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SHORT ARTICLE

Radiocarbon and dendrochronology

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Abstract

The radiocarbon dating method relies on calibration through an independent dating method. Dendrochronology is an ideal partner of radiocarbon, because tree-rings are close-to-perfect archives of the atmospheric ^{14}C level, and the tree-ring time scale can be built beyond doubt with high replication. Over the past 30 years, several stages of ^{14}C calibration data sets have been constructed from the work of tree-ring laboratories in Europe and North America. This process is outlined and the present state is documented. In turn, ^{14}C age fluctuations, caused mainly by helio-magnetic changes, can be used to anchor floating tree-ring sections to the calendar scale with a precision of a few decades.

Keywords: Radiocarbon calibration; Solar activity; ^{14}C wiggle-matching

Introduction

Dendrochronology and radiocarbon (^{14}C) are powerful dating methods in prehistory and geosciences. In several aspects these two 'clocks' appear complementary. Dendrochronology provides dates of annual accuracy on a regional scale, constrained by the common range of climate signals and the species- and altitude-specific response. On the other hand radiocarbon can be applied globally (due to the fast mixing of CO_2 in the atmosphere), but requires calibration by an independent dating tool, because the ^{14}C production and the distribution among carbon reservoirs varied in the past, leading to fluctuations in the atmospheric ^{14}C level. Tree-rings are the preferred source for radiocarbon calibration, because tree-ring cellulose is a direct sample of the atmospheric ^{14}C level in the year of growth, preserving the information reliably over millennia-long intervals of deposition, e.g. in high-altitude stands, alluvial sediments or peat bogs. Thus, in the history of radiocarbon and dendrochronology we find many examples of beneficial collaborations between those distant fields of botany and nuclear physics, often exemplified in unlikely pairs of authors, and the advances in either field are reflected in reviews of the key protagonists, e.g. Becker (1992) and Suess (1992).

The pioneering work of Hans Suess, de Vries and Wes Ferguson demonstrated the reality of substantial variations of the ^{14}C level in the past, but detailed studies were made possible only when European oak chronologies were developed, providing virtually an unlimited amount of samples for high-precision ^{14}C analyses and inter-laboratory comparison. Thus in the first part of this review we will focus on the contribution of the European tree-ring community to ^{14}C calibration in a time interval that parallels the publishing history of the journal 'Dendrochronologia'.

Beyond ^{14}C calibration (and related dating aspects) tree-ring-based ^{14}C is a unique proxy of solar activity fluctuations, which may be related to natural climate variability. This aspect provides links between a fundamental part of tree-ring research, i.e. dendro-climatology, solar physics and paleo-climate studies, which we will review in the second part.

In the final section we will demonstrate how ^{14}C fluctuations in the past ('wiggles') can be used to anchor

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floating tree-ring sections within a few decades to an absolute date.

Tree-ring-based ^{14}C calibration

As outlined above, tree-ring chronologies provide an ideal source of carbon for ^{14}C calibration. The initial insight into the varying atmospheric ^{14}C level in the past came through ^{14}C analyses of bristlecone pines (Suess, 1970) but a far wider basis was created when European oak chronologies (Irish oak and German oak) were made available to ^{14}C laboratories for high-precision analyses, starting in the late 1970s, and published first as calibration data set back to 2500 BC in 1986 (Pearson and Stuiver, 1986; Stuiver and Becker, 1986). The next step was an extension of this data set back to 6000 BC (Stuiver and Becker, 1993; Stuiver and Pearson, 1993). Back to 5500 BC Irish oak and German oak provided independent samples for ^{14}C analyses in several radiocarbon laboratories (Seattle, Belfast, Groningen, Pretoria, Heidelberg). For the older part, all samples submitted for calibration rest on the Hohenheim chronologies.

The Hohenheim tree-ring laboratory and the Heidelberg radiocarbon laboratory collaborated closely in fieldwork at the rivers Main, Rhine and Danube. Assisted by ^{14}C pre-dating of sections, the German oak chronology was finally extended back to the times when oak re-immigrated into Central Europe at the start of the Boreal chronozone (Becker, 1992; Kromer and Becker, 1993). The oldest oak in the Hohenheim collection starts at 10429 BP (8480 BC).

Together with oak, in the alluvial deposits of the rivers Danube and Rhine pines were found, pre-dating the oak, and covering the Late Glacial and the Preboreal chronozone. The linkage of the Preboreal pines to the oak master proved difficult, and initially ^{14}C wiggle-matching was used (Kromer and Spurk, 1998; Spurk et al., 1998). On this basis for the first time a tree-ring-based ^{14}C calibration data set IntCal98 covering the full Holocene was created (Stuiver et al., 1998). Additional finds then allowed a dendro-synchronization of pine and oak (just 8 years different from the ^{14}C match) (Friedrich et al., 2004) and resulted in an update of the ^{14}C calibration, IntCal04 (Reimer et al., 2004), which dates back to 12410 cal BP. The first centuries of the chronology were built from pines found in Zurich, Switzerland (Kaiser, 1993) and Cottbus, Eastern Germany. Fig. 1 shows the present state of the tree-ring-based calibration studies, both for the tree-ring chronologies involved and for the ^{14}C laboratories.

For the Late Glacial, two independently built pine chronologies exist. In the Hohenheim tree-ring laboratory a 1116 ring chronology from the Danube river and from the lignite area of Eastern Germany was built, and

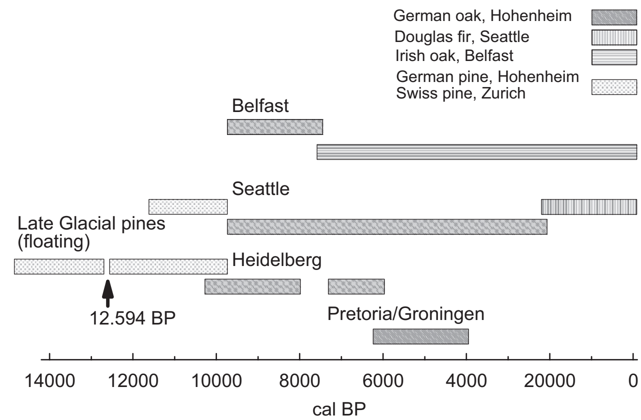

Fig. 1. Tree-ring-based ^{14}C data series obtained from three tree-ring chronologies. The names of the ^{14}C labs are given above the bars. The species and the tree-ring laboratories are shown in the legend.

from the Zurich area the Dättnau series of Kaiser (1993) were extended by important finds from the Uetliberg construction site (Schaub et al., 2005) into a 1605 ring Late Glacial Swiss chronology. Recently the two chronologies from Zurich and Hohenheim could be synchronized dendrochronologically into a combined chronology, which is still floating. ^{14}C dates place the main part of the chronology in the Bølling and Allerød interval, but the youngest sections extend into the Younger Dryas (Kromer et al., 2004). At present ^{14}C calibration in this interval rests on marine data sets, but it is already evident that the terrestrial ^{14}C data obtained from the Late Glacial pines are crucial to resolve discrepancies noted, e.g. for the onset of the Younger Dryas (Muscheler et al., 2008).

For even earlier times pine and larch sections exist from Northern Italy, Avigliana (211 rings), Carmagnola (254 rings) in the Turin area, dating back to 12600 ^{14}C BP, ca. 14400 cal BP, and from Revine (471 rings) with ^{14}C ages around 15000 ^{14}C BP, ca. 17500 cal BP (Casadoro et al., 1976; Corona, 1984; Kromer et al., 1998).

Solar variability

Solar variability, e.g. evident in varying numbers of sunspots, leads to a modulation of the magnetic shielding of the earth against cosmic rays, and hence to changes in the production of cosmogenic isotopes, such as ^{14}C and ^{10}Be. Here absolutely dated tree-ring chronologies are ideal archives to reconstruct solar activity, because the time scale is annual and accurate to one year, and high-precision ^{14}C analyses are possible. The first studies were made on the calibration data of the bristlecone chronology (Sonnet and Suess, 1984), but the full spectrum of solar variability again became

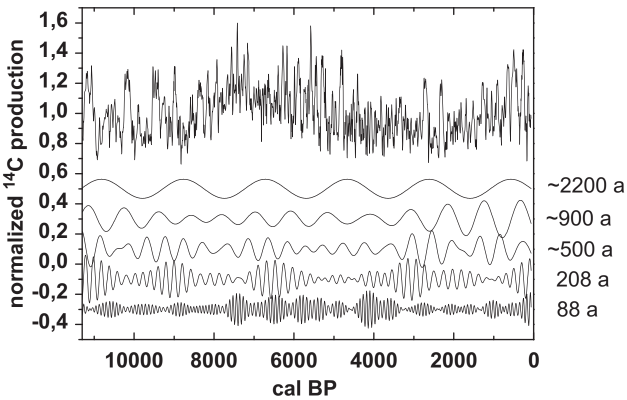

Fig. 2. Spectral features of ^{14}C production, obtained from tree-ring chronologies, using a carbon cycle model (Born, 1994). The production is bandpass-filtered with a center wavelength (in years) given at the right-hand side.

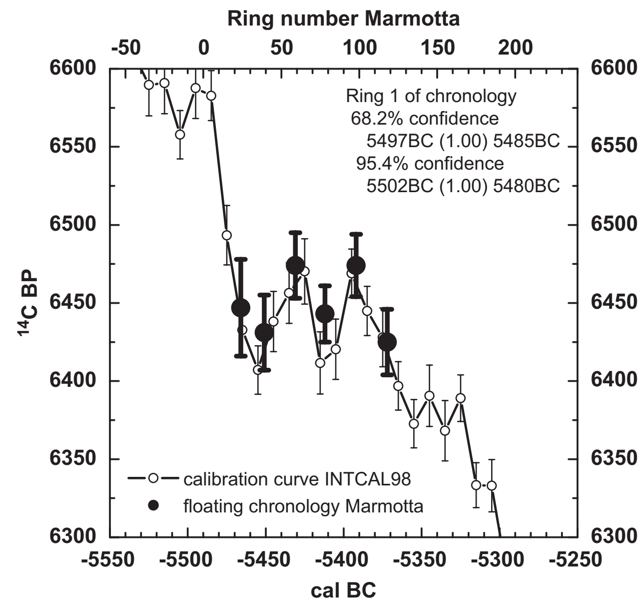

Fig. 3. ^{14}C wiggle-matching of the floating oak chronology Marmotta. The calibrated position of the first ring of the sequence is given in the inset text.

apparent only with the European series. A detailed study was published by Stuiver et al. (1991) and Stuiver and Braziunas (1993), who also showed the 11-year solar cycle in ^{14}C data of single-year samples over the past 500 years. A recent review of solar variability and cosmogenic isotopes was published by Usoskin (2008).

Solar variability has elements of (non-stationary) cycles, which is evident from a band-filtered series of ^{14}C production, shown in Fig. 2. The 88-year Gleisberg cycle is known from the record of sunspots; the longer cycles can be determined only by cosmogenic isotopes.

Precise calendar ages of floating tree-ring chronologies

Generally the atmospheric ^{14}C fluctuations are limiting the precision of calibrated radiocarbon ages, due to multiple matches of radiocarbon ages with the calibration curve. However, the fluctuations ('wiggles' of the curve) can be turned to good use if an ordered sequence of ^{14}C dates is measured. The sequence will show the same ^{14}C age structure compared to the calibration curve, because of the uniform level of ^{14}C at any time within one hemisphere, and the structure can thus be anchored precisely in time. Tree-rings again are ideal for such an exercise, because the underlying order is known on an annual scale. The technique was employed already early to date Swiss lake dwellings (Ferguson et al., 1966) and statistical procedures were developed to estimate confidence intervals (Clark and Renfrew, 1972; Pearson, 1986). With the advent of Baysean concepts in ^{14}C calibration (Ramsey et al., 2001), objective criteria for optimal wiggle-match solutions and optimal numbers of samples (Galimberti et al., 2004) can be obtained.

Here we show an example of the wiggle-match approach to date floating tree-ring chronologies, from the Neolithic lake site of Marmotta, Lazio, Italy. The site dates back to the 6th millennium BC. From a local oak chronology of the settlement we determined ^{14}C ages of 6 decades within a range of 130 rings on a section, and using the 'sequence' option of the OxCal calibration program (Ramsey, 1995) the calibrated range of the start of the floating sequence could be fixed within a range of 22 years (2σ). In contrast, the calibrated age of a single sample would have a confidence interval of 110 years (1σ) (Fig. 3).

A similar situation is observed in the dating of the Minoan eruption of the Santorini volcano, where single dates, even at highest precision, cannot distinguish with high statistical confidence between dates in the 17th and 16th century, whereas recently a wiggle-matching exercise of a ^{14}C series obtained from an Olive branch gave a secure date in the late 17th century (Friedrich et al., 2006).

Conclusions

The radiocarbon dating technique would be far less precise without the calibration data sets based on tree-ring chronologies. The European oak and pine chronologies are the backbone of radiocarbon calibration, and they hold the potential to extend the tree-ring-based range well into deglaciation times. With the accurate annual time scale of tree-ring chronologies ^{14}C could be developed into a reliable proxy of solar activity beyond the period of telescopic and instrumental observations. On the other hand, ^{14}C pre-dating of new sub-fossil tree finds and wiggle-matching of floating tree-ring sections became important tools in dendrochronology.

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