DATING RECENT PEAT ACCUMULATION IN EUROPEAN OMBROTROPHIC BOGS

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ABSTRACT. This study compares age estimates of recent peat deposits in 10 European ombrotrophic (precipitation-fed) bogs produced using the ^{14}C bomb peak, ^{210}Pb, ^{137}Cs, spheroidal carbonaceous particles (SCPs), and pollen. At 3 sites, the results of the different dating methods agree well. In 5 cores, there is a clear discrepancy between the ^{14}C bomb peak and ^{210}Pb age estimates. In the upper layers of the profiles, the age estimates of ^{14}C and ^{210}Pb are in agreement. However, with increasing depth, the difference between the age estimates appears to become progressively greater. The evidence from the sites featured in the study suggests that, provided aboveground plant material (seeds, leaves) is selected for dating, the ^{14}C bomb peak is a reliable dating method, and is not significantly affected by the incorporation of old carbon with low ^{14}C content originating from sources including air pollution deposition or methane produced by peat decomposition. ^{210}Pb age estimates that are too old may be explained by the enrichment of ^{210}Pb activity in the surface layers of peat resulting from a hypothesized mechanism where rapidly infilling hollows, rich in binding sites, may scavenge ^{210}Pb associated with dissolved organic matter passing through the hollow, as part of the surface drainage network. Until further research identifies and resolves the cause of the inaccuracy in ^{210}Pb dating, age estimates of peat samples based only on ^{210}Pb should be used with caution.

INTRODUCTION

The increased human impact on the environment and climate during the last few centuries has given added importance to the reconstruction of environmental change during this period. In addition, the overlap between the environmental monitoring programs of the last 50–100 yr and paleoenvironmental data provides the opportunity to calibrate paleoenvironmental records (Charman and Garnett 2005). The high-precision dating of recent peat deposits has consequently found use in a number of applications, such as linking short-term (<50 yr) ecological monitoring programs with longer-term paleoecological records of 100–200 yr duration for nature conservation (Birks 1996); validating and calibrating peat-based paleoclimate records with instrumental data (e.g. Charman et al. 2004); reconstructions of high-resolution time series of pollutants such as Hg and Pb to evaluate the effect of emission controls and calibrate atmospheric transport models (Shotyk et al. 2003); and investigating long-term process of carbon sequestration in peatlands (e.g. Oldfield et al. 1995; Mauquoy et al. 2002).

Holocene peats are most often dated using radiocarbon dating (see Piotrowska et al. 2011). Often, this is the only dating technique applied on a peat profile. Conventionally, ^{14}C dating of near-surface horizons was avoided, for fear of obtaining dates indistinguishable from "modern," and so the ages of these horizons might be estimated by extrapolating to the surface a deposition rate derived from ^{14}C dating of lower peat layers. However, this does not take into account possible changes in peat accumulation rates related to the likely lack of auto-compaction near the surface or, in drained bogs, the countervailing effect of peat shrinkage. Improved dating methods are therefore desirable to improve the accuracy and precision of age estimates of recent peat.

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A number of techniques are available for dating recent peat deposits (see Turetsky et al. 2004 for a review), with each method having advantages and limitations. This paper describes the recent chronology of 10 northern European ombrotrophic peat bogs as part of the EU project ACCROTELM (http://www2.glos.ac.uk/accrotelm/) and the Dutch NWO-ALW program "Climate Change and the Long-Term Dynamics of Bog Ecosystems." The upper layers of peat at each site have been dated using the ^{14}C "bomb peak," ^{210}Pb, and in some cases, stratigraphic markers such as ^{137}Cs, spheroidal carbonaceous particles (SCPs), and pollen. This study compares the results of these methods.

DATING TECHNIQUES

Bomb ^{14}C Dating

A relatively new method for dating near-surface horizons makes use of the "spike" in ^{14}C concentration related to nuclear weapons testing: so-called bomb ^{14}C dating. Nuclear weapons testing during the 1950s and early 1960s approximately doubled the amount of ^{14}C in the atmosphere (e.g. Wild et al. 1998). After the Limited Nuclear Test Ban Treaty of 1963, the ^{14}C concentration of the atmosphere began to decline owing to the exchange of carbon with the ocean and biosphere, and by dilution of atmospheric $^{14}CO_2$ with the burning of ^{14}C-free fossil fuels. The biosphere is generally in equilibrium with the atmosphere, and some of this atmospheric $^{14}CO_2$ would have been fixed by terrestrial plants during photosynthesis. The remains of these plants in peat profiles will therefore provide a record of past atmospheric ^{14}C concentration. The large temporal changes in atmospheric ^{14}C concentrations enable the calibration of ^{14}C concentrations in peat deposits against a timescale, and based on direct measurements of atmospheric $^{14}CO_2$ and plant specimens (tree rings and seeds) of known age, there are now several databases of atmospheric ^{14}C concentrations that allow this (e.g. Levin and Kromer 1997). Nevertheless, relatively few studies have used the ^{14}C bomb peak technique to date peats (e.g. Goodsite et al. 2001; Donders et al. 2004; Garnett and Stevenson 2004; Goslar et al. 2005; Sjögren et al. 2006; van der Linden and van Geel 2006; Hua 2009; Piotrowska et al. 2010).

Goslar et al. (2005) observed that any depth increment will likely correspond to more than a single year of peat growth, with an incorporation of ^{14}C activities in the *Sphagnum* within that increment. This was suggested to lead to a situation where specific dated levels contain a mixture of ^{14}C assimilated over a number of years (integration). An additional source of integration may be CO_2 or CH_4 produced by the decomposition of older plant tissue (Jungner et al. 1995); and Raghoebarsing et al. (2005) showed experimentally that 5–20% of the carbon fixed by *Sphagnum cuspidatum* is the product of symbiotic bacteria oxidizing methane originally derived from decomposing peat. However, this may not affect ^{14}C content significantly in all situations, as Nilsson et al. (2001) found that ^{14}C measurements of living *Sphagnum* from a variety of mire habitats did not differ from atmospheric levels. Contamination of vegetation by soot particles has also been suggested by Garnett and Stevenson (2004) to dilute the ^{14}C signal in recently accumulated peat, and was shown earlier by Chambers et al. (1979) to yield dates on the fine particulate fraction of peat from South Wales that were thousands of years older than the humic acid fraction. *Sphagnum* is particularly effective at trapping soot particles (Punning and Alliksaar 1997), and soot is derived from fossil fuel without any ^{14}C.

^{210}Pb Dating

^{210}Pb is a naturally occurring isotope of Pb with a half-life of 22.26 yr. The half-life makes it suitable for dating material deposited during the last 150 yr. ^{210}Pb is produced by the decay of ^{238}U into radon gas (^{222}Rn). ^{210}Pb can accumulate in lacustrine sediments and terrestrial soils. The constant rate of

supply (CRS) method has been found to be more applicable for peat deposits, owing to the conditions of organic decay in the aerobic acrotelm (e.g. Appleby et al. 1997).

Laboratory experiments by Vile et al. (1999) showed that Pb (and therefore ^{210}Pb) is immobilized in the peat column by physiochemical binding to organic matter. There is also evidence to suggest that ^{210}Pb-derived dates from ombrotrophic unsaturated peat deposits may be reliable where ^{210}Pb-derived age-depth profiles have been validated by independent evidence such as pollution records, pollen analysis, and other radioisotopes including ^{241}Am (e.g. Appleby et al. 1997; Mackenzie et al. 1998). However, some controversy surrounds the reliability of ^{210}Pb-derived dates from ombrotrophic peat deposits, and there are several studies demonstrating that ^{210}Pb age estimates are too young (e.g. Oldfield et al. 1979; Urban et al. 1990). Damman (1978) showed that Pb profiles in hummocks and hollows corresponded to the position of the water table on the day of sampling. Damman suggested that Pb was immobilized as PbS in waterlogged conditions, and oxidized to soluble $PbSO_4$ when the water table lowered, enabling mobility. Following this, Clymo and Hayward (1982) suggested that the vertical distribution of Pb (and other heavy metals) is significantly influenced by changes in redox potential resulting from variations in the water table.

^{137}Cs Dating

^{137}Cs is an artificial radionuclide produced by nuclear weapons testing and nuclear power plants (Ritchie et al. 1973). ^{137}Cs chronologies are based on known concentration peaks; atmospheric concentrations have been monitored from 1954 onwards (Appleby et al. 1991), the main example being the 1963 bomb peak. The vertical mobility of ^{137}Cs in ombrotrophic peat deposits of very low mineral content has been demonstrated in a number of studies (e.g. Mitchell et al. 1992; Mackenzie et al. 1997). ^{137}Cs can have both downwards and upwards mobility in the peat column (Schell et al. 1989). Upwards transport occurs as a result of biological activity in the root zone, and saturated and unsaturated conditions at different times of year (Aaby and Jacobsen 1978).

Spheroidal Carbonaceous Particles and Pollen Stratigraphic Markers

The high-temperature combustion of fossil fuels gives rise to several types of emissions including fine particulate matter, sometimes called fly ash (Rose et al. 1994). These particulates are widely dispersed and deposition usually occurs 5–100 km from the source (Rose and Juggins 1994). Soot particles can be divided into 2 types: 1) spheroidal carbonaceous particles (SCP) with 1–50 μm diameter have a high content of elemental carbon, and their presence in the environment is entirely due to anthropogenic emissions, particularly from oil combustion (Rose 1990a); 2) inorganic ash spheres (IAS) are mainly produced by coal burning, in addition to natural processes such as volcanic eruptions and meteorite impacts (Rose 1990b, 1996), and the small size (<20 μm diameter) enables long-distance transport in the atmosphere. Techniques such as energy dispersive X-ray analysis (Alliksaar et al. 1998) or the use of different chemical extraction techniques (Rose 1990a,b) can be used to distinguish types of soot particles, and so provide more information for dating. In this study, the different types of soot particles have not been distinguished. If historical records of fossil fuel combustion are available, soot particles can provide a useful stratigraphic marker. However, long-distance transport may complicate the interpretation of the soot particles, as suggested by observations of soot in the Arctic (Rosen et al. 1981).

If historical records of land use are available, then pollen can serve as a useful stratigraphic marker. Problems with the method can arise from postdepositional mobility in the surface layers of peat, which has been demonstrated in the uncompacted surface layers of *Sphagnum* peat (Rowley and Rowley 1956; Clymo and Mackay 1987). In this study, increases of *Pinus* and *Picea* pollen during

the 19th and 20th centuries around the northern England (GB) and Danish (DK) sites have been dated using local evidence of land use.

METHODS

The 10 European peat bogs sampled were Butterburn Flow (GB); Lille Vildmose (DK); Männikjärve Bog (ES); Kontolanrahka (FI); Ballyduff Bog (IR); Pedrido Bog (SP); Lappmyran (LPM); Åkerlänna Römosse (ARM); Saxnäs Mosse (SNM); and Fischbruch (FBR). Their locations are shown in Figure 1. The mid–late Holocene ^{14}C chronologies of the ACCROTELM sites GB, DK, ES, and FI have been described in an earlier article (Yeloff et al. 2006). Cores were taken during 2003 from lawns at the deepest "ombrotrophic" zone of each bog, close to the highest point of the mire. Where available, a Wardenaar corer (Wardenaar 1987) was used to remove the top 1 m of peat. Otherwise, large diameter (>7 cm) Russian corers were used for sampling. In the laboratory, peat samples were taken at 1-cm depth intervals. The vegetation composition of the peat profiles is reported elsewhere (van der Linden and van Geel 2006; Sillasoo 2007; Mauquoy et al. 2008; van der Linden et al. 2008).

Figure 1 The ombrotrophic peat bogs featured in the study: (GB) Butterburn Flow; (DK) Lille Vildmose; (ES) Männikjärve Bog; (FI) Kontolanrahka; (IR) Ballyduff Bog; (SP) Pedrido; (LPM) Lappmyran; (ARM) Åkerlänna Römosse; (SNM) Saxnäs Mosse; (FBR) Fischbruch.

Selected aboveground plant remains, mainly seeds and *Sphagnum* stems and branches, were carefully cleaned manually under a stereomicroscope by removing fungal hyphae and other contamination, and pretreated by the AAA method (Mook and Streurman 1983) in order to remove humic acids and recently introduced CO_2 (CO_2 can be potentially absorbed by the sample from the sur-

rounding air). They were then placed in a petri dish containing some clean (Milli-Q™) water, checked again under the microscope for contamination, and placed in preweighed tin capsules. After drying at 80 °C for 72 hr, the tin capsules containing the samples were weighed again, closed, and processed further at the Groningen Radiocarbon Laboratory. The tin capsules containing the dried samples were combusted into CO_2 and purified using an elemental analyzer (EA) connected to an isotope ratio mass spectrometer (Aerts-Bijma et al. 2001). The EA/MS also enabled the monitoring of quality parameters such as organic carbon content and the $\delta^{13}C$ value of the sample. The CO_2 was then collected cryogenically for graphitization. The graphite powder was pressed into targets that were placed in the sample carousel of the Groningen accelerator mass spectrometer (AMS) ion source. The AMS system measures the isotopic ratios $^{14}C/^{12}C$ and $^{13}C/^{12}C$ of the graphite (van der Plicht et al. 2000). From these measured isotopic ratios, the ^{14}C activities were calculated (including a correction for isotopic fractionation).

The method for spheroidal carbonaceous particle (SCP) analysis was adapted from Rose (1990a, 1994). Small aliquots of peat (~1 cm^3) were first oven-dried at 50 °C. The resulting dried samples (100–400 mg) were weighed and subsequently digested in 25 mL of concentrated HNO_3 at 180 °C for 1 hr. The remaining residues were washed and decanted into preweighed vials. A small amount of each residue was mounted onto separate microscope slides and individual particles were counted under 400× magnification. Final weights of the vials and remaining residues were established to permit the calculation of the number of SCPs per gram of dried sediment (ACCROTELM 2006).

Further subsamples of peat were taken from 1-cm intervals throughout the upper 0.5 m of each core. Each was dried at 50 °C, yielding aliquots of ~0.5 g. These were milled, the <1-mm fraction separated by sieving, and then compressed and sealed in 10-cc (26 mm diameter) polystyrene pots using polyethylene lids, resulting in negligible gaseous diffusion. Samples were stored for 3 weeks in an attempt to build up and retain ^{222}Rn. Measurement of unsupported ^{210}Pb and anthropogenically generated ^{137}Cs was undertaken by gamma spectrometry using an Ortec GEM-S HPGe coaxial system. The Ge crystal was 71 mm diameter and 24 mm thick, contained within an oxygen-free, high-conductivity Cu cup and endcap and in a vertical cryostat arrangement. The system was shielded using a low-background Pb (100 mm thick, 50-mm undershield) and Cu (0.9 mm)/Cd (0.5 mm) lining. Uncertainties are expressed at 1σ confidence, reflecting errors combined in quadrature and arising from peak fitting, efficiency calibration, and calculation of unsupported ^{210}Pb activity.

RESULTS

The deposition of ^{210}Pb and ^{137}Cs for the 10 sites is shown in Figure 2. The 1986 Chernobyl event is not clear in the ^{137}Cs profiles at any of the sites, and the 1963 peak in fallout from nuclear weapons is not distinguishable in the ^{137}Cs record of the IR, SP, SNM, and FBR cores. As noted previously, only the GB and DK cores had pollen marker horizons available. SCP horizons were available for the DK and ES sites. Details of the pollen and SCP marker horizons are included in Appendix 1.

Full details of the ^{14}C measurements are presented in Appendix 2, and expressed as $F^{14}C$ (the ^{14}C activity ratio after correction for $\delta^{13}C$, Reimer et al. 2004; van der Plicht and Hogg 2006). Online calibration was conducted using the CALIBomb program (Reimer et al. 2004), using the NH1 data set of Hua and Barbetti (2004), covering the area from ~40°N to the North Pole and spanning the period 1955–1999. Calibration of ^{14}C measurements using the bomb peak will always result in multiple (in most cases, double) solutions of age ranges. By assuming that the ^{14}C measurements are in an undisturbed stratigraphic order (shown in Figure 2), with no reworking of older material, it was possible to disregard the age ranges that did not fit with the stratigraphy, and to select the more realistic solution.

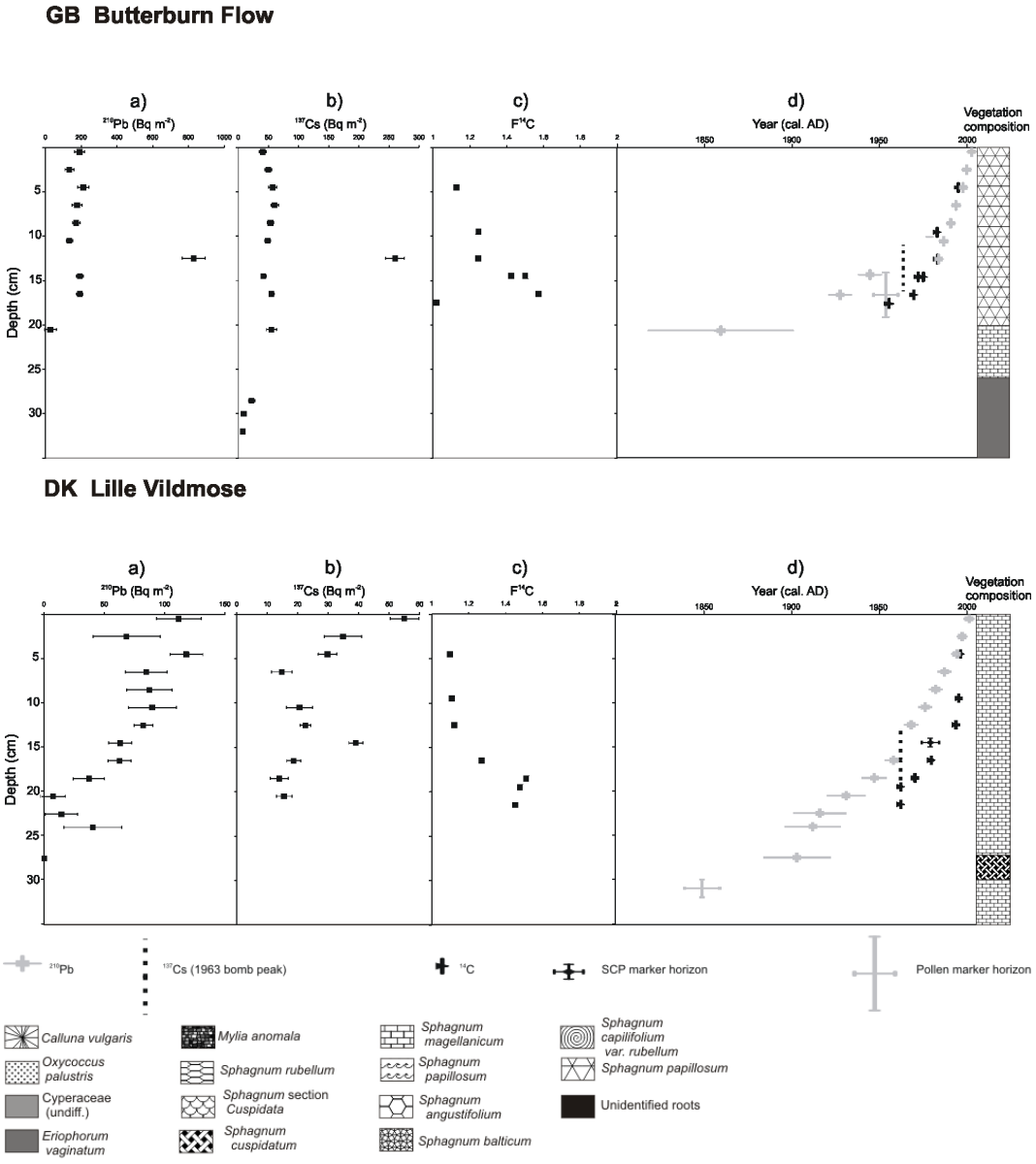
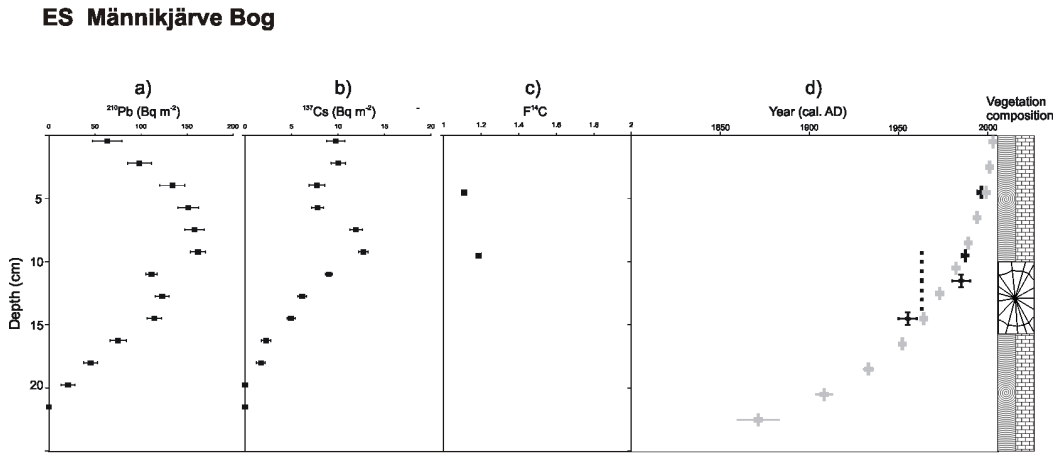
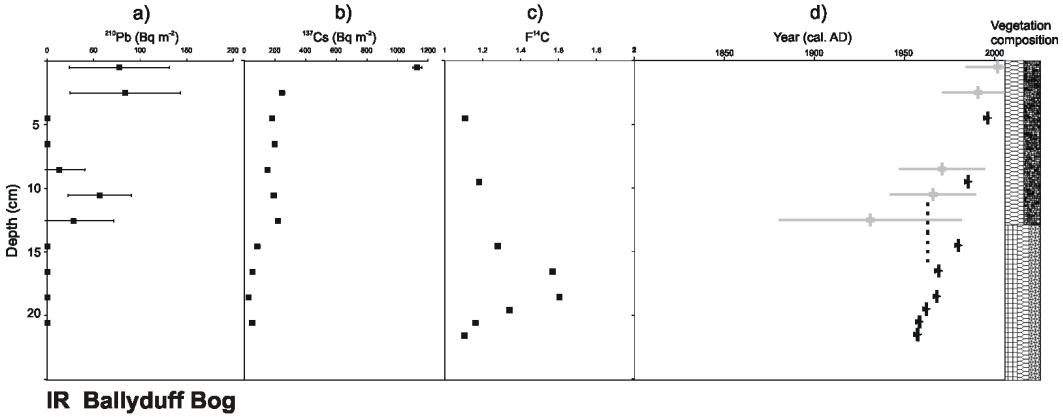


Figure 2 Profiles of ^{210}Pb, ^{137}Cs, and ^{14}C shown together with the chronology of recent peat accumulation: a) ^{210}Pb deposition (Bq m^{-2}); b) ^{137}Cs deposition (Bq m^{-2}); c) F^{14}C of plant macrofossils (see Appendix 2 and the text for details); d) age-depth model. Symbols according to the key at the bottom of the diagram. Figure 2-1: Butterburn Flow (GB); Figure 2-2: Lille Vildmose (DK).

Figure 2 shows the results of a) the ^{14}C calibrations and b) age estimates from the different dating techniques used in the study. At 3 sites (GB, ES, and ARM), the results of the different dating methods agree well. At Ballyduff Bog (IR), only the ^{14}C bomb peak and SCP age estimates were available, and the results of these 2 methods appear to agree. In a number of cores (DK, SP, LPM, FBR, and SNM), there is a clear discrepancy between the ^{14}C bomb peak and ^{210}Pb age estimates. In all





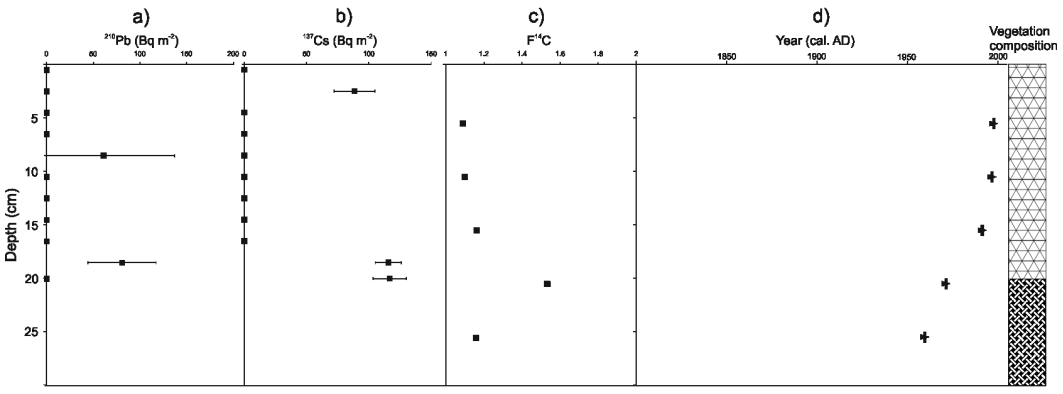


Figure 2-3: Männikjärve Bog (ES); Figure 2-4: Kontolanrahka (FI); Figure 2-5: Ballyduff Bog (IR).

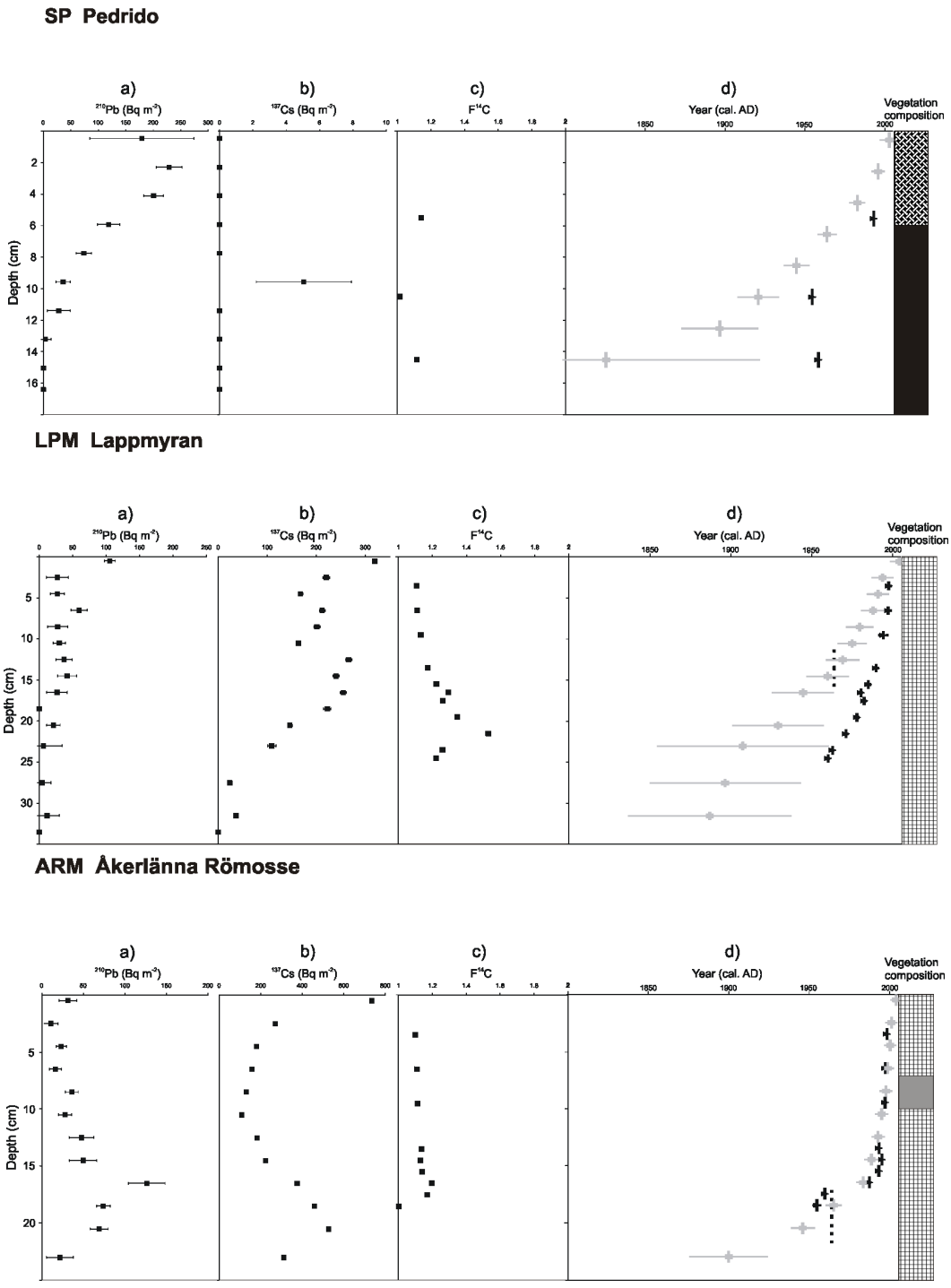


Figure 2-6: Pedrido (SP); Figure 2-7: Lappmyran (LPM); Figure 2-8: Åkerlänna Römosse (ARM)

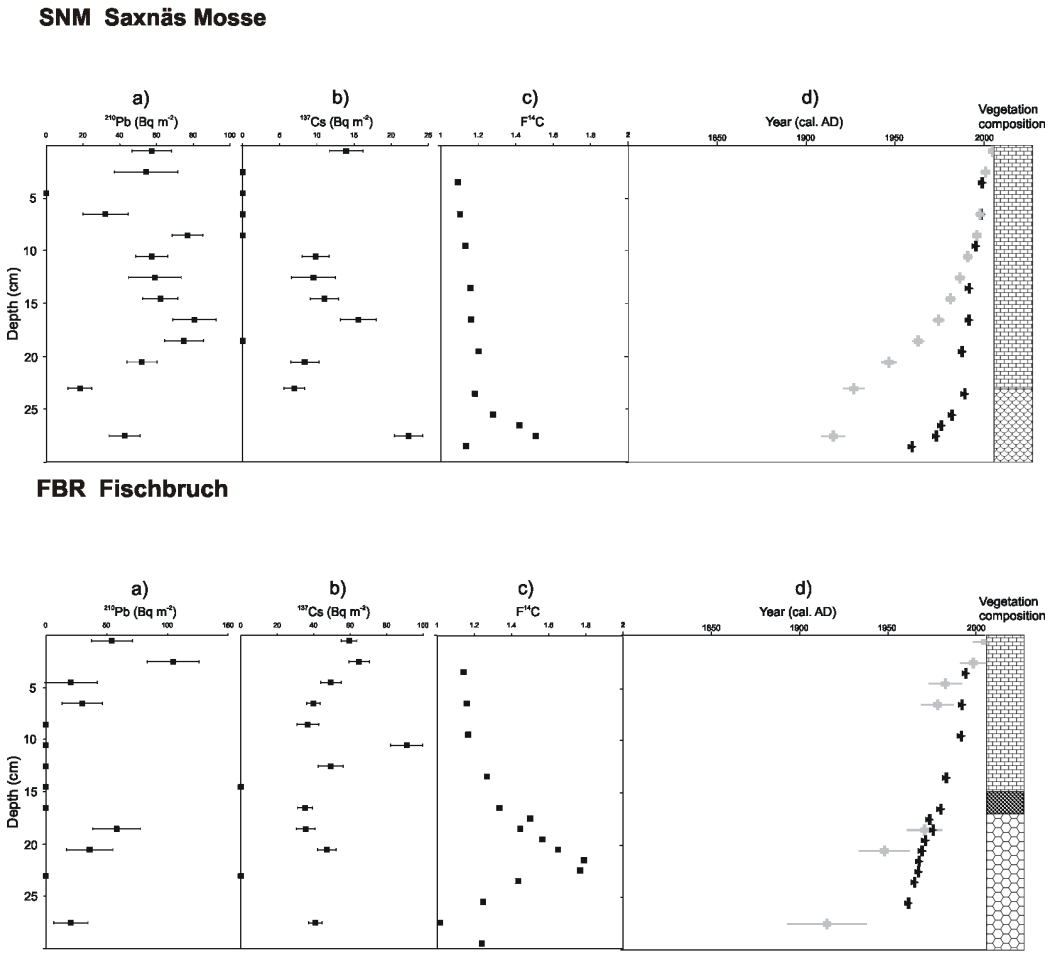


Figure 2-9: Saxnäs Mosse (SNM); Figure 2-10: Fischbruch (FBR)

these cases, the ^{210}Pb age estimates are older than those based on the ^{14}C bomb peak. In the upper layers of the profiles, the age estimates of ^{14}C and ^{210}Pb are in agreement. The difference between the age estimates appears to become progressively greater with depth. At the DK and SNM sites, the difference in age estimates between the ^{14}C and ^{210}Pb methods is as much as ~31 yr and ~65 yr in the lower part of the sequences, respectively.

The ^{137}Cs 1963 bomb peak generally agrees with the other dating methods. In the DK and LPM sites, where there is a discrepancy between the ^{210}Pb and ^{14}C results, the ^{137}Cs 1963 peak falls within the distribution of the ^{210}Pb age estimates.

The relatively few SCP and pollen marker horizons available generally agree with the other dating methods. At the DK site, where there is a discrepancy between the ^{210}Pb and ^{14}C results, the SCP marker horizon falls within the distribution of the ^{14}C age estimates.

DISCUSSION

The key issue arising from the results of this study is the discrepancy between ^{210}Pb and ^{14}C age estimates. The age estimates produced by one (or both) of these methods are prone to significant inaccuracy. Goodsite et al. (2001) also found a discrepancy between ^{210}Pb and ^{14}C age estimates of peat profiles from Greenland and Denmark, where the ^{14}C dates were much younger than ^{210}Pb age estimates in the pre-1963 section of the core. In this study, the FI and SP cores also have a few ^{14}C dates before 1963 that are much younger than the ^{210}Pb age estimates. However, the DK, SP, LPM, FBR, and SNM sites (Figure 2) clearly have numerous ^{14}C dates younger than the ^{210}Pb age curve, which are above the 1963 bomb peak. Incorporation of older carbon from lower levels in the samples has been proposed by Goslar et al. (2005) to be a cause of problematic ^{14}C age estimates. This phenomenon has also been reported in studies of long-term peat accumulation by Kilian et al. (1995), who reported a reservoir effect in AMS measurements of plant remains from Holocene raised bog deposits, where "older" carbon was proposed to have been incorporated into plant remains through microbial activity. The shift in age estimates resulting from the incorporation of older carbon may be related to the shape of the atmospheric ^{14}C curve. The 1963 peak itself was very rapid and short lived, and $^{14}CO_2$ and $^{14}CH_4$ resulting from the decomposition of the relatively thin layers containing the 1963 peak may not have been consistently incorporated into peat accumulated after 1963. Therefore, the more likely incorporation of older (pre-bomb) carbon into the plant remains could conceivably have resulted in significantly lower ^{14}C content ("dampening"). Based on estimated integration times ranging from 0.7 to 8 yr for peat profiles from a variety of European sites, Goslar et al. (2005) suggested that before and shortly after the 1963 atmospheric peak, integration resulted in dampened ^{14}C values of samples, and a shift towards age estimates that were too old. After 1963, dampened ^{14}C values resulted in age estimates that were too young.

In addition to the fixing of carbon produced by the decomposition of older plant tissue, Charman and Garnett (2005), following Chambers et al. (1979), suggested the dampening of ^{14}C values may result from contamination with the "old" carbon of industrial pollution deposition. Figure 3 shows the spheroidal carbonaceous particle (SCP) concentrations for sites where there is a discrepancy between ^{210}Pb and ^{14}C age estimates (SCPs were not measured in the LPM and SNM cores). In the DK profile, increased levels of SCPs below 5 cm depth coincide with the divergence between the ^{14}C and ^{210}Pb age estimates. The SP site does not show any clear coincidence between soot particle deposition and the divergence between the ^{14}C and ^{210}Pb age estimates. Also, it must be noted that in the GB core where the results of the different dating methods agree with each other (Figure 3), SCP concentrations reach very high values, with a maximum of about 63×10^3 g^{-1}.

However, if the incorporation of older carbon does have a significant effect, and ^{210}Pb age estimates are more accurate, a number of the samples with ^{210}Pb ages before 1950 (and in some cases in the 19th century) would have an anomalously high ^{14}C content—the source of which is difficult to explain. Furthermore, if the incorporation of older carbon is a significant factor, many of the samples in the layers of peat closest to the surface should have F^{14}C values lower than 1 (i.e. a pre-1950 ^{14}C age), but this did not occur at any of the 10 sites featured in this study. This suggests that ^{14}C bomb peak dating is a reliable method, and ^{210}Pb dating of peat is problematic. ^{210}Pb dating of peat has been suggested to be unreliable in previous studies, owing to postdepositional mobility—the downward migration of ^{210}Pb through the peat profile (e.g. Urban et al. 1990). However, downward migration would produce age estimates that are too young (i.e. greater activity at lower levels), and cannot explain the results of this study where ^{210}Pb age estimates may be too old. Oldfield et al. (1995) hypothesized a mechanism where rapidly infilling hollows, rich in binding sites, may scavenge ^{210}Pb associated with dissolved organic matter passing through the hollow, as part of the sur-

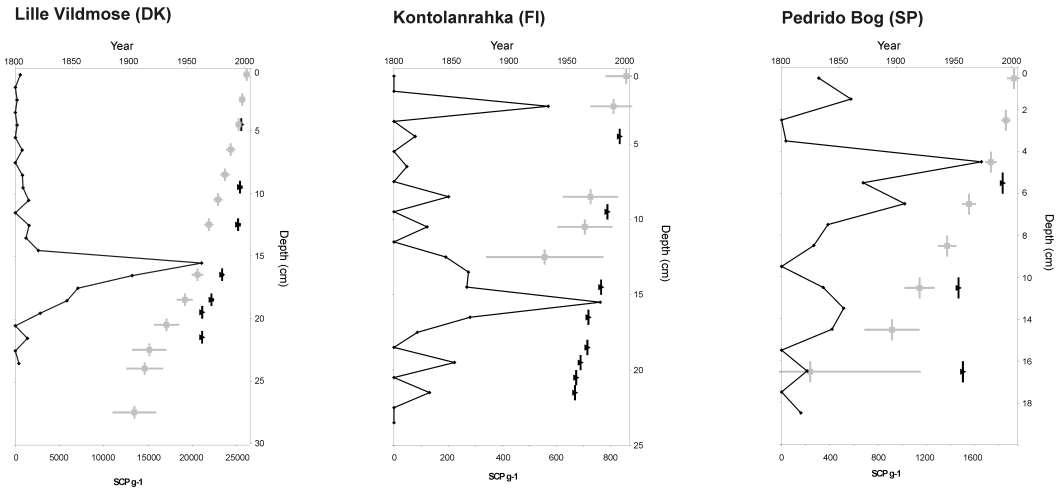


Figure 3 Spheroidal carbonaceous particle (SCP) concentrations (solid black line), ^{210}Pb and ^{14}C age estimates. Symbols for ^{210}Pb and ^{14}C age estimates are according to the key in Figure 2.

face drainage network. The enrichment of ^{210}Pb activity by this mechanism would invariably result in age estimates that are too old. Oldfield et al. cited evidence from excessive ^{210}Pb inventories of "lawns" at Ellergower Moss, a raised bog in Scotland (Clymo et al. 1990) to support this hypothesis. At the DK and LPM sites, the ^{137}Cs bomb peak falls within the distribution of ^{210}Pb age estimates, suggesting that ^{137}Cs may also be providing age estimates that are too old.

The mechanism by which the ^{137}Cs profiles were disturbed may be different to that of ^{210}Pb, as studies of ombrotrophic bogs from northern England and Northern Ireland by Oldfield et al. (1979) suggested that the active uptake of ^{137}Cs by living plants on the bog surface was the most likely explanation for the problematic results.

Whatever the reason(s) for the unreliability of the ^{210}Pb age estimates, it must be related to the occurrence of specific local environmental conditions, as 3 sites out of the 10 featured in this study showed good agreement between the results of the different dating methods. Until further research identifies and resolves the cause of the inaccuracy in ^{210}Pb dating, age estimates of peat samples based only on ^{210}Pb should be used with caution.

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APPENDICES

Appendix 1 Pollen and SCP marker horizons. The dates of the SCP horizons are based on histories of local industrial emissions. The pollen markers in both the GB and DK cores are the increases in *Picea* and *Pinus* pollen resulting from the documented planting of these trees in the areas of the 2 sites.

Site	Type of stratigraphic marker (reference)	Depth (cm)	Date (year AD)
GB	Pollen (Yeloff et al. 2007a)	16.5 ± 2.5	1953 ± 7
	SCP (Odgaard 1993)	14.5 ± 0.5	1980 ± 5
DK	Pollen (Yeloff et al. 2007b)	31 ± 1	1850 ± 10
ES	SCP (Nõges et al. 2006)	14.5 ± 0.5	1955 ± 5
		11.5 ± 0.5	1985 ± 5

Appendix 2 AMS ^{14}C measurements (expressed as F^{14}C). Calibrated using CALIBomb (Reimer et al. 2004) and the NH1 data set (Hua and Barbetti 2004).

Lab nr (GrA-)	Site	Sample composition	Mid-point sample depth (cm)	^{14}C activity (F^{14}C)	δ^{13}C (‰)	Calibrated age ranges 2σ (yr AD)[1]
26623	ARM	*Sphagnum fuscum* stems and leaves	3.5	1.0976 ± 0.0046	–27.25	1997–1998
26624	ARM	*Sphagnum fuscum* stems and leaves	6.5	1.1079 ± 0.0044	–27.28	1995–1998
25968	ARM	*Sphagnum fuscum* stems and leaves	9.5	1.1116 ± 0.0062	–27.09	1995–1998
26626	ARM	*Sphagnum fuscum* stems and leaves	13.5	1.1352 ± 0.0045	–26.97	1991–1994
29024	ARM	*Sphagnum fuscum* stems and leaves	14.5	1.1289 ± 0.0048	–27.87	1993–1996
29010	ARM	*Sphagnum fuscum* stems and leaves	15.5	1.1405 ± 0.0050	–27.05	1991–1994
26627	ARM	*Sphagnum fuscum* stems and leaves	16.5	1.1964 ± 0.0046	–24.59	1985–1988
31252	ARM	*Sphagnum fuscum* stems and leaves	17.5	1.1697 ± 0.0036	–28.86	1958–1959
29013	ARM	*Sphagnum fuscum* stems and leaves	18.5	1.0027 ± 0.0044	–28.42	1951–1957
29762	DK	*Sphagnum magellanicum* stems, leaves and branches	4.5	1.0980 ± 0.0045	–28.16	1997–1998
29764	DK	*Sphagnum magellanicum* stems, leaves and branches	9.5	1.1095 ± 0.0048	–31.22	1995–1998
30600	DK	*Sphagnum* stems and leaves	12.5	1.1232 ± 0.0044	–28.12	1993–1996
30959	DK	*Sphagnum* stems and leaves and *Calluna* wood	16.5	1.2713 ± 0.0055	–27.21	1980–1981
30989	DK	*Sphagnum* stems	18.5	1.5115 ± 0.0146	–25.92	1970–1973
29757	DK	*Sphagnum* stems	19.5	1.4778 ± 0.0060	–22.58	1963–1963; 1972–1973

Appendix 2 AMS ^{14}C measurements (expressed as $F^{14}C$). Calibrated using CALIBomb (Reimer et al. 2004) and the NH1 data set (Hua and Barbetti 2004). *(Continued)*

Lab nr (GrA-)	Site	Sample composition	Mid-point sample depth (cm)	^{14}C activity ($F^{14}C$)	$\delta^{13}C$ (‰)	Calibrated age ranges 2σ (yr AD)[1]
30990	DK	*Sphagnum* stems	21.5	1.4525 ± 0.0064	–24.67	1963–1963; 1973–1974
29974	ES	*Sphagnum* stems	4.5	1.1074 ± 0.0044	–24.72	1995–1998
29976	ES	*Sphagnum* stems	9.5	1.1864 ± 0.0047	–24.56	1986–1989
30497	FBR	*Sphagnum angustifolium* stems	3.5	1.1431 ± 0.0045	–28.07	1990–1994
30498	FBR	*Sphagnum angustifolium* stems	6.5	1.1598 ± 0.0046	–27.80	1989–1991
26007	FBR	*Polytrichum strictum* stems and leaves	9.5	1.1671 ± 0.0060	–27.27	1988–1991
30500	FBR	*Sphagnum angustifolium* stems	13.5	1.2680 ± 0.0048	–27.35	1980–1982
30501	FBR	*Sphagnum angustifolium* stems	16.5	1.3341 ± 0.0051	–27.45	1977–1979
30502	FBR	*Sphagnum angustifolium* stems and *Calliergon cordifolium* stems and leaves	17.5	1.5002 ± 0.0056	–26.62	1971–1972
30504	FBR	*Sphagnum angustifolium* stems	18.5	1.4474 ± 0.0054	–27.66	1973–1974
26008	FBR	*Sphagnum angustifolium* stems, *Oxycoccus palustris* branch with flower, 1 *Rhynchospora alba* fruit	19.5	1.5665 ± 0.0071	–26.47	1968–1970
30506	FBR	*Sphagnum angustifolium* stems	20.5	1.6504 ± 0.0059	–28.63	1967–1968
30507	FBR	*Sphagnum angustifolium* stems	21.5	1.7905 ± 0.0065	–26.16	1965–1966
30508	FBR	*Sphagnum angustifolium* stems	22.5	1.7702 ± 0.0064	–27.43	1965–1966
30510	FBR	*Sphagnum angustifolium* stems	23.5	1.4366 ± 0.0055	–26.81	1963–1963; 1973–1975
30511	FBR	*Sphagnum angustifolium* stems	25.5	1.2472 ± 0.0048	–27.81	1959–1960; 1981–1983
29769	FI	*Sphagnum* section *Acutifolia* stems, branches and leaves	4.5	1.1074 ± 0.0044	–26.88	1995–1998
29768	FI	*Sphagnum* section *Acutifolia* stems, branches and leaves	9.5	1.1810 ± 0.0047	–25.50	1985–1986
29771	FI	*Sphagnum* section *Acutifolia* stems, branches and leaves	14.5	1.2791 ± 0.0049	–26.90	1979–1981
30856	FI	*Sphagnum* section *Acutifolia* stems, branches and leaves	16.5	1.5679 ± 0.0059	–25.42	1968–1970
31030	FI	*Sphagnum* section *Acutifolia* stems, branches and leaves	18.5	1.6051 ± 0.0051	–25.95	1968–1969
29772	FI	*Sphagnum* section *Acutifolia* stems, branches and leaves	19.5	1.3412 ± 0.0052	–24.60	1962–1962; 1977–1978
30858	FI	*Sphagnum* section *Acutifolia* stems, branches and leaves	20.5	1.1617 ± 0.0046	–27.14	1958–1959
30859	FI	*Sphagnum* section *Acutifolia* stems, branches and leaves	21.5	1.1046 ± 0.0044	–24.84	1957–1958
29859	GB	*Sphagnum papillosum* stems, leaves and branches	4.5	1.1272 ± 0.0054	–29.57	1993–1996
29775	GB	*Sphagnum papillosum* stems, leaves and branches	9.5	1.2464 ± 0.0050	–28.19	1981–1984
30987	GB	*Sphagnum* stems and leaves	12.5	1.2450 ± 0.0059	–27.13	1981–1984
29776	GB	*Sphagnum papillosum* stems, leaves and branches	14.5	1.5003 ± 0.0058	–25.86	1971–1972
30792	GB	*Sphagnum* stems and leaves	14.5	1.4231 ± 0.0053	–26.29	1974–1975
30794	GB	*Sphagnum* stems and leaves	16.5	1.5731 ± 0.0059	–26.01	1968–1970
30595	GB	*Sphagnum* stems and leaves	17.5	1.0186 ± 0.0040	–25.86	1953–1957
30140	IR	*Sphagnum papillosum*, *Sphagnum capillifolium* stems	5.5	1.0897 ± 0.0046	–29.23	1996–1996; 1957–1958

Appendix 2 AMS ^{14}C measurements (expressed as $F^{14}C$). Calibrated using CALIBomb (Reimer et al. 2004) and the NH1 data set (Hua and Barbetti 2004). *(Continued)*

Lab nr (GrA-)	Site	Sample composition	Mid-point sample depth (cm)	^{14}C activity ($F^{14}C$)	$\delta^{13}C$ (‰)	Calibrated age ranges 2σ (yr AD)[1]
30142	IR	*Sphagnum papillosum*, *Sphagnum capillifolium* leaved stems	10.5	1.0981 ± 0.0044	–28.29	1995–1995
30143	IR	*Sphagnum papillosum*, *Sphagnum cuspidatum*, *Calluna* leaves	15.5	1.1619 ± 0.0049	–30.74	1989–1991
30144	IR	*Sphagnum papillosum*, *Sphagnum capillifolium* leaved stems	20.5	1.5328 ± 0.0058	–26.23	1969–1971
28725	IR	*Sphagnum cuspidatum* stems	25.5	1.1595 ± 0.0046	–30.81	1958–1958; 1989–1991
26368	LPM	*Sphagnum fuscum* stems and leaves	3.5	1.1069 ± 0.0040	–29.10	1996–1998
26369	LPM	*Sphagnum fuscum* stems and leaves	6.5	1.1115 ± 0.0040	–27.80	1995–1998
25369	LPM	*Sphagnum fuscum* stems and leaves	9.5	1.1317 ± 0.0059	–26.97	1991–1996
26371	LPM	*Sphagnum fuscum* stems and leaves	13.5	1.1738 ± 0.0042	–28.40	1988–1990
27755	LPM	*Sphagnum fuscum* stems and leaves	15.5	1.2232 ± 0.0050	–27.10	1983–1985
26372	LPM	*Sphagnum fuscum* stems and leaves	16.5	1.2927 ± 0.0045	–26.90	1979–1980
27756	LPM	*Sphagnum fuscum* stems and leaves	17.5	1.2598 ± 0.0051	–27.50	1981–1982
25371	LPM	*Sphagnum fuscum* stems and leaves	19.5	1.3454 ± 0.0068	–25.34	1976–1978
27757	LPM	*Sphagnum fuscum* stems and leaves	21.5	1.5275 ± 0.0061	–23.90	1970–1971
26381	LPM	*Sphagnum fuscum* stems and leaves	23.5	1.2593 ± 0.0044	–24.90	1962–1962
27759	LPM	*Sphagnum fuscum* stems and leaves	24.5	1.2223 ± 0.0051	–24.00	1959–1959
26501	SNM	*Sphagnum magellanicum* stem and leaves	3.5	1.0927 ± 0.0054	–28.20	1997–1998
26395	SNM	*Sphagnum magellanicum* stem and leaves	6.5	1.1028 ± 0.0043	–27.10	1996–1998
24430	SNM	*Sphagnum magellanicum* stems and leaves	9.5	1.1299 ± 0.0060	–25.92	1992–1996
27752	SNM	*Sphagnum magellanicum* stems and leaves	13.5	1.1589 ± 0.0049	–25.50	1989–1991
26397	SNM	*Sphagnum magellanicum* stem and leaves	16.5	1.1602 ± 0.0045	–27.20	1989–1991
24431	SNM	*Sphagnum magellanicum* stems and leaves	19.5	1.2016 ± 0.0074	–26.05	1984–1988
26399	SNM	*Sphagnum magellanicum* stem and leaves	23.5	1.1832 ± 0.0047	–26.50	1986–1989
26400	SNM	*Sphagnum* stems	25.5	1.2783 ± 0.0049	–26.30	1980–1981
27754	SNM	*Sphagnum magellanicum* stems and leaves and *Sphagnum* stems	26.5	1.4181 ± 0.0059	–25.80	1974–1975
26621	SNM	*Sphagnum* stems and opercula	27.5	1.5058 ± 0.0056	–26.35	1971–1972
27683	SNM	*Sphagnum* stems and *Erica tetralix* branch	28.5	1.1360 ± 0.0076	–26.40	1958–1958; 1991–1995
30145	SP	*Molinia* stems and leaves, *Campylopus* leaved stems	5.5	1.1417 ± 0.0045	–27.73	1991–1994
30383	SP	*Eriophorum*, *Molinia* stems, *Andromeda* seeds	10.5	1.0161 ± 0.0059	–25.24	1952–1956
30384	SP	*Campylopus*, *Hypnum*, *Eriophorum*, *Molinia*	14.5	1.1163 ± 0.0066	–25.81	1957–1958; 1994–1998