RADIOCARBON, Vol 47, Nr 1, 2005, p 115–134

RADIOCARBON DATING OF MODERN PEAT PROFILES: PRE- AND POST-BOMB ^{14}C VARIATIONS IN THE CONSTRUCTION OF AGE-DEPTH MODELS

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ABSTRACT. We present studies of 9 modern (up to 400-yr-old) peat sections from Slovenia, Switzerland, Austria, Italy, and Finland. Precise radiocarbon dating of modern samples is possible due to the large bomb peak of atmospheric ^{14}C concentration in 1963 and the following rapid decline in the ^{14}C level. All the analyzed ^{14}C profiles appeared concordant with the shape of the bomb peak of atmospheric ^{14}C concentration, integrated over some time interval with a length specific to the peat section. In the peat layers covered by the bomb peak, calendar ages of individual peat samples could be determined almost immediately, with an accuracy of 2–3 yr. In the pre-bomb sections, the calendar ages of individual dated samples are determined in the form of multi-modal probability distributions of about 300 yr wide (about AD 1650–1950). However, simultaneous use of the post-bomb and pre-bomb ^{14}C dates, and lithological information, enabled the rejection of most modes of probability distributions in the pre-bomb section. In effect, precise age-depth models of the post-bomb sections have been extended back in time, into the "wiggly" part of the ^{14}C calibration curve.

Our study has demonstrated that where annual resolution is concerned, tissues of *Sphagnum* are the only representative material for ^{14}C dating, although even samples of pure *Sphagnum* collected from a very thin slice of the peat section contain tissues grown in different years, so they integrate the atmospheric ^{14}C signal over a period of time. This time period (0.5–8 yr, depending on the site) seems to correlate with the peat accumulation rate, but it also depends on how the sampled peat sections were handled. When constructing age-depth models, for some peat sections we used the strategy of multi-stage ^{14}C dating. This led to a drastic reduction in the uncertainty of the age-depth models, by dating only a few additional samples in the profile.

Our study is the first in which peat sections from the late pre-bomb time (AD 1900–1960) have been precisely dated at a high temporal resolution. In this time interval, ^{14}C ages of all the samples dated were younger than those derived from the atmospheric calibration curve, apparently due to the effect of integration. Evidently, the determination of calendar ages based on ^{14}C dating of single peat samples from that interval may be affected by a serious error if the possibility of integration is ignored.

INTRODUCTION

Recent scientific work has demonstrated the capability of peat mires to store information of past environments with a high temporal resolution (Goodsite et al. 2001). Peat sections have served as archives of heavy metal pollutants of the atmosphere (Shotyk et al. 1998; Benoit et al. 1998) and yielded records of both climate and atmospheric CO_2 content (Martínez-Cortizas et al. 1999; White et al. 1994). Recently, the global importance of peatlands as a carbon sink has been documented (Smith et al. 2004). In every case, a precise age control was required and achieved by using either the ^{210}Pb or the ^{14}C method.

Because of past variations in atmospheric ^{14}C content, individual ^{14}C dates do not usually allow a precise determination of calendar age. The situation is much better if a series of ^{14}C dates is available and additional information about the time intervals between dated samples is known. Then, one may try to use the wiggle-matching technique, which was successfully applied in some old peat sections where thick sections of almost constant accumulation rate were documented (Kilian et al. 1995, 2000; Blaauw 2003).

Here, we deal with 9 peat profiles from Slovenia, Switzerland, Austria, Italy, and Finland (Figure 1), investigated in the framework of a project called PINE (Predicting Impacts on Natural Ecotones).

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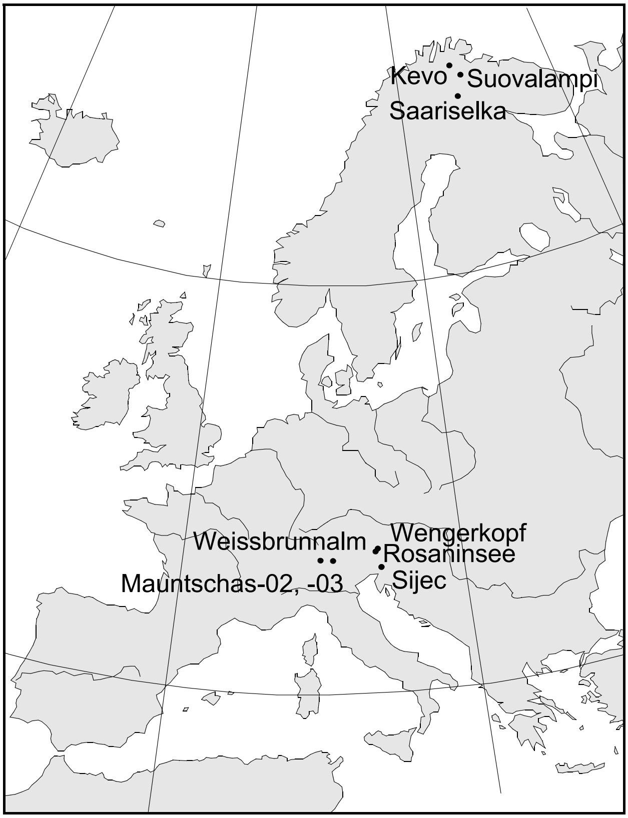


Figure 1 Locations of the studied peat sections

This project requires pollen accumulation rates (grains cm^{-2} yr^{-1}) to be calculated at high temporal resolution for the last 300 yr, then compared with the tree-ring records. The project therefore requires a precise and robust age-depth chronology. The pollen calculations will be discussed in future publications. The present paper is concerned with the problems of ^{14}C dating and the determination of age-depth models for the peat sections studied.

Age determination by ^{14}C dating individual modern (post-1950 AD) samples is possible due to the large bomb peak of atmospheric ^{14}C concentration in 1963 and the following rapid decline in the ^{14}C level (Nydal and Lövseth 1983). Accurate calibration of older ^{14}C dates, from AD 1650 to 1950, is more problematic because of large wiggles in the ^{14}C calibration curve (Stuiver et al. 1998). Moreover, because the peat accumulation rate in young sections of peat mires changes with depth, the wiggle-matching technique is not applicable.

In the present study, we treated jointly the series of dates encompassing both the pre-bomb and post-bomb periods, which enabled us to derive precise age-depth models even in the critical period of the wiggly calibration curve (about AD 1650–1950).

MATERIAL AND METHODS

At each of the sites studied (Figure 1), the material was collected in the form of a peat monolith. In order to obtain high-resolution records, samples for ^{14}C dating were taken from within 3–5-mm-thick slices, and within vertical columns of about 2 × 2 cm wide. From most of the sections sampled, pure *Sphagnum* was selected for ^{14}C dating.

Although peat is generally regarded as a reliable material for ^{14}C dating, Kilian (1995) found that ^{14}C dates of bulk material are sometimes affected by the reservoir effect. The same appears to be true when the samples are not completely cleaned of rootlets (e.g. of *Ericaceae*) or fungal remains (Kilian et al. 2000; Speranza et al. 2000). Therefore, when accurate ^{14}C dating of peat is desired, the use of only aboveground plant material is recommended (Blaauw 2003).

Sphagnum is used because it forms the bulk of most peat deposits; it is a moss and therefore does not have roots, so its growth is upward from the apex only. This means that there is little possibility for this plant to derive carbon from the underlying older peat. Other types of plant material were used for ^{14}C dating, in only a few cases where *Sphagnum* was not available.

As the amount of pure *Sphagnum* available in each sample was small, only the accelerator mass spectrometry (AMS) technique was applicable in ^{14}C dating. Most samples were dated in the Poznań Radiocarbon Laboratory. The samples for ^{14}C dating were treated chemically according to the standard AAA (acid-alkali-acid) procedure (e.g. de Jong 1981). After chemical pretreatment, the samples were combusted in sealed quartz tubes (with CuO and Ag), and the CO_2 produced was purified and graphitized by reduction with H_2, using Fe powder as a catalyst. The details of the laboratory procedure are described by Czernik and Goslar (2001). The graphite targets were then loaded into the AMS spectrometer, which enabled measurements of $^{14}C/^{12}C$ and $^{13}C/^{12}C$ ratios (Goslar et al. 2004). A few samples from one of the peat sections were dated earlier in the ^{14}C laboratory in Utrecht (Hicks et al. 2004), and these earlier results were included in the present study.

All the ^{14}C dates used in this paper are shown in Table 1 and Figure 2a. The younger parts of the peat sections reveal modern ^{14}C ages (>100 pMC), reflecting the bomb peak of atmospheric ^{14}C. Most of the dates in the older parts fall within the interval 0–200 ^{14}C BP, representing the wiggly part of the ^{14}C calibration curve between AD 1650 and 1950.

Joint Calibration of ^{14}C Dates in the Pre-Bomb and Post-Bomb Periods

In previous studies using the bomb peak for ^{14}C dating, ^{14}C concentrations in dated samples were expressed as pMC (percent modern carbon) and compared with the ^{14}C levels ($\Delta^{14}C$) recorded in the past in atmospheric air (Goodsite et al. 2001; Jungner et al. 1995). However, concentrations of ^{14}C measured in peat samples dated today are not directly comparable with those in the atmospheric $\Delta^{14}C$ records, which were determined in particular years in the past, i.e. several years or decades ago. In each case, the records of atmospheric $\Delta^{14}C$ have to be corrected for radioactive decay back to the measurement year.

Therefore, we decided to express the decay-corrected bomb atmospheric ^{14}C data in terms of ^{14}C age (negative in this case) in order to compare them directly with ^{14}C ages measured in the dated peat samples. In this approach, the ^{14}C data in the post-bomb period are treated in exactly the same manner as classic calibration of "normal" (i.e. pre-bomb) ^{14}C dates. In the approach of joint calibration, the uniform sets of (positive and negative) ^{14}C ages measured along the peat section are calibrated using the ^{14}C calibration curve, which extends into the post-bomb period.

In order to construct the extended "calibration curve" (Figure 2b), we used the Washington single-year tree-ring data for the period AD 1600–1950 (Stuiver and Braziunas 1993), supplemented by the $\Delta^{14}C$ biweekly data from Nordkapp (Nydal and Lövseth 1996) in 1963–1997 and Schauinsland (Levin et al. 1997) in 1977–1996. For each year, the biweekly data were averaged over the growing season only. In the transition period 1950–1963, we used the compilation made by Goodsite et al. (2001), while the data after 1997 were obtained by extrapolation of the Nordkapp record using an exponential function.

Table 1 Results of radiocarbon dating of the peat sections studied, expressed as conventional ^{14}C age and as content with respect to the modern standard (pMC = percent modern carbon).

Depth (mm)	Material dated	Lab nr[a]	^{14}C BP	pMC	Year AD[b]
Kevo (collected 1997. lat 69°45′N, long 27°00′E)					
20	*Betula nana* leaf	UtC-8183	–1067 ± 56	114.2 ± 0.8	1994.9
40	*Betula nana* leaf	UtC-8184	–1518 ± 33	120.8 ± 0.5	1992
51	*Betula nana* leaf	UtC-9195	–1185 ± 42	115.9 ± 0.6	1990.1
52	*Betula nana* leaf	UtC-8134	–1857 ± 32	126.0 ± 0.5	1989.9
52.5	*Sphagnum*	Poz-4403	–1404 ± 24	119.1 ± 0.3	1989.8
70	*Betula nana* leaf	UtC-8135	–1391 ± 122	118.9 ± 1.8	1986.4
90	*Betula nana* leaf	UtC-8136	–2145 ± 43	130.6 ± 0.7	1981.6
100	*Betula nana* leaf	UtC-8158	–2236 ± 36	132.1 ± 0.6	1979
142	*Sphagnum*	Poz-2375	–3825 ± 20	161.0 ± 0.4	1966
182	*Sphagnum*	Poz-2376	75 ± 25	99.1 ± 0.3	1945.8
227	*Sphagnum*	Poz-2377	75 ± 25	99.1 ± 0.3	1909
262	*Sphagnum*	Poz-3680	120 ± 30	98.5 ± 0.4	1870
560	Peat	Poz-2378	2475 ± 30	73.5 ± 0.3	
550	*Sphagnum*	Poz-2951	90 ± 25	98.9 ± 0.3	1819.6
600	*Sphagnum*	Poz-2952	190 ± 25	97.7 ± 0.3	1750
Suovalampi (collected 1997. lat 69°36′N, long 28°51′E)					
20	*Sphagnum*	Poz-2391	–1282 ± 22	117.3 ± 0.3	1990
40	*Sphagnum*	Poz-2392	–2068 ± 22	129.4 ± 0.4	1982
60	*Sphagnum*	Poz-2393	–2470 ± 22	136.0 ± 0.4	1979
80	*Sphagnum*	Poz-2395	–2519 ± 31	136.8 ± 0.5	1976
105	*Sphagnum*	Poz-2396	–3216 ± 28	149.2 ± 0.5	1963
115	*Sphagnum*	Poz-3679	55 ± 25	99.3 ± 0.3	1948
140	*Sphagnum*	Poz-2397	130 ± 35	98.4 ± 0.4	1862
180	*Sphagnum*	Poz-2398	195 ± 30	97.6 ± 0.4	1792
220	*Sphagnum*	Poz-2399	680 ± 30	91.9 ± 0.3	1707
220	*Sphagnum*	Poz-2724	845 ± 30	90.0 ± 0.3	1707
280	*Sphagnum*	Poz-2401	355 ± 30	95.7 ± 0.4	1550
Saariselkä (collected 2002. lat 68°25′N, long 27°26′E)					
30	*Sphagnum* leaves	Poz-1823	–851 ± 25	111.2 ± 0.3	1996.1
50	*Sphagnum* leaves	Poz-1829	–1414 ± 25	119.2 ± 0.4	1987.8
70	*Sphagnum* leaves	Poz-1825	–3367 ± 25	152.1 ± 0.5	1972.4
90	*Sphagnum* leaves	Poz-1827	40 ± 35	99.5 ± 0.4	1950.5
120	*Sphagnum* leaves	Poz-1826	20 ± 35	99.8 ± 0.4	1892.3
140	*Sphagnum* leaves	Poz-1824	–17 ± 103	100.2 ± 1.3	1852.3
150	*Sphagnum* leaves	Poz-2388	75 ± 25	99.1 ± 0.3	1833
165	*Sphagnum* leaves	Poz-1831	–68 ± 33	100.9 ± 0.4	1789.3
168	*Sphagnum* leaves	Poz-2389	0 ± 25	100.0 ± 0.3	1791.4
190	Fine (<0.18 mm) fraction of peat	Poz-1834	75 ± 30	99.1 ± 0.4	1728.3
220	Fine (<0.18 mm) fraction of peat	Poz-1830	220 ± 30	97.3 ± 0.4	
250	*Carex*, *Eriophorum*	Poz-3678	475 ± 30	94.3 ± 0.4	
260	Fine (<0.18 mm) fraction of peat	Poz-1833	670 ± 30	92.0 ± 0.3	
320	Fine (<0.18 mm) fraction of peat	Poz-1822	1055 ± 30	87.7 ± 0.3	
1045	Peat	Poz-1835	6340 ± 40	45.4 ± 0.2	

Table 1 Results of radiocarbon dating of the peat sections studied, expressed as conventional ^{14}C age and as content with respect to the modern standard (pMC = percent modern carbon). *(Continued)*

Depth (mm)	Material dated	Lab nr[a]	^{14}C BP	pMC	Year AD[b]
Wengerkopf (collected 2002. lat 13°52′E, long 47°10′N)					
115	*Sphagnum*	Poz-1842	−860 ± 26	111.3 ± 0.4	1996
213	*Sphagnum*	Poz-1840	−1236 ± 29	116.6 ± 0.4	1991
260	*Sphagnum*	Poz-951	−1333 ± 25	118.1 ± 0.4	1988.1
275	*Sphagnum*	Poz-1839	−1305 ± 26	117.6 ± 0.4	1987.1
290	*Sphagnum*	Poz-3599	−1575 ± 34	121.7 ± 0.5	1986.1
320	*Sphagnum*	Poz-1838	−1702 ± 27	123.6 ± 0.4	1982.1
354	*Sphagnum*	Poz-1813	−3325 ± 40	151.3 ± 0.8	1972.7
380	*Sphagnum*	Poz-1099	−4423 ± 20	173.4 ± 0.4	1965.8
386	*Sphagnum*	Poz-3600	−4441 ± 27	173.8 ± 0.6	1964.2
406	*Sphagnum*	Poz-1819	−1663 ± 28	123.0 ± 0.4	1959.2
430	*Sphagnum*	Poz-1814	2 ± 29	100.0 ± 0.4	1952.4
458	*Sphagnum*	Poz-1820	95 ± 50	98.8 ± 0.6	1942
500	*Sphagnum*	Poz-952	100 ± 30	98.8 ± 0.4	1924.9
515	*Sphagnum*	Poz-1821	120 ± 30	98.5 ± 0.4	1919.5
549	*Sphagnum*	Poz-1837	100 ± 30	98.8 ± 0.4	1906.8
585	*Sphagnum*	Poz-956	60 ± 30	99.3 ± 0.4	1881.5
615	Fine (<0.2 mm) fraction of peat	Poz-947	90 ± 30	98.9 ± 0.4	1831.5
665	Fine (<0.2 mm) fraction of peat	Poz-3409	85 ± 30	98.9 ± 0.4	1708.4
690	*Sphagnum*	Poz-3944	310 ± 30	96.2 ± 0.4	1630
715	Fine (<0.2 mm) fraction of peat	Poz-3581	470 ± 30	94.3 ± 0.4	
Weissbrunnalm-01 (collected 2002. lat 46°28′N, long 10°49′E)					
110	*Sphagnum*	Poz-1100	−2477 ± 23	136.1 ± 0.4	1977
160	*Sphagnum*	Poz-949	−4116 ± 21	166.9 ± 0.4	1968.1
210	*Sphagnum*	Poz-953	−1693 ± 27	123.5 ± 0.4	1959.2
230	Fine (<0.2 mm) fraction of peat	Poz-955	−288 ± 26	103.7 ± 0.3	1954.5
275	*Potentilla* seeds	Poz-3737	110 ± 30	98.6 ± 0.4	1938
Rosaninsee (collected 2002. lat 13°46′E, long 46°57′N)					
90	*Sphagnum*	Poz-2434	−1036 ± 21	113.8 ± 0.3	1993
170	*Sphagnum*	Poz-2435	−1681 ± 20	123.3 ± 0.3	1985
250	*Sphagnum*	Poz-1849	−2279 ± 26	132.8 ± 0.4	1978.1
300	*Sphagnum*	Poz-1850	−2982 ± 25	145.0 ± 0.5	1973.3
335	*Sphagnum*	Poz-2498	−4156 ± 20	167.8 ± 0.4	1966.9
366	Fine (<0.2 mm) fraction of peat	Poz-2499	−275 ± 27	103.5 ± 0.3	1954
366	Seeds and spores	Poz-3763	155 ± 30	98.1 ± 0.4	1954
400	Mosses	Poz-3761	195 ± 30	97.6 ± 0.4	1931
Mauntschas-02 (collected 2002. lat 46°29′N, long 9°51′E)					
60	*Sphagnum*	Poz-2949	−940 ± 23	112.4 ± 0.3	1995.2
115	*Sphagnum*	Poz-2414	−1427 ± 21	119.4 ± 0.3	1987.7
177	*Sphagnum*	Poz-2415	−2747 ± 20	140.8 ± 0.4	1972.2
207	*Sphagnum*	Poz-2950	−2969 ± 29	144.7 ± 0.5	1963.6
215	*Sphagnum*	Poz-3597	−1478 ± 46	120.2 ± 0.7	1961.2
238	*Sphagnum*	Poz-2416	10 ± 25	99.9 ± 0.3	1954.3
278	*Sphagnum*	Poz-2417	75 ± 25	99.1 ± 0.3	1944.1
320	*Sphagnum*	Poz-2418	95 ± 25	98.8 ± 0.3	1934.9
370	*Sphagnum* + moss	Poz-2420	150 ± 25	98.2 ± 0.3	1922.9
430	*Sphagnum*	Poz-2421	95 ± 25	98.8 ± 0.3	1908
495	*Sphagnum* + moss	Poz-2422	80 ± 25	99.0 ± 0.3	1883.1

Table 1 Results of radiocarbon dating of the peat sections studied, expressed as conventional ^{14}C age and as content with respect to the modern standard (pMC = percent modern carbon). *(Continued)*

Depth (mm)	Material dated	Lab nr[a]	^{14}C BP	pMC	Year AD[b]
518	*Sphagnum* + *Calluna* branches	Poz-2424	105 ± 25	98.7 ± 0.3	1860.4
550	*Sphagnum*	Poz-2951	90 ± 25	98.9 ± 0.3	1819.6
600	*Sphagnum*	Poz-2952	190 ± 25	97.7 ± 0.3	1750
Šijec (collected 2002. lat 46°20′N, long 14°00′E)					
50	*Sphagnum*	Poz-1527	–789 ± 28	110.3 ± 0.4	1999
100	*Sphagnum*	Poz-1530	–918 ± 29	112.1 ± 0.4	1996.1
150	*Sphagnum*	Poz-1525	–1073 ± 26	114.3 ± 0.4	1992.8
200	*Sphagnum*	Poz-1531	–1318 ± 29	117.8 ± 0.4	1988
250	*Sphagnum*	Poz-1524	–1854 ± 27	126.0 ± 0.4	1981.8
300	*Sphagnum*	Poz-1532	–2844 ± 27	142.5 ± 0.5	1974.5
350	*Sphagnum*	Poz-1526	–4435 ± 23	173.7 ± 0.5	1966.9
400	*Sphagnum*	Poz-1533	–1393 ± 30	118.9 ± 0.4	1957.3
450	*Sphagnum*	Poz-2746	80 ± 25	99.0 ± 0.3	1933.6
475	*Sphagnum*	Poz-3629	65 ± 30	99.2 ± 0.4	1918.5
500	*Sphagnum*	Poz-2747	0 ± 30	100.0 ± 0.4	1901.7
550	*Sphagnum*	Poz-1523	90 ± 30	98.9 ± 0.4	1864.3
585	*Sphagnum*	Poz-2748	105 ± 25	98.7 ± 0.3	1835.7
620	*Sphagnum*	Poz-3630	620 ± 50	92.6 ± 0.6	
650	Organic sediment	Poz-1529	595 ± 30	92.9 ± 0.3	
Mauntschas-03 (collected 2003. lat 46°29′N, long 9°51′E)					
110	*Sphagnum*	Poz-3998	–1247 ± 24	116.8 ± 0.4	1988
170	*Sphagnum*	Poz-5181	–3280 ± 26	150.4 ± 0.5	1973
220	*Sphagnum*	Poz-3999	–4607 ± 24	177.4 ± 0.5	1963
272	*Sphagnum*	Poz-5445	110 ± 35	98.6 ± 0.4	1949
320	*Sphagnum*	Poz-4055	135 ± 30	98.3 ± 0.4	1936
420	*Sphagnum*	Poz-4000	130 ± 25	98.4 ± 0.3	1905
520	*Sphagnum*	Poz-4001	120 ± 25	98.5 ± 0.3	1870
550	*Sphagnum*	Poz-5179	80 ± 30	99.0 ± 0.4	1858
680	*Sphagnum*	Poz-5484	235 ± 30	97.1 ± 0.4	1795.5
720	*Sphagnum*	Poz-4002	225 ± 30	97.2 ± 0.3	1762.5
770	*Sphagnum*	Poz-5180	200 ± 30	97.6 ± 0.4	1638
820	*Sphagnum*	Poz-4004	450 ± 30	94.6 ± 0.3	1450
920	*Sphagnum*	Poz-3762	865 ± 30	89.8 ± 0.3	1180

[a]Most samples were dated in the Poznań Radiocarbon Laboratory (code Poz-). The laboratory numbers with the code UtC- are samples dated in the AMS ^{14}C laboratory in Utrecht (Hicks et al. 2004).
[b]The calendar ages of peat samples are derived from the age-depth models described in the text.

Relevant for the calibration of ^{14}C dates is whether the dated organisms derived their carbon in equilibrium with the atmosphere. This problem is evident in marine environments where the marine ^{14}C calibration curve has to be applied, which takes into account a site-specific reservoir age. The problem of reservoir age does not seem to be applicable for peat. Nevertheless, Jungner et al. (1995) in their studies of modern peat sections did show a bomb peak in peat distinctly smaller than in the atmosphere, and they concluded that the ^{14}C content in the air near a peatbog surface was seriously affected by ^{14}C-depleted CO_2 produced by the decomposition of older plant tissues, and emanating from the underlying layers. Goodsite et al. (2001), on the other hand, found that the ^{14}C peaks in 2 peat profiles from Denmark and Greenland were as large as in the atmosphere, suggesting absence of ^{14}C depletion in those profiles.

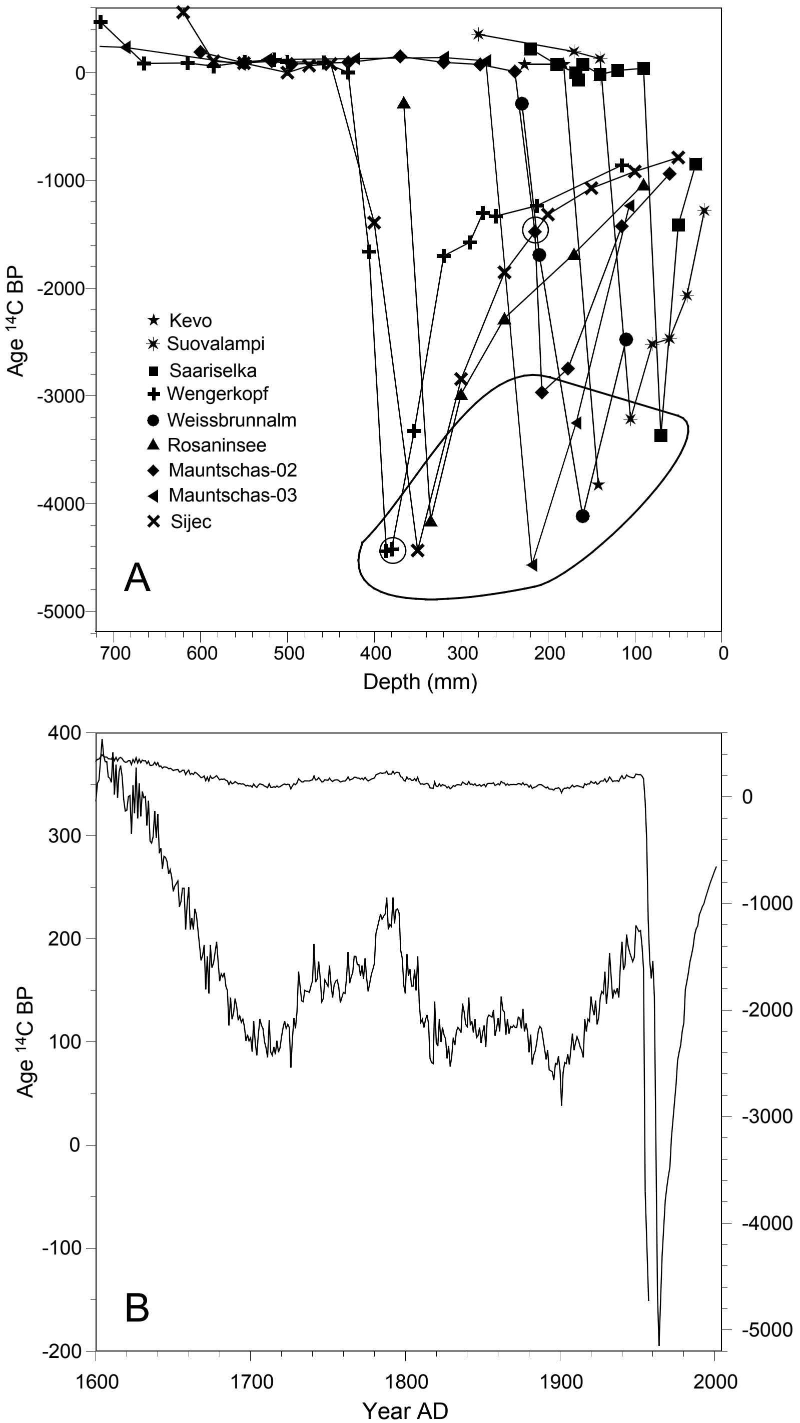


Figure 2 a) ^{14}C dates of samples from the peat sections studied plotted as a function of depth. Negative ^{14}C ages correspond to samples with a ^{14}C concentration higher than in the standard of the modern biosphere (due to the atomic bomb effect). The points representing the maximum ^{14}C values measured in each peat section are enclosed with a band. The 2 dates from levels sampled intentionally to meet the absolute ^{14}C maxima are circled. b) The single-year ^{14}C calibration curve extended onto the post-bomb period. Note that the curve is shown on 2 different vertical scales.

In this study, we note that the ^{14}C maxima in all the peat profiles are smaller than the atmospheric bomb peak (Figure 2), and we observe a correlation between the maximum ^{14}C measured in a peat section and the peat accumulation rate (expressed as the depth at which the ^{14}C maximum occurs). This correlation is significant ($r^2 = 0.43$, $df = 8$) at a level of 0.05, implying a relationship between the 2 variables.

One potential reason for that correlation could be that the maximum ^{14}C levels in the peat profiles were just missed because of limited sampling resolution. Indeed, the chance of sampling at the maximum decreases with decreasing sampling resolution, which in turn might be related to the peat accumulation rate. However, the height of the ^{14}C maximum and the sampling resolution are not directly correlative.

Another mechanism could be that both the maximum ^{14}C level recorded in the peat section and the peat accumulation rate were controlled by the same factor, e.g. the length of the vegetation period. Indeed, most of the peat sections with a slow accumulation rate occur in northern Finland, where the growing season is shorter than that in central Europe. However, the shorter vegetation season means higher seasonal averages of ^{14}C in peat, which is the opposite of the observed relationship.

The ultimate reason for the correlation described above is that the samples dated encompassed several years, so that the bomb ^{14}C maxima were flattened simply by integration. We must stress that the samples analyzed came from very thin layers (2–5 mm), which would scarcely correspond to more than 1 yr based on the mean peat accumulation rate between the mid-1960s and today. Nevertheless, it seems possible that the dead *Sphagnum* fragments in the peat are mixed due to compression of peat layers, and tissues grown in different years may be found at the same level. Such a mixing would result in the situation where the specific levels analyzed from the peat sections contain a mixture of ^{14}C assimilated over a number of years. In other words, we must agree that the ^{14}C concentration in peat from a specific level reflects the atmospheric record integrated over some period of time. An additional integration of ^{14}C concentration would also be caused by CO_2 or CH_4 produced by decomposition of older plant tissues, and emanating from the underlying peat, taken up by overlying peat layers.

Site-Specific Integration Time of Atmospheric ^{14}C in Peat

We assume that the integration of the atmospheric ^{14}C record in peat might be expressed by a Gaussian curve with a site-specific width (expressed as integration time τ). Therefore, the longer the integration time is, the more flattened the bomb ^{14}C maximum in peat would be expected (see Figure 3).

The integration time τ in a particular peat section can be quantified using the information on the height of the ^{14}C maximum and the sampling resolution (Figure 3). For example, the maximum ^{14}C measured in Mauntschas-02 (at 207 mm) is distinctly lower than the atmospheric peak (which corresponds to –5150 ^{14}C BP). If there would be no integration, this would imply that the sampling has missed the absolute peak of atmospheric ^{14}C and the sample at 207 mm would correspond to AD 1973. This, however, is unlikely as the underlying sample (at 215 mm) has a lower ^{14}C content of atmospheric ^{14}C, whereas a higher content corresponding to around AD 1967 would be expected. This contradiction disappears when we assume that in the peat section the atmospheric ^{14}C record is integrated, with an integration time as long as 8 yr.

Another situation is represented in the Šijec peat section. Here, the maximum ^{14}C is also lower than the atmospheric peak. If no integration took place, the maximum sample (350 mm) would originate from AD 1966, which is possible since the underlying sample with lower ^{14}C content would represent AD 1960 (400 mm), the year when the atmospheric ^{14}C concentration was indeed lower.

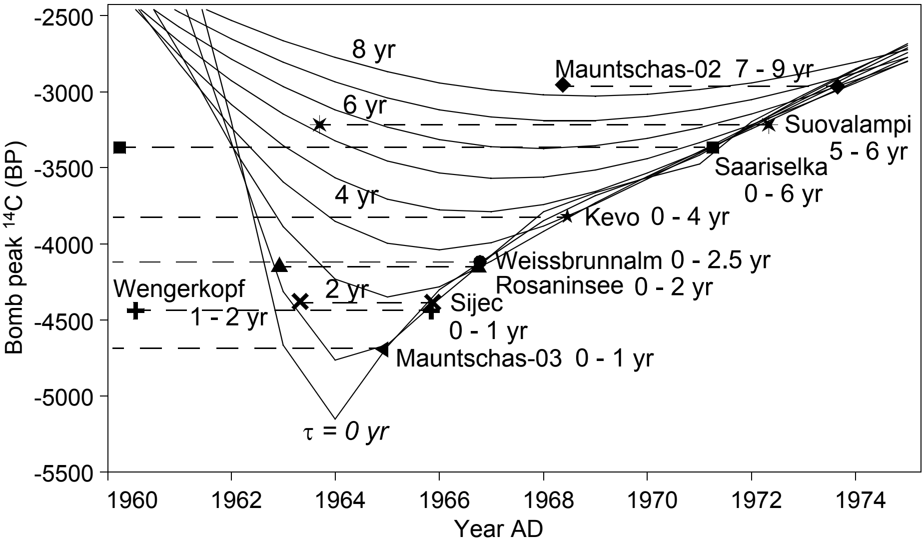


Figure 3 Illustration of the assessment of the integration time τ. The smooth lines represent "theoretical" profiles of ^{14}C age, obtained for different values of integration time. The maximum ^{14}C values measured in particular profiles are represented by horizontal segments. The lengths of the segments correspond to the time intervals between adjacent samples in particular peat profiles.

As shown in Figure 3, the integration time is longer (3–6 yr) in the northern sites (Suovalampi, Kevo, Saariselkä) and shorter in the Alps (0.7–2 yr), which is clearly correlative with the slower peat accumulation rate in the north. An exception is Mauntschas-02, where the integration time is long (8 yr) despite a relatively high accumulation rate.

Surprised by the large integration time in Mauntschas-02, we sampled the twin peat section Mauntschas-03 (taken a few tens of meters away from the -02 section). Although the accumulation rate was the same (Figure 2a), the ^{14}C peak in Mauntschas-03 appeared much higher and the integration time much shorter than in Mauntschas-02. One reason for this difference could be that before we started our work on Mauntschas-02, the section had been sampled by other researchers for a variety of studies, and it may be that the section was not handled carefully with regard to the peat stratigraphy. We sampled Mauntschas-02 by cutting a sub-section from one edge of the section over the full length and 4×4 cm in surface area with a sharp knife; samples for AMS ^{14}C dating were taken from this sub-section. Mauntschas-03 was treated very carefully with regard to the peat stratigraphy, both in the field and in the laboratory as follows. A sub-section about 10×10 cm in surface area was sawed from the larger peat section in the frozen condition. The samples for AMS ^{14}C dating were taken from the cleaned surface below a saw cut, away from the original outer surface of the section.

The case of the Mauntschas site leads us to believe that the difference in the length of the estimated ^{14}C integration time between Mauntschas-02 and -03 may have resulted from differences in handling the peat sections. The estimated short ^{14}C integration time in Mauntschas-03 (<1 yr) suggests that the peat layers in the mire are not vertically mixed. We infer that the same was the case at the location Mauntschas-02 before the section was collected, because the 2 sections comprise very similar peat types. We think that the initial sampling of Mauntschas-02 and the position of the dated sub-section at the edge of the section have caused distortion of the peat layers, which resulted in the inclusion of material from several consecutive years in the dated samples, and therefore a long ^{14}C integration time (8 yr).

Age-Depth Models of the Peat Sections

In constructing the age-depth models, we applied the specially developed computer program PozCal. Using a standard algorithm for calibration of ^{14}C ages (e.g. Michczyńska et al. 1990; Bronk Ramsey 2003), PozCal calculates probability distributions of calendar age for individual samples in the peat section via a comparison with the "extended" calibration curve integrated over the site-specific calibration time τ. These distributions are displayed with vertical positions proportional to sample depths (Figure 4a–e). On each plot, the age-depth model is directly represented by a curve passing through (or close to) the maxima of the probability distributions.

When deriving the age-depth curve, one should be aware of some additional facts. First, abrupt lithological boundaries (transitions in the peat stratigraphy) at certain levels in the peat sections studied indicate abrupt changes in peat accumulation rate. Second, the degree of preservation/humification of the peat strongly suggests that between these abrupt boundaries, peat growth was rather regular, without inversions and with a gradual decrease of the peat accumulation rate down the section, because of plant decomposition and compaction increasing with depth. Therefore, monotonic and smooth age-depth curves were expected, except at lithological boundaries where abrupt changes in their slopes were possible. However, these transitions in lithology could be expressed only qualitatively and are displayed at the right-hand side of the plots in Figure 4.

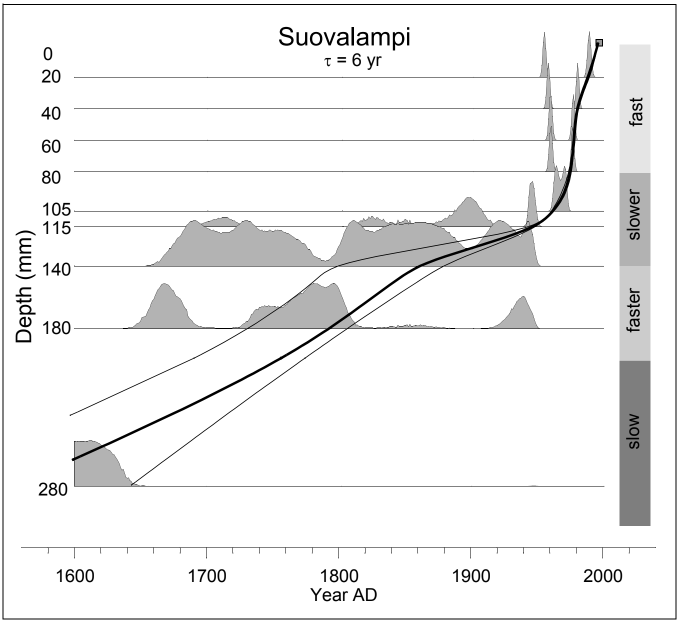
In the post-bomb parts of the majority of the peat sections, the probability maxima are thin and clearly placed along smooth lines, unequivocally tracing the age-depth curves. The only exception is Kevo, where the ages of the samples at 20, 40, and 51 mm appear too old with respect to those suggested by the samples at 52, 70, and 90 mm. In all probability, this is related to the fact that the anomalous dates (represented in Figure 4 by white silhouettes) were obtained on dwarf-birch leaves. Such leaves, unlike *Sphagnum* stems, may undergo redeposition, so it is probable that these leaves were actually older than the peat at the same depths. This interpretation seems to be confirmed by the date of the *Sphagnum* sample at 52.5 mm (gray silhouette in Figure 4a), which lies perfectly on the smooth age-depth curve.

It is worth noting that the age-depth curves traced by the probability maxima (Figure 4) bend at just the levels of the lithological boundaries. This is especially clear in Wengerkopf at 320 mm (Figure 4b), Mauntschas-02 at ~170 mm (Figure 4d), Šijec at ~400 mm (Figure 4d), Rosaninsee at ~330 mm (Figure 4c), and Saariselkä at ~35 mm (Figure 4b).

In the pre-bomb sections, the probability distributions for individual samples are multi-modal and about 300 yr wide. However, the simultaneous use of post-bomb and pre-bomb dates enables the rejection of most maxima of the probability distributions in the pre-bomb section. Considering the example of Mauntschas-02 (Figure 4d), passing the age-depth curve through the older maxima at 430–278 mm would mean either an inversion in the peat or an abrupt major increase in the peat accumulation rate down the peat section, which is in disagreement with the degree of peat preservation and the lithology. Therefore, the most probable age-depth curve is that passing around AD 1900 at 495 mm. An alternative model has the age-depth curve passing at about AD 1800 at 518 mm.

The Strategy of Multi-Stage ^{14}C Dating

In Mauntschas-02, a discrimination between the 2 age-depth models shown (Figure 4d) would be possible after dating one additional sample between 550 and 518 mm. It is worth noting that the selection of the level to be dated for such discrimination was not possible before the dates at 600, 550, and 518 mm were available. On the other hand, the dates at 495 and 320 mm provide no additional information to that given by the other dates. This example shows that the selection of samples for ^{14}C dating should be made in stages—the sampling depths at each stage being dependent on the results obtained in the previous stage.



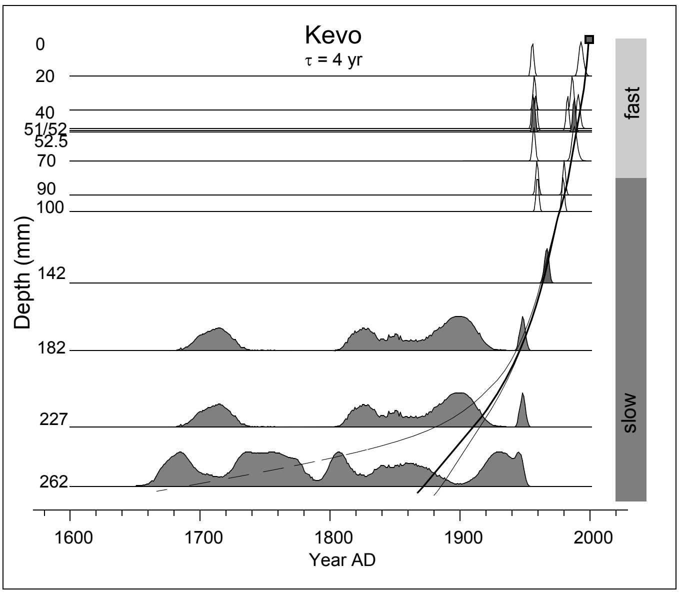


Figure 4 a–d) Diagrams illustrating the construction of the age-depth models. For each peat section, the probability distributions of calibrated ^{14}C ages of individual samples are shown with gray silhouettes and displayed at vertical positions proportional to sample depths. White silhouettes correspond to samples of dwarf-birch leaves (Kevo) or samples with clearly outlying ^{14}C ages (Saariselkä). The rectangles in the upper-right corners represent the year of collection of the peat sections (depth = 0). The left-pointing arrows at the lower-left corners represent peat samples with calendar ages beyond the range of the diagram. The smooth lines passing through the maxima of probability distributions represent the most probable age-depth curves; the 2 dashed lines drawn beside represent the uncertainties of the age-depth models. The gray bars at the right-hand side illustrate changes of peat accumulation rate, derived from the lithology. e) Illustration of the evolution of the age-depth models of Mauntschas-03, after 3 stages of ^{14}C dating. The meaning of all diagram components is the same as in parts a–d. (Figures 4b–e are on the following pages.)

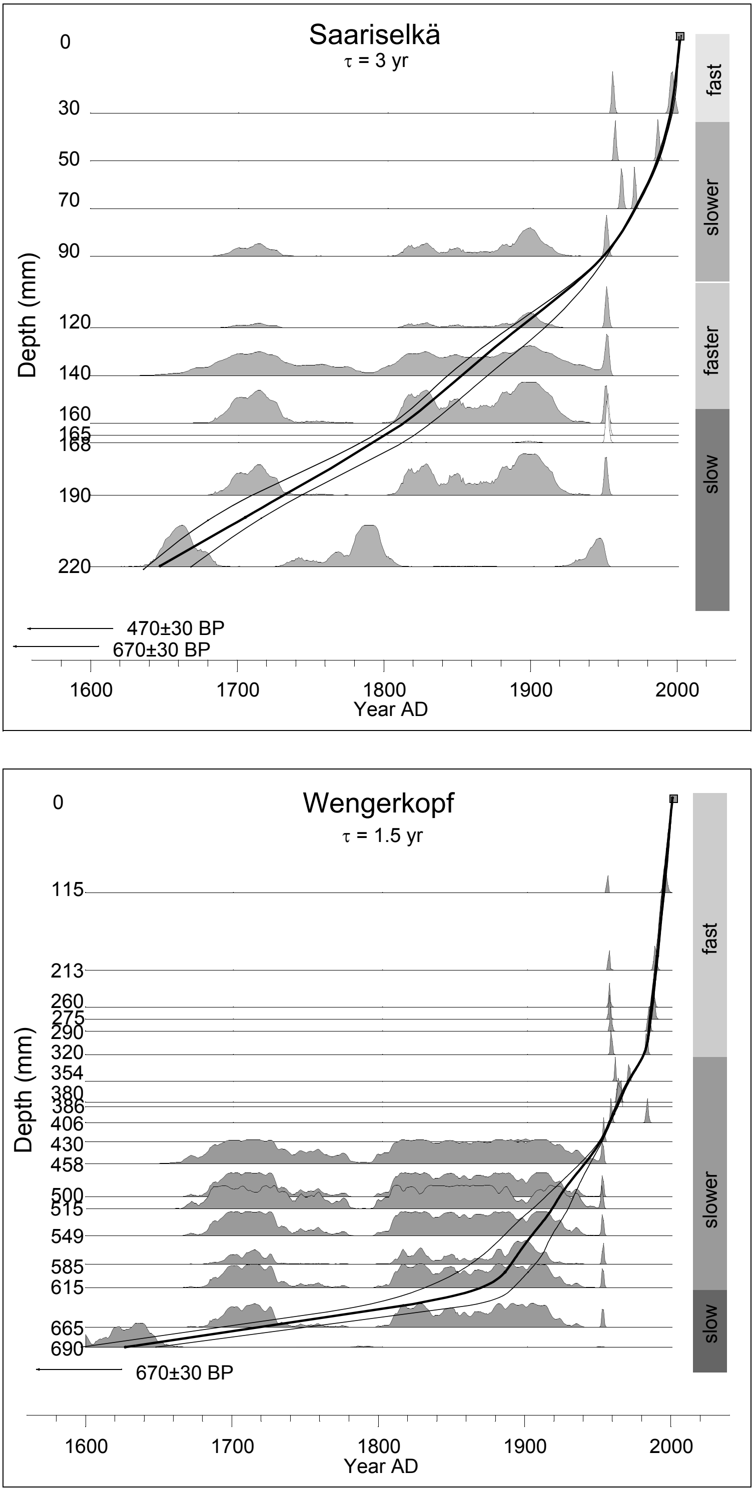
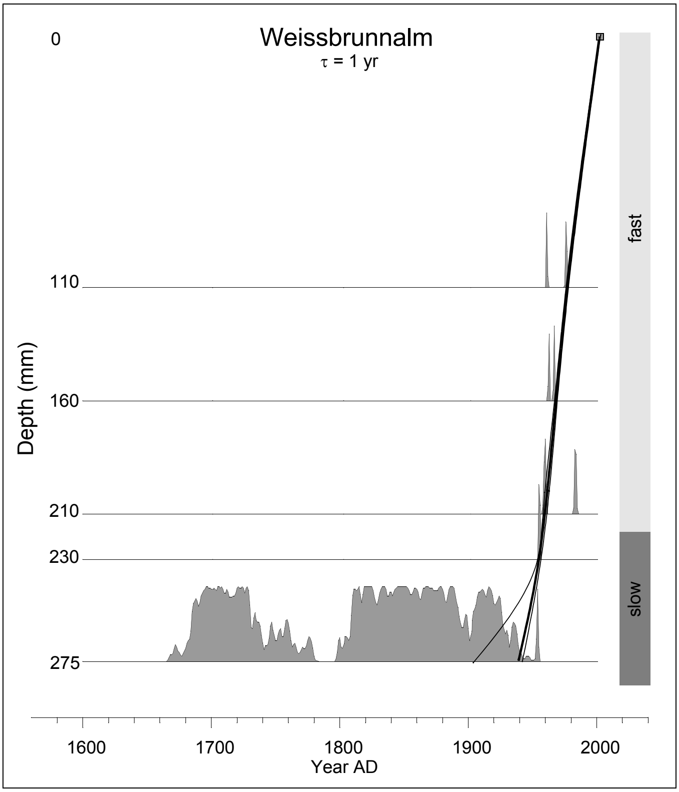


Figure 4b See Figure 4a for description



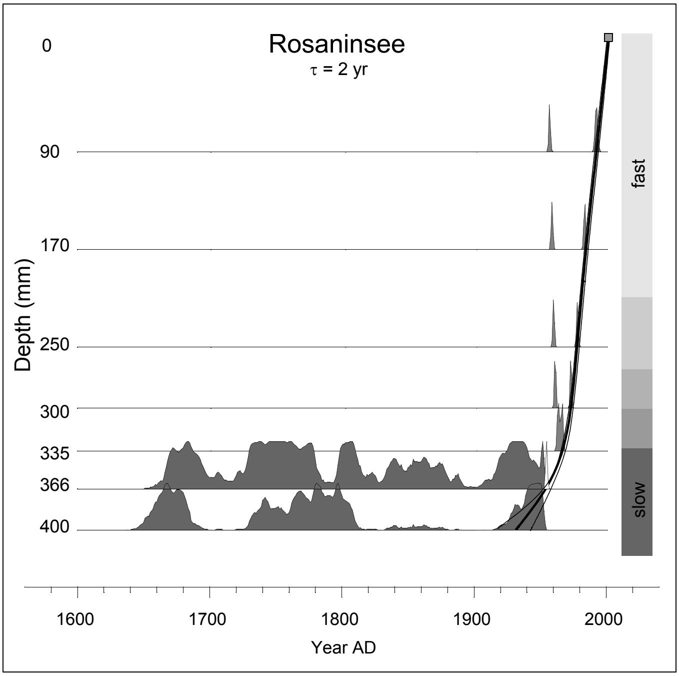
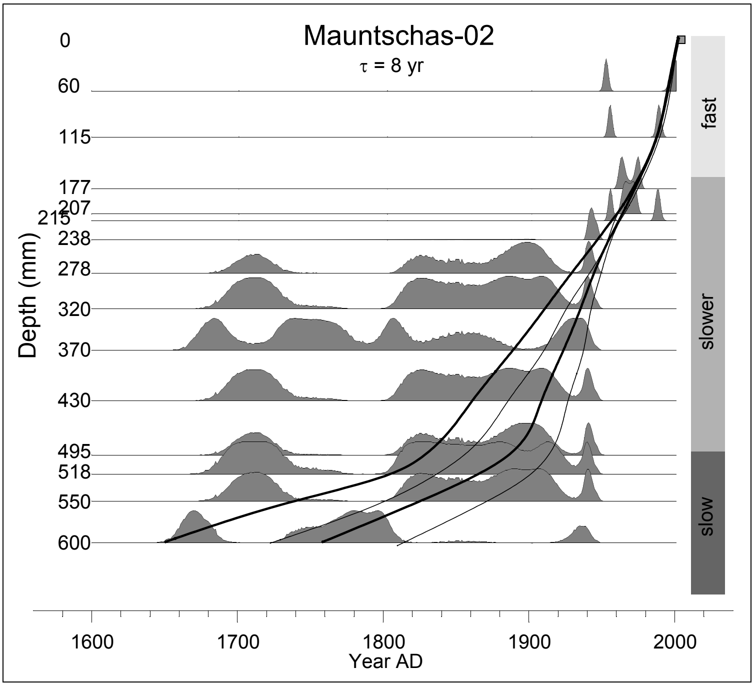


Figure 4c See Figure 4a for description



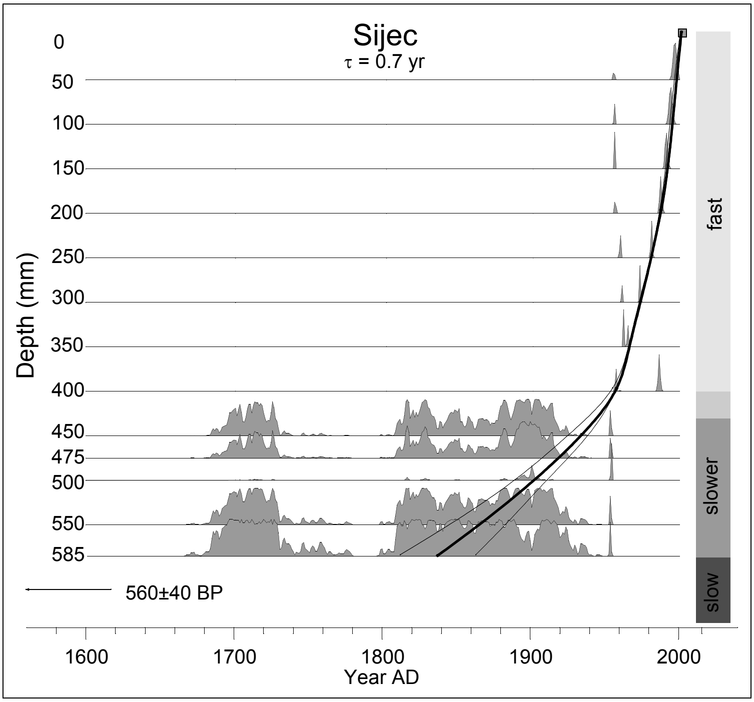


Figure 4d See Figure 4a for description

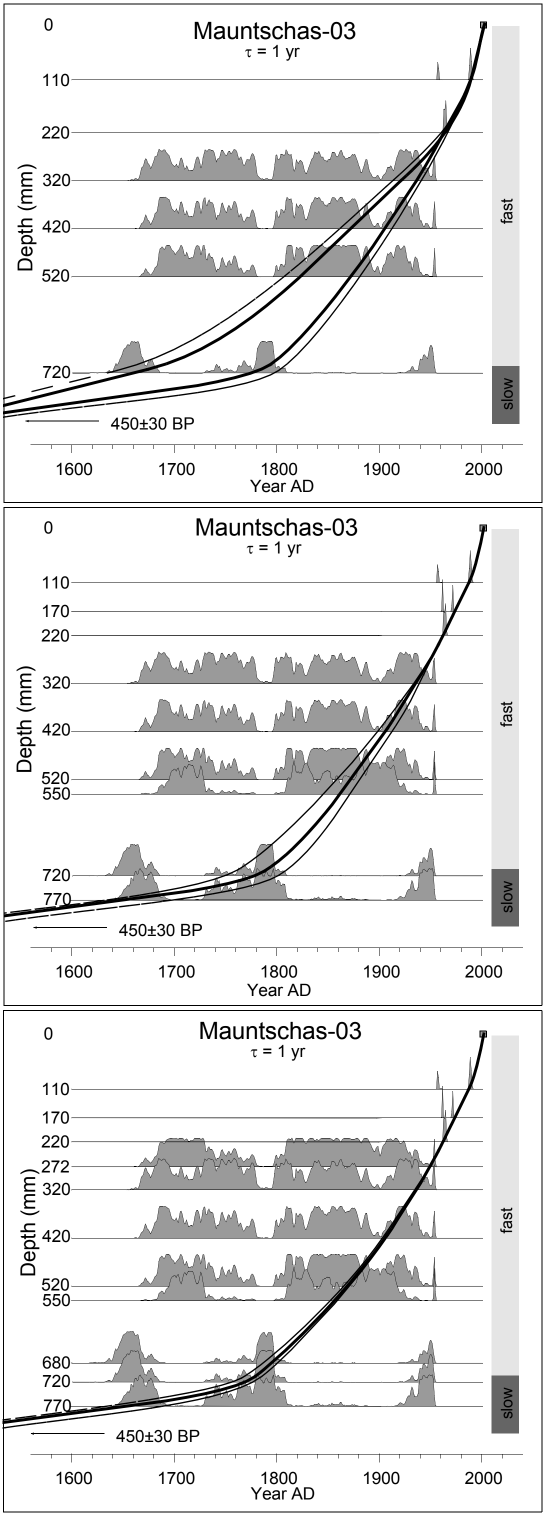


Figure 4e See Figure 4a for description

The strategy of multi-stage ^{14}C dating, with selection of samples for the next stage depending on the results already obtained, was applied to Mauntschas-03. Seven samples dated in the first stage (Figure 4e, top) allowed us to estimate the level of the bomb peak (at 220 mm) and to approximate the depth corresponding to the beginning of the wiggly part of the ^{14}C calibration curve age (about AD 1650; 820–720 mm). However, 2 different age-depth models were possible, with calendar ages at 720 mm differing by as much as 150 yr. Two additional ^{14}C dates (at 550 mm and 770 mm) allowed the "older" model to be rejected, and reduced the uncertainty of the calendar age at 720 mm to about ±30 yr (Figure 4e, center). A further reduction of this uncertainty (to about ±15 yr) was brought about by the ^{14}C date at 680 mm (Figure 4e, bottom).

It is noteworthy that in the pre-bomb period, both age-depth models for Mauntschas-03 show a change of accumulation rate around 720 mm, which is in close agreement with the lithology (Figure 4e). Abrupt increases in peat accumulation rates above ~140 mm in Suovalampi (Figure 4a), 620 mm in Wengerkopf (Figure 4b), 500 mm in Mauntschas-02 (Figure 4d), and ~100 mm in Saariselkä also agree with the lithological changes. The agreement of accumulation rate changes shown by the age-depth models with those suggested by the lithological boundaries supports the reliability of the age-depth models.

An integration with $\tau = 0.7–8$ yr affects the ^{14}C concentration in peat mainly in periods of rapid atmospheric ^{14}C changes, but very little in the pre-bomb period with its slow atmospheric ^{14}C changes. In fact, it has only a minor effect on the age-depth models of the peat sections studied (Figure 5), causing a slight shift towards older ages before and shortly after the atmospheric ^{14}C peak, and a shift towards younger ages in the later period. It is symptomatic that the check ^{14}C sample from Mauntschas-02 (Figure 2a), taken from the depth ascribed to AD 1963 by an age-depth model without integration, actually appeared older (not younger) than AD 1963. This demonstrates that neglecting integration would produce an erroneous age-depth model for Mauntschas-02. On the other hand, neglecting integration in the Wengerkopf profile would have no visible influence on the model (cf. the result of the check sample in Figure 2a), which is reasonable because the inferred integration time in that section is very short.

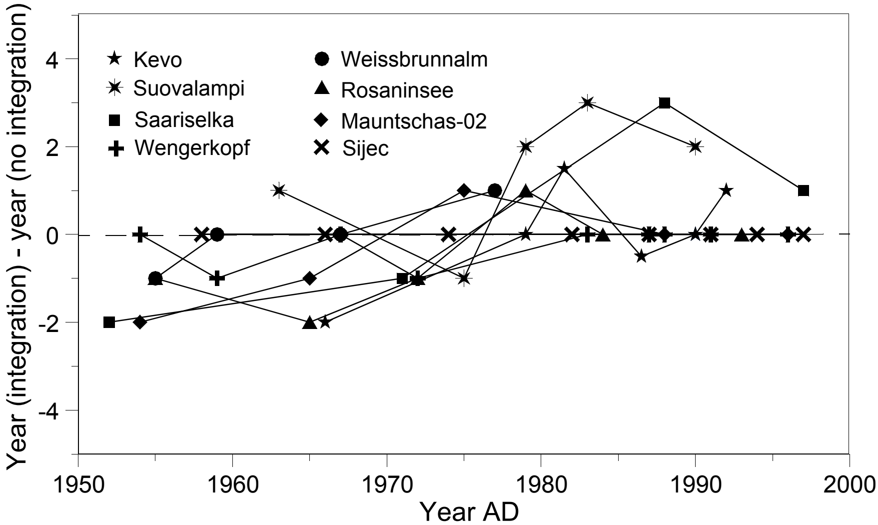


Figure 5 Differences between calendar ages of samples from the studied peat sections and derived from 2 scenarios of the age-depth models (with and without integration).

^{14}C Dates of Peat Sections Compared to Atmospheric Calibration Data

Having established robust chronologies for the peat sections, we are able to plot the ^{14}C ages of the dated samples versus calendar age and compare them directly with the atmospheric ^{14}C records (Figure 6). The effect of ^{14}C integration within the peat sections is illustrated by the fact that around AD 1963, all the peat ^{14}C data points lie below the atmospheric ^{14}C curve, while after AD 1970 they are all placed above the atmospheric curve.

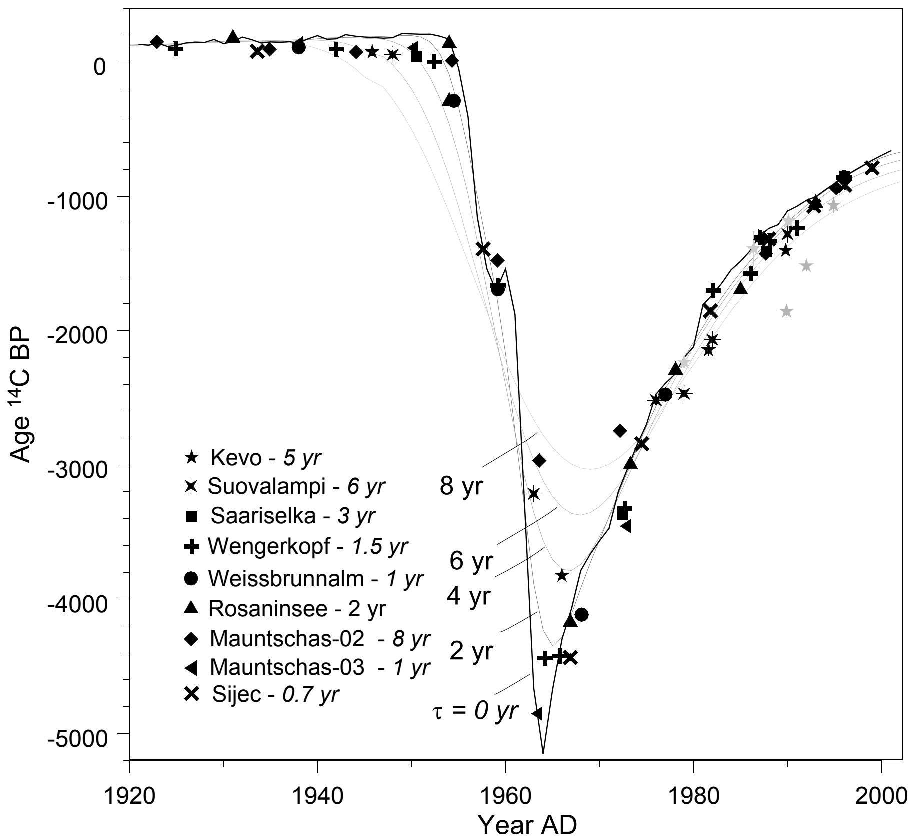


Figure 6 ^{14}C dates of samples from the peat sections studied are plotted against calendar ages derived from the age-depth models in the time interval AD 1920–2000. The smooth lines show the "theoretical" ^{14}C profiles in peat, calculated for different values of the integration time τ. The ^{14}C dates obtained on dwarf-birch leaves (Kevo) are marked with light gray symbols.

One might suspect that the location of the peat data-points above the atmospheric curve in Figure 6 is an artifact of the integration time used in the age-depth models, and therefore does not confirm the existence of integration. Indeed, slight modifications of the age-depth curves after AD 1970 would provide a perfect match of the peat ^{14}C dates with the atmospheric curve.

However, integration is verified by the ^{14}C dates in the interval AD 1930–1955 as follows. The situation is similar to that after AD 1970, in that all the ^{14}C data points in the period AD 1930–1955 (Figure 6) lie above the atmospheric ^{14}C curve. However, unlike the situation after AD 1970, matching these points with the atmospheric curve would require *large* distortions of *all* age-depth models, which is unlikely as these models are robust in the period before AD 1920. It is symptomatic that, although most ^{14}C dates between AD 1600 and 1930 fit the atmospheric curve quite well (Figure 7), all the dates between 1930 and 1955 are younger than the atmospheric ones.

The period just preceding the bomb-induced increase of ^{14}C in the atmosphere appears to be especially problematical in the ^{14}C dating of sediments where some dispersion of the ^{14}C signal occurs. In fact, this is the only period where peat layers of "originally natural" ^{14}C concentration (which varied at a rate slower than 20‰ per 100 yr) are in touch with layers with ^{14}C concentrations higher by hundreds of per mil. So, even slight contamination with carbon from overlying layers may totally corrupt the ^{14}C dating in the late pre-bomb section.

Goodsite et al. (2001) noted that below the ^{14}C bomb peak, the Danish and Greenland peat sections with elevated ^{14}C levels were abnormally thick in comparison with the peat growth rate deduced from the thickness of the post-bomb sections. Therefore, the age-depth models of the Goodsite peat sections assume extremely high peat accumulation rates in the period AD 1950–1960, a feature in clear disagreement with indications given by the ^{210}Pb data.

A similar effect is observed in the peat sections studied here. However, large sets of ^{14}C dates in the pre-bomb peat layers make the age-depth models prior to AD 1960 very robust and leave no space for large variations in peat accumulation rates. Therefore, we are sure that this is the effect of ^{14}C integration, and we strongly believe that the thick layers of elevated ^{14}C levels in the Goodsite et al. (2001) peat sections reflect the same mechanism and have nothing to do with an increase in peat accumulation rate. It must be noted that this conclusion could not be drawn on the basis of Goodsite et al. data alone, because ^{14}C dates in the pre-bomb period were lacking and their age-depth models for that time interval could not be well anchored.

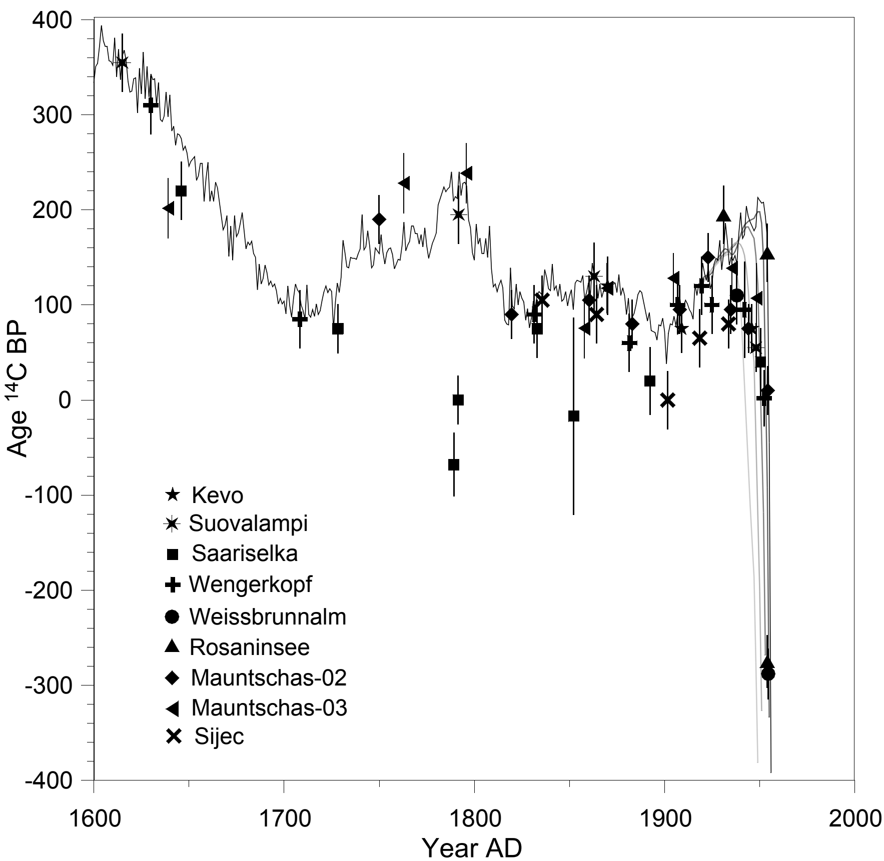


Figure 7 ^{14}C dates of samples from the peat sections studied plotted against calendar ages derived from the age-depth models. The dates from the post-bomb period are beyond the range of this graph.

CONCLUSIONS

This study is the first where modern peat profiles were ^{14}C dated at a high resolution in both the pre-bomb and post-bomb periods. Joint treatment of the series of dates from both periods enabled us to derive precise age-depth models for all the profiles analyzed. In the parts of the peat sections covered by the bomb peak, calendar ages of individual peat samples could be determined almost immediately, with an accuracy of 2–3 yr. In the pre-bomb sections, the construction of unequivocal age-depth relationships was more difficult, as the calendar ages of individual samples have the form of multi-modal probability distributions of about 300 yr wide (about AD 1650–1950). However, the simultaneous use of the post-bomb and pre-bomb ^{14}C dates, and lithological information on abrupt changes in peat accumulation rates, enabled the rejection of most modes of probability distributions in the pre-bomb section. Our results refute the concluding statement of the recent paper on age-depth modeling (Telford et al. 2004) that "uncertainties may always be high during radiocarbon plateaux."

Despite the fact that the samples for ^{14}C dating were carefully selected (pure *Sphagnum* in the majority of cases), we note some integration of the atmospheric ^{14}C record in the dated peat sections. The most probable reason for this integration is that below the surface of a peat mire, the dead *Sphagnum* fragments are mixed, so that tissues grown in different years may be found at the same level. The degree of integration, expressed in form of integration time τ, seems correlative with the peat growth rate, but it also depends on the manner of handling the peat sections to be sampled. The case of the 2 peat sections from the Mauntschas site clearly shows that careless handling affects the time resolution of the peat section and produces a large increase in the integration time.

The strategy of multi-stage ^{14}C dating, with the selection of samples for the next stage depending on the results obtained previously, enables a significant reduction in the uncertainty of the age-depth model, by dating only a few additional samples in a peat section. This strategy allows pinpointing a ^{14}C date at the bomb peak maximum, which is crucial for determining the ^{14}C integration time.

Our study is the first in which peat sections from the late pre-bomb period (AD 1900–1960) have been precisely dated at a high temporal resolution. This study demonstrates that during this time interval, ^{14}C ages of all the samples dated were younger than those derived from the atmospheric calibration curve, which strongly supports the concept of integration. Evidently, the determination of calendar ages based on ^{14}C dating of single samples from that interval may be affected by a serious error if the possibility of integration is ignored.

ACKNOWLEDGMENTS

The authors are grateful to Dr K van der Borg (University of Utrecht) for sharing ^{14}C dates of the Kevo peat section obtained in his laboratory. This paper is a contribution to the EU project PINE (Predicting Impacts on Natural Ecotones, Contract nr EVK2-CT-2002-00136)

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