APPLICATION OF ^{14}C DATA FOR THE ESTIMATION OF SPHAGNUM PEAT INCREMENT IN ESTONIAN OMBROTROPHIC MIRES

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ABSTRACT. We calculated apparent increment values based on the radiocarbon dates of 21 Estonian ombrotrophic mires (raised bogs). For short periods, the values vary significantly, but the integrated increment for the total complex of ombrotrophic peat shows a strong increasing tendency with decreasing peat age. This is probably due to the decay of accumulated organic matter. Our hypotheses concern the mechanisms of decay and methods for increasing the reliability of the interpolation and extrapolation of ^{14}C data.

INTRODUCTION

The study of spatial and temporal regularities of the development of ombrotrophic mires (raised bogs) is scientifically important. Due to continuous accumulation, peat sequences are a good source of palaeogeographical information. In addition, the increment-decay ratio of a bog contributes to the global carbon balance. For this reason, more precise chronologies of peat sequences must be obtained.

Since early in this century, many attempts have been made to date peat sequences. Weber (1910) was among the first to conduct research on the reference horizons of chronological importance. He linked the formation of a Grenzhorizont with the deterioration of climatic conditions during the limit of the Subboreal and the Subatlantic climatic periods dating back to *ca.* 2500 BP. Granlund (1932) distinguished several well-decomposed interlayers in the peat-bog deposit and assumed that their formation was related to changes in climatic conditions. These conclusions were based on the assumption that the degree of decomposition has a negative correlation with the accumulation rate of the ombrotrophic peat.

The application of the radiocarbon method to peat dating allowed for the possibility of reconstruction of past environments using peat deposits. Peat is a comparatively reliable material for dating because of the slow migration of the organic carbon. However, the main problem with using the ^{14}C method concerns the penetration of roots and rhizomes into deeper layers. In recent years, many attempts were made to find new possibilities for high-resolution dating of peat sequences (Kilian *et al.* 1995). This is because today palaeoecological studies need a more precise age scale. As the peat accumulation is not constant in time, there exist problems with interpolation and extrapolation of ^{14}C data, and additional methods for high-resolution dating are necessary. A common assumption is that the substance considered has a constant input rate. It may be total pollen rain (Middeldorp 1982), dry matter of peat (Clymo 1983; Ilomets 1980), or a particular chemical element (Menke 1987). Punning *et al.* (1993) developed an approach thath takes into account the data on cumulative pollen and chemical element curves, as well as the bulk density of peat, for dating subsamples between the ^{14}C-dated layers.

The dynamics of peat accumulation reflect the difference between the production of organic matter by photosynthesis and the decay of organic substances (Clymo 1992). The diplotelmic nature of a peat deposit indicates that intensive peat formation is occurring in the uppermost aerobic thin layer or acrotelm (Ingram 1982). When the anoxic catotelm has been reached, the microbial processes cease, and it is assumed that decay through methanogenesis may take place. As postulated by Clymo (1984), a slow anaerobic decay of peat may be reached in the steady-state when the addition of the uppermost section of the catotelm amount of peat is equalized by the total anaerobic decomposition

Proceedings of the 16th International ^{14}C Conference, edited by W. G. Mook and J. van der Plicht
RADIOCARBON, Vol. 40, No. 2, 1998, P. 833–839

of the peat in the catotelm. For this reason, only apparent peat accumulation can be measured. However, a mathematical model is required to estimate the true rate of net accumulation.

Present interest in global climatic change led to carbon-accumulation studies in peat lands, since Boreal peat lands can work as a carbon sink. In Finland, the rate of carbon accumulation was based on 325 ^{14}C dates, encompassing most of the Holocene (Tolonen *et al.* 1992). In Estonia, Ilomets (1994) calculated mean increment values for 16 different peat types on the basis of ^{14}C data from 40 mires (including 30 bogs). The main aim of this study was to find relationships between the apparent increment and the age of Estonian ombrotrophic peat and to investigate the possibilities of the extrapolation and interpolation of ^{14}C data.

Methods

In Estonia, the ^{14}C method was used for dating *ca.* 100 peat deposits. From these data, age *vs.* depth curves for 21 sequences were obtained. From these curves, the ages of basal layers of ombrotrophic peat were deduced. Because the other sequences are related either to fen deposits or the fen-bog, contact is not dated exactly. All the dates were calibrated dendrochronologically by the program Cal 15 (van der Plicht 1993), and the mean calibrated age values were used (Table 1). The apparent rate of peat accumulation was calculated for all single intervals dated by ^{14}C and also for the total ombrotrophic *Sphagnum*-peat complex (Table 1). To calculate carbon accumulation and loss, we used the bulk density value of 120 kg m^{-3}. This is typical for slowly decomposed *Sphagnum*-dominated peat types (Ilomets 1994). The average carbon content in dry organic matter was taken as 50%.

TABLE 1. Characteristics of the Ombrotrophic Peat Deposits Studied

No.	Ombrotrophic mire	Ombrotrophic peat thickness (cm)	Calibrated age of basal layer of peat (cal BP)	Mean increment (mm yr^{-1})
1	Kõivasoo	105	5000	0.2
2	Vaharu	260	2500	1.0
3	Teosaare	110	1600	0.7
4	Orgita	220	1350	1.6
5	Laukasoo 1	300	6000	0.5
6	Laukasoo 2	320	5700	0.6
7	Ruunasoo 1	297	2050	1.4
8	Ruunasoo 2	400	4600	0.9
9	Nigula 51	270	1400	1.9
10	Nigula 19	345	2200	1.6
11	Nigula 22	440	5800	0.8
12	Nigula 46	273	1800	1.5
13	NigulaI	470	4500	1.0
14	NigulaII	600	7400	0.8
15	Liivjärve	450	6000	0.75
16	Mõksi	455	4800	0.9
17	Männikjärve 2	490	3900	1.2
18	Karuniidu	520	4900	1.1
19	Vällamäe 1	1200	6400	1.9
20	Vällamäe 3	782	5700	1.4
21	Niinsaare	370	4080	0.9

RESULTS

The apparent increment values for short-term periods calculated for the layers between the single ^{14}C dated horizons vary markedly in all the ombrotrophic peat sequences studied. For the ombrotrophic peat sequence in the Männikjärve section, we have eight ^{14}C dates spaced over 400–600 yr. The apparent increment for single time intervals varies from 0.7 to 2.8 mm yr^{-1}. During longer periods (the total ombrotrophic peat complex), fluctuations are smoothed out, and the mean increments decrease with increasing age of basal peat layers (see Fig. 1).

The correlation between the total age of formation of the ombrotrophic peat and its apparent increment is relatively high. Also, there are data clearly inconsistent with the general trends. The increment in sections Teosaare and Kõivasoo is lower, and in sections Vällamäe 1 and Vällamäe 3, the values are significantly higher than the statistical mean values for those ages of peat (Fig. 1). There may be different reasons for these deviations. For example, the genesis of Vällamäe mire in the small glaciokarstic kettle hole differs principally from the genesis of the other raised bogs studied, and the mires Kõivasoo and Teosaare are drained. The general regularity shows that the best correspondence between the apparent increment and the age of Sphagnum peat is for sections with thickness of peat from *ca.* 250–600 cm (Table 1).

For the correlation between the apparent increment (v, mm a^{-1}) and age of basal peat (cal BP) we calculated a straight line. After removing the four outliers (nos. 1, 3, 19 and 20 from Table 1), the data are described by a straight line with a correlation factor $R^2 = 0.80$ (Fig. 1). Using these values, it is also possible to calculate the mean apparent increment values for millennia time scales (Table 2). This shows a clear increase of mean apparent increment in the course of the time periods during which the ombrotrophic peat deposits were formed.

TABLE 2. Values of Long-Term Apparent Increment Rate (v)

^{14}C age (yr BP)	Increment: Range (mm yr^{-1})	Increment: Mean value (mm yr^{-1})
1000–3000	1.0–1.9	1.5
3000–5000	0.8–1.2	1.0
5000–7000	0.2–0.8	0.5

DISCUSSION

There may be several reasons why the apparent increment rate is increasing in time. As a hypothesis, the most reliable may be:

1. There is an overall increase in the peat accumulation rate of acrotelm since 6000 BP.
2. There is an overall decrease in the peat decomposition rate of acrotelm since 6000 BP.
3. The continuous decay of organic matter in the catotelm resulted in the autocompression of the matter, which is reflected in the apparent increment increase.
4. The increase of the apparent mean increment is caused, for instance, by changes in the degree of humification, losses of organic matter by fires, or successional peculiarities of plant communities in the acrotelm.

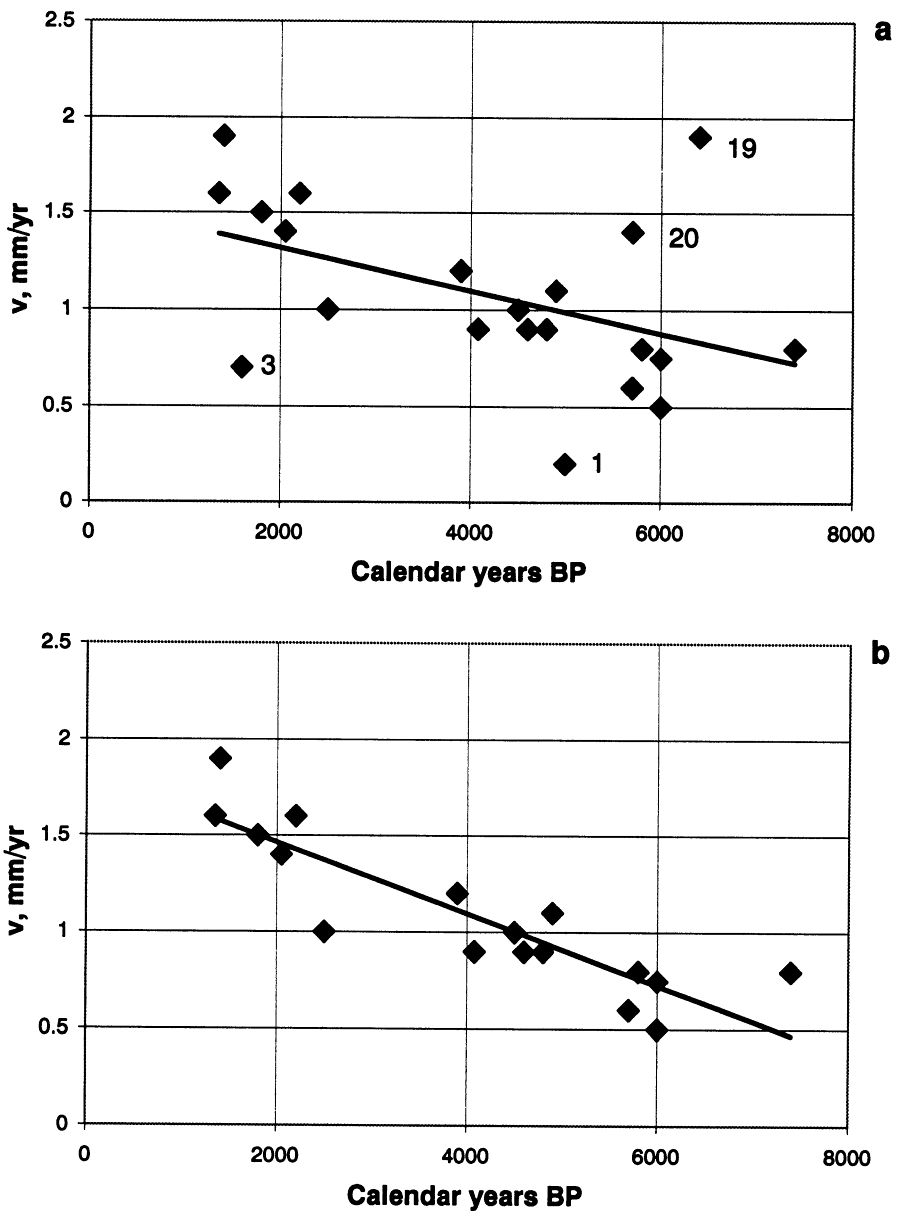

Fig. 1. Apparent increment values for the total ombrotrophic peat complex as a function of the age of their basal layers. a: all data from Table 1; b: selected data, with inconsistencies removed (corresponding to numbers in Table 1).

Hypotheses 1 and 2 require a change in the environmental conditions. Though significant trends existed in the climatic conditions throughout the Holocene, it is rather difficult to understand processes that could lead to one-directional changes in the accumulation of peat in such a comparatively well-autocompensated ecosystem as mires.

It is well known that the increment rate depends strongly on regional and local hydrothermic conditions. This is why the values of increment vary significantly. We must note that no common views exist on the decay mechanism of organic matter in peat sequences. The results for European raised bogs, obtained by Aaby and Tauber (1975), yield values from 1.8 to 0.2 mm yr^{-1} and show that the apparent increment is gradually increasing from the Atlantic to the Subatlantic. Tolonen *et al.* (1992) have calculated mean long-term increment values of 0.2–1.2 mm yr^{-1} for 21 mires in Finland. For mires in Maine (USA, 5 mires), values range from 0.7 to 0.4 mm yr^{-1}.

Detailed studies have been carried out by Ilomets (1994) in Estonia. He found that the increment values for ombrotrophic peat range from 0.4 to 2.7 mm yr^{-1}, being highest for *Eriophorum-Sphagnum* (0.8–2.7) and lowest for *Eriophorum* (0.4–1.4) peat. Furthermore, he calculated the relation between the peat increment and its degree of decomposition, and found that an increase in the degree of decomposition from 5% to 30% will, in general, decrease the apparent increment rate by a factor of 2 (Ilomets 1994).

The continuous decay of organic matter all over the sequence seems to explain the data shown in Figure 1. An analysis of these data shows that the decay was relatively constant and caused an increase of *ca.* 0.1–0.2 mm yr^{-1} in the apparent increment rate for the time interval from 6000 to 1000 yr cal BP (Table 2). At the mean density value of 120 kg m^{-3}, it is equivalent to the decay rate of 0.0036 g cm^2 yr^{-1}, which is *ca.* seven times lower than the decay rate for the Point Escuminac peatland (New Brunswick, UK) (Clymo 1992).

Using the obtained mean values of the apparent increment, it is also possible to calculate the long-term rate of carbon accumulation. For the time interval 1000 BP to the present, it is *ca.* 100 g m^2yr^{-1} and for 5000–4000 BP, *ca.* 60 g m^2yr^{-1}. The mean values for 21 Estonian ombrotrophic mires are, in general, a factor of 2 higher than Tolonen and his colleagues have calculated for ombrotrophic mires in Finland (Tolonen *et al.* 1992). Presuming that the decrease of the apparent increment is caused fully by the decay of organic matter in the catotelm, it is possible to find the yearly carbon loss. Calculations show that the decay rate, which has been relatively constant within the last 6000 yr, has a value of 12 g C m^2yr^{-1}. This value corresponds well with annual fluxes of carbon in methane from boreal wetlands (Crill *et al.* 1992). We note here that our calculations are based on the mean density and carbon content values. Nevertheless, the good correspondence supports the hypothesis that the increase in apparent increment values is caused by the decrease of the length of the period during in which the decay of organic matter took place.

The rate of peat accumulation dynamics may be closely related to peculiarities in the development of a bog, reflected in the sequential pattern of peat layers and their degree of decomposition. Tolonen *et al.* (1985) showed that a logarithmic relationship exists between the degree of decomposition (in von Post's 10-grade scale) and the linear vertical increment. The data given by Aaby (1986) showed that in the studied Danish ombrotrophic peat section, a clear relationship between growth rate and degree of humification is absent. Unfortunately, the data on the bulk density values and values of decomposition degrees for the sequences studied by us are not available. In all sequences used for calculations, the dominating type of peat was *Sphagnum*.

Fires, as indicated by deposits and charred micro- and macroparticles, also had an influence on the changes in the apparent increment. Therefore, it is very important to perform a high-resolution study of the lithology and the botany as well as the peat sequences.

A non-constant peat accumulation must be apparent in the distribution of atmospherically transported matter in the peat sequence. When a hiatus exists in the sequence, caused either by a break in peat accumulation or by the intensive decay of accumulated organic matter, then the concentration of pollen grains or mineral matter in these layers must be higher than in continuously accumulated layers. Though this problem has been studied by many researchers (Hicks 1975; Donner *et al.* 1978; Middeldorp 1982), reliable data about breaks in peat accumulation are still absent. The problem is complicated because many factors influence the influx. For example, the formation of pollen spectra is influenced by factors such as the size of the bog studied and its changes over time, the profile distance from the forest border, and chemical elements taken up by the recovered vegetation, which smooths concentration variations, *etc.*

Our studies in the Niinsaare bog (Punning *et al.* 1993) showed that in the lower level of peat, which was formed *ca.* 4000 BP, a high concentration of pollen grains is typical. This is characterized by a sharp rise of the cumulative curve of pollen grains. In the middle of the peat sequence, it is stable until 1000 BP, when it slows down. Similar increments in pollen-grain concentration in the lower level of peat profiles have been observed in Holland, in the Engbertsdijksveen peat profile (Middeldorp 1982). These examples support the results shown in Table 2: a continuous increase of the apparent increment. The pollen concentration diagram in the Liivjärve section (Koff 1994) shows an analogous situation. In this case, however, the changes are caused by the development of the bog. Here, by uniting, small patches of fen formed a large bog, and the forest border moved off the given profile, thereby decreasing the local pollen influx.

To succeed in a particular study, it is crucial to determine a suitable time period within which changes can be observed. Fires, which may affect the mean increment on the decade scale, become unimportant if the focus is on the age scale of several thousand years. Our fourth hypothesis applies to the changes within a shorter time scale. However, here again the data of pollen analysis do not confirm significant influence of fires on the changes of peat increment. For instance, in the Niinsaare profile, the two burnt layers were found at depths of 21 and 157 cm. Since pollen grains are rather resistant to fire (Veski 1996), the pollen-grain concentration in the upper peat layer would have increased, since the burning is most intense here. The pollen diagram, however, does not show this.

Conclusion

The ^{14}C data of 21 Estonian ombrotrophic mires demonstrate that there is a continuous increase in the apparent accumulation of peat, depending on the age of its formation. Though it is not possible to find the precise values for changes in the increment, this phenomenon is significant for estimating a detailed time scale for the ombrotrophic peat sequence. In the extrapolation or interpolation of ^{14}C data over the long term (hundreds of years), the calculated increment values (Table 2) could be used. Establishing a high-resolution time scale (tens of years) is more complicated, because of occasional events (*e.g.*, fires, droughts) and the change of extralocal conditions. To increase the reliability of the time scale, it is necessary to perform a comprehensive study of the peat sequence and analyze the atmospheric influx (*e.g.*, pollen, chemical element, mineral matter). In addition, the ^{14}C wiggle-matching technique can be applied.

References

Aaby, B. 1986 Palaeoecological study of mires. *In* Berglund, B. E., ed., ***Handbook of Holocene Palaeoecology and Palaeohydrology.*** New York, John Wiley & Sons: 145–164.

Aaby, B. and Tauber, H. 1975 Rates of peat formations in relation to degree of humification and local environment, as shown by studies of a raised bog in Denmark. *Boreas* 4: 1–17.

Clymo, R. S. 1983 Peat: Ecosystems of the world. *In* Gore, A., ed., ***Mires: Swamp, Bog, Fen and Moor.*** Ecosystems of the World 4. New York, Elsevier: 159–224.

____1984 The limits to peat bog growth. *Philosophical Transactions of the Royal Society, London* B303: 605–654.

____1992 Models of peat growth. *Suo* 43(4–5): 127–136.

Crill, P., Barlett, K. and Roulet, N. 1992 Methane flux from boreal peatlands. *Suo* 43: 173–182.

Donner, J., Alhonen, P., Eronen, M., Jungner, H. and Vuorela, I. 1978 Biostratigraphy and radiocarbon dating of the Holocene lake sediments of Työtjärvi and the peats in the adjoining bog Varrassuo west of Lahti in southern Finland. *Annales Botanici Fennici* 15: 258–280.

Granlund, E. 1932 De svenska högmossarnas geologi. *Sveriges Geologiska Undersökning* C373, Arsbok 26: 1–193 (in Swedish).

Hicks, S. 1975 Variations in pollen frequency in a bog at Kangerjoki, N.E. Finland during the Flandrian. *Commentationes Biologica* 80: 1–28.

Ilomets, M. 1980 The determination of the age of peat layers based on the peat bulk density method. *Proceedings of the Academy of Sciences of the ESSR, Geology* 29: 121–127 (in Russian, summary in English).

____1994 On the growth of peats in Estonia. Yearbook of the Estonian Geographical Society. Estonian Academy Publishers 13–17 (in Estonian, summary in English).

Ingram, H. A. P. 1982 Size and shape in raised mire ecosystems: A geophysical model. *Nature* 297: 300–303.

Kilian, M. R., van der Plicht, J. and van Geel, B. 1995 Dating raised bogs: New aspects of AMS ^{14}C wiggle matching, a reservoir effect and climatic change. *Quaternary Science Reviews* 14: 959–966.

Koff, T. 1994 The development of vegetation. *In* Punning, J. M., ed., *The Influence of Natural and Anthropogenic Factors on the Development of Landscapes. The Results of a Comprehensive Study in NE Estonia*. Institute of Ecology, publication 2/1994, Tallinn: 24–57.

Menke, B. 1987 Geobotanische und geochemische Untersuchungen an einem Torfprofil zur Frage natürlicher und anthropogener Elementverfrachtungen. *Geologisches Jahrbuch* A95: 3–102.

Middeldorp, A. 1982 *Functional Paleoecology of Raised Bogs – An Analysis by Means of Pollen Density Dating in Connection with the Regional Forest History.* Amsterdam: 124 p.

Punning, J.-M., Ilomets, M. and Koff, T. 1993 Possibilities for detailed dating of peat bog deposits. *Radiocarbon* 35(3): 379–385.

Tolonen, K., Huttunen, P. and Jungner, H. 1985 Regeneration of two coastal raised bogs in eastern North America. *Annales Academiae Scientarum Fennicae A* III 139: 1–51.

Tolonen, K., Vasander, H., Damman, A. W. H. and Clymo, R. S. 1992 Preliminary estimate of long-term carbon accumulation and loss in 25 Boreal peatland. *Suo* 43(4–5): 277–280.

van der Plicht, J. 1993 The Groningen radiocarbon calibration program. *In* Stuiver, M., Long, A. and Kra, R. S., eds., Calibration 1993. *Radiocarbon* 35(1): 231–237.

Veski, S. 1996 History of vegetation and human impact in northern Saaremaa, Estonia based on the biostratigraphy of the Surusoo mire: Preliminary results. *In* Hackens, T. *et al.*, eds., *Coastal Estonia: Recent advances in environmental and cultural history.* PACT 51. Strasbourg, Conseil de l'Europe: 57–66.

Weber, C. A. 1910 Was lehrt der Aufbau der Moore Norddeutschlands über den Wechsel des Klimas in postglazialer Zeit? *Zeitschrift der Deutschen geologischen Gesellschaft* 62: 2–5.