Title
Radiocarbon Calibration and Age Estimation

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Word Count
1990

Abstract

Radiocarbon dating can be applied to archaeological materials which contain radiocarbon from the atmosphere or the oceans. In order to interpret radiocarbon measurements as dates it is necessary to compare them against measurements on known-age samples which have been dated by other methods. This allows calibration onto a timescale derived from either dendrochronology or Uranium Series dating. Multiple analyses can be interpreted through the use of Bayesian statistical methods allowing for the incorporation of relative age constraints and the grouping of events in phases.

Keywords
Radiocarbon, Dating, Calibration, Diet, Bayesian Statistics

Main Text

Radiocarbon dating is one of the most widely used methods used to provide age estimates for archaeological material. The method is most often applied to organic material but in principle can be used to date any carbonaceous material where the carbon is drawn from a reservoir which contains radiocarbon. Critical to the application of dating in Archaeology is the selection of suitable material which relates closely the archaeological events under consideration.

Radiocarbon Measurement

Determining the radiocarbon carbon isotopic ratio ($^{14}C/^{12}C$) is a multi-stage process. The first stage is the extraction of chemical components of the sample which are original to the material being dated and free of any contaminants. For archaeological samples where there are a number of possible contaminants, this can be technically complex, and is normally carried out by laboratories who specialize in these types of material. The actual measurement of the radiocarbon isotope ratio can be made using a number of different technologies: originally methods based on decay rate counting were used but the majority of measurements are now undertaken using Accelerator Mass Spectrometry (AMS). Corrections are made for mass-dependent fractionation by measurement of the stable isotope $^{13}C/^{12}C$ ratio, and for background levels, and the result of such measurements are reported either in terms of fraction modern ($F^{14}C$)

or converted to a nominal conventional radiocarbon age estimate using Libby's original half-life estimate of 5586 years (Libby 1949). The activity of a modern sample is defined as that which a natural sample would have had in 1950 had there been no fossil fuel effect, and is estimated from measurements on wood from 1850. In practice, all measurements are made relative to standards with precisely known characteristics. The radiocarbon age, *A*, is expressed in units of years before present (BP) which in this case means before 1950 and is a simple scaled logarithm of the fraction modern, *F*:

$$A = -8033 \ln(F)$$

This would give the true age of the sample if the amount of radiocarbon in the atmosphere had always been the same as that estimated for the natural atmosphere in 1950 and if the half-life was 5586 years (Stuiver and Polach 1977). Neither of these is the true and so the radiocarbon age is best thought of as a convenient logarithmic equivalent to the fraction modern which gives an order of magnitude estimate of true age.

Radiocarbon Reservoirs

In order to use radiocarbon as a precise dating technique requires a detailed record of how radiocarbon has changed in the atmosphere (or other related reservoirs) over time to do this requires material which has been dated by other methods. For the Holocene and Late Glacial periods, wood dated by dendrochronology is used which is ideal both because it can be dated to the year and the carbon in wood is directly drawn from the atmosphere through photosynthesis. For earlier periods, a number of different archives are used including Uranium-Series dated corals and speleothems along with marine and terrestrial records. There are estimates for the levels of atmospheric radiocarbon covering the last 50,000 years (Reimer et al 2013). From the 1950s onward there are also direct atmospheric measurements.

Radiocarbon is mostly generated in the upper atmosphere and becomes incorporated into the global carbon cycle, entering the biosphere through photosynthetic fixing of CO_2. The mixing rates are such that the radiocarbon in the atmosphere is fairly constant within each hemisphere, with a slightly lower level (about 0.5%) in the southern hemisphere (Hogg et al 2013) because of the much larger ocean surface. Terrestrial plants within each hemisphere fix this radiocarbon directly and so short-lived plants mirror the values found the atmosphere (albeit with isotopic fractionation) and animals feeding on these plants or higher up the food chain do the same but with some time-averaging which depends on the tissue concerned. Such effects are usually of the order of a decade or less and are often ignored. Woody plants lay down cellulose over time and so, for example in trees that have annual tree rings, each ring reflects the prevailing atmospheric radiocarbon level when it grew. When you come to date wood this can give a very significant 'old wood effect' which needs to be considered in the interpretation.

Through exchange with the atmosphere, radiocarbon is also incorporated into the oceans but here the mixing rates are much slower and so different bodies of water have very different levels of radiocarbon. The surface oceans on average are about 5% (or 400 years) depleted relative to the atmosphere (Reimer et al 2013) but different regions are affected by ocean upwelling, freshwater runoff and other effects. In some cases, the offset between the local ocean and marine ocean average (ΔR) can be estimated by looking at paired marine and terrestrial samples (Stuiver and Braziunas, 1993) but these offsets are likely to be variable in time and are not available for some regions. These additional uncertainties mean that radiocarbon dating of marine organisms is almost always less precise.

Rivers and other freshwater systems exchange CO_2 with the atmosphere. However, this is mixed with carbon from other sources including that from detrital carbon in soils, which is depleted in radiocarbon compared to the atmosphere and dissolved carbonate from the underlying geology (usually virtually free of radiocarbon). This has implications for dating material from fluvial systems and for the radiocarbon dating of speleothems in caves. In practice, it is usually necessary to undertake a local case-study to determine such effects.

For humans and other omnivores there is the additional complication that they can, in some cases, source their food from a combination of terrestrial, marine and freshwater sources. To account for this, where it might be relevant, requires a detailed dietary analysis as such offsets can be significant (Fernandes et al 2015).

The Calibration Process

In order to use a radiocarbon measurement for age-estimation we have to calibrate it against known-age material from the relevant reservoir. The first stage in any calibration is therefore the choice of reservoir. Agreed calibration curves are published by the IntCal group and cover the three best understood and most widely applicable reservoirs: the atmosphere of the northern hemisphere (currently IntCal13, Reimer et al 2013), the southern hemisphere atmosphere (SHCal13, Hogg et al 2013) and the oceans (Marine13, Reimer et al 2013). These curves give the expected radiocarbon age as a function of true age over the last 50,000 years based on a compilation of different datasets.

Conceptually, the process of calibrating a single sample involves considering each possible year the sample might be from and comparing the measured radiocarbon for the sample to that of the calibration curve estimate for that year. The closer the two values are the more likely the sample is to be of that age. The mathematical formalism used assumes normally distributed errors and so strictly is better defined in terms of $F^{14}C$ rather than radiocarbon age. If the radiocarbon calibration curve is defined as a function of time with a standard uncertainty $r_c(t) \pm \sigma_c(t)$ and the sample has a corresponding measurement given by $r_s \pm \sigma_s$ then the likelihood of any date t is proportional to:

$$\frac{\exp\left(-\frac{\left(r_s - r_c(t)\right)^2}{2(\sigma_s^2 - \sigma_c^2(t))}\right)}{\sqrt{\sigma_s^2 - \sigma_c^2(t)}}$$

The probability density distribution is normalized so that the integrated probability over the full range of the curve is one. Note that the calibration process is independent of the half-life of radiocarbon. It is often useful to express the calibration as a range and usually this is given as the highest probability density (HPD) range either at 95% or 68% to be equivalent to the one and two standard deviation ranges for a normal distribution. The 95% range is usually considered to be the most useful as it is unlikely (<5%) that the date lies outside this. The 68% range gives the 'most likely' date range. For single date calibrations, it is not considered useful to use to use the mean and standard deviation as the distributions following calibration are often multimodal and

not normally distributed. Dates ranges after calibration are usually expressed in the form of cal BP (where the year 1950 is 0 cal BP), cal AD, cal BC, cal CE or cal BCE.
Software is available for performing the calibration process including the widely used Calib (Stuiver and Reimer 1993) and OxCal (Bronk Ramsey 2009) packages. Figure 1 shows an example calibration diagram using OxCal. Note that the ranges, as in this case, can be split into several sub-ranges because the probability distribution is multimodal.
Calibration of single samples can also take account of offsets from the reservoir level, most commonly in the case of marine samples with a local oceanic ΔR offset (Stuiver and Braziunas, 1993). Allowance for mixed reservoirs can also be made when calibrating dates from humans with a mixed terrestrial and marine diet.

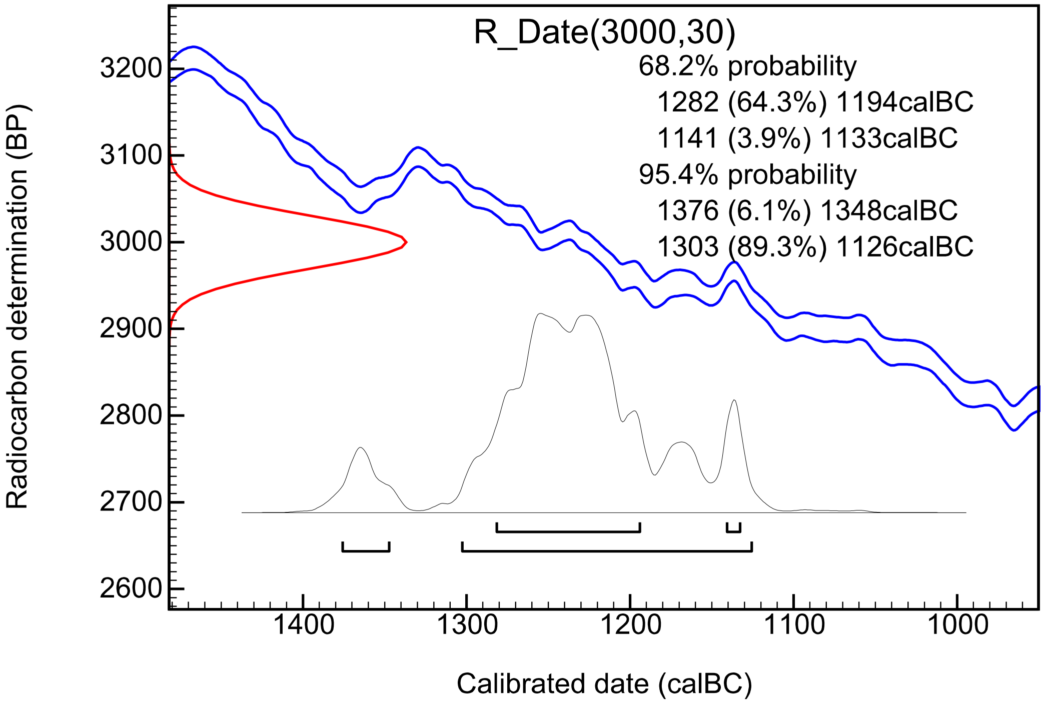

Figure 1: Example calibration diagram
The red normal distribution on the left shows normal probability distribution associated with the radiocarbon determination 3000 ± 30, expressed in radiocarbon years BP on the y-axis. The blue band shows the calibration curve at ± 1σ as a function of true age on the x-axis. The grey probability distribution shows the likelihood that the sample is of any particular age. The ranges are given at two different probability levels: for example, there is a 95.4% probability that the sample dates to between 1376 and 1126 cal BC.

Analysis of multiple dates

When there is more than one radiocarbon date to be used for age estimation it is possible to take into account other information using Bayesian statistical approaches (Buck and Millard 2004, Bronk Ramsey 2009). The types of information that are included in such analyses include: samples that share the same age, samples from the same period, and constraints on relative age. In some circumstances, such as lake sediments, we might also have information on the sedimentation process. In the Bayesian approach this information is included as *prior* probabilities, the radiocarbon measurements themselves are the *likelihood* and from these the *posterior* estimate, which includes all information, can be derived. Bayesian chronologies are often site-based making use of the physical stratigraphy but they can also be based on regional cultural assemblages or constrained with historical information from written sources.

SEE ALSO:
[Include cross-references here (related articles).]

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Further Readings

- Calib Software: http://calib.org
- OxCal Software: http://c14.arch.ox.ac.uk/oxcal.html
- IntCal special issues in the journal Radiocarbon

See Also

saseas0154, saseas0488, saseas0491, saseas0492