

Refining prehistoric timelines: the power of high-precision radiocarbon dating



Figure 1: Revine trees collected in 2021 by the RESOLUTION team (photo provided by S.T.).

Introduction

For decades, radiocarbon dating has been the cornerstone of reconstructing human prehistory, environmental changes and past climate variations. However, until recently, the precision of radiocarbon calibration models has been limited, particularly for the Late Pleistocene. Advances in radiocarbon science, especially the development of Radiocarbon 3.0 (Talamo *et al.*, 2023a), are transforming our understanding of prehistoric events. By leveraging high-resolution tree-ring datasets, researchers are refining radiocarbon calibration curves, revealing previously undetected variations in atmospheric radiocarbon levels, and improving the accuracy of archaeological chronologies.

One of the most significant breakthroughs comes from a recent study at Revine, Italy, where subfossil larch trees have provided a millennium-long record of atmospheric radiocarbon fluctuations. This research challenges existing calibration models and sheds light on the relationship between solar activity, climate shifts and human prehistory.

Unlocking the past with ancient trees

Tree rings serve as natural time capsules, recording annual changes in atmospheric radiocarbon levels with unparalleled precision. Because trees

absorb carbon from the atmosphere during photosynthesis, their rings reflect year-by-year variations in radiocarbon (^{14}C) production. This makes dendrochronologically dated tree-ring sequences the most reliable archives for radiocarbon calibration, far superior to other natural records such as marine sediments, lake macrofossils and speleothems, which often have lower temporal resolution and higher statistical errors.

The IntCal20 calibration curve currently relies on absolutely dated tree-ring chronologies extending back 14 200 years BP, providing decadal to annual resolution with statistical uncertainties as low as 15 to 30 years (1σ) (Reimer *et al.*, 2020). However, for older periods, extending back to 55 000 years BP, calibration relies on indirectly dated records such as speleothems, marine sediments and lake macrofossils. These sources, while invaluable, offer much lower resolution, with statistical errors of 250 to 400 years and only one measurement every 200 to 400 years in some age ranges.

Fortunately, scientists have discovered glacial-age trees, which offer the potential to extend high-resolution tree-ring calibration further into the past. While floating chronologies (tree-ring sequences not yet anchored to an absolute calendar date) have been constructed from these trees, they were historically excluded from calibration models due to their lack of absolute dating.

However, a breakthrough in cosmogenic isotope analysis—specifically, the ability to match ^{14}C variations with beryllium-10 (^{10}Be) signals—has now made it possible to link floating tree-ring sequences to absolute timescales (Muscheler *et al.*, 2020). This method has allowed researchers to incorporate high-precision tree-ring sequences into radiocarbon calibration models, significantly improving dating accuracy and revealing short-term variations in ^{14}C levels that were previously undetectable.

A key dataset comes from New Zealand's Kauri trees, which cover 44 000 to 41 000 years BP. These trees provide a high-resolution calibration segment with a temporal resolution of 40 years

and errors between 120 and 220 years (Cooper *et al.*, 2021). The Kauri dataset also recorded major deviations in ^{14}C production, caused by a period of intensified cosmic ray flux during the Laschamps event, a dramatic weakening of Earth's magnetic field that altered atmospheric radiocarbon production.

Why are European trees important?

While the Kauri dataset is critical for calibrating radiocarbon levels in the Southern Hemisphere during the Laschamps event, it is not sufficient for global calibration, especially for European prehistoric contexts. The ideal scenario is to obtain tree-ring sequences from Europe that align with key climatic and archaeological periods in the Northern Hemisphere, where most Late Pleistocene archaeological records are found.

This is where the Revine dataset plays a transformative role (Talamo *et al.*, 2023b).

Revine and radiocarbon calibration: a game changer

The Revine study analysed subfossil larch trees from the Venetian Prealps, dating between 18 475 and 17 350 years BP (Figure 1–3), a critical period that marked the end of the Last Glacial Maximum and the beginning of large-scale ice retreat in Europe. This time frame, known as Heinrich Stadial 1 (HS-1), was characterised by massive iceberg discharges into the North Atlantic, disrupting ocean circulation, altering global climate patterns and influencing human settlement strategies.

By applying high-resolution accelerator mass spectrometry (AMS) to tree-ring cellulose, researchers obtained sub-decadal radiocarbon measurements, significantly improving the resolution of existing datasets. These results demonstrated that atmospheric radiocarbon levels fluctuated much more dynamically than previously assumed, with ten times higher resolution than earlier calibration models such as IntCal20. A major discovery from this dataset is its strong correlation with solar activity, revealed through comparisons with ^{10}Be fluxes in Greenland ice cores.

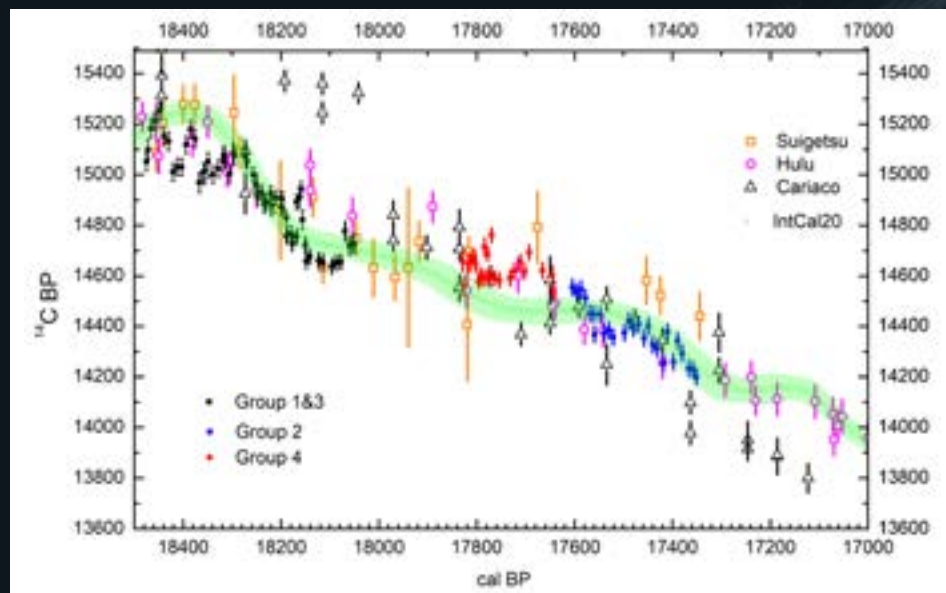


Figure 2: Taken by Talamo et al., 2023b. Revine groups placed at their marginal posterior mode calendar ages following comparison with ^{14}C measurements from Hulu Cave (purple circle) and Lake Suigetsu (green square) using the MCMC scheme described later. Also shown are the ^{14}C measurements of marine foraminifera from the Cariaco basin (black triangles).

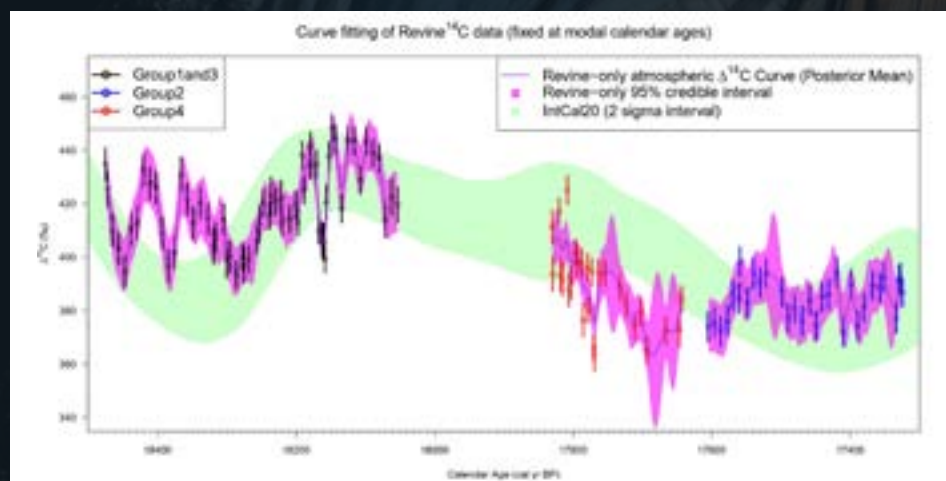


Figure 3: Taken by Talamo et al., 2023b: A reconstruction of $\Delta^{14}\text{C}$ based only upon the Revine ^{14}C tree-ring sequences located at their most likely (marginal posterior mode) calendar ages according to our MCMC calendar placement method, which splices them in alongside the Hulu and Suigetsu ^{14}C records. We show the much less precise (more uncertain) IntCal20 estimate as an underlay in green. The Revine observations are plotted with 1 σ error bars, while the IntCal and Revine curves show 95% (or 2 σ) probability intervals.

Cosmogenic isotope analysis and solar activity

Both ^{14}C and ^{10}Be are cosmogenic isotopes produced by cosmic rays interacting with Earth's atmosphere. While ^{14}C is absorbed into the biosphere and incorporated into tree rings, ^{10}Be settles in ice layers, making it an independent proxy for solar variability. When solar activity is low, Earth's magnetic field weakens, allowing more cosmic rays to enter the atmosphere, leading to an increase in both ^{14}C and ^{10}Be production.

By comparing high-resolution radiocarbon data from the Revine tree rings with ^{10}Be deposition in Greenland ice cores, researchers observed a remarkable alignment between peaks in ^{14}C production and increased ^{10}Be flux. This independent verification provides compelling evidence that the observed radiocarbon fluctuations are not artefacts of measurement inconsistencies but are directly linked to solar variability. The findings further reinforce the idea that solar forcing played a dominant role in atmospheric radiocarbon fluctuations during the Late Pleistocene, influencing the calibration

of radiocarbon dates for this period.

Refining calibration models with Bayesian analysis

To quantify the impact of these findings on existing radiocarbon calibration frameworks, a rigorous statistical analysis was conducted. Using Bayesian modelling techniques, researchers compared the Revine dataset against IntCal20 to determine whether the observed fluctuations were adequately represented in current calibration models.

The analysis revealed that IntCal20 tends to smooth out short-term radiocarbon variations, potentially leading to inaccurate age estimates for archaeological and paleoenvironmental records during periods of rapid change. To address this, Bayesian age modelling was applied to refine the floating tree-ring chronology and align it more accurately with existing calibration datasets. The results demonstrated that integrating high-resolution tree-ring sequences into radiocarbon calibration models provides a more detailed and precise Late Pleistocene chronology, improving the accuracy of radiocarbon dating for key prehistoric events.

Implications for archaeology and climate studies

Incorporating high-resolution tree-ring sequences into radiocarbon calibration models has far-reaching implications for both archaeology and paleoenvironmental research. The enhanced calibration of radiocarbon dates enables (Talamo et al., 2023a):

- more precise dating of human migrations, allowing researchers to reassess the movement and adaptation of prehistoric populations
- a better understanding of climate transitions, particularly those driven by solar variability and their impact on ecosystems and human societies
- improved chronological accuracy for key events, such as cultural transformations, faunal extinctions and the timing of glacial and interglacial phases.

By integrating cosmogenic isotope analysis, Bayesian statistical modelling and high-resolution tree-ring data, the Revine study offers a new level of accuracy in radiocarbon calibration. These advancements not only refine our understanding of past climatic and solar activity cycles but also provide archaeologists and climate scientists with a more reliable framework for interpreting the deep past.

The future of radiocarbon science

The Revine dataset represents just one step toward a broader effort to improve radiocarbon calibration. Researchers are

now expanding their investigations to include other high-resolution tree-ring records from different climatic regions, as well as integrating genetic and paleoenvironmental data to build a more complete picture of the past.

With the continued advancement of Radiocarbon 3.0, we are entering a new era of prehistoric research, one where the timelines of human history, climate fluctuations and environmental changes are reconstructed with unprecedented precision. The next frontier lies in expanding these datasets and integrating them into global calibration models, ensuring that we continue to refine our understanding of the past and its impact on the present.



For those eager to delve deeper into these breakthroughs, the research presented here is extensively documented in Sahra Talamo's latest book: "Misurare la storia La nuova linea del tempo dell'evoluzione umana" Raffaello Cortina Editore (Talamo, 2024), which explores the revolutionary findings of the ERC RESOLUTION project and its implications for the future of time measurement in archaeology.

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PROJECT SUMMARY

RESOLUTION aims to achieve an accurate and highly resolved chronology back to 55 000 years BP (Before Present), using some new floating sections of fossil trees. In fact, with tree rings, the resolution will be an order of magnitude higher, and using the most recent advances in the AMS technique, we will obtain confidence intervals of only a few centuries in glacial times.

In this way, we can establish in a precise way the timing of when *Homo sapiens* arrived in Europe, their interaction with Neanderthals and the final cause of the Neanderthal extinction.

The project involves fieldwork in the Mediterranean and Southeast Europe to find more glacial trees, study the existing collection of glacial conifers, exceptional ^{14}C precision for ^{14}C dates in the glacial, and the cutting-edge methodology linking floating tree-ring chronologies to ^{10}Be on the ice core scale.

PROJECT LEAD

Professor Sahra Talamo has been in the Department of Chemistry G. CIAMICIAN at Bologna University since 2019 and is the project lead for RESOLUTION. Talamo is the author of several international scientific papers concerning the chronology and interaction between the Neanderthal and *Homo sapiens*. Director of the new radiocarbon laboratory, BRAVHO (Bologna Radiocarbon laboratory devoted to Human Evolution).

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