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An open-source toolkit for radiocarbon dating and calibration

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Abstract

The analysis and interpretation of radiocarbon dates can involve many steps, such as switching between units or time-scales, assessing the impacts of contamination, applying marine or other offsets, inspecting calibration curves, calibrating dates, extracting probabilities from calibrated distributions, and analysing and plotting multiple dates. Here, we present *rice*, a new open-source *R* package which, together with other packages such as *rbacon*, *Bchron*, *coffee* and *clam*, enables users to perform such calculations within *R*, thus allowing most of the steps from data entry to calibration, age-modeling and subsequent analysis and interpretation of time-series to be performed within a single widely-used, multi-platform, transparent and open-source software environment. All calculation steps are documented and can be inspected, and users can also write new/enhanced functions. The package could thus prove useful in both educational and research settings.

Introduction

Depending on the application, many steps may be involved with the reporting, calibration and interpretation of radiocarbon dates. These steps currently require several software packages, e.g. *CALIB*[1] (Stuiver and Reimer 1993) or *OxCal*[2] (Bronk Ramsey et al. 2010) for calibration, the online marine database (Reimer and Reimer 2001) for calculating regional offsets, *OxCal* or *ChronoModel*[3] (Lanos and Philippe 2018) for age-modeling and possibly a spreadsheet program such as *MS-Excel* to estimate potential contamination or to export age estimates for subsequent usage/analysis. This fragmentation of workflows can cause a lack of reproducibility if not all steps are documented. Additionally, although both *CALIB* and *OxCal* are reliable, freely available and widely used, and their methods are described in a range of publications (e.g., Bronk Ramsey 1995; Bronk Ramsey et al. 2010; Stuiver and Reimer 1993), since neither are open-source users cannot follow the exact calculation steps taken.

R is an open-source language and environment for numerical analysis and visualization (*R* Core Team 2025). It is freely available for download[4] and its script-based approach enables reproducibility and transparency of results. *R* is widely used in many research disciplines and currently has over 23,000 user-contributed packages available. Here we present *rice* (*r*ad*i*o*c*arbon *e*quations), an *R* package which

[1]https://calib.org/
[2]https://c14.arch.ox.ac.uk/oxcal.html
[3]https://chronomodel.com/
[4]https://cloud.r-project.org/

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aims to enable radiocarbon users to perform many numerical steps related to radiocarbon dating, calibration, analysis and plotting within a single, open-source framework. It could be useful for educating early-career researchers, and also be helpful for other users to better understand which calculations are performed in order to obtain, calibrate, query and interpret radiocarbon dates.

Theory

The *rice R* package uses concepts fundamental to radiocarbon dating. Internally, radiocarbon measurements are expressed as fractions of a standard adjusted to AD 1950 (Reimer et al. 2004; Stuiver and Polach 1977):

$$F^{14}C = A_{SN}/A_{ON}, \tag{1}$$

where A_{SN} is the activity of the sample and A_{ON} that of the oxalic acid standard (both are corrected for fractionation using $\delta^{13}C$). For reporting however, $F^{14}C$ values are most often transformed into ^{14}C ages:

$$^{14}C\ BP = -1/\lambda * ln\left(F^{14}C\right) \tag{2}$$

where $1/\lambda = 5568/ln(2) \approx 8033$ is based on the Libby half-life (Stuiver and Polach 1977). Estimates of the depletion or enrichment of atmospheric radiocarbon relative to the standard (age-corrected Δ as in Table 1 of Stuiver and Polach 1977, but written as $\Delta^{14}C$ by more recent sources such as Heaton et al. 2021) use the more accurate Cambridge half-life of 5730 ± 30 yr. Sometimes, percent modern carbon (pMC) values are reported instead of $F^{14}C$, but since pMC has historically been calculated with or without isotope fractionation correction, $F^{14}C$ is preferred by many since it is more clearly defined (Reimer et al. 2004).

Sometimes, radiocarbon-dated material consists of multiple carbon sources (either through contamination or natural processes). In such cases, a mass-balance equation (Donahue et al. 1990) can be used:

$$F_{measured} = \sum_{i=1}^{n} p_i F_i, \tag{3}$$

where for each fraction i, p_i is its proportion (all p_i summing to 1) and F_i is its $F^{14}C$ (Donahue et al. 1990).

Owing to variations in atmospheric ^{14}C concentration over time, calendar ages are not linearly related to radiocarbon ages. This causes the need for calibration of ^{14}C dates, using calibration curves such as IntCal20 (Reimer et al. 2020), SHCal20 (Hogg et al. 2020), Marine20 (Heaton et al. 2020) or postbomb curves (Hua et al. 2022). Each of these curves provides a range of calendar ages (θ in cal BP, years before AD 1950) and their associated ^{14}C ages (mean $\mu(\theta)$ ± $\sigma(\theta)$). For a given calendar age θ_i, a radiocarbon age $y \pm \sigma$ is assumed to be normally distributed via $\mu(\theta_i)$:

$$y \sim N(\mu(\theta_i), \omega), \tag{4}$$

where $\omega = \sqrt{\sigma^2 + \sigma(\theta_i)^2}$ combines the errors of the date with that of the calibration curve. Instead of the normal distribution, a student-t distribution can also be used to accommodate additional scatter (Christen and Pérez 2009). Calculating the date's calibrated distribution involves taking a sufficiently wide and dense range of θ_i and calculating the probability for each using equation (4), interpolating linearly where necessary. Since calibrated distributions are often multi-modal and asymmetric, they are often summarized by their 95% highest posterior densities (hpds; the shortest calendar age intervals that contain 95% of the calibrated distribution; Bronk Ramsey 2009).

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Implementation

The *rice* R package is available on R's Comprehensive R Archive Network CRAN[5], and a development version is available on github[6], both under an open-source GPL-3 license[7]. It provides functions useful for a range of radiocarbon-related calculations, outlined below. To install *rice*, within R (or RStudio[8]) users should type `install.packages('rice')` (note that quotation marks are required here). This will also install the accompanying data package *rintcal* which contains the calibration curves. Whenever an updated version of *rice* is available, it can be installed using the previous command, or through `update.packages()`. Once *rice* is installed, to enable access to its functions it must be loaded into the R session, using `require(rice)` or `library(rice)`.

A tutorial can be found as Supplementary Information, by typing `vignette('rice')` or by browsing CRAN's *rice* page[9]. Each function comes with documentation, which can be accessed by typing a question mark followed by the function's name. To inspect what calculations are made within each function, its name can be typed without the brackets, followed by pressing *Enter*. Below, some of the main functions and their usage are reported.

Time-scales and units

The multitude of time-scales and units reported in radiocarbon analysis can be confusing to non-specialists as well as to students and the general public. For example, whereas larger numbers represent older ages on the cal BP (calendar years before AD/CE 1950) time-scale, this relation is reversed for AD ages. Converting cal BP ages into cal BC/AD (or BC/BCE) ages also requires excluding the year zero (Bronk Ramsey 2009). Cal BP ages are almost but not quite the same as b2k (years before AD 2000), a popular time-scale among the ice core community (e.g., North Greenland Ice Core Project Members 2004).

The *rice* package provides functions to convert values between the above time-scales and units (Figure 1). To give some examples, the function `calBPtoBCAD(5000)` converts 5000 cal BP into –3,051 cal BC/AD (BC ages are indicated by negative numbers), `F14CtoC14(0.405, 0.002, roundby=0)` translates an $F^{14}C$ value of 0.405 ± 0.002 into 7261 ± 40 ^{14}C BP, and `calBPtoC14(25000)` finds the IntCal20 (Reimer et al. 2020) ^{14}C age and error belonging to 25,000 cal BP (20,706 ± 47 ^{14}C BP, interpolating where necessary; the output of functions like these will contain the means and the uncertainties as the first and second columns, respectively). Material with a calendar age of 100 cal BP and a ^{14}C age of 150 ± 10 BP would have an age-corrected $\Delta^{14}C$ of `C14toDelta14C(150, 10, 100)` ≈ −6.55 ± 1.24‰. Other curves such as SHCal20 (Hogg et al. 2020), Marine20 (Heaton et al. 2020) and postbomb curves (e.g., Hua et al. 2022) are provided, as well as previous calibration curves back to IntCal98 (Stuiver et al. 1998) and some of the earliest calendar/^{14}C comparisons presented by Arnold and Libby (1951).

Calibration

The IntCal20 calibration curve and its underlying datasets can be investigated, and functions to calibrate radiocarbon dates are provided (Figure 2). For example, to visualize, store and return the datasets contributing to IntCal20 between 25 and 24 kcal BP, type `sets <- intcal.data(25e3,24e3)`, followed by typing `sets`. Options for calibration include a choice of calibration curves (including options to mix, stack or smooth curves, or to provide a custom-built curve), addition of reservoir effects (see later), and calculations using the normal or student-t distributions (Christen and Pérez 2009), as

[5]https://CRAN.R-project.org/package=rice
[6]https://github.com/Maarten14C/rice
[7]https://www.gnu.org/licenses/gpl-3.0.html
[8]https://posit.co/download/rstudio-desktop/
[9]https://cran.r-project.org/web/packages/rice/vignettes/rice.html

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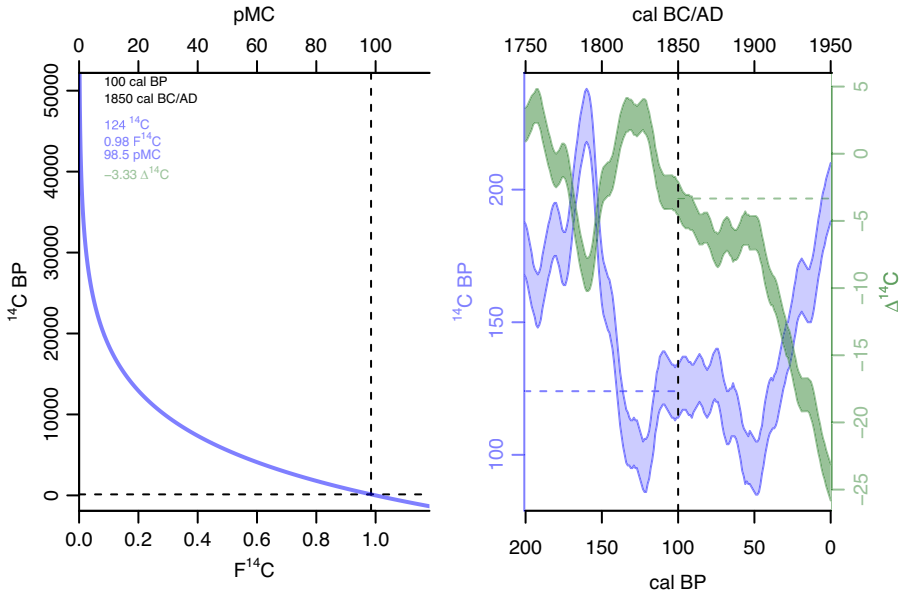


Figure 1. *Output of the "fromto" conversion command for 100 cal BP. The left panel shows the relationship between $F^{14}C$, pMC and ^{14}C age, and the right panel shows cal BP, cal BC/AD, ^{14}C BP (blue) and $\Delta^{14}C$ (green). In both panels, dashed lines show translations of 100 cal BP into the other time-scales: 1850 BC/AD, 124 (± 10) ^{14}C BP (the ^{14}C age and error of the calibration curve at 100 cal BP), 0.98 (± 0.001) $F^{14}C$, 98.47 (± 0.12) pMC, and –3.33 (± 1.24) age-corrected $\Delta^{14}C$ (all using IntCal20).*

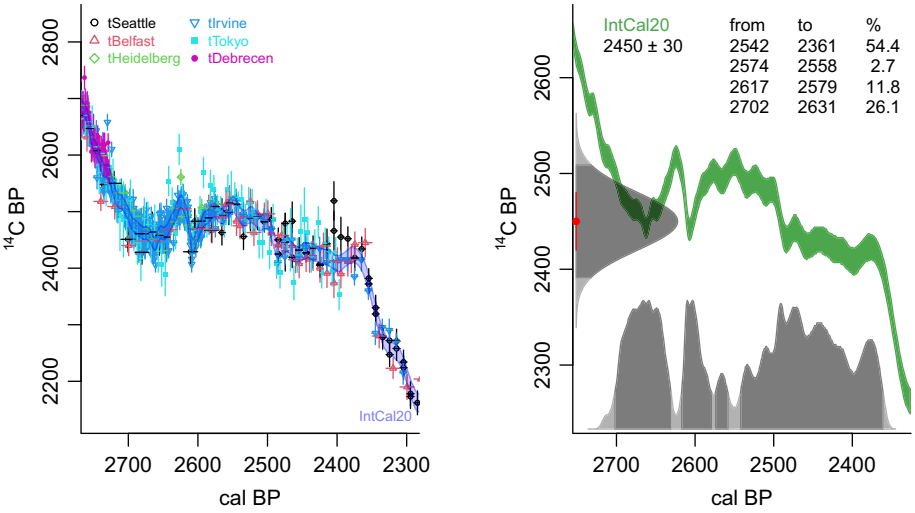


Figure 2. *Left panel: visualization of the IntCal20 calibration curve (blue ribbon shows 1 standard deviation envelope) and its data (see legend for colours), for 2750 to 2300 cal BP. Right panel: calibration of a ^{14}C age of 2450 ± 30 ^{14}C BP. Calibration curve in green, uncalibrated distribution in grey on the vertical axis, calibrated distribution on horizontal axis. 95% highest posterior density ranges are shown in dark grey and at top right.*

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well as using ^{14}C age or F^{14}C. Dates at the old or young extremes of the calibration curve will get truncated, with warnings provided.

The calibrated distributions of a ^{14}C date $y_i \pm er_i$, can be calculated and analysed using equation (4). Let's take a radiocarbon date of 2450 ± 30 ^{14}C BP as an example. Its calibrated distribution can be found as `cal <- caldist(2450,30)` and its hpds as `hpd(cal)`. The calibrated date's point estimates (weighted mean, median, mode and midpoint of the extremes of the hpd ranges) can be found through `point.estimates(cal)`.

We can also query calibrated distributions, for example to find out what proportion of the calibrated distribution of our date lies between 2700 and 2600 cal BP, one can use `p.range(2700,2600,2450,30)`. Additional functions exist to find the proportions of calibrated distributions that are younger/older than a certain calendar age (e.g., `younger(2600,2450,30)`), to calculate the likelihood of a specific calendar age (e.g., `l.calib(2600,2450,30)`), or to sample 100 random calendar ages from a calibrated distribution (e.g., `r.calib(100,2450,30)`), where higher peaking calibrated ages are proportionally more likely to be sampled. Calibrated dates can be "pushed" toward older/younger ages by adding/subtracting a normal or gamma distribution (e.g., if we want to account for an inbuilt age, we could use `push.gamma(2450,30,20,2, subtract=TRUE)` to subtract a gamma distribution with mean 20 and shape 2 from our calibrated date). This is done by sampling n random ages from the calibrated distribution and adding random normal/gamma jumps. Dates can also be corrected for fractionation or background, if they haven't been already (`adjust.fractionation, adjust.background`). The hpd ranges of multiple dates can be listed in a table using the function `calibratable`.

Multiple dates

Populations of dates can be assessed—for example, the twelve dates reported by three laboratories of the Shroud of Turin (Damon et al. 1989). These dates are include in *rice* and can be loaded into R using `data(shroud); y <- shroud$y; er <- shroud$er`. We can use a χ^2 goodness-of-fit test to check if these samples can statistically be assumed to stem from a single population with a common underlying true mean (Ward and Wilson 1978; see also Christen and Pérez 2009). If we try to combine all twelve ^{14}C dates and their lab errors, `pool(y, er)`, the function reports that the scatter is too high to calculate a pooled mean (χ^2 20.697, p-value 0.037 < 0.05). We could then proceed to check if dates from a single laboratory could still be pooled, e.g. those with lab IDs containing ETH: `ETH <- grep("ETH", shroud$ID); pool(y[ETH], er[ETH])`. The scatter is narrow enough to allow for a pooled mean to be reported for the ETH dates (676.1 ± 23.7 ^{14}C BP). Alternative pooling methods exist, e.g., by assuming that all dates belong to the same bin of a certain width (e.g., 100 years: `as.bin`), or even to the same year (`as.one`). Especially the latter approach must be treated with extreme care and should only be used for samples that are known to stem from the exact same year (e.g., a single batch of seeds). Other approaches to assess populations of dates include `spread(y, er)`, which samples random ages from all dates and from their differences calculates the spread in calendar years (returning a plot of the distribution and the mean, median and 95% range), and `overlap(y, er)`, which for each calendar year within a sequence finds the minimum calibrated likelihood among all dates. All shroud dates together show a very small overlap of just 4%, but the calibrated distributions of the ETH dates (`overlap(y[ETH], er[ETH])`) show c. 39% overlap.

We can also query the relationship between distributions. Imagine, say, calibrated date A <- `caldist(130,10)` and another estimate B for the age of A (e.g., an age-model output based on multiple dates). Here we simulate B by sampling from a normal distribution and then extracting its density: `b <- dnorm(20:220, mean=120, sd=20); B <- cbind(20:220, b)`. The degree to which distribution B agrees with distribution A can be assessed by checking whether any of the 95% hpd ranges of both distributions overlap: `hpd.overlap(A, B, 0.95)`.

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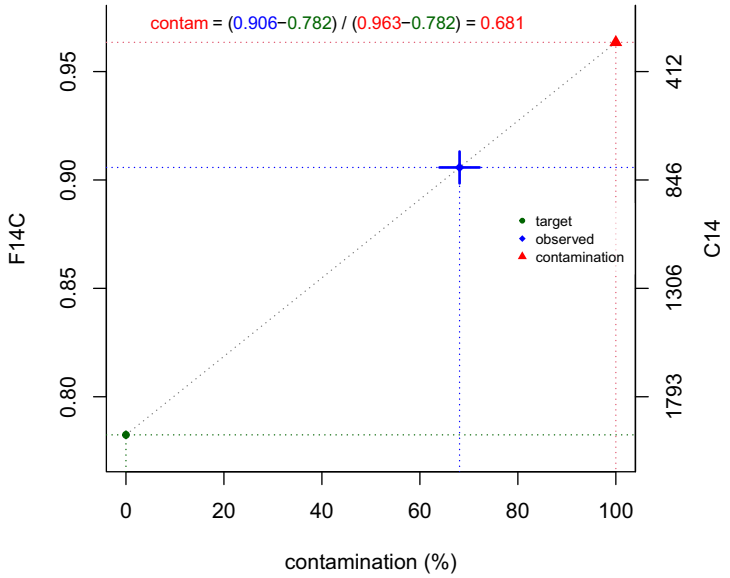


Figure 3. *Amount of contamination (horizontal axis) versus $F^{14}C$ (left axis) and ^{14}C age (right axis; logarithmic). The target age (green; AD 30 = 1971 ± 15 ^{14}C BP = 0.782 ± 0.001 $F^{14}C$) has 0% contamination, whereas the x position of 100% shows the "pure" contamination (red, here assumed to be of age AD 1532 = 0.963 ± 0.001 $F^{14}C$). Working on the $F^{14}C$ scale, the observed age (blue, Ox-2575.1 = 795 ± 65 ^{14}C BP = 0.906 ± 0.007 $F^{14}C$) can be visualized as lying on a straight line between the target and contamination, and the resulting percentage contamination can be estimated at c. 68.2%.*

Occasionally, multiple measurements are taken from chemical or physical fractions of single samples, for example different size fractions of a soil sample. If the age of the entire/bulk sample has been measured, as well as all-but-one of the fractions (for example if its mass is too low for ^{14}C dating), and if the carbon concentrations (%C) and masses of all fractions are known, then the age of the missing fraction can be estimated by calculating the contribution to the carbon pool of each fraction using equation (3). Examples are provided in the Supplementary Material (section 9).

Contamination and carbon sources

Samples are easily contaminated with non-contemporaneous carbon sources, for example in the field, during storage/preservation, or in the laboratory during sample pretreatment and analysis. Examples include older terrestrial carbon incorporated into marine sediments (e.g. Rosenheim et al. 2008), or finite ages from background samples such as feldspar, anthracite or other material known to be well over 50,000 years old (Vogel et al. 1987). The impacts of contamination with carbon of a certain $F^{14}C$ can be modeled using equation (3) using two components, e.g., `contaminate (5000, 20, 5, 1, F.contam=1)` ≈ 4661 ± 69 ^{14}C BP will model the impact of 5 ± 1% modern contamination (with a $F^{14}C$ of 1) on material dating to 5000 ± 20 ^{14}C BP. Similarly, a contaminated date can be 'cleaned' of its (5%, modern) contamination: `clean (2000, 20, 5, F.contam=1)` ≈ 2121 ± 21 ^{14}C BP. We can also calculate what percentage (or $F^{14}C$) of contamination would be required to "explain away" an observed age. E.g., what if the Shroud of Turin really dates to around AD 30 but has been contaminated by carbon from repairs following a known AD 1532 fire? Taking one of the observed Shroud's ^{14}C dates, Ox-2575.1, we can see that this sample would need to be contaminated by c. 68% of AD 1532 material (see Figure 3). The *muck* function can also be used to estimate the required $F^{14}C$ of the

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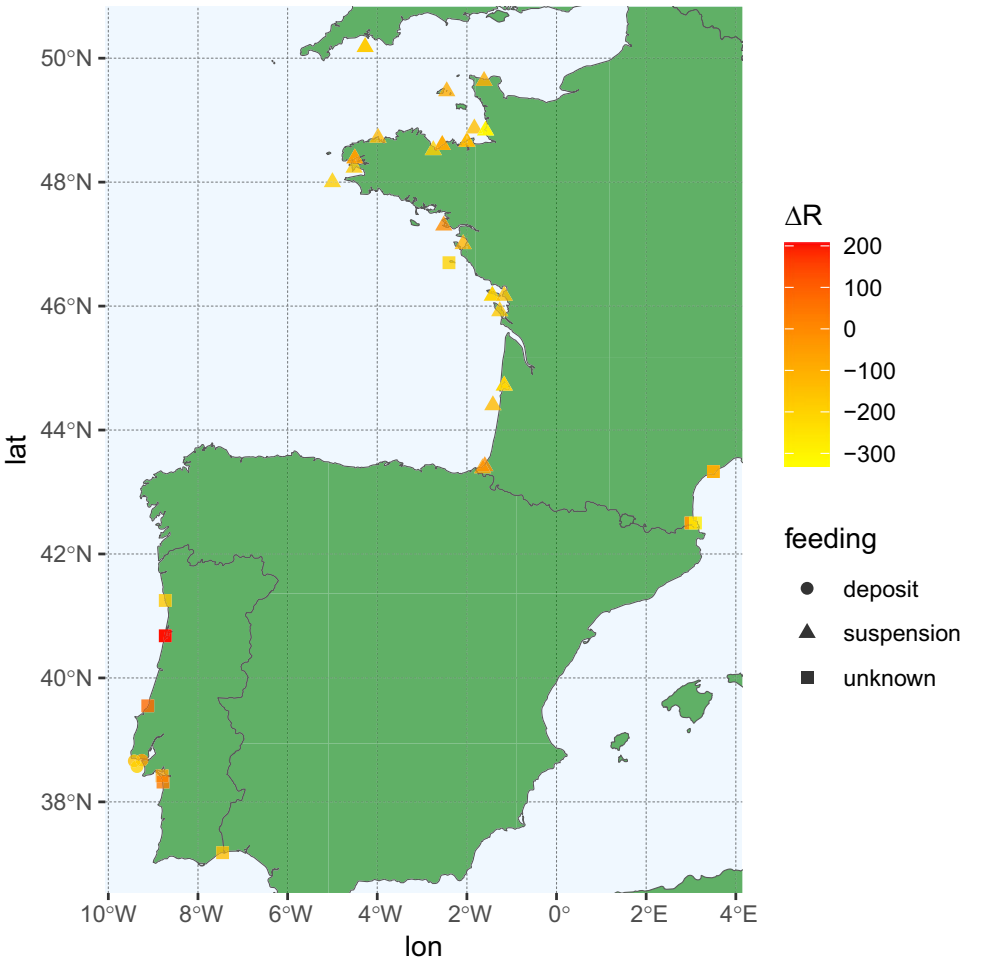


Figure 4. *A map of shell-based estimates of the regional marine reservoir offset. Red-to-yellow gradient shows ΔR, symbols show feeding ecology. Data were downloaded from the marine database (Reimer and Reimer 2001) with ΔR based on Marine20 (Heaton et al. 2020).*

contamination if its percentage is known. The *contaminate*, *clean* and *muck* functions use Monte Carlo sampling by default to estimate uncertainties (therefore, slight output variations may exist across multiple runs).

Marine offsets

Radiocarbon dates on oceanic material tend to have older radiocarbon ages than contemporaneous terrestrial material and require calibration with the marine calibration curve (Heaton et al. 2020, 2023; Keith and Anderson 1963). Besides this global marine offset, ocean circulation patterns including upwelling cause local or regional marine offsets, which have been estimated in many coastal regions by ^{14}C dating shells that were collected before bomb ^{14}C influence (Reimer and Reimer 2001). A copy of the marine reservoir correction database[10] (Reimer and Reimer 2001) is available within *rice*. It can be queried using, e.g., `Atlantic <- find.shells(-6, 45, 50)` which will return a map and the details of the 50 shells closest to 6° west and 45° north (Figure 4; alternatively, supply the longitude and

[10]https://calib.org/marine/

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latitude ranges through `map.shells`). Optionally, the data can be plotted on a browsable satellite map (setting browse=TRUE), and ocean currents for the region can be shown separately[11]. The output can be made to return only shells with certain feeding ecologies, e.g., `map.shells(-6, 45, feeding="suspension")`. Weighted means can be calculated from multiple shells, using for example `Brazil <- map.shells(-30, -60, 0, -30); shells.mean(Brazil)` $\approx -118 \pm 113$ (the reported error is the maximum of the weighted uncertainty and the standard deviation).

Where relevant, *rice* functions return their output to enable subsequent analysis, e.g., `oldwood <- push.gamma(2450,30,20,2); plot(oldwood$shifted)`. Some of the functions are available as online applications[12].

The figures in this manuscript were produced using the following *rice* commands:

- Figure 1. `fromto(100, from="calBP")`
- Figure 2. `layout(t(1:2)); intcal.data(2750,2300,cal.lab="cal BP"); calibrate(2450,30)`
- Figure 3. `muck(795, 65, 1971, 15, .9635, .0012)`
- Figure 4. `find.shells(-6, 44, 50)`

Discussion

The *rice* package has been designed to make it easier to analyse and interpret radiocarbon dates within the *R* platform without the need to switch between applications such as Internet browsers and spreadsheets.

Many radiocarbon-related calculations such as calibration, correction for reservoir offsets, stratigraphical modeling (Blaauw et al. 2026), age-depth modeling (*BChron* [Haslett and Parnell 2008], clam [Blaauw 2010], or *Bacon* [Blaauw and Christen 2011]) and dates-as-data (*rcarbon* [Crema and Bevan 2021], Heaton et al. 2025) can now be performed within the same software environment *R*. For example, if some ^{14}C dates within a sediment core stem from marine material, are of postbomb age or could be contaminated with modern carbon, then *rice* could be used to correct the dating information prior to age-modeling. Additionally, *R* scripts can be made available to others so that they can see exactly what was done, thus increasing reproducibility and transparency in research software (Barker et al. 2022).

The *rice* package has been tested at training workshops for postgraduate students and other early-career researchers. By showcasing and discussing the functions, the participants were able to quickly cover the basics of radiocarbon dating, calibration and corrections. Some prior experience with *R* is required, but since *R* has become widely used in many disciplines (with over 23,000 user-contributed packages available on CRAN), this has gradually become less of an issue.

For future iterations of the package, we are considering adding options such as kriging-based spatial interpolation of ΔR (e.g., Ulm et al. 2023). The open nature of *rice* enables users to write additional or enhanced functions, either for their own use or for sharing with the wider community.

Conclusion

We developed *rice,* a flexible toolkit for a range of radiocarbon-related calculations, such as transformation between time-scales and units, modeling carbon sources, and calibration. The toolkit can be used within *R*, a single, scriptable and open-source environment, both for research and teaching purposes.

Supplementary material. A *rice* tutorial is available at [Radiocarbon https://doi.org/10.1017/RDC.2026.10221]

[11]https://earth.nullschool.net/

[12]https://radiocarbon.shinyapps.io/contaminate/

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Competing interests. The authors declare that they have no competing interests.

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