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CORRECTING ^{14}C HISTOGRAMS FOR THE NON-LINEARITY OF THE RADIOCARBON TIME SCALE

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ABSTRACT. Large numbers of ^{14}C dates of the base and top of Holocene peat layers may be plotted in ^{14}C histograms in order to establish statistically a chronology of periods of essentially clastic sedimentation and peat formation. Due to the non-linearity of the ^{14}C time scale in terms of calendar years, clustering of ^{14}C dates on random peat growth may occur. This seriously hampers the interpretation of histograms. A quantitative method and computer program were developed to correct the histograms for this effect. The correction factor that has to be applied depends on the calibration curve and the interval width of the correction parameter dy. For peat samples, an interval width of 100 ^{14}C yr and a calibration curve based on a 100-yr moving average seems to be a reasonable choice.

INTRODUCTION

In the Holocene coastal lowland of The Netherlands, clastic marine sediments alternate with peat. The observed alternation is generally attributed to an alternation of transgressions (periods in which the sea invaded the land) and regressions that occurred presumably more-or-less synchronously along the coasts of northern Germany, The Netherlands, Belgium and northern France (Bakker, 1954; Bennema, 1954; Jelgersma, 1961; Brand *et al,* 1965; Geyh, 1966; Hageman, 1969; Roeleveld, 1974; Griede, 1978).

Large numbers of ^{14}C dates of the base and top of peat layers in these coastal lowlands have been used to establish statistically a chronology of alternating periods of essentially clastic sedimentation and peat formation, which is in geological terms explained by an alternation of (marine) transgressions and regressions. However, no single stretch of coast is likely to have documented and preserved a complete record of Holocene transgressions and regressions. Non-concordance of chrono-stratigraphic and lithostratigraphic levels in the Holocene sedimentary sequence renders it difficult to determine, even if large numbers of borehole data are available, whether geological events like transgressions occurred synchronously over large areas. With many ^{14}C determinations available, the danger lies in the selection of dates that accord with preconceptions of Holocene geologic evolution. To overcome these problems, ^{14}C histograms (Fig 1) have been constructed by many authors (eg, Geyh, 1966; Roeleveld, 1974; Griede, 1978; Mulder & Bosch, 1982; Berendsen, 1982; Zagwijn, 1983; Berendsen, 1984; van de Plassche, 1985). The validity of this approach was accepted as early as 1955 in a discussion at the Royal Statistical Society.

However, the non-linearity of the ^{14}C time scale, in terms of calendar years, may result in clustering of ^{14}C dates on random peat growth (Fig 2). This seriously hampers the interpretation of histograms, because ^{14}C histograms may show maxima or minima that are not at all related to geologic events (de Jong & Mook, 1981). On the other hand, the danger exists that maxima and minima may be erroneously attributed only to the non-linearity of the ^{14}C time scale. Until now, there was no universal method to correct the histograms quantitatively.

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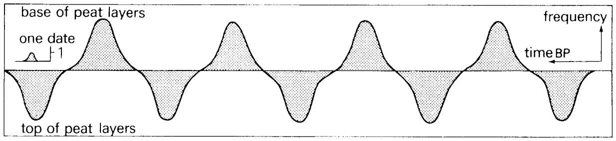

Fig 1. Idealized ^{14}C histogram of a coastal lowland, with a clear alternation of transgressions and regressions. Dates of the top of peat layers are plotted under the horizontal time axis, dates of the base of peat layers above it. Standard Gaussian curve indicates frequency 1.

We now present a method to correct ^{14}C histograms quantitatively for the non-linearity of the ^{14}C time scale. In a second paper attention will be focused on the interpretation of corrected ^{14}C histograms and on how transgressions and regressions may be defined.

CONSTRUCTION OF ^{14}C HISTOGRAMS

A ^{14}C histogram is obtained by graphic superposition of individual ^{14}C dates. Each date is represented by a Gaussian distribution of equal area (in some earlier publications rectangles or polynomes were used instead of Gaussian distributions, eg, Roeleveld, 1974; Shennan, 1979). The width of each Gaussian curve depends upon the standard deviation of the ^{14}C date. A date with a large standard deviation is represented by a Gaussian distribution with a low height, and thus contributes less to the histogram peaks. A date with a standard deviation of ± 45 yr has been chosen to represent frequency 1. All dates are expressed in conventional ^{14}C yr BP.

Roeleveld (1974, p 21) has shown that dates taken from the base and the top of peat layers should be represented in separate histograms. Thus, dates from the top of peat layers are often plotted under the horizontal time axis; dates from the base of peat layers, above it. Peaks in the "base of peat" histogram then represent maxima in the occurrence of the beginning of peat formation. Likewise, peaks in the "top of peat" histogram represent maxima in the ending of peat formation. Thus, in an ideally simple situation

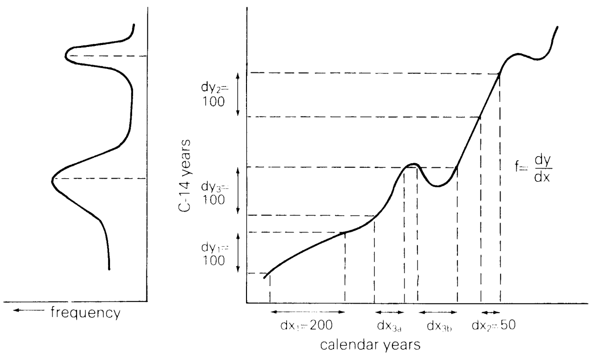

Fig 2. The influence of the ^{14}C calibration curve on histograms and the principle of the correction method

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in which transgressions and regressions of equal time span alternate, the histogram could be expected to take the form shown schematically in Figure 1.

GENERAL PROBLEMS OF ^{14}C HISTOGRAMS

In interpreting and comparing histograms, care should be taken that all periods and areas are equally well represented by ^{14}C dates. Over- or under-representation may occur because certain areas or peat layers are less accessible or because researchers deliberately focus interest on certain areas and/or periods (Geyh, 1980). A similar problem arises from the non-linearity of the ^{14}C time scale.

Because the atmospheric ^{14}C content has not been constant in the past, ^{14}C ages expressed in years on the basis of a half-life of ^{14}C of 5568 yr, are different from astronomical ages (solar or calendar years). By carrying out ^{14}C measurements on dendrochronologically dated wood, various calibration curves have been created (Suess, 1970; Damon, Long & Wallick, 1972; Ralph, Michael & Han, 1973; Klein *et al*, 1982). At the 12th International Radiocarbon Conference in 1985, the more accurate curves constructed by Stuiver and Pearson (1986) and Pearson and Stuiver (1986), that span AD 1950–2500 BC, were accepted as an international standard of reference. In the same calibration issue, Pearson *et al* (1986) extended the limit to 5210 BC.

Clustering of ^{14}C dates on random peat growth may occur in ^{14}C histograms due to non-linearity of the ^{14}C time scale in calendar years (Fig 2). This effect has not yet been evaluated quantitatively (de Jong & Mook, 1981), and thus it is often underestimated (eg, Berendsen, 1982; Berendsen, 1984). Only Geyh (1971, 1980) attempted correction for part of the ^{14}C time scale.

CORRECTION OF ^{14}C HISTOGRAMS

In principle, there are two possibilities for correcting histograms for the non-linearity of the ^{14}C time scale: 1) calibrating the dates first, and successively plotting them in a histogram; 2) plotting the dates in a histogram and correcting the histogram. Although both methods should give similar results, we have chosen method 2 for several reasons. Calibrated ^{14}C dates cannot simply be described as a Gaussian curve (Renfrew & Clark, 1974; Warner, 1975; van der Plicht & Mook, 1989); this makes the plotting procedure of method 1 mathematically more complicated. Geologists are used to the ^{14}C time scale. With method 2, the ^{14}C time scale is maintained which enables direct comparison with histograms in the literature. Another advantage of method 2 is that, together with the corrected histogram, an uncorrected version is available for comparison. Also, if necessary, correction based on other calibration curves is possible.

Figure 2 shows the principle of correcting a histogram, eg, 100 ^{14}C yr at dy_1 equal 200 calendar yr. This means that peat formed in a time span of 200 yr will be represented by dates that fall within a time span of 100 ^{14}C yr, *ie,* clustering occurs. The frequency in the ^{14}C histogram will be twice as high as in a histogram based on calendar years. In the case of dy_3 the equivalent time span on the calendar (solar) time axis is: $dx_3 = dx_{3a} + dx_{3b}$ (Fig 2).

To correct the histogram, the frequency at all points should be multiplied by a factor f = dy/dx (dy = number of years on the ^{14}C time scale, dx = number of years on the calendar time scale). The factor, f, depends on the calibration curve and the interval width, dy. For both, a choice has to be made.

Mook, de Jong and Geertsema (1979) and Mook (1983) have shown that a calibration curve should be used that is in accordance with sample time width. ^{14}C dates of peat samples represent a weighted average of plant materials grown over a range of time. This time range is difficult to quantify, but is likely to be greater than the ± figure on the ^{14}C date. According to Berendsen (1984), peat samples in the Netherlands coastal lowland generally cover 50–200 yr. Thus, the use of a smoothed calibration curve is necessary. Based on the data of Stuiver and Pearson (1986), Pearson and Stuiver (1986) and Pearson *et al* (1986), a calibration curve based on a 100-yr moving average was constructed, by spline-smoothing with $\sigma = 40$ yr for the period 120–6150 BP (Fig 3). For every calendar year, the equivalent number of ^{14}C yr is calculated. From this, a data set has been selected with, for every fifth ^{14}C year, the equivalent number of calendar years. This data set has been used to calculate the correction factors.

If the interval, dy, is very small, f will closely follow the slope of the calibration curve at any point. Such detail in correcting a histogram made up of peat samples is unnecessary, and even meaningless. If dy is too large, irregularities in the calibration curve will be smoothed too much. Figure 4 shows the correction factor for dy = 50, dy = 100, dy = 150 and dy = 200 ^{14}C yr. An interval of 100 yr seems a reasonable choice for peat samples. Geyh (1980) proposed an interval width, $dy = 2\sigma$, which leads to comparable results.

The variation of the correction factor with time is shown in Figure 5. Periods in which a correction of >25% has to be applied to the original histogram are indicated on the time axis. In these periods, the non-linearity of the ^{14}C time scale will result in major virtual maxima and minima.

The computer program, KORHIS, is written in BASIC and has been designed for use on an IBM or compatible personal computer. It is available on diskette, together with instructions for use. The program uses laboratory number, age and standard deviation as input. The output is a data file with values for ^{14}C yr BP (x) and frequency (y), that can be plotted into a histogram. The histogram can be corrected for the non-linearity of the ^{14}C time scale by multiplying all y values with the correction factor, f. At present, only a data file with correction factors based on dy = 100 yr is available on floppy disk. The file contains a correction factor for every fifth ^{14}C year from 300–6100 BP. The corrected data are also stored as a data file and can be plotted as a histogram. An example is given in Figure 6, which shows both the original and the corrected histograms of 117 dates of the base of peat layers in the western part of The Netherlands.

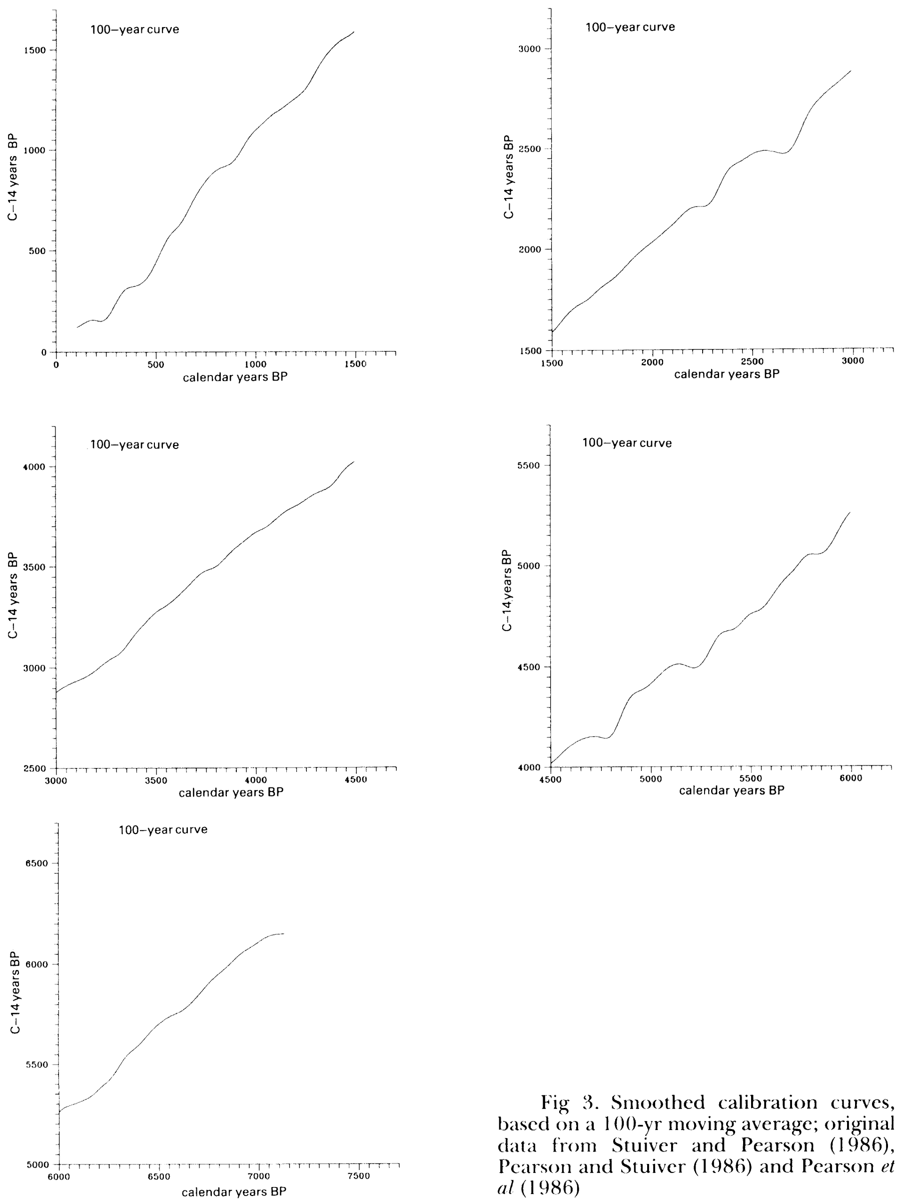

Fig 3. Smoothed calibration curves, based on a 100-yr moving average; original data from Stuiver and Pearson (1986), Pearson and Stuiver (1986) and Pearson *et al* (1986)

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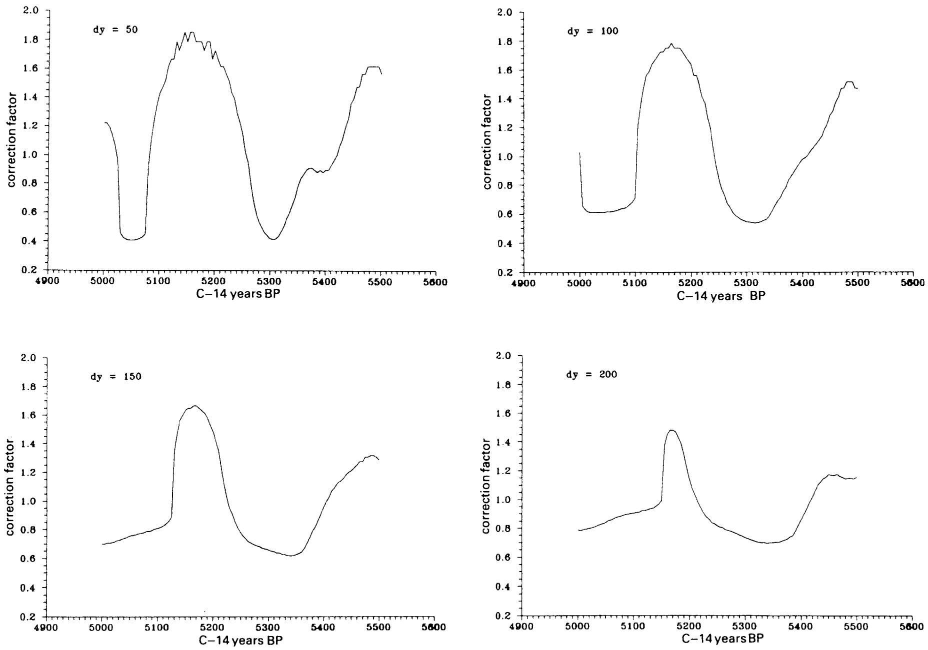

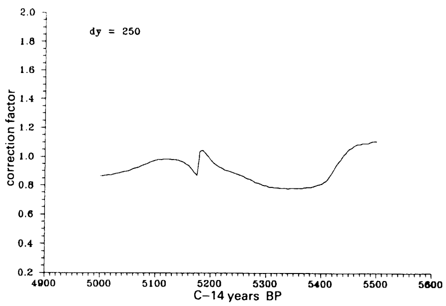

Fig 4. Correction factors for various choices of the interval width dy

NUMBER OF DATES REQUIRED

Many dates should be scattered over a large area to obtain reliable results. Not only the number of dates is important, but especially the "density" (no. dates/1000 yr). In a computer simulation, Shennan (1979) showed that histograms with >100 dates/1000 yr are reliable. Histograms with <40 dates/1000 yr must be considered unreliable.

According to Geyh (1980), the standard deviation should be considered in relation to the density. Per class (each class = twice the average standard deviation) there should be >25 dates in order to get reliable results. For a class of 100 yr, it follows:

reliable:	>250	dates/1000 yr
possibly useful:	40–250	dates/1000 yr
unreliable:	<40	dates/1000 yr

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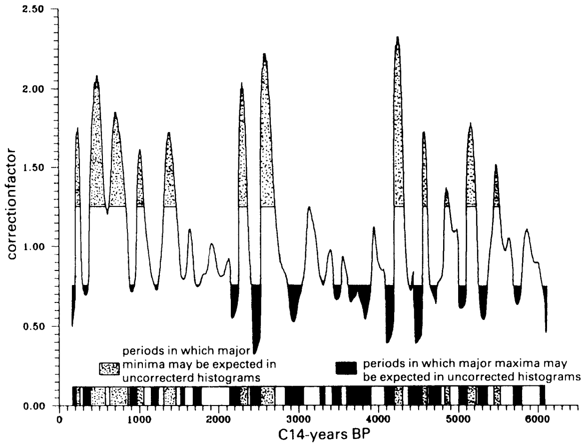

Fig 5. Variation of the correction factor with time, based on dy = 100 yr. Periods in which histograms have to be corrected by >25% are indicated on the ^{14}C time scale.

A ^{14}C histogram usually will not have the same reliability at all points. The KORHIS computer program gives not only the total number of dates used, but also the number of dates per millennium. An evaluation of histograms published so far shows that most histograms have to be classified as unreliable, or at best, possibly useful for only certain parts of the time scale (Stolk *et al*, ms). However, ^{14}C dates that lack statistical significance in histograms may well have geological significance. The geological evaluation of the data used in histograms therefore remains of primary importance.

CONCLUSIONS

^{14}C histograms are used for the statistical treatment of large numbers of ^{14}C dates, in order to establish a chronology of periods of essentially clastic sedimentation and peat formation. Histograms must be corrected for

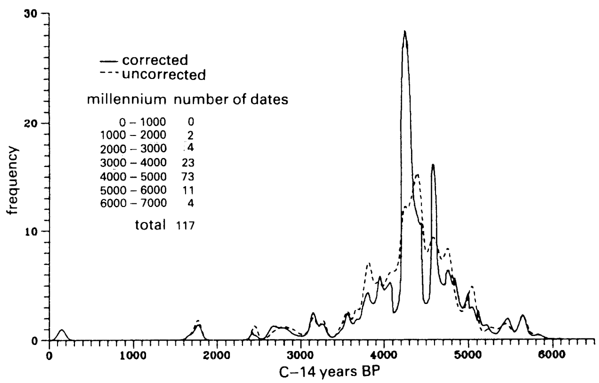

Fig 6. Corrected and uncorrected ^{14}C histograms of 117 dates of the base of peat layers in the western Netherlands

the non-linearity of the ^{14}C time scale; the KORHIS computer program offers a quantitative correction method. The correction factor used depends on the calibration curve and the interval width of the correction parameter. For correcting histograms, a smoothed version of the curves of Stuiver and Pearson (1986), Pearson and Stuiver (1986) and Pearson *et al* (1986) based on a 100-yr moving average, is used. For peat samples, an interval width of 100 yr is appropriate. In order to get reliable results, >100 dates/1000 yr seem to be necessary.

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