Technical Report

TR-06-46

Physical parameters and accumulation rates in peat in relation to the climate during the last 150 years

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December 2006

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Summary

The safety assessment made by SKB (SR 97) states that radionuclides can be accumulated in higher amounts in peatlands than in other recipients. Therefore is knowledge about the nature and properties of peat very important. Here is the decay of peat and the accumulation rate of the most important elements of peat examined further.

Two ombrotrophic peat bogs located in Uppland have been investigated in order to evaluate the influences of climate on the accumulation of carbon and nitrogen. Peat humification, content of carbon and nitrogen has been used for interpretation of peat forming processes. The long temperature and precipitation records from Uppsala have been used to compare the results to known climate variations.

Various models and equations assess the contribution of peatlands to the global carbon economy and the role that peat accumulation plays in global climate due to global carbon cycling and the concern of increasing levels of greenhouse gases. The importance of peatlands in the global carbon economy is stressed by that it is approximately the same amount of carbon in peatlands as in the atmosphere. Estimations of the total amount of carbon stored in Boreal and Arctic peatlands are in the magnitude of 400–500 Pg.

The peat accumulation rate varies by at least a magnitude in peatlands with different conditions in internal and external hydrology, length in growth season, effective precipitation, temperature etc. Accumulation rates have been reported from a variety of temperate and boreal bogs ranging between 0.2–2.0 mm yr^{-1} and a Boreal and northern Sub-artic region average of carbon accumulated in the catotelm has been calculated to ca 21 g C m^{-2} yr^{-1}. The proportion of nitrogen in the dry mass is usually in the order of 0.5–5%.

The mean accumulation rate of carbon and nitrogen during the last 157 years at Ältabergsmossen are 73 g C m^{-2} y^{-1} and 1 g N m^{-2} y^{-1}, these levels are similar to the ones found in other investigations as well as more theoretical deduced numbers. In this study the temporal resolution is relatively high, with ca 3 years/sample, and therefore it has been possible to detect leads/lags between the proxies, as opposed to longer sequences with lower time resolution. Biological proxies, e.g. plant macrofossils and testate amoebae, reflect the actual wetness conditions at the time when the plants and amoebae lived. Peat humification and C/N ratio on the other hand reflect the conditions during the decay-process of the organic material, i.e. processes that influence already deposited material. In this data it is evident that there is a discrepancy between peat decomposition and dry bulk density/C-N accumulation rates, this might be a result of secondary decomposition, or it could reflect different responses in decomposition and growth rates to changes in temperature and precipitation.

Increasing temperature is likely to increase CO_2 and CH_4 emissions to the atmosphere, this is said to be the only direct climatic effect on existing Boreal peatlands but indirect effects as increased peat oxidation induced by falling water tables are exceedingly important, however extremely difficult to forecast. Despite these apprehensions the positive carbon balance in the Boreal peatlands could be expected to be maintained for several thousands of years.

Sammanfattning

SKB:s säkerhetsrapport SR 97 anger att radionuklider kan ackumuleras i högre halter i torv än i andra mottagare. Därmed är det viktigt att förbättra kunskapen om torvens innehåll och egenskaper. I denna rapport undersöks nedbrytningsgraden och ackumulationshastigheten hos två av de viktigaste grundämnena i torv.

Två Uppländska mossar har undersökts för att utvärdera klimatets inverkan på ackumulationen av kol och kväve. Torvens nedbrytningsgrad och halterna av kol och kväve har använts för tolkning av torvbildande processer. Den långa serien av temperatur- och nederbördsdata från Uppsala har använts för att jämföra resultaten med kända svängningar i klimatet.

En mängd modeller och beräkningar uppskattar bidraget från torvmarker till den globala kolbudgeten samt den roll som torvackumulation spelar i det globala klimatet beroende på den globala kolcykeln och oron för ökande halter av växthusgaser i atmosfären. Vikten av torvmarker i den globala kolbudgeten betonas av att det finns ungefär lika mycket kol i torv som i atmosfären. I torvmarkerna i de kalltempererade (Boreala) och subarktiska klimatzonerna uppskattas det att det finns i storleksordningen 400–500 Pg kol bundet.

Ackumulationshastigheten i torv varierar med åtminstone en magnitud, beroende på olikheter i intern och extern hydrologi, längd på växtsäsongen, effektiv nederbörd och temperatur etc. Från ett antal torvmarker i Boreala och tempererade klimat har ackumulationshastigheter mellan 0,2–2,0 mm/år rapporterats. Ett medelvärde på ackumulation av kol i Boreala och subarktiska torvmarker har beräknats till 21 g C m^{-2} $år^{-1}$. Halten kväve i torv ligger oftast runt 0,5–5 % av torrmassan.

Under de senaste 157 åren har Ältabergsmossen haft medelackumulationshastigheter av kol och kväve på 73 g C m^{-2} $år^{-1}$ samt 1 g N m^{-2} $år^{-1}$. Dessa värden är i paritet med de nivåer funna i andra undersökningar såväl som med mer teoretiska beräkningar. I den här studien är den temporala upplösningen relativt hög med ca 3 år/prov, därmed har det varit möjligt att upptäcka förskjutningar mellan de olika parametrarna, i motsatts till längre sekvenser med sämre tidsupplösning. Biologiska proxies, t.ex. växtmakrofossil och testata amöbor, reflekterar de faktiska fuktighetsförhållandena vid tiden då växten och amöban levde. Torvens humifieringsgrad och C/N kvot reflekterar å andra sidan förhållandena under nedbrytningen av organiskt material, d.v.s. processer som påverkar redan avsatt material. I dessa data är det tydligt att det existerar en skillnad mellan humifieringsgrad och torrdensiteten/C-N ackumulationshastighet som kan bero på sekundär nedbrytning eller reflektera olika respons hos nedbrytning och tillväxthastighet på förändringar i temperatur och nederbörd.

Ökande temperaturer ökar sannolikt emissionen av CO_2 och CH_4 till atmosfären, detta är troligtvis den enda direkta klimatpåverkan på Boreala torvmarker, men indirekta effekter såsom ökad oxidation av torv på grund av sjunkande grundvattenytor är ytterst viktiga med de är oerhört svåra att förutsäga. Trots dessa farhågor är det troligt att Boreala torvmarker kommer att behålla den positiva kolbalansen flera årtusenden.

Contents

1 Introduction

In the safety assessment made by SKB (SR 97) wetlands are reported to be able to accumulate radionuclides in higher amounts than other recipients /Bergström et al. 1999, SKB 1999/. In this context is knowledge about the nature of peatlands very important and in this report is the decomposition of peat and accumulation of carbon and nitrogen and its relation to climate analysed.

1.1 Investigation area

1.1.1 Geological setting

The two investigated bogs are situated ca 10 km from the coast in southern Roslagen, Uppland (Figure 1-1). Uppland is part of the uplifted and eroded sub-cambrian peneplain /Lidmar-Bergström 1994/. The bedrock belongs to the Svecocarelian orogenetic belt and consists mainly of vulcanites, granites and gneisses /Möller and Stålhös 1974, Persson 1990/. The Quaternary deposits are dominated by sandy till with sparse occurrences of glaciofluvial material and clays in lower areas /Möller and Stålhös 1974, Persson 1990/. Deglaciation of the area took place around 8.300 BC and the highest coastline is situated around 160 m above sea level /Lundqvist 1994/.

Both bogs are ombrotrophic mires and are surrounded by large forested areas and have no visible traces of peat-cutting, drainage, recent changes in forestry or other disturbances. Ältabergsmossen (59°58’ N, 18°41’ E) is small (0.2 km^2) and is situated at c 25 m above sea level. The bog is surrounded till and bedrock with a thin till cover and the bog surface is dominated by open *Sphagnum* and *Eriophorum vaginatum* vegetation and some small pine trees. Till, coarse clays and bedrock surrounds Gullbergbymossen (59°38’ N, 18°26’ E). This bog is somewhat larger than Ältabergsmossen, with an area of about 0.5 km^2 and is situated at 40–45 m above sea level. The bog surface is sparsely forested with pine trees growing on Sphagnum peat and has a large pool dominated by *Carex* species.

1.1.2 Climatic conditions

The long instrumental temperature /Bergström and Moberg 2002/ and precipitation records (provided by SMHI) from Uppsala have been used in order to compare the data from the sub-recent peat with known climatic variations.

The climate around the investigation area is characterised by relatively maritime conditions. The wind directions differ somewhat from the basic South Swedish, trough frequent northerly directions. This causes often heavy snowfall in the winter /Larsson-McCann et al. 2002/. The closest meteorological station (Figure 1-1) reports a mean annual temperature of ca +5.1°C and a total precipitation of about 555 mm y^{-1} /Alexandersson et al. 1991/. The highest amount of precipitation falls in July and the lowest amounts fall in February/March. The temperature spans about 20 degrees; the coldest month (February) has an average of ca –5°C and the warmest (July) has an average of ca +15°C (Figure 1-2).

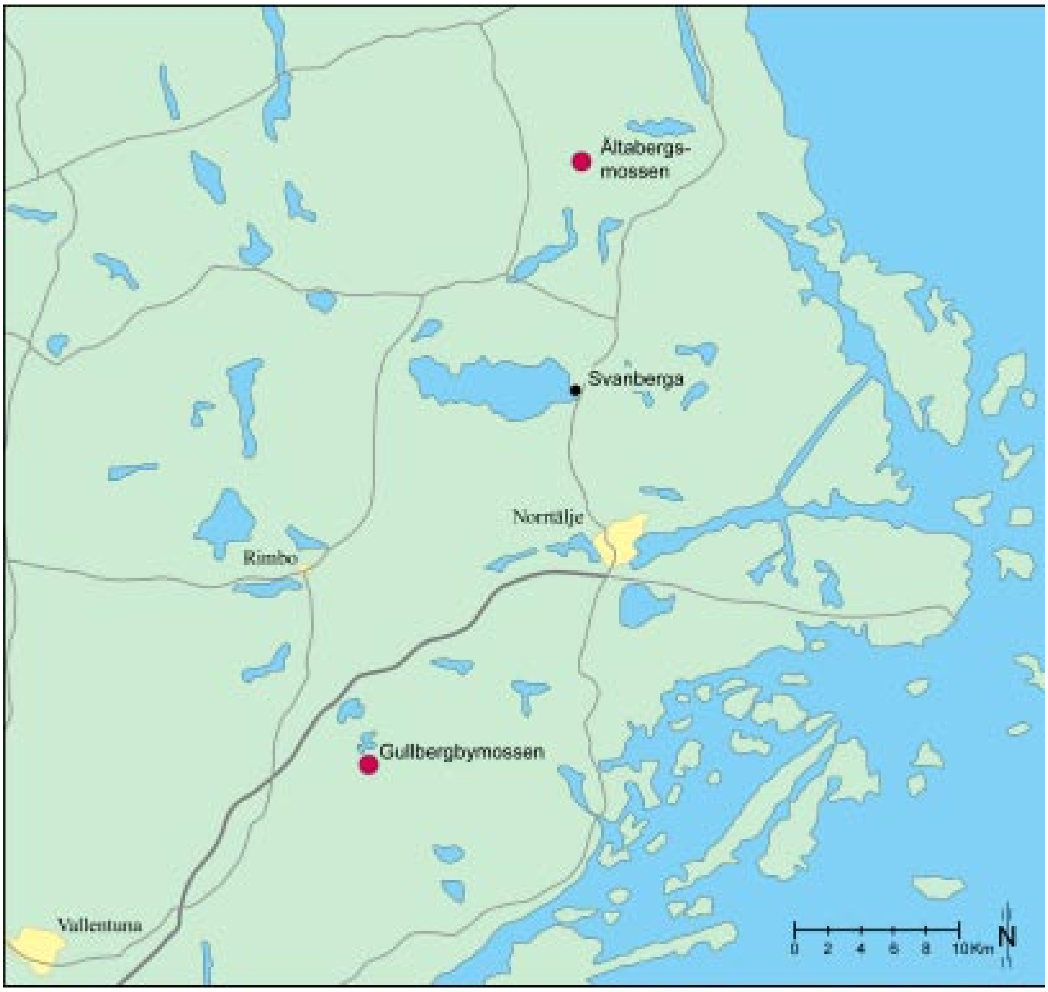

Figure 1-1. *Location of the investigated bogs and the location of the meteorological station Svanberga.*

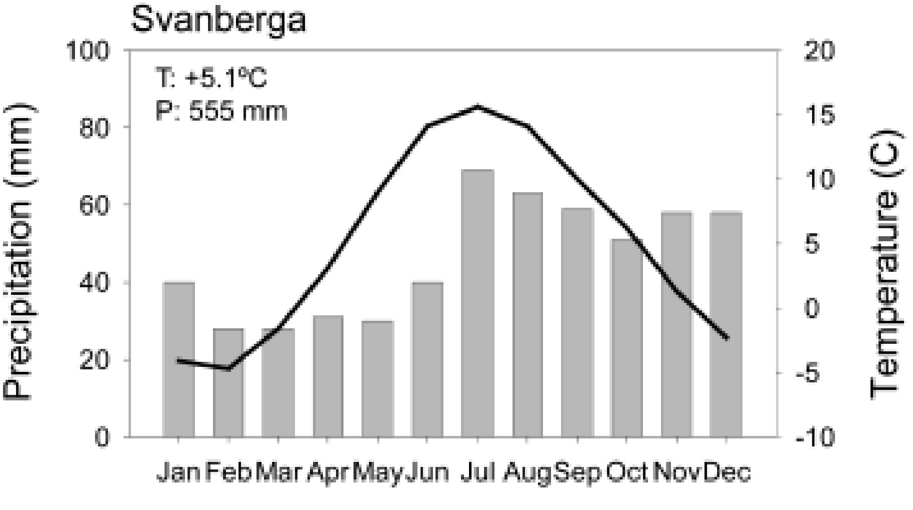

Figure 1-2. *Precipitation (bars) and temperature (line) averages 1961–1990 /Alexandersson et al. 1991/ at Svanberga. Annual mean temperature (T) and total annual precipitation (P) is also shown.*

1.2 Peat as a palaeoenvironmental record

Peat has been used as an archive for climate variations for over a hundred years, and Scandinavian peatlands provided the basis for the first Holocene climatostratigraphy /Chambers and Charman 2004/. The pioneer work of e.g. A Blytt, R Sernander and C A Weber /Blytt 1876, Sernander 1908, 1909, 1912, Weber 1926/ was followed by several investigations in Sweden /von Post and Sernander 1910, von Post and Granlund 1926, Granlund 1932/, which established peatland stratigraphy as a tool for the interpretation of past climate changes.

At the Geological Congress in Stockholm in 1910 the hypothesis of a cyclic regeneration of peat growth i.e. from hollow to hummock and back to hollow, was presented /von Post and Sernander 1910/. This and other hypothesises, such as the one on autogenic succession of peat /Osvald 1923/, led to a misconception on how ombrotrophic peatlands develop /Backéus 1990/. For many years the predominating view was that peatlands grow primarily through autogenic processes and not under the control of allogenic processes (i.e. climate). The focus on autogenic processes led to a decline in peat-based palaeoclimatic science /Chambers and Charman 2004/.

The view of cyclic regeneration as the primary process for peat accumulation in ombrotrophic mires was challenged in the early 1980's /Barber 1981, Frenzel 1983/. /Barber 1981/ rejected the hypothesis by extensive plant macrofossil analyses of peat stratigraphies along transects, showing that the hummock/hollow complexes could be stationary for long periods of time, and he concluded that the growth of a bog is to a large extent controlled by climate. /Barber 1981/ concluded that different thresholds could influence regional as well as local variations in bog growth, but factors such as hydrology, drainage, plants life cycles and pool-size are all subordinate to climate.

Today a wide range of methods are used to reconstruct past climate from peat stratigraphies /Chambers and Charman 2004/. Quantitative macro- and microfossil analysis /Charman and Warner 1997, Barber et al. 1998, Barber et al. 1999, Charman et al. 2000, Hughes et al. 2000, Mauquoy et al. 2004a/ together with peat humification /Nilssen and Vorren 1991, Blackford and Chambers 1993, Caseldine et al. 2000, Langdon and Barber 2004, Roos-Barraclough et al. 2004, Blundell and Barber 2005/ are the most widely used methods. The range of biological, physical and chemical methods that are now available make multiproxy investigations possible.

Although some of the proxies may not be independent of each other e.g. a plant-species signal within the degree of humification, they can nevertheless be used as high resolution proxies with excellent possibilities for interpretation /Chambers and Charman 2004/.

As mentioned above, most of the early peat studies were performed in Scandinavia. /Blytt 1876/ and Sernander /Sernander 1908, 1909, von Post and Sernander 1910, Sernander 1912/ conducted pioneer research, which was followed by von Post and Granlund with the inventory of peatlands in southern Sweden /von Post 1921, von Post and Granlund 1926, Granlund 1932/. These extensive spatial and stratigraphical studies led to Granlund's thesis /Granlund 1932/ on the geology of raised bogs in Sweden. In his thesis he studied the relationship between the dome-shape of bogs and the amount of precipitation in different areas of southern Sweden, investigated the capillarity of different types of *Sphagnum* peat and formulated the concept of recurrence surfaces (Swedish: *rekurrensyta*, RY). A recurrence surface is a distinct change from dark well humified peat, representing drier conditions on the bog, to light less humified peat, representing wetter conditions /Granlund 1932/. Granlund identified five different surfaces in southern Sweden, where most recurrence surfaces were found in Småland and further northwest towards Värmland /Granlund 1932/. Two older recurrence surfaces were theoretically deduced /Lundqvist 1932/ and later described by /Sandegren and Magnusson 1937/.

Detailed stratigraphical work on peatlands continued during the regional mapping of Quaternary deposits /Lundqvist 1958/. During the late 1940's and 1950's the radiocarbon dating technique was developed and tested on peat. However, this novel dating method also introduced a problem: the radiocarbon ages did not exactly fit into the previously established chronology /Lundqvist 1957, Möller and Stålhös 1964/. Subsequently, the ages of known recurrence surfaces were interpreted as being asynchronous /Lundqvist 1957/. Therefore, the concept of recurrence surfaces as indicators of regional climate changes was questioned /Lundqvist 1962/. The scientific community in Finland has been sceptical to the notion of climatic influence on the development of recurrence surfaces since the theory was introduced /Aario 1932, Tolonen et al. 1985, Tolonen 1987/ and is, according to /Korhola 1992/, still placing major emphasis on autogenous succession. Due to the national and international scepticism, recurrence surfaces became considered to be of minor use as indicators of palaeohydrological changes and as exact stratigraphical markers in Sweden /Fries 1951, Lundqvist 1957, Lundqvist 1962, Nilsson 1964/. Despite the general decline in peat-based studies a number of investigations have been conducted in Fennoscandia regarding different aspects of peat growth, peat accumulation rates, bog development, local environment and degree of humification /Nilsson 1964, Tolonen 1973, Aaby and Tauber 1975, Aaby 1986, Tolonen 1987, Foster et al. 1988, Svensson 1988/. Aaby /Aaby and Tauber 1975, Aaby 1976/ made attempts to identify cyclic variations in the climatic signal from raised bogs in Denmark and this important work has been followed by a number peat-based studies on palaeoclimate in Scandinavia /Thelaus 1989, Nilssen and Vorren 1991, Korhola 1992, Korhola 1995, Oldfield et al. 1997, Mauquoy et al. 2002, Barber et al. 2004, Björck and Clemmensen 2004, Bergman 2005, Schoning et al. 2005/. /Barber et al. 2004/ stated that there is a need for more peat-based palaeoclimatic research from this part of Europe and several bogs in Sweden seem to provide valuable records for palaeoclimatic reconstructions /Svensson 1988, Björck and Clemmensen 2004, Bergman 2005, Schoning et al. 2005/.

1.3 Accumulation of peat and carbon

Theoretical determination of peat and carbon accumulation rates has been the interest primarily of the ecological community. Various models and equations have been set up in order to assess the contribution of peatlands to the global carbon economy /Clymo et al. 1998/ and the role that peat accumulation plays in global climate due to global carbon cycling and the concern of increasing levels of greenhouse gases /Charman 2002/. Estimations of the total amount of carbon stored in Boreal and Arctic peatlands are in the magnitude of 400–500 Pg /Gorham 1991, Clymo et al. 1998/. The importance of peatlands in the global carbon economy is stressed by that it is approximately the same amount of carbon in peatlands as in the atmosphere /Houghton et al. 1990/. See also /Kellner 2004/ for a review of peat formation and development.

1.3.1 Models of accumulation

There are two basic categories of peatland models; Conceptual- and simulation models. Conceptual models aims at describing relations between different processes in order to examine the outcome of various assumptions /Clymo 1992/. A simulation model is built upon a conceptual model with the purpose to mimic and reproduce the behaviour of actual ecosystems, through changing one or several parameters over time /Yu et al. 2001a/.

The most developed conceptual model at present is the Clymo peat growth model /Clymo 1984, 1992, Clymo et al. 1998/. This model uses a two-layer system to describe the accumulating peat, i.e. the acrotelm and catotelm (Figure 1-3, Table 1-1). The boundary between the relatively thin acrotelm and the catotelm, representing the bulk of the peat, is approximately at the mean depth of the lowest water table. The model assumes a constant proportional decay and that the rate of mass loss is directly proportional to the amount of material remaining. A further development of this model includes three different decay models /Clymo et al. 1998/. Other conceptual models include the more hydrological oriented model by /Ingram 1982/, this model is set up in relation to cross-sectional shapes of bogs with a drier climate resulting in a flatter bog surface.

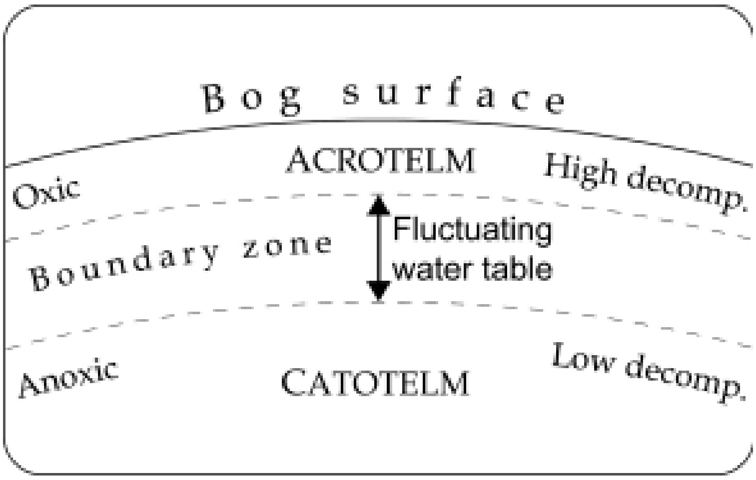

***Figure 1-3.** Schematic picture showing the position of the acrotelm, where the active decomposition takes place, and the catotelm, with very a low decay rate, in relation to the fluctuating groundwater table near the bog surface. The fluctuations of the groundwater table determine the depth of the acrotelm.*

The model fits relatively well to smaller raised bogs, but fails to describe larger more complex bogs /Yu et al. 2001a/. /Kirkby et al. 1995/ presented a modified version of Ingram's model which incorporates effective precipitation and also recognises the importance of the acrotelm depth. The basis for this model is that effective precipitation and its variability determine the height of the bog, resulting in that high effective precipitation increases the height and that high variability reduces the bog height. This model has been used to predict initiation and growth on suitable sites in Europe. In an integrated model by /Almquist-Jacobson and Foster 1995/, both internal and external processes were set to determine peat accumulation and bog shape and expansion. As in Ingram's model this model uses an elliptical cross-section of the bog and the water balance determines the size and shape of the bog. As a consequence of this is peat accumulation and lateral expansion decreasing under stable climate.

The simulation models incorporates usually a higher number of parameters than the conceptual ones, they do also often use climate as a driving factor. One model that is very complex in its design is the Forrester's systems model /Forrester 1961, Clymo 1992/, using numerous parameters representing virtually all components of peatland systems. However, several parameters and functional specifications are not specified. An empirical topography-driven 3D model /Korhola 1992, Korhola 1995, Korhola et al. 1996/ uses peat initiation dates and estimated parameters (Bulk density, production and decay rates and CH_4 efflux) for reconstructing an observed peat bog. This model assumes that terrain slope determines the lateral and vertical bog expansion. In another model of peatland dynamics, which emphasize on the interaction between water table depth and peat production, is two coupled non-linear differential equations representing change in depth of peat and depth to the water table /Hilbert et al. 2000/.

Table 1-1. Main properties of the acrotelm and catotelm in peatlands. Modified from /Charman 2002/.

Property	Acrotelm	Catotelm
Water content and movement	Variable, rapid movement	Constant, very slow movement
Oxygen supply	Aerobic (periodically)	Anaerobic
Microbial activity	High	Low
Decay rate	Rapid	Slow

The model provides an integrated view of how peatlands function over long time scales, by focusing on the non-linear interactions among peat production, decomposition and hydrology, and shows that equilibrium peat accumulation and water table depth depend on the net water input to the peatland. In very wet conditions peatlands have water tables near the surface and peat accumulation is limited by low production rates. There is no interaction between acrotelm and catotelm in this model (constant bulk density). /Frolking et al. 2001/ developed a peat decomposition model. This cohort-based model relates long-term peat accumulation directly to decomposition rates of fresh vegetation litter. In the model is the two vegetation types of mosses and vascular plants recognised together with root input from vascular plants into deep peat. The model is static and assumes constant vegetation production and initial litter decomposition. The model integrates the acrotelm and catotelm with use of prescribed anoxic factors and bulk density profiles. The concept and development of a three-dimensional peatland initiation, expansion and decay model is described by /Yu et al. 2001a/. In this model is a digital elevation model used to generate a non-peat mineral soil starting point, and bogs initiate when certain predefined conditions are met, however, bogs can only initiate from fens and only grow vertically. The model is also evaluated with re-analysis of Canadian field data with the conclusion that wiggles in peat age-depth profiles often are caused by changes in peat addition rates, which are determined by climatically sensitive processes including photosynthesis and acrotelm decomposition /Yu et al. 2001b/.

1.3.2 Rates of accumulation

The peat accumulation rate varies by at least a magnitude in peatlands with different conditions in internal and external hydrology, length in growth season, effective precipitation, temperature etc. Accumulation rates have been reported from a variety of temperate and boreal bogs ranging between 0.2–2.0 mm yr^{-1} /Aaby and Tauber 1975, Anderson 2002/. These rates fits into the accumulation rates reported in three bogs situated in Värmland /Borgmark 2005b, Borgmark 2005a/.

The amount of carbon that accumulates within the peat varies both spatially and temporally. In a comparison between the boreal and subalpine parts of Sweden is the carbon input to the acrotelm in sub-alpine peatlands about 5/8 of the levels in southern Sweden /Malmer and Wallén 2004/. At Walton Moss have large variations in carbon accumulation rates (range ca 5–55 g C) been found in multiple cores /Mauquoy et al. 2002/, decreasing accumulation rates by up to 40 g C m^{-2} yr^{-1} are associated with high occurrences of *Sphagnum cuspidatum* and higher peat humification (the unit in the article is incorrect [cm^{-2}], an error by the authors; Dmitri Mauquoy pers. com.). In three Scottish bogs have carbon accumulation rates ranging about 5–30 g C m^{-2} yr^{-1} been recorded /Anderson 2002/. At Store Mosse in Sweden has accumulation rates of about 20 to >650 g C m^{-2} yr^{-1} been measured /Malmer and Wallén 2004/. In an extensive analyse of 1,028 peat cores from Finnish peatlands has a range of 2.8 to 88.6 g C m^{-2} yr^{-1} been found /Tolonen and Turunen 1996/. The Finnish data reveals higher carbon accumulation rates in bogs than in fens and higher values have been found in mires along the eastern shore of the Gulf of Bothnia, where climatic conditions are more oceanic /Tolonen and Turunen 1996/. A Boreal and northern Sub-artic region average of carbon accumulated in the catotelm has been calculated to ca 21 g C m^{-2} yr^{-1} /Clymo et al. 1998/.

Very few data are available regarding accumulation rates of nitrogen, however, in studies where nitrogen has been measured are the levels usually in the same order as in the present study i.e. around 0.5–5% of the dry mass /Anderson 2002, Keller et al. 2004, Malmer and Wallén 2004/.

1.4 Links to climate

Changes in climate have many underlying causes, of which many remain unknown and the effects on climate are often poorly constrained. Both external and internal forcing causes changes in an extremely complex climatic system /Emeis and Dawson 2003/. Lately solar variation has emerged as an important external forcing mechanism for climatic variability on decadal to millennial timescales /Chambers et al. 1999, Bond et al. 2001/ and changes in $\Delta^{14}C$ have been attributed to the changes in solar activity /Karlén and Kuylenstierna 1996, Stuiver and Braziunas 1998, Chambers et al. 1999, Beer et al. 2002/. A number of correlations have been made between climate proxy records and solar variability in terms of $\Delta^{14}C$ and ^{10}Be values /Denton and Karlén 1973, Reid 1987, O'Brien et al. 1995, Stuiver et al. 1998, van Geel et al. 1999, Bard et al. 2000, van Geel et al. 2000, Björck et al. 2001, Blaauw et al. 2004, Mauquoy et al. 2004b, Mayewski et al. 2004/. Exactly how the relatively small changes in solar irradiance can affect the climate is not clear, possible forcing mechanisms have been discussed e.g. changes in ocean circulation /Bond et al. 2001/, variations in UV irradiance leading to altered production of ozone and absorption of heat in the atmosphere and as a consequence shifts in the atmospheric circulation /van Geel et al. 1999, Blaauw et al. 2004/ and influence of cosmic rays on cloud formation /Carslaw et al. 2002/.

2 Methods

2.1 Peat humification

The method to chemically analyse and determine the decomposition of peat was originally developed by Overbeck (according to /Bahnson 1968/) and later modified by /Bahnson 1968/. The method is based on colorimetric determination of an alkaline extract of the peat, where the alkaline absorbance is proportional to the amount of dissolved humic substances /Aaby 1976, 1986/. Highly decomposed peat is usually dark brown/blackish whereas low decomposed peat is light brown/yellowish in colour corresponding to the amount of extractable humic substances.

The methodology has been modified and improved by /Blackford and Chambers 1993/, and this method is now the standard used for determining peat decomposition. In this study a slightly modified version has been used in order to better suite a large number of samples. Here 0.100±0.01 g dry peat was dissolved in 25 ml 8% NaOH in 50 ml plastic tubes, and boiled in a water bath at 95°C for 1.5 hr.

The boiled samples were than centrifuged and filtered and, in order to maintain the same dilution rate as in the original procedure, 12.5 ml of the resulting extract was diluted with distilled water to 100 ml. Each sample was then measured three times in a UNICAM spectrophotometer at 540 nm and the average was calculated and corrected to the normal-weight of 0.1 g.

2.2 Carbon and nitrogen

For carbon and nitrogen analyses 0.5–1 mg of dried and ground peat was enclosed in metal capsules. The analyses were performed with a Carlo Erba NC2500 analyzer connected, via a split interface to reduce the gas volume, to a Finnigan MAT Delta plus mass spectrometer at the Department of Geology and Geochemistry, Stockholm University. The results are presented as weight percentages carbon and nitrogen.

2.3 Accumulation rates

In order to be able to calculate the accumulation rates of carbon and nitrogen at Ältabergsmossen was the dry bulk density determined. Samples of a determined volume (5 cm^3) were picked out at the same depths and intervals as the previous sampling. The samples were weighted, dried at 105°C for ca 24 h and weighted again. Determination of dry bulk density was conducted according to /Bengtsson and Enell 1986/ and the accumulation rates of carbon and nitrogen was calculated by transforming the percentages into units of weight per volume and division of this product by the number of calendar years spanning the sample /Anderson 2002/. The results are expressed as $g\ m^{-2}\ y^{-1}$ in order to facilitate comparison with other studies (Figure 2-1).

$$Acc. = \frac{\left(\frac{S}{V}\right)\left(\frac{S_D}{S}\right) \times P}{Y} \times 100$$

Acc. – Accumulation rate (g m^{-2} y^{-1})

S – Wet sample weight (g)

S_D – Dry sample weight (g)

V – Volume (cm^3)

P – Percentage C, N (%)

Y – Number of years represented in sample according to age-depth model

Figure 2-1. *Equation used to calculate accumulation rates.*

2.4 Chronology and data analysis

The chronologies for Ältabergsmossen and Gullbergbymossen were constrained by /Schoning et al. 2005/ by means of SCP-counting (Spherical Carbonaceous Particles), tephra-horizons and AMS radiocarbon dating. For the Ältabergsmossen profile was a second-order regression line used and for the Gullbergbymossen profile was a linear interpolation used to calculate the age-depth relations /Schoning et al. 2005/. All ages are expressed as calendar years AD.

Correlation between C, N percentages and humification values were calculated and thereafter tested using the t-test at a 5% significance level /Davis 1986/. The degrees of freedom have been determined by calculating the effective number of observations ($N_{eff.}$) according to the autocorrelation that are evident in the data series, using the equation: $N_{eff.} = N*(1–r1r2)/(1+r1r2)$, were N is the number of observations and r1 and r2 are the lag-1 autocorrelation for series 1 and 2 /Quenouille 1952/ (Table 2-1).

Table 2-1. Correlation coefficients (r) between the proxies from Ältabegsmossen. Degrees of freedom (DoF) calculated according to /Quenouille 1952/. Results from the t-test and critical values of t at 5% significance level, using the calculated degree of freedom /Davis 1986/.

Proxies	r	DoF	*t*-test	Critical *t* value
abs-N	0.617	14	2.716	1.761
abs-C	0.69	23	4.371	1.714
N-C	0.842	25	7.483	1.708

3 Results and interpretation

3.1 Bog surface wetness

Peat humification is relatively uniform in the lower part of the sequence from Ältabergsmossen (Figure 3-1a). From 1855 to c 1890 the humification values are more or less stable. Thereafter a gradual transition to lower humification starts, reaching the lowest values in the sequence around 1910–1920. This period of low humified peat ends c 1930. From 1930 humification values start to rise somewhat and from c 1945 the rise in humification is more pronounced. This period lasts to c 1975 and is only intersected by two samples indicating lower humification c 1955–1960. From c 1980 until the top sample the humification is nearly stable with only minor changes.

The sequence from Gullbergbymossen contains a period of very slow peat accumulation or even a hiatus /Schoning et al. 2005/, due to this is only the uppermost 21 cm of peat used, corresponding to the last 60 years. The peat humification record (Figure 3-1a) displays a general increase until the mid 1970's thereafter decreases the humification to the top of the sequence. According to the testate amoebae assemblage (Figure 3-1b) a rise in water table took place around 1950 and lasted until approximately 1970 where a decline in water table starts and the water table has since then remained low /Schoning et al. 2005, Borgmark and Schoning 2006/.

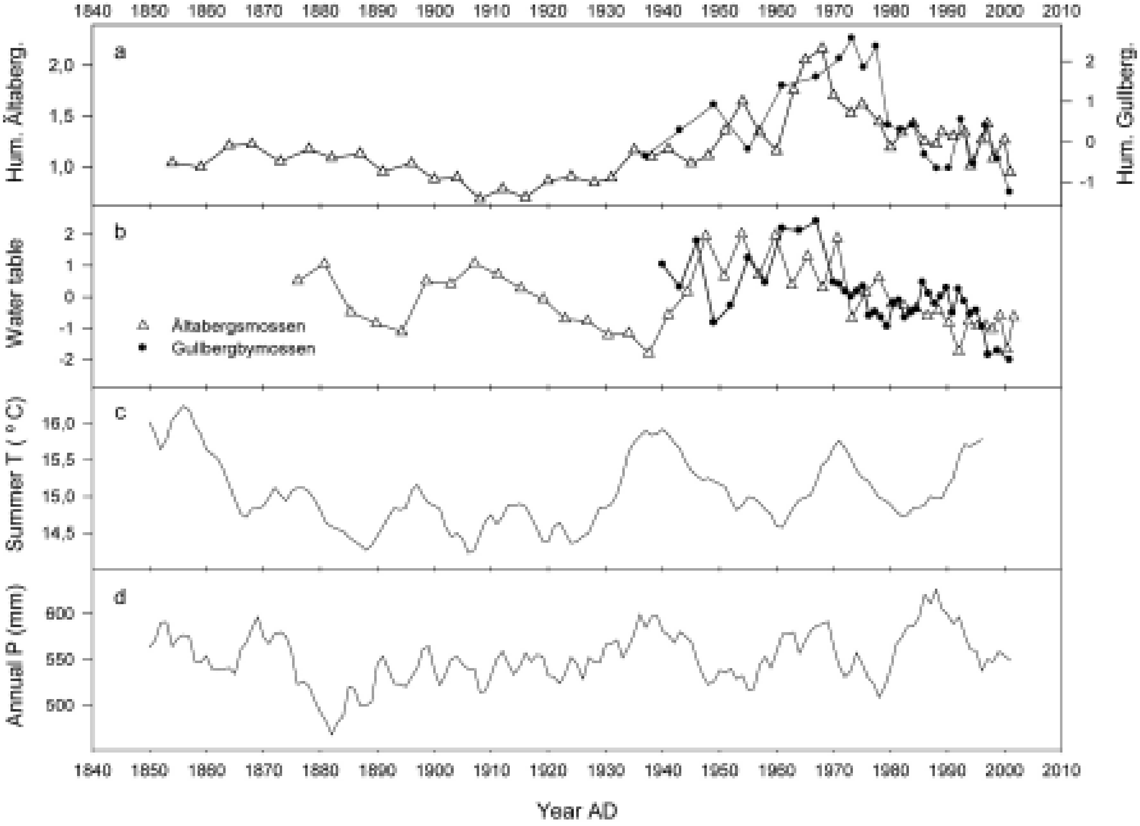

__Figure 3-1.__ (a) humification values for Ältabergsmossen and Gullbergbymossen, (b) inferred water table from /Schoning et al. 2004/, (c) summer temperature and (d) annual precipitation from the Uppsala series.

Humification values and testate amoebae assemblages /Schoning et al. 2005/ in Ältabergsmossen show significant changes in surface wetness, which could reflect natural climate changes. Due to the relatively few data points obtained it is not possible to measure to a statistically significant level the responses or the lag of the chemical/physical versus the meteorological/biological parameters here. The inferred water table changes show the same trends in both records, suggesting that the changes in water table are driven by external forcing, i.e. climate. The humification data is similar at both sites, the same distinct changes in peat humification are present at both sites and occurs approximately at the same time.

3.2 Carbon and nitrogen

Carbon and nitrogen (Figure 3-2a, b) show some distinct features; both elements correlate to a high degree (r=0.842), and do also correlate to the humification ($r_{abs,C}$=0.69 and $r_{abs,N}$=0.617) (Table 2-1). From 1855 until around 1930 N shows a generally decreasing trend. After a small rise N percentages increase rapidly and reach the highest numbers between c 1960–1980 followed by a marked decline c 1980–1995. The last 5–10 years show very high N percentages. Trends in C and N values are very similar. However, the C content is somewhat more irregular and displays a weaker decreasing trend until the distinct increase at c 1955. These high C percentages last for about 25 years until c 1970. During the last 20 years high and low C percentages alternate.

The carbon accumulation rate (Figure 3-2e) displays a generally decreasing trend from 2001 to 1845. A high rate of carbon accumulation is present in the uppermost part of the sequence, this could represent the acrotelm, with ongoing decomposition of the organic material, and this is also supported by the fact that the lowest values in dry bulk density are found in this part of the sequence. The peak in accumulation that is present between ca AD 1970–1980 coincides with a rapid increase in dry bulk density (Figure 3-2d) and predates a period of higher humified peat. During this time was the climate characterised by relatively low precipitation and by a temperature drop of almost 1.5°C, from a warm peak around 1971 towards a more “normal” level (Figure 3-1c, d).

The nitrogen accumulation rates follows the same pattern as the rates of carbon, this is also evident in the strong correlation between the two elements (Table 2-1, Figure 3-2e, f).

The average carbon accumulation rate is 73 g m^{-2} y^{-1} and the average rate for nitrogen is 1 g m^{-2} y^{-1} and coupled with the estimated area of the bog of 0.2 km^2, this result in a yearly accumulation of 14.6 tons of carbon and 0.2 tons of nitrogen at Ältabergsmossen. In total could about 2,200 tons of carbon and 30 tons of nitrogen have been accumulated in Ältabergsmossen during the 157 years that are studied here.

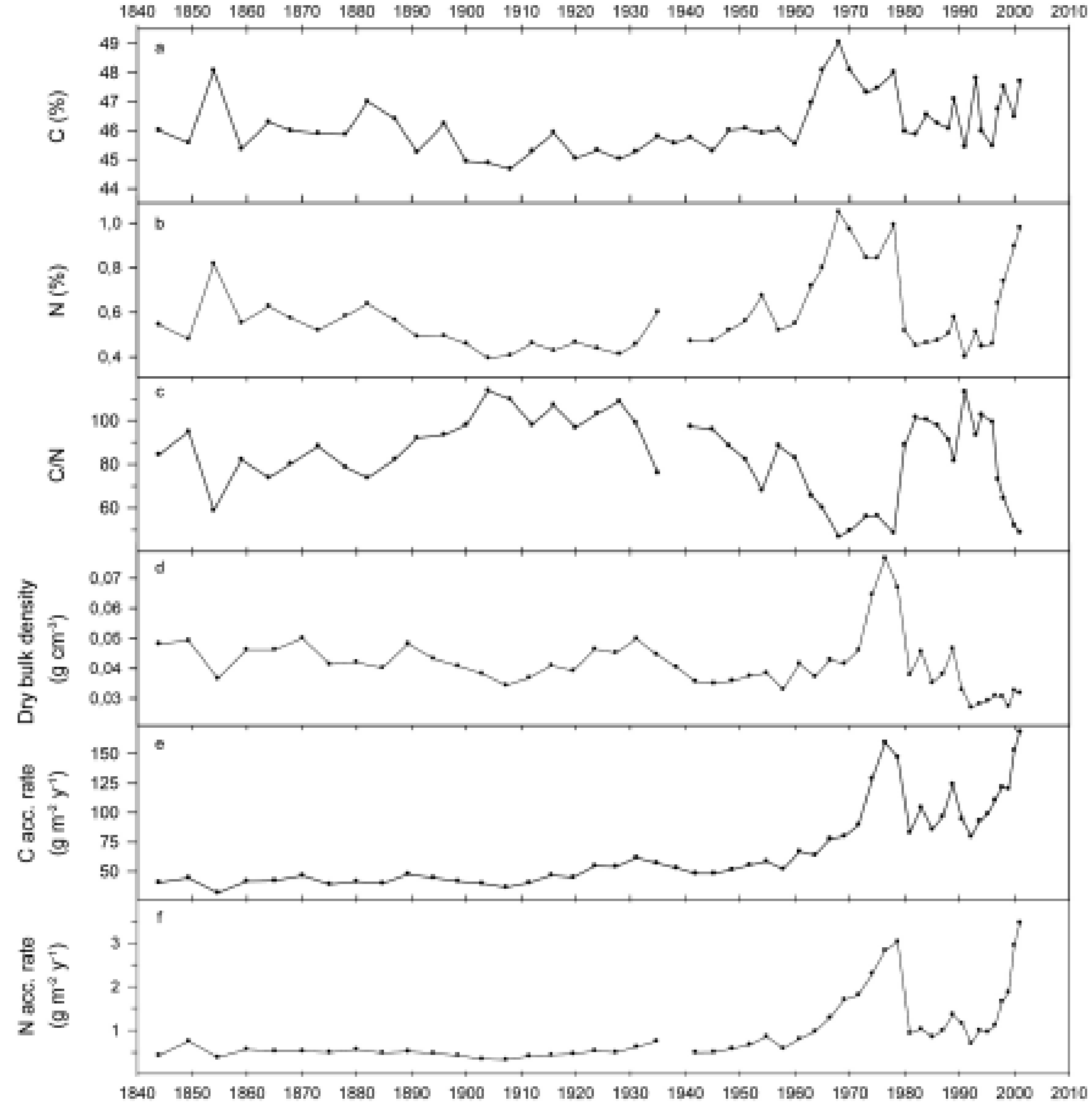

Figure 3-2. *(a, b) carbon (C) and nitrogen (N) content, (c) C/N ratio, (d) dry bulk density and accumulation rates (e, f) for Ältabergsmossen.*

4 Discussion

In this study the C/N ratio is constantly above 50 (Figure 3-2c), which is indicative of decomposition under mainly aerobic conditions /Kuhry and Vitt 1996/. The decay process of peat is characterized by negligible loss of N under anaerobic conditions /Kuhry and Vitt 1996/ and there are indications that anaerobic conditions lead to a preferential loss of C /Mauquoy et al. 2002/. Anaerobic decay takes place at about 0.1% of the aerobic decay rate /Ingram 1978, Belyea and Clymo 2001/ and, considering the short time-span of the investigated record and rapid peat accumulation in the analysed sequence, there is little time for any anaerobic decay to take place and to change the C/N ratio.

The relatively high C/N ratios and low humification values in the lower part of the sequence are interpreted as a result of rapid peat accumulation and wet surface conditions. Low C/N ratios in combination with high nitrogen concentrations between ca 1965 and 1980 suggest an intensified decay of the peat /Belyea and Warner 1996/. This is further supported by the high humification levels in this part of the sequence. The high C/N ratios combined with low N values recorded between ca 1996 and 1980 (Figure 3-2b, c) are interpreted as being due to loss of N in the aerobic decay processes in the acrotelm.

The correlation between N and humification in this study are consistent to the study by /Mauquoy et al. 2002/ of two north-west European bogs, but contrasts with the results by /Jauhiainen et al. 2004/ who showed that in a Finnish bog the highest N concentrations occurred in low humified peat.

The instrumental record during the time interval between c 1955 and 1970 is characterised by high annual precipitation and low summer temperatures, resulting in high water table levels, but also high humification levels (Figure 3-1a) and a low C/N ratio (Figure 3-2c). This is normally not the case since high precipitation and low temperature, with a resulting high water stand, should lead to low humification values /Caseldine et al. 2000, Mauquoy and Barber 2002/. The time between 1970 and 1980 was characterised by drier conditions, as indicated in the meteorological data and inferred from testate amoebae. During this dry period the C/N ratio remains low and humification is relatively high. This shift to drier conditions resulted in a lowering of the water table and the acrotelm and subsequently the aerobic zone to reach further downward into already decomposed peat. The lowering of the aerobic zone leads to further decay of already deposited peat and increases the degree of humification in that part. The result would thus be an increase in humification, predating the actual climate shift towards drier conditions (with in this case ca 10 years) and resulting in the high humified peat deposited during the 1960's (Figure 3-1a). This decomposition of peat that already has passed into the catotelm has been called secondary decomposition /Tipping 1995/. The same features are evident in the peat humification record from Gullbergbymossen, indicating that secondary decomposition have been simultaneously effective at both sites.

In the multiproxy study by /Mauquoy et al. 2002/ similar periods were found when the macrofossil record indicated wet (pool) conditions and humification was high together with low C/N ratios. This was interpreted as pool microforms drying out during summers and/or increased decay of aquatic Sphagna. In a study of seven peat-lands in the UK /Langdon and Barber 2004/, three proxies (plant macrofossils, humification and testate amoebae) are correlated and compared. Dry-shifts occur in these records, and when closely examined, humification often increases before at least one and often both of the other proxies increase, indicating that secondary decomposition might have occurred.

Accumulation rates of carbon and nitrogen at Ältabergsmossen are similar to the ones found in other investigations as well as more theoretical deduced numbers. The range of ca 30–150 g C m^{-2} y^{-1} and 0.5–3.5 g N m^{-2} y^{-1} in the upper part of the peat profile seems plausible. The increase and peak in both carbon and nitrogen accumulation rate between 1960 and 1980 coincides with climatic changes as the temperature started to increase around 1960 and when that peaked and started to decrease 10 years later started a period of lower precipitation that prevailed until ca 1980. The increase in accumulation rates is evident both in the carbon and nitrogen content and in the dry bulk density. High accumulation rates are to be expected during times of warmer climate, with an increased growth rate and possibly prolonged growth season /Mauquoy et al. 2002/. Peat accumulation might be favoured by precipitation being slightly increased, too wet conditions as well as too dry might be constraining factors regarding peat accumulation /Tolonen and Turunen 1996, Clymo et al. 1998, Yu et al. 2001a, Yu et al. 2001b, Mauquoy et al. 2002, Malmer and Wallén 2004/. In this data it is evident that there is a discrepancy between peat decomposition and dry bulk density/C-N accumulation rates, this might be a result of the earlier mentioned secondary decomposition, or it could reflect different responses in decomposition and growth rates to changes in temperature and precipitation. Increasing temperature is likely to increase CO_2 (carbon dioxide) and CH_4 (methane) emissions to the atmosphere /Gorham 1991/, this is said to be the only direct climatic effect on existing Boreal peatlands but indirect effects as increased peat oxidation induced by falling water tables are exceedingly important, however extremely difficult to forecast /Gorham 1991/. Despite these apprehensions the positive carbon balance in the Boreal peatlands could be expected to be maintained for several thousands of years /Tolonen and Turunen 1996/.

5 Conclusion

In this study the temporal resolution is relatively high, with ca 3 years/sample, and therefore it has been possible to detect leads/lags, as opposed to longer sequences with lower time resolution. The potential secondary decomposition process has implications for the interpretation of multi- and single-proxy data from ombrotrophic mires. Biological proxies, e.g. plant macrofossils and testate amoebae, reflect the actual wetness conditions at the time when the plants and amoebae lived. Peat humification and C/N ratio on the other hand reflect the conditions during the decay-process of the organic material, i.e. processes that influence already deposited material.

Discrepancies between the biological and physical/chemical proxies in a dry shift are to be expected and are therefore probably not an error in one or several proxies. Where only one single proxy (e.g. humification) is analysed, secondary decomposition processes could lead to misinterpretation of high-resolution peat stratigraphic data, and a dry shift would be assumed to be of older age and/or of longer duration than it actually is. In longer sequences with lower time-resolutions could this process be less important, due to low sample density and compression of the peat.

The mean accumulation rate of carbon and nitrogen during the last 157 years at Ältabergsmossen are 73 g C m^{-2} y^{-1} and 1 g N m^{-2} y^{-1}, these figures are representative of Boreal bogs.

5.1 Acknowledgement

Kristian Schoning provided the inferred water-table data and chronology of the peat sequences, he did also took part in the interpretation. Stefan Wastegård and Dmitri Mauquoy gave valuable comments to many of the conclusions drawn here. The field work was led by Kristian Schoning and Stefan Wastegård assisted us with the field sampling.

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