidence also supports the claim of Barber (2003) who concluded that where a single *Sphagnum* species is dominant, such as the *Sphagnum fuscum* bogs of Finland, then the assemblage is unable to respond to changes in climate. As has already been shown, the DCA (Detrended Correspondence Analysis) results from all four sites appear to produce a poor palaeohydrological interpretation of the data, possibly because of the dominance of a single species and/or outliers, which in this case may be *Sphagnum fuscum.*

Blackford (2000) suggests that inter-species competition, rather than climatic factors, may also play a role in changes to the plant assemblage. This view is shared by many Baltic researchers who believe that autogenic succession is the primary control of changes to the peat assemblage. Interestingly, at all of the sites *Sphagnum magellanicum* values increase quite markedly, typically at the expense of *Sphagnum fuscum.* However, this change appears to be a time transgressive event and it is therefore unlikely that the replacement of species represents a pronounced shift in climate. It may be that intra-site competition provides an alternative explanation and that the short-term replacement of S. *Juscum* by S. *magellanicum* may be similar to the situation in the UK and much of Europe, where *Sphagnum imbricatum* has effectively been replaced by S. *magellanicum.*

The lack of inter-site correspondence between the proxy datasets means that it is difficult to determine how effective this technique is at identifying fluctuations in mire hydrology that may be a function of climate. Whilst some of the shifts in mire hydrology are replicated in both proxy records it is also clear that other possible changes are either absent from the record or at best appear to exhibit a time-lag. This, however, may be expected; it is possible that the size of the peat bogs in Finland and Estonia may result in a certain amount of inertia. In effect, owing to the relatively large size of these mires it is possible that they are simply able to absorb the effects of short-lived and/or low-magnitude hydrological changes. An additional factor may be that, owing to snow cover, which lasts for approximately 6 months of the year, the mire is again effectively insulated against the possible effects of climate/hydrological change. Baltic researchers have also suggested that because of a relatively short period when the bog is snow free there is potentially less time for the bog plant community to respond to changes in climate. This may be exacerbated when a particularly dominant species with a broad ecological and hydrological tolerance, such as *Sphagnum fuscum,* is well established on the mire. Spring snow-melt also artificially raises the level of the water table and this in conjunction with a relatively short summer may help to maintain a stable plant community and minimize water table fluctuations.

Fundamentally, in order for the plant macrofossil assemblage to record changes in mire hydrology it is obviously a prerequisite that several species are already present on or near the site that are able to migrate effectively across the mire in the event of fluctuating water table levels. This may also be problematic, particularly as in most palaeo-research (and in this project) the coring site is located towards the centre of the mire. It may be difficult for certain species to migrate to this area, especially if the hydrological (climate) change was relatively short-lived and/or low amplitude. If the invading species are not already close to or on the mire or if the dominant species have a broad ecological niche it may be that the vegetation mosaic does not properly reflect the prevailing climatic/hydrological conditions. It may be overly simplistic, particularly on Baltic mires, to assume that there is a transient mire plant assemblage that is able to respond rapidly and sensitively to changes in mire hydrology.

It is unclear from the macrofossil datasets whether changes in mire hydrology have in fact been recorded in the peat profile. A perhaps overly simplistic, visual approach would appear to suggest that certain episodes may well have been identified. This is particularly the case where increases in S. *lindbergii,* S. *riparium,* S. *cuspidatum* and *Rynchospora alba* are found at the expense of *Sphagnum fuscum* and *Eriophorum vaginatum.* Unfortunately, however, when the data are subject to more rigorous statistical analyses it seems that the dominance of S. *fuscum* together with a sustained presence of root material, monocots and *Vaccinium oxycoccus* appears to mask or lessen the amplitude of these possible hydrological changes.

5.2.3 Testate amoebae analysis

In this project the use of testate amoebae was restricted to indicator species and used primarily as an independent source of data to corroborate the signals indicated by either of the two principal proxies. Recent studies have shown that the testate amoebae assemblage is especially sensitive to changes in the depth of the water table from the peat surface (Charman, 2002). However, whilst this technique has again been successfully applied to mires in the UK and Europe it has not been extensively used on Baltic mires.

In terms of its effectiveness in this project, a major constraint was that no modern training set was available and so the ecology of species in the Baltic region was poorly documented. This is perhaps illustrated by the choice of *Amphitrema jlavum,* as a wet indicator species. When choosing the methodologies adopted in this project, advice was sought from a number of researchers that included both Prof. Dan Charman & Dr. Dimitri Mauquoy who both agreed that the choice of indicator species was suitable for the project. Unfortunately, the datasets indicate that on Baltic mires *Amphitrema jlavum* in particular, has a broad environmental and hydrological tolerance. It appears that it may be similar to *Sphagnum Juscum* in this respect. It is noted however that this problem may have been exacerbated by the exclusion of other species and perhaps if the whole testate amoebae assemblage had been counted then this may not have been so much of an issue.

Despite these limitations, the technique has generally been in agreement with either of the two primary methodologies and the varying proportions of either hydrophilous or xerophilous testate amoebae appear to correlate with shifts to either wetter or drier conditions.

5.3 Autogenic succession or climatically driven mire vegetation change

The origin, growth pattern and stability of bog micro-forms have been the subject of considerable debate and research during the 20th and continuing on in to the 21st century. Early models such as those developed by von Post & Sernander (1910) and later by Osvald (1923) suggested that bog microtopography was typically transient and characteristically unstable. However, later research by Walker & Walker (1961) demonstrated that these features were mostly stable. Similar conclusions were reached by Aartolahti (1965, 1967) who conducted detailed research on peat bogs in southwest Finland. Tolonen (1977) also concluded that hummocks and hollows were stable features and no cyclic regeneration had taken place.

Mire palaeoclimatic research in Britain and throughout much of Europe has demonstrated that by retrieving a peat core, taken from the more sensitive lawn microform, it is possible to reconstruct past climates based on a number of different proxy indicators. It is assumed that in the case of plant macrofossils, a shift to drier conditions results in an expansion of hummock species on the lawn microform whilst conversely a shift to wetter conditions results in an increase in pool species. A similar premise is assumed for the humification technique, with wet or dry shifts indicated by either poorly or highly humified peat. In this way numerous projects have demonstrated that climatic teleconnections can be made between different sites (van Geel *et al.,* 1996; Barber *et al.,* 2003; Blaauw *et al.,* 2004). However, all of these projects assume that the mire is in fact responding primarily to changes in hydrology driven by climate rather than internal processes. It is reasonable, however, where cores replicate the same palaeoclimatic data to assume that this is indeed the case.

In the Baltic, mires have not been extensively used as an archive of palaeoclimatic data. Researchers have traditionally ascribed changes in the mire ecology and particularly to the bog plant composition to autogenic succession and internal mire dynamics rather than as a response to climate. Observable factors such as the direction and pattern of running water, the peat botanical composition and anaerobic gas production are known to play a pivotal role in the dynamism of the mire. Glasser *et al.* (1986) found that de-gassing of the mire resulted in the mire surface being lowered between 10-20 em. Seppa (2002) suggests that these events may keep the surface unstable and inhibit the spread of vegetation. Foster *et al.* (1986) concluded that mires are inherently dynamic systems, and their development includes both low-frequency and high-frequency changes caused by local factors that may be independent of climate or other regional environmental controls.

The results generated from this project seem to support the view advocated by Baltic researchers. As has already been discussed the lack of agreement between sites suggests that changes in the mire are being driven by internal processes rather than climate. This is also corroborated by the lack of accord between proxies. Notwithstanding the problems associated with each technique it seems unlikely that major shifts in climate would not have been recorded at two or more of the sites.

However, there may be alternative explanations as to why events such as the Medieval Warm Period (MWP) and Little Ice Age (LIA) are not recorded. Firstly, it is possible that these events did not result in a significantly different hydrological regime at these sites. This may be the case particularly during theLIA when the melting of winter snow cover may not have changed significantly from the long-term average. Similarly, conditions during the MWP may not have been either of a high enough magnitude or of long enough duration to result in mire hydrological change. An additional element to this equation is that there is limited evidence to indicate that there was less precipitation during this period. Secondly, it may be that the bog macrofossil assemblage is essentially complacent and is unable to record changes in mire hydrology. In the Baltic this may be because of the dominance of particular species and the relatively short period of time the bog plant assemblage has to react to these changes. Finally, it is possible that the techniques used in this project are unsuitable for the task of identifying hydrological changes in Baltic mires.

Several of the datasets for this project demonstrate that the assumptions that are currently accepted by palaeo-researchers may need further investigation and possible re-evaluation in determining whether they can be applied successfully to Baltic mires. The statistical analysis of the plant macrofossil datasets generated for this project is a good example of this. The results of the DCA (Detrended Correspondence Analysis) analysis show clearly that the technique is not able to yield a hydrological gradient between species on the mire. The WAO (Weighted Average Ordination) macrofossil datasets are also equivocal in producing a clear hydrological interpretation of the fossil assemblage.

As has been discussed in the previous sections, several problems and limitations of each technique have become apparent during this project. However, whilst acknowledging that further research into the methodologies and proxies is necessary, it is worth noting that the results generated here may simply imply that the primary control of mire vegetation change is not climate change as has been previously proposed. It is possible that the lack of correspondence between sites reflects interplay between some and/or all of the above factors.

Chapter 6 Conclusions and Further Research

6.1 Conclusions

At the outset of this project it was anticipated that high-resolution multi-proxy analyses of the data would enable the identification of major periods of climate change within the last c.2000 years. As with other peat-based palaeoclimate studies it was thought that changes in mire stratigraphy were primarily a function of fluctuating water-tables that in turn, on an ombrotrophic peat bog, is primarily controlled by climate. However, the results generated in this project indicate that this is possibly not the case.

Although the wiggle-matched radiocarbon chronology has been problematic for this project it is still clear from the datasets that there is little or no agreement between the timing of shifts to either relatively wetter or drier mire conditions. This has been corroborated by the lack of intra-site agreement between proxies. Therefore, it is likely that interplay between some and/or all of the factors detailed below may apply:

1. The development and plant composition of ombrotrophic mires in the Baltic is primarily controlled by autogenic succession driven by internal processes rather than climate.

2. That Baltic mires are essentially complacent and are not able to record short-lived and/or low-magnitude changes in climate. This may include factors such as snow cover, single species dominance, bog inertia and the absence of replacement species at or near the coring site.

3. The proxy indicators used in this study are not suitable for deriving palaeoclimatic data from Baltic mires.

4. Finally, that the known periods of climate change in the last 2000 years, namely the Little Ice Age and the Medieval Warm Period did not result in a high enough magnitude change in mire hydrology to be recorded.

Evidence from this study supports the view taken by many Baltic researchers whereby changes in the peat composition are driven mainly by internal processes. Aartolahti (1965) suggests that the form of Finnish mires occurs very quickly after mire initiation and does not appear to change. This observation supports the hypothesis that Baltic mires are essentially stable and able effectively to absorb and minimise the possible effects of climate change. Conversely, the hypothesis of Barber (1981), which assumes that mire taxa respond synchronously to changes in climate, appears to be refuted by the evidence from this project. This is particularly interesting because it contradicts the established view of many UK researchers.

Despite the difficulties and limitations apparent in this study it is clear from the results that it cannot be assumed that either the palaeo techniques used successfully elsewhere can be applied to sites in the Baltic region and/or rather more fundamentally that these mires are controlled by the same factors.

6.2 Further Research

There are several aspects of this research project that could be developed further. Firstly, in order to improve the reliability and confidence of inferred episodes of climate change additional independent proxy data could be used. Charman *et al.* (1999) claim that testate amoebae are one such proxy and in the future with an applicable hydrological transfer function developed specifically for Baltic species this methodology may be advantageous in helping to determine whether the mire plant assemblage is climatically driven or to what extent autogenic processes predominate. Similarly, other relatively new techniques such as isotope analysis as used by Hong *et al* (2000) and biological and chemical analyses as pioneered at Bristol University may help in trying to differentiate between climatically driven and autogenic changes in peat bog stratigraphy.

Furthermore, as has been carried out at UK sites (Barber *et al.* 1998), it would be useful to take replicate cores from a single site in the Baltic and subject them to multi-proxy analyses. Again this would help to provide data that would either support or refute the claim that a climate signal can be obtained from peat bogs in the Baltic region.

Another aspect that has not been developed in this project is additional statistical analysis of the data. Recent research has used spectral analysis in order to identify cycles within the palaeo-record. This has been particularly useful in identifying possible 'solar-driven' shifts in climate change. Aaby (1976) identified a 260-year cycle from raised bogs in Denmark, whilst more recently an 80-and 210-year signal was identified from blanket peat bogs in the UK (Chambers & Blackford, 2001). These data contrast with an 800-year signal derived from spectral analysis of plant macrofossil data from Bolton Fell Moss, Cumbria, which Barber *et al.* (1994a) suggest is an ocean-driven cycle.

Whilst a reasonably secure chronology has been provided for this project by the use of high-precision ^{14}C AMS wiggle-matched dates this could be improved by the identification of tephra layers. As has been demonstrated in several projects these tephra layers can act as an isochronous marker and help provide an accurate and precise calendar date that can help anchor a radiocarbon chronology.

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APPENDICES

METHOD FOR HUMUS DETERMINATION

1. Sample sufficient peat (e.g. for very fibrous and/or very wet peat, use 1 x 1 x 0.5 cm; for less fibrous peat, use less) and place in weighing boat. Cut up peat if very stringy; otherwise just leave in boat. Dry samples in boats in an oven (~50°C) or under infra-red heat lamps.

2. Prepare 1 litre 8% NaOH solution. To do this, dissolve 80g NaOH granules of AnalaR grade in about 500 mL deionised H_2O and make up to 1 litre.

3. Grind up each peat sample separately in an agate pestle and mortar, returning to weighing boats. *Note: clean the pestle and mortar between each grind using dry paper or clean cloth – do not wash.

4. Weigh out 0.2 g of sample accurately on a top-loading balance (to 3 dp) – use a piece of paper and tare weight – then shake into 150 ml beaker.

5. Turn on hotplate to preheat.

6. Add 100 ml of 8% NaOH solution to each beaker using a 100 ml measuring cylinder.

7. Place beaker on hotplate and simmer. Do not cover or boil fiercely.

8. Top up beaker occasionally with deionised H_2O to prevent drying out and to ensure solution does not become too concentrated.

9. Turn hotplate off after 1 hour of slow boiling (simmering).

10. Pour beaker's contents into 200 ml **labelled** volumetric flask **using a funnel**, and wash all residue into flask with deionised water.

11. Top up flasks (when slightly cooled) to mark; stopper flask, then shake well.

12. Filter 50 ml of contents of each flask into separate 50 ml **labelled** volumetric flask, through **filter** funnel in rack using Whatman No. 1 grade papers (size 15 cm). Use filter paper in a corrugated folding mode. Ensure only 50 ml filtrate is transferred.

13. Decant filtrate into labelled 100 ml volumetric flask.

14. Turn on spectrophotometer to stabilise. Set to 540 nm.

15. Top 100ml flask up to mark with distilled water and stopper. Then **shake well**.

16. When all flasks are ready, pipette small volume from first one into each of three* cuvettes and using spectrophotometer (previously allowed to stabilise), measure absorbance (upper scale) and % transmission of first cuvette and record it. (* alternatively, re-use cuvette twice more for the same sample only)

Plant macrofossil analysis protocol for peat bog samples: Dmitri Mauquoy

This protocol is a combination of The Quadrat and Leaf Count macrofossil analysis technique (QLCMA) developed at the Southampton Palaeoecology Laboratory (Barber *et al.,* 1994) and used by Barber *et al.* (1998) and Mauquoy and Barber (1999) and the technique used by Bas van Geel, University of Amsterdam (see Speranza *et al.*, 2000; Mauquoy *et al.*, 2002).

- Peat sub-samples of 4-8 cm^3 volume need to be cut from the core (usually a 'Russian' pattern corer with a 7 or 9 cm diameter or 50x15x10 cm metal boxes). As an alternative, peat sub-samples can also be taken from a horizontal 1 cm thick slice with a cylindrical sampler of 2.6 cm diameter. Please note that 'standard' size Russian corers of 5 cm diameter used for the collection of samples for pollen analysis will NOT provide a big enough sample for macrofossil analysis and subsequent ^{14}C dates. Before sub-sampling the core should be trimmed to avoid contamination and only clean instruments used to avoid the introduction of 'modern' carbon and/or contamination with older or younger macro/microfossils, which could potentially cause problems with future ^{14}C dates.
- Plant macrofossil samples should be gently boiled with 5% KOH (to dissolve humic and fulvic acids) and disaggregated on a 100 or 125 µm sieve using a 'squeezy' bottle of distilled water to rinse the sub-sample on the sieve. When sieving, the plant remains in the sieve must be kept just under the water surface (to avoid too much damage and disintegration of, for example, *Sphagnum* stems with leaves still attached. This can be very important for *Sphagnum* identification, because stem leaves can help in identification to species level). Where preservation is good, complete *Sphagnum* plants also make collection of ^{14}C samples much easier (a less time consuming task).
- Macrofossils retained on the sieve are then transferred to a glass beaker/bowl (approximately 20x10 cm) and only enough distilled water should be added to *float* the remains, which are scanned using a low power (x10-x50) stereo-zoom microscope. If a large beaker/bowl is unavailable, the sample can be poured into a petri-dish a little at a time, inspected, then more of the sample added to another petri-dish, until all of the remains have been scanned for that sample. Plant macrofossils are then estimated as percentages by using a 10x10 square grid graticule inserted into one of the microscope eyepieces and moving the trough of remains randomly to 15 different views and averaging the results (this is where the total *Sphagnum* volume percentages within the total macrofossil sample are estimated, in addition to the other main peat components, for example ericaceous rootlets or remains of *Eriophorum,* and/or volume percentages of *Aulacomnium palustre* and *Polytrichum* spp (where present)). Sub-samples which contain well preserved epidermal tissues of monocotyledon species need to be mounted onto slides (temporary slides can be made using water) and identified at x400 magnification. If remains of *Eriophorum vaginatum* are present there is no need to make microscope slides, because with experience, the characteristics of *E. vaginatum* are already evident under the stereo-zoom microscope A random selection of at least 100 *Sphagnum* leaves also need to be mounted on slides and identified at x400

magnification, and the results expressed as percentages of the total identifiable *Sphagnum* estimated in the first part of the macrofossil analysis.

- Fruits/seeds and macroscopic charcoal fragments are simply counted as the number (n) found in each sub-sample. Charcoal fragments can be placed into size classes, e.g., charcoal fragments <0.5mm (length), 0.5-1mm, 1-1.5mm, 1.5-2mm and >2mm. Volume percentages of 'above-ground' ericaceous remains are normally very low, for example *Calluna vulgaris* stems, *Andromeda polifolia* leaves, *Calluna vulgaris* leaves, *Empetrum nigrum* leaves, *Erica tetralix* leaves, *Vaccinium* spp. These remains should also be counted separately.
- Once macrofossil analyses are completed, store samples in sealed plastic bags or tubes and add a few drops of HCL (5%) to prevent further decomposition and contamination by bacteria or fungi. Store sub-samples in the dark in a cold room at 3-4°C (where possible). This procedure needs to be completed, because some of the sub-samples will be subsequently ^{14}C dated.

General comments

- The use of a reference collection of type material is highly recommended, owing to the lack of keys. There are however, good plant macrofossil photographs in Grosse-Brauckmann (1972; 1974; 1992), and Katz *et al.* (1977). Bas van Geel also has an excellent reference collection of raised bog material in Amsterdam, which will certainly be very useful for ACCROTELM scientists.
- Leaves of *Sphagnum* can be identified using 'The Moss Flora of Britain and Ireland', A. J. E. Smith, 1980, Cambridge University Press, Cambridge and 'Vit Mossor I Norden', Mossornas Vänner 1986, Fjärde upplagen 1995, Vasastadens Bokbinderi AB, Göteborg 1995, ISBN 91-971274-2-7 (this one is good for the Scandinavian *Sphagnum* species).

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