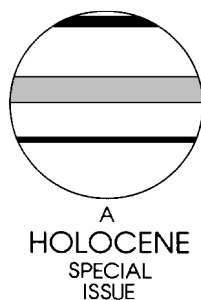


Changes in solar activity and Holocene climatic shifts derived from ^{14}C wiggle-match dated peat deposits

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Abstract: Closely spaced sequences of accelerator mass spectrometer (AMS) ^{14}C dates of peat deposits display century-scale wiggles which can be fitted to the radiocarbon calibration curve. By wiggle-matching such sequences, high-precision calendar age chronologies can be generated which show that changes in mire surface wetness during the Bronze Age/Iron Age transition (c. 850 cal. BC) and the 'Little Ice Age' (Wolf, Spörer, Maunder and Dalton Minima) occurred during periods of suddenly increasing atmospheric concentration of ^{14}C . Replicate evidence from peat-based proxy climate indicators in northwest Europe suggest these changes in climate may have been driven by temporary declines of solar activity. Carbon-accumulation rates of two raised peat bogs in the UK and Denmark record low values during the 'Little Ice Age' which reflects reduced primary productivity of the peat-forming vegetation during these periods of climatic deterioration.

Key words: Solar forcing, $\Delta^{14}\text{C}$, ^{14}C wiggle-match dating, palaeoclimate, *Sphagnum*, carbon accumulation, late Holocene, 'Little Ice Age'.

Introduction

The practice of dating peat samples using ^{14}C wiggle-match dating has greatly improved the precision of radiocarbon chronologies since its first applications by van Geel and Mook (1989) and Clymo *et al.* (1990). In addition to this, correlations between increases in mire surface wetness from rain-fed peat bogs and periods of transition to increasing atmospheric ^{14}C concentration during the Bronze Age/Iron Age transition (c. 850 cal. BC 'event') and 'Little Ice Age' climatic deteriorations have been noted in peat deposits from The Netherlands (Kilian *et al.*, 1995; van Geel *et al.*, 1996; 1998), the Czech Republic (Speranza *et al.*, 2000; Speranza, 2000) and the UK and Denmark (Mauquoy *et al.*, 2002a; 2000b). Because the production of radiocarbon is regulated by solar activity, these periods of increased mire surface wetness have been interpreted as evidence for solar forcing of climatic change given that ombrotrophic raised peat bogs are sensitive to changes in climate, in particular the amount of effective precipitation they receive (precipitation minus losses through evapotranspiration). In this review, we will discuss the principles of ^{14}C wiggle-match dating, its limitations and the insights it has given us in understanding the timing and possible causes of

palaeoclimatic change and the rate of carbon accumulation in ombrotrophic raised peat bogs.

^{14}C wiggle-match dating – high-precision chronologies

Production of ^{14}C has not remained constant over time, but has varied due to changes in the intensity of the geomagnetic dipole moment, modulation of the magnetic field within the solar wind and changes in the carbon cycle, for example changes in atmospheric/oceanic CO_2 ventilation and changes in biomass within the biosphere (Damon and Peristykh, 2000). Most of the long-term variability in ^{14}C production is due to changes in the Earth's magnetic field (Mazaud *et al.*, 1991; Tric *et al.*, 1992), while short-term variability is driven by changes in the solar wind (Stuiver and Quay, 1980; Stuiver, 1994). Because of these changes in production, wiggles ('kinks', 'windings' or 'warps', Taylor *et al.*, 1996) are readily visible when the ^{14}C ages of tree rings are plotted against calendar age (see for example the INTCAL98 radiocarbon age calibration curve within the OxCal v3.5 program, <http://www.rlaha.ox.ac.uk/brau/index.htm>).

Calibration of a ^{14}C age estimate allows one to obtain a calendar age range for each sample. Software packages which

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contain both the algorithms and the primary calibration data (IntCal98 data set, Stuiver *et al.*, 1998) to perform this transformation are readily available, for example Calib 4.2 (<http://depts.washington.edu/qil/calib/> – see also Stuiver and Reimer, 1993), OxCal v3.5 (Bronk Ramsey, 1995) and CAL25 (van der Plicht, 1993) allow one to rapidly calibrate ^{14}C sample measurements. Graphical displays of the results show the probability distributions in calendar ages. Points where radiocarbon sample measurements intersect the calibration curve a number of times (Pearson *et al.*, 1986), or where the slope of the calibration curve is almost flat, can be readily identified. In problem areas, even a high-precision radiocarbon measurement may represent a considerable period of time, or even more than one time interval, on the calendrical scale (Buck *et al.*, 1994), due to the ‘elastic’ nature of ^{14}C time (Taylor *et al.*, 1996). Clearly, in these instances, the precision of the calendar age assignment is low, but unless one selects new samples which fall outside the calibration plateaux or ‘time warps’, *sensu* Taylor *et al.* (1996), there is little one can do to remedy this. The problems associated with the calibration of ^{14}C dates and the selection of appropriate age/depth models has been explored by Bennett and Fuller (2002), with regard to the age of the *Tsuga canadensis* decline. An example is illustrated using OxCal v3.5 (Figure 1) for a single radiocarbon measurement of 310 ± 30 BP (Date 6 from Lille Vildmose, after Mauquoy *et al.*, 2002b). The two sigma age range extends from AD 1480 to 1650 and illustrates the problems associated with single calibrated dates when trying to date precisely palaeoecological and palaeoclimatic events in peat stratigraphic samples. In these circumstances it is all too easy to become a victim of the ‘suck in and smear’ syndrome astutely termed by Baillie (1991).

An elegant way to overcome these problems is to use ^{14}C wiggle-match’ dating (WMD) in combination with accelerator mass spectrometer (AMS) measurements of ^{14}C . This involves the selection of a stratigraphic sequence of closely spaced samples, which once dated can be matched to the shapes of the wiggles in the tree-ring calibration curve (van Geel and Mook, 1989; Clymo *et al.*, 1990). Dating samples using AMS (measurement of $^{14}\text{C}/^{12}\text{C}$ and $^{13}\text{C}/^{12}\text{C}$ ratios) rather than using conventional radiocarbon dating, where radiocarbon is measured indirectly by counting the emission of electrons during decay, confers some distinct advantages at the price of some loss of precision. One advantage of AMS ^{14}C dating is the higher sensitivity of the measurement. Because atoms of ^{14}C are directly detected rather than decay products, much shorter measurement times are required. In addition, sample sizes are in the order of 1000 times smaller, allowing the selection of species-specific samples, for example *Sphagnum* stems, or fruits of *Rhynchospora alba* from stratigraphically consecutive levels. In contrast, the large sample sizes required for conventional radiocarbon dates (1–5 g of carbon required) may compromise dating control, in that relatively thick slices of peat may slice across sloping (time transgressive) boundaries in the peat stratigraphy (Oldfield *et al.*, 1997). Dating specific peat components is of particular value when dating samples from ombrotrophic raised peat bogs in order to avoid problems of contamination. The large sample sizes of peat samples required for conventional ‘bulk’ ^{14}C dating may cause serious problems with regard to accuracy, since the different chemical fractions within these samples (humin, humic and fulvic acids) may differ in age by as much as 1000 years (Shore *et al.*, 1995). The results of Shore *et al.* are particularly alarming in that the age differences between the different peat chemical components were variable both between and within the two sites investigated, although one of the peat bog sites (Lanshaw Moss), is a soligenous mire (not rain-fed), and would therefore not be used for palaeoclimate reconstruction. The selection of specific macrofossils for AMS ^{14}C dating (largely *Sphagnum* stems, leaves, branches and

opercula) under low-power microscopy (Mauquoy *et al.*, 2002b) allows one to avoid any roots, which may introduce current atmospheric CO_2 -carbon to deeper layers which are to be dated. This is particularly the case with the roots of *Eriophorum vaginatum*, since these can extend to c. 60 cm below the surface (Boggie *et al.*, 1958; Gore and Urquhart, 1966). Stem bases and attached lower parts of leaves of *Eriophorum vaginatum* can also be avoided since these have been shown to be younger than bryophyte fragments in the same ^{14}C dated stratigraphic levels (Kilian *et al.*, 2000; Nilsson *et al.*, 2001).

Conversely, samples to be dated by AMS need to be treated with particular caution, since the smaller the sample the greater the effect of any contaminant present (Shore *et al.*, 1995). Contamination of samples with older or younger material can occur in the field and/or while taking and handling the samples in the laboratory. Long-term storage of wet macrofossil samples may increase the risk of contamination by modern carbon taken up by microorganisms, while samples of low carbon content (<1.4 mg) may result in low-precision measurements of radiocarbon (Wohlfarth *et al.*, 1998). *Sphagnum* macrofossils which are to be dated are first boiled in 5% KOH to dissolve humic and fulvic acids, sieved (100 μm mesh), then placed into a bath of demineralized water. These are then cleaned using watchmakers’ forceps to remove ericaceous roots and fungal mycelia. The latter are identified using a stereo-zoom microscope at magnifications of $\times 10$ –40. The cleaned *Sphagnum* macrofossils are then subjected to acid-alkali-acid pretreatment to remove any remaining humic/fulvic acids and bacterial CO_2 formed during decomposition processes (Mook and Streurman, 1983; Speranza *et al.*, 2000).

Once measured, the ‘floating’ stratigraphic depth series of peat chronology AMS dates are simply moved, stretched or compressed to match the tree-ring real-time wiggles. This can be undertaken using the Groningen ^{14}C calibration program CAL25 (van der Plicht, 1993), although other techniques are possible (see, for example, Oldfield *et al.*, 1997, where the ^{14}C dates were fitted to the calibration curve using the best least squares match based on the assumption of a smoothly varying peat-accumulation rate). Using CAL25 one can compress or expand the floating series of ^{14}C dates to simulate lower/higher peat-accumulation rates for the entire data set. A goodness-of-fit is automatically calculated with CAL25, measured as a standard deviation between the ^{14}C dated ordered depth series data and the calibration curve data (see Kilian *et al.*, 2000, for details). It is important to note that the simulated peat-accumulation rate will apply to the complete series of dates with the assumption that peat accumulation rates have remained constant over the dated depth interval. Changes in pollen concentrations and bulk density suggest that this is not the case. Low accumulation rates result in relatively high arboreal pollen concentrations (Middeldorp, 1982). Changes in bulk density are also likely to reflect changing peat-accumulation rates. Bulk density analyses have been used to identify peat samples which are highly decomposed, as the peat structure disintegrates during these periods (van der Molen and Hoekstra, 1988). Given this high decomposition, peat-accumulation rates are likely to have been lower compared to samples which have lower bulk density values. By measuring pollen concentration and/or bulk density changes, areas of accumulation-rate change within a peat sequence to be dated can be identified and subgroups of radiocarbon dates from intervals which display similar pollen concentrations/bulk density can then be separately wiggle-matched in order to produce a better ^{14}C wiggle-match fit. Subdivision of a series of ^{14}C AMS dates using pollen concentration data was adopted and enhanced by Speranza *et al.* (2000) who modelled peat depths of the ^{14}C dated samples based on the deviation of each sample from the average arboreal pollen concentration. Changes in bulk density in the four 1 m peat profiles investigated by Mauquoy *et al.* (2002a) were

used to subdivide all the samples into subgroups, and this procedure was essential, given that these samples contained acrotelm/catotelm peat which had clearly accumulated at different rates, given the structural collapse of peat matrices following their passage from the acrotelm (shallow, non-decomposed and non-compacted surface layer including the living and recently dead vegetation) into the catotelm (the relatively compressed body of accumulated organic remains below the acrotelm; Clymo, 1984).

In Figure 1, an example of a successful wiggle-match is illustrated. The fit of the 19 AMS ^{14}C dates from the Danish raised bog Lille Vildmose was obtained by dividing the stratigraphic sequence into two subgroups based upon changes in bulk density (Mauquoy *et al.*, 2002b). In this instance, changes in pollen influx were not used as a basis to subdivide the sequence of ^{14}C dates, since clear evidence for human impact (tree clearance) was visible in the pollen diagram for this site (Mauquoy *et al.*, 2002a). Given this, changes in the regional arboreal pollen influx may not reflect real changes in peat-accumulation rates. Because of the presence of pronounced wiggles in the calibration curve related to the Wolf, Spörer and Maunder Minima and the close fit of the ^{14}C AMS samples to the calibration curve (note the sharp decrease in radiocarbon age because of increased atmospheric concentration of ^{14}C between samples 10 and 3), the precision of this chronology during the seventeenth century may be as good as *c.* 20 years (the 10-year INTCAL98 calibration curve of Stuiver *et al.*, 1998, was used in this instance). This figure can be compared to the single calibrated date range for date 6 from Lille Vildmose (Figure 1) whose true age may lie between AD 1480 and 1650 at the 95.4% probability level.

Unfortunately, however, even this WMD approach has its limi-

tations. Where the calibration curve does not show pronounced fluctuations, WMD will not work well, since it is dependent on the shape of wiggles to perform a match. Clearly WMD cannot be applied in all instances to secure a precise chronology.

Evidence for a possible reservoir effect detected using ^{14}C wiggle-match dated peat sequences

Dating specific physical peat components (for example *Sphagnum* leaves and stems) rather than chemical fractions does not guarantee an accurate ^{14}C date (Turney *et al.*, 2000). There is evidence for a reservoir effect within peat samples which have been dated using AMS, since Kilian *et al.* (1995) found that *Sphagnum* samples which contained 2–4% of minute Ericaceae rootlets and root fragments were 100–250 ^{14}C years too old (see Figure 1a in Kilian *et al.*, 1995, where the ^{14}C AMS dates float above the calibration curve). This problem, however, can be overcome by carefully cleaning *Sphagnum* macrofossils before pretreatment and submission for dating, but carries a penalty, in that it is very labour-intensive. Nevertheless, this time investment is worth it, in that there was no evidence for a reservoir effect in the pure *Sphagnum* samples of Kilian *et al.* (1995) and the four wiggle-match dated peat profiles of Mauquoy *et al.* (2002a; 2002b). The source of older carbon has been investigated by Pancost *et al.* (2000), in order to discover whether it originated from bacterial methanotrophs (organisms dependent on methane as a carbon source), based on the hypothesis that the methanotrophs use old methane formed in deeper, anaerobic levels of peat stratigraphy. In this

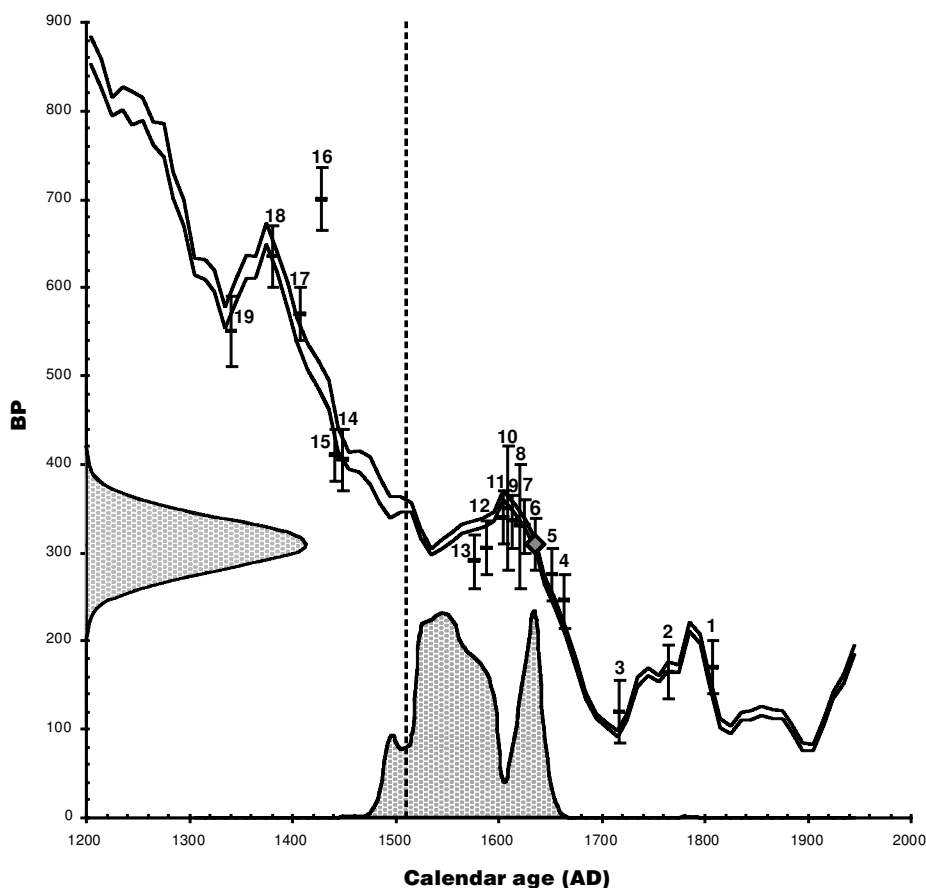


Figure 1 Wiggle-match dating of 19 radiocarbon samples from Lille Vildmose (after Mauquoy *et al.*, 2002b). The vertical broken line shows where the two subsets of radiocarbon samples were wiggle-matched individually. For one of the radiocarbon dates (date 6, 310 ± 30 BP, marked with a diamond), the Gaussian curve on the BP axis and the probability distribution on the calendar age axis have been added (fill pattern). The example shows the advantage in precision of wiggle-match dating: while a sixteenth century age would have been most probable after calibration of the separate date, the wiggle-match shows that the calendar age of this sample is around AD 1640.

instance, compound-specific AMS radiocarbon dating of biomarkers from plant macrofossils and bacteria (using extremely small samples of 100 µg) were compared to see if they differed substantially in age. The results were negative and suggested that the reservoir effect does not originate from compounds extracted from bacterial methanotrophs, but from a currently unknown source. The ^{14}C activity of living *Sphagnum cuspidatum* growing on an old peat surface did not differ from modern ^{14}C activities, which suggests the 'old' carbon does not come from this source (Kilian *et al.*, 2000). Nilsson *et al.* (2001) also suggested that assimilation of 'old' CO_2 by *Sphagnum* species growing in different microforms does not occur (*Sphagnum fuscum* in hummocks, *Sphagnum papillosum* in lawns and *Sphagnum majus* in pools). In these species no difference was again observed between their measured ^{14}C values and the current ^{14}C atmospheric value. The possible source of the old carbon in peat deposits at the present time therefore remains elusive.

Evidence for solar forcing of climatic change using ^{14}C wiggle-match dated peat sequences

^{14}C wiggle-match dating of raised-bog deposits has served to create precise chronologies of palaeoclimatic change, given the sensitivities of these ecosystems in recording changes in effective precipitation. The technique has also been used to investigate the relation between palaeoclimatic change and increases in the concentration of atmospheric ^{14}C , because the production of this radioisotope is anticorrelated with solar activity. Radiocarbon is produced in the upper atmosphere by neutrons reacting with nitrogen nuclei. Neutrons are produced by cosmic radiation entering the upper atmosphere. When solar activity is high, there is an extended solar magnetic field which provides more protection against cosmic rays, and production of ^{14}C declines. Conversely, decreases in solar activity allow more cosmic rays to enter the upper atmosphere since there is less magnetic shielding and production of ^{14}C increases (van Geel *et al.*, 1999).

Analyses of microfossils and macrofossils from raised peat bogs by Kilian *et al.* (1995), van Geel *et al.* (1996), Speranza *et al.* (2000), Speranza (2000) and Mauquoy *et al.* (2002a; 2002b) have shown that climatic deteriorations occurred during periods of transition from low to high $\Delta^{14}\text{C}$ (the relative deviation of the measured ^{14}C activity from the standard after correction for isotope fractionation and radioactive decay; Stuiver and Polach, 1977). The sites investigated by the above authors and the dates for the inception of increased mire surface wetness have been tabulated (Table 1) and plotted in Figure 2. The close correspondence between the peat-based evidence for palaeoclimatic changes and increases in the production of atmospheric ^{14}C suggest that changes in solar activity may well have driven these changes during the Bronze Age/Iron Age transition around c. 850 cal. BC (discussed in detail by van Geel *et al.*, 1996; 1998; 1999; 2000) and the 'Little Ice Age' series of palaeoclimatic changes. Major, abrupt increases in $\Delta^{14}\text{C}$ occurred (around 20‰), although the change in solar activity at these moments in time was small, for example reconstructed solar irradiance during the Maunder Minimum is estimated to have varied by 0.24% compared to the present (Lean and Rind, 1998). Given the potential small reduction in solar activity, some amplification mechanism must operate to cause the reconstructed abrupt climatic changes. There are currently two hypotheses (van Geel *et al.*, 1999): increased cosmic ray intensity, stimulating cloud formation and precipitation (Svensmark and Friis-Christensen, 1997) and reduced solar UV intensity, causing a decline of stratospheric ozone production and cooling as a result of less absorption of sunlight (Haigh, 1996; 2001).

In the 'Little Ice Age' peat sequences investigated by Mauquoy *et al.* (2002b) the largest increase in mire surface wetness based on the presence of *Sphagnum* macrofossils occurred during the early Maunder Minimum (at c. AD 1600), which was one of the coldest phases of the 'Little Ice Age' (Wanner *et al.*, 2000). The extreme nature of the seventeenth century in terms of global Northern Hemisphere temperatures has also been presented by Jones *et al.* (2001). Based on high-resolution proxy climate records (tree rings, ice cores and corals) they claim it was 'probably the longest period of sustained cold conditions during the millennium'. This date range can be compared to the most extreme cooling event identified and dated to AD 1601 in Northern Hemisphere tree-ring density chronologies (Briffa *et al.*, 1998). Equally noteworthy is the eruption of the Peruvian Huaynaputina volcano in AD 1600 (Zielinski *et al.*, 1994), suggesting that volcanic forcing of climatic change may have acted in tandem with solar forcing to cause the marked climatic change at this time.

The response of the proxy climate indicators to cooler/wetter conditions in all of the research illustrated in Figure 2 appears similar, in that the registration of climate change often predates by several years to several decades the high values of $\Delta^{14}\text{C}$. The delayed response of radiocarbon to changes in solar activity may reflect the complex interplay between different carbon reservoirs (the atmosphere, biosphere, mixed/deep sea) compared to ^{10}Be (Beer, 2000). Once formed, ^{10}Be precipitates with aerosols and stays in the geosphere and no recycling takes place (Beer, 2000). The ^{10}Be signal is considered to reflect a true production signal for changes in cosmic rays, and increases in ^{10}Be have been found to predate those of ^{14}C by 10–20 years (Bard, 1997). Modelled $\Delta^{14}\text{C}$ changes as derived from ^{10}Be data (Beer, 2000) show that the strong increase in cosmic ray intensity followed climatic change registered in peat bogs. Based on this evidence, the hypothesis that changes in cosmic ray intensity affect cloud formation and thus planetary albedo and temperature as proposed by Svensmark and Friis-Christensen (1997), may be incorrect (van Geel *et al.*, 2001). The alternative solar UV mechanism proposed by Haigh (1996; 2001) may be more likely, where solar UV mediated changes in ozone concentration modulate the stratospheric temperature, causing changes in the stratospheric circulation which in turn influence global atmospheric circulation patterns.

Evidence for carbon-accumulation rate changes using ^{14}C wiggle-match dated peat sequences

The northern peatlands of Russia, Scandinavia and Canada contain 455 Pg or c. one-third of the world's pool of soil organic carbon (Gorham, 1991). In order to understand how these peatlands may respond to future changes in climate, for example whether they may cease to sequester CO_2 if atmospheric CO_2 continues to increase (Heijmans *et al.*, 2001), palaeoecological analyses can show how carbon accumulation in these ecosystems has changed during former periods of climatic change. High time-resolution chronologies offered by ^{14}C wiggle-match dating have shown that variable carbon-accumulation rates appear to have occurred during the 'Mediaeval Warm Period' and 'Little Ice Age' series of climatic deteriorations (Oldfield *et al.*, 1997; Mauquoy *et al.*, 2002a).

Based on the ^{14}C wiggle-match chronology of Oldfield *et al.* (1997), the rate of dry mass increment in a northern Swedish aapa mire slowed down between c. AD 1400 and 1800. The carbon-accumulation rates ($\text{g C m}^{-2} \text{yr}^{-1}$) of three ^{14}C wiggle-match dated replicate cores from an intact ombrotrophic raised peat bog in the UK (Walton Moss cores 19, 20, 21) and a single core from a ^{14}C wiggle-match dated raised peat bog in Denmark (Lille Vildmose,

Table 1 Periods of increased mire surface wetness detected using ^{14}C wiggle-match dating

Time period	Site	Region	Date range	Evidence
Bronze/Age Iron Age transition (Homeric Minimum)	Engbertsdijkswenen XIV	Eastern Netherlands	862–784 cal. BC	<i>Sphagnum</i> macrofossils Kilian <i>et al.</i> (1995)
Bronze/Age Iron Age transition (Homeric Minimum)	Engbertsdijkswenen I	Eastern Netherlands	850–760 cal. BC	<i>Corylus avellana</i> pollen percentages, <i>Sphagnum</i> macrofossils van Geel <i>et al.</i> (1996)
Bronze/Age Iron Age transition (Homeric Minimum)	Pancavská Louka	Giant mountains, Czech Republic	858 cal. BC	Decreased tree pollen influx, <i>Sphagnum</i> macrofossils Speranza <i>et al.</i> (2000), Speranza (2000)
Wolf, Spörer, Maunder, Dalton Minima ('Little Ice Age')	Walton Moss 19, 20, 21, Lille Vildmose	NW England, Jutland, Denmark	AD 1197–1231 (Walton Moss 19, 20) AD 1378–1449 (Walton Moss 19, 21, Lille Vildmose) AD 1583–1604 (Walton Moss 19, 21, Lille Vildmose) AD 1771 (Walton Moss 20)	<i>Sphagnum</i> macrofossils Mauquoy <i>et al.</i> (2002a; 2002b)

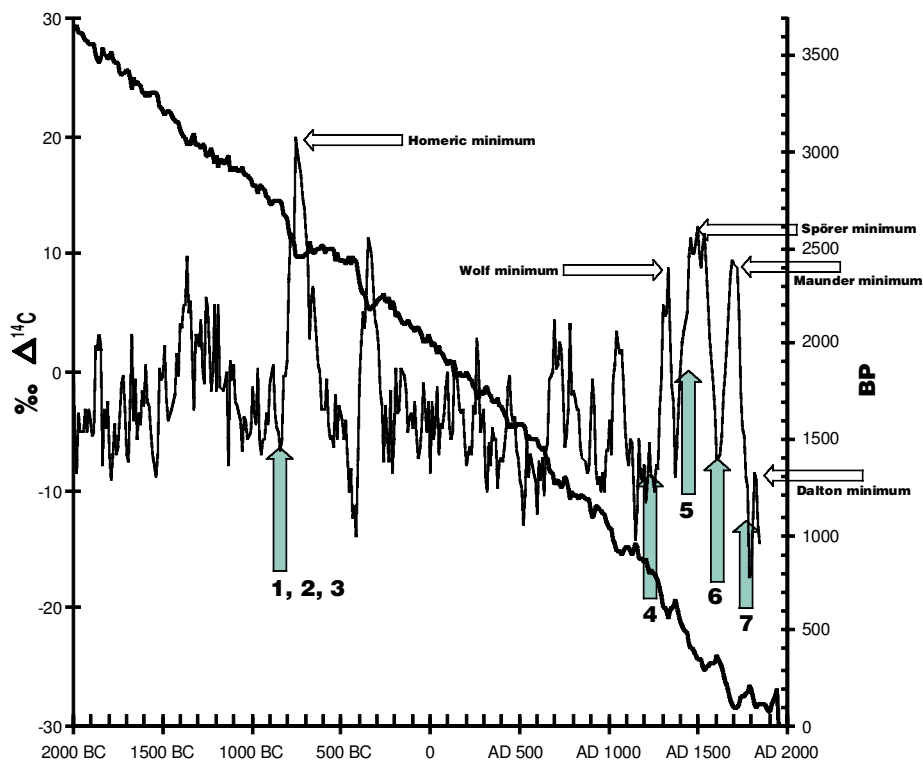


Figure 2 Detrended $\Delta^{14}\text{C}$ versus calendar age (thin line). Radiocarbon versus calendar ages (thick line) of the INTCAL98 calibration curve (Stuiver *et al.*, 1998). Arrows mark the initiation of climatic deteriorations registered by *Sphagnum* macrofossils, *Corylus avellana* pollen and tree pollen influx changes. (1) Kilian *et al.* (1995); (2) van Geel *et al.* (1996); (3) Speranza (2000), Speranza *et al.* (2000); (4, 5, 6, 7) Mauquoy *et al.* (2002a; 2002b). Climatic deteriorations at the Bronze Age/Iron Age transition and during the 'Little Ice Age' appear to have occurred during periods of sharp increases of the atmospheric production of ^{14}C . This suggests a solar origin for the climatic changes registered at these times.

LVM) also recorded reductions between *c.* AD 1300 and 1800 (Figure 3). The lowest carbon-accumulation rate values for the Walton Moss monoliths occurred between *c.* AD 1300 and 1800 and between AD 1492 and 1577 for LVM (Figure 3). It therefore appears that during solar minima of the 'Little Ice Age' *Sphagnum*-dominated peatlands may have accumulated carbon at a slower rate. This may reflect reduced primary productivity of the peat-forming vegetation due to lower spring-summer temperatures between AD 1570 and 1750 (Briffa *et al.*, 1992) and possibly

earlier. During these periods of shorter growing seasons, growth of the bog vegetation may have slowed down and stopped during prolonged, cold winters when the peat bog surface was frozen. There is also evidence for a species signal in the reconstructed carbon-accumulation rates, because in two monoliths (WLM-19 and WLM-20) carbon accumulation was negatively correlated with the presence of *Sphagnum cuspidatum* (Mauquoy *et al.*, 2002a). This species has smaller branch leaves than those belonging to *Sphagnum* Section *Sphagnum* (*S. imbricatum* and *S.*

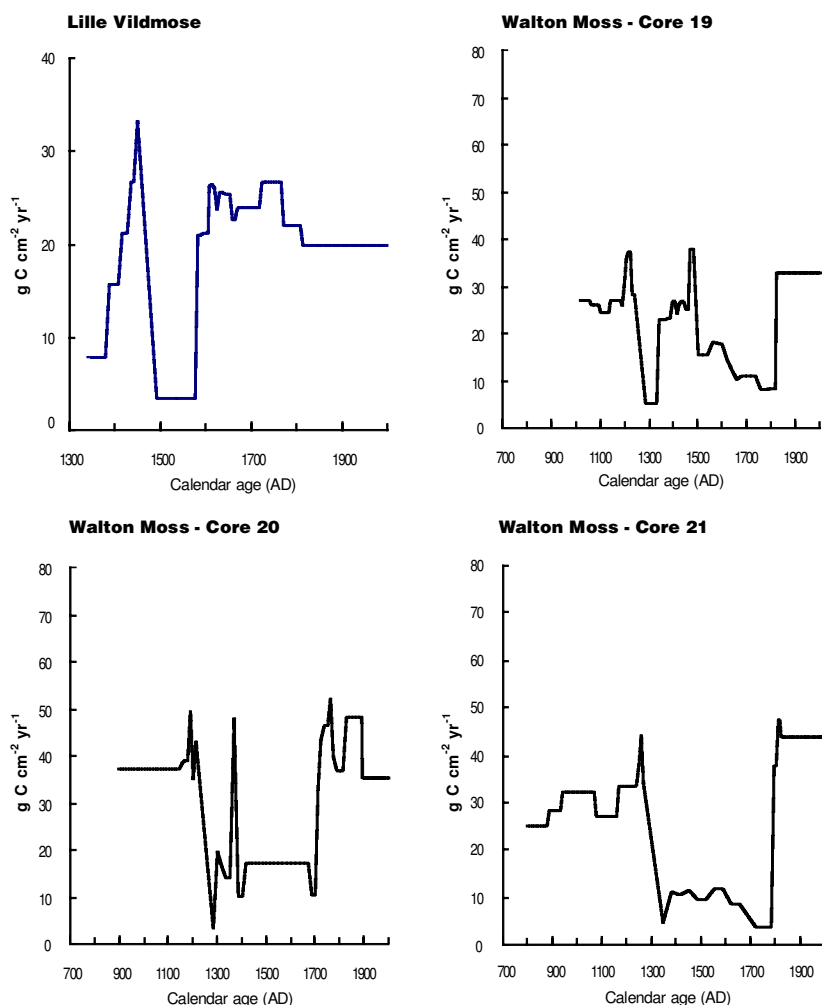


Figure 3 Carbon-accumulation rates ($\text{g C m}^{-2} \text{yr}^{-1}$) for Lille Vildmose and Walton Moss cores 19, 20 and 21 (Mauquoy *et al.*, 2002a).

magellanicum), and disintegrates more readily. Given this finding, the lower carbon-accumulation rates may in part be explained by the presence of wet-growing *Sphagnum cuspidatum*, which is more susceptible to decomposition at the acrotelm/catotelm boundary. The low reconstructed carbon-accumulation rates during 'Little Ice Age' climatic deteriorations may therefore relate either to higher decomposition of the aquatic *Sphagna* or to shorter growing seasons and lower spring/summer temperatures.

Final comments

With the exception of securely dated historical tephra layers, for example the AD 1104 eruption of Hekla (Thorarinsson, 1967), known as Hekla-1 (Pilcher *et al.*, 1995), dating of Holocene peat deposits using ^{14}C wiggle-match dating currently offers the best possible dating precision. However, in order to make the best use of this technique, clear wiggles in the calibration curve need to be present and a sufficient density of samples must be dated in order to achieve a convincing wiggle-match fit. It is difficult to suggest an absolute minimum recommended number of dates, but the example illustrated in Figure 1 from Mauquoy *et al.* (2002b) required 19 dates of the top metre of peat stratigraphy alone, but appears to be justified in that the dated samples 4–13 *must* fit this part of the calibration curve (no other shape will match). Given this very close match, the age precision for the dated levels extending from sample 4–13 may be as good as 20 years (1σ level; Blaauw, unpublished data).

Macrofossils of *Sphagnum* are 'extremely suited for ^{14}C AMS

dating' (Kilian *et al.*, 2000), since they do not record a lower ^{14}C activity even when an older carbon source is present. They can be encountered frequently as whole subfossil plants, with leaves, branches and stems still intact (these can easily be pretreated), and offer the best source of material for dating, since errors associated with botanically mixed samples can be avoided (Kilian *et al.*, 2000; Nilsson *et al.*, 2001).

The ^{14}C wiggle-matched peat sequences which form the subject of this review have served to precisely date palaeoclimatic change during the Bronze Age/Iron Age transition and the 'Little Ice Age'. They have also revealed a correspondence between these changes in climate and changes in solar activity as recorded by variations in $\Delta^{14}\text{C}$. Research using techniques other than peat-based proxy climate data has also demonstrated a link between climatic change and changes in solar activity (Magny, 1993; Tyson *et al.*, 2000; Bond *et al.*, 2001; Björck *et al.*, 2001; Kerr, 2001). The modelling results of Shindell *et al.* (2001) suggest solar-induced variations of ozone production could drive temperature changes in the middle and lower atmospheres, which in turn could cause changes in the North Atlantic Oscillation and the Arctic Oscillation. Solar mediated changes in these pressure patterns may explain the large regional temperature changes recorded during the Maunder Minimum (Briffa *et al.*, 1998; Jones *et al.*, 1998; Mann *et al.*, 1999; Crowley, 2000).

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