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Analysing intra- and inter-site large-scale radiocarbon datasets: current approaches, challenges, and future perspectives

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Abstract - Analysing intra- and inter-site large-scale radiocarbon datasets: current approaches, challenges, and future perspectives - Large-scale radiocarbon databases are essential tools for studying broad-scale phenomena such as dispersal processes, socio-cultural transformations, and palaeodemographic fluctuations. The objective of this paper is to serve as a primer to help users navigate an increasingly complex landscape involving the analysis of such datasets. We review fundamental tools for understanding the use and potential of working with large radiocarbon datasets, while also highlighting the main caveats and methodological biases that may be encountered. The paper focuses on both intra-site chronological models, such as Bayesian and age-depth models, and inter-site modelling applied to various objectives, including the modelling of diffusion processes, and the use of dates as data as a proxy for reconstructing palaeodemographic trends and to infer socio-cultural changes in the past. Additionally, the paper discusses novel approaches for using radiocarbon dates in human biology and biochemistry, with a specific focus on the potential for integrating radiocarbon dates with other data types, such as archaeogenetic and isotope data.

Riassunto - Analisi intra- e inter-site attraverso l'uso di dataset di datazioni al radiocarbonio: approcci metodologici, sfide attuali e prospettive future: approcci metodologici, sfide attuali e prospettive future - I database di datazioni al radiocarbonio rappresentano strumenti fondamentali per l'analisi, attraverso l'uso di ampie serie di datazioni al radiocarbonio, di fenomeni su larga scala, come i processi di diffusione, le trasformazioni socioculturali e le variazioni paleodemografiche. Questo articolo si propone come una guida per orientare gli utenti in un panorama sempre più complesso, fornendo strumenti essenziali per comprendere sia l'utilizzo sia il potenziale dei grandi dataset di datazioni al radiocarbonio, mettendo al contempo in luce i principali rischi metodologici che possono sorgere. Il focus dell'articolo è duplice: da un lato, vengono esaminati i modelli cronologici intra-site, tra cui i modelli Bayesiani e gli age-depth models; dall'altro, si esplora la modellazione inter-site, applicata per vari scopi, come la simulazione dei processi di diffusione e l'utilizzo delle datazioni al radiocarbonio come proxy per ricostruire le variazioni paleodemografiche e i cambiamenti socioculturali nelle società del passato. Inoltre, vengono esaminati nuovi approcci per l'impiego delle date al radiocarbonio in biologia e biochimica umana, con particolare attenzione all'integrazione di date ^{14}C con altri tipi di dati, quali quelli archeogenetici e isotopici.

Introduction

More than seven decades have elapsed since the first archaeological objects dated by radiocarbon (^{14}C), wood samples from the Egyptian tombs of Zoser at Sakkara and Sneferu of Meydum (Libby- Anderson-Arnold 1949; Hajdas 2009). Radiocarbon dating has since become the most widely used technique for the dating of carbon-bearing organic and inorganic remains of past societies that lived up to 55,000/60,000 years ago. The development of this method for dating organic, such as wood, charcoal, collagen from bone, textiles (wool, silk, linen), seeds, soil, etc., and in some cases also inorganic (e.g. shells, cremated bones, mortars) materials by Libby and colleagues (Anderson *et al*. 1947; Arnold and Libby 1949) at the University of Chicago in 1946 was made possible by their studies on the radioactive decay of the isotope carbon-14. The technique has constituted a radical revolution in the fields of archaeology and Earth sciences.

Despite the frequent reference by archaeologists to radiocarbon dating as an absolute method for dating carbon-containing samples, the technique is not as absolute or precise as it may appear. Rather, it provides a probabilistic estimate of the true date. Uncertainty is inherent to every radiocarbon chronological estimate, such that the dating result is expressed as a time interval within which the true age is likely to be found. Two main sources of error affect the process of radiocarbon dating. The first category of errors pertains to the symmetric errors, whereas the second category encompasses asymmetric errors. The probabilistic symmetric errors are expressed by a Gaussian normal distribution, with a central point and an error that is homogeneously distributed around it. Consequently, this uncertainty can be modelled and described easily. As an example, the error associated with the measurement process in the laboratory, which is incorporated into the standard deviation. The treatment of asymmetric errors is more challenging since they do not follow a Gaussian distribution. This category encompasses a range of potential errors, including those related to the calibration and the intrinsic properties of the sample. These may include discrepancies arising from the different lifespans of samples (short-lived samples vs long-lived samples), the old-wood effect, and the influence of marine or freshwater reservoir effect. Short-lived samples, such as seeds, small twigs, and bone samples derive from organisms characterised by a relatively short time span; their radiocarbon ages therefore closely approximate the event being dated. On the contrary, long-lived samples, including wood from fully-grown trees or charcoal derived from them, may incorporate an inbuilt age, as the carbon fixed during the organism's lifetime can be older than the event under study by various decades or even centuries. The old-wood effect occurs when radiocarbon dating is performed on wood or charcoal samples that comes from the inner (older) growth rings of a long-lived tree or from reused timber. Since the carbon in the wood reflects when the tree tissue formed, and not when the tree was cut or used, the resulting date can be significantly older than the actual event of human activity associated with it. Eventually, the marine and freshwater reservoir effects occur because aquatic organisms can incorporate 'old' carbon from dissolved inorganic sources, making them appear artificially older in radiocarbon dates than their true age. Radiocarbon dating is therefore a probabilistic inference, the result of uncertainty and measurement error (Buck *et al*. 1991; Bayliss *et al*. 2007; Bayliss 2009; Weninger *et al*. 2011). The precision and accuracy of radiocarbon dates depend on the sample collection in the field, the protocol followed in the process of dating (including sample pretreatment, CO_2 extraction, graphitization, and measurement), the shape of the calibration curve, and the algorithm used to construct the probability interval within which the true date may be found.

The fundamental unit in radiocarbon dating is the ^{14}C date, which corresponds to a single event. This event involves the separation of a carbon-bearing material from the source from which that carbon was obtained (van Strydonck *et al*. 1999: 434). In practical terms, this event usually represents the death of an organism, the moment from which its radiocarbon content begins to decline and can be measured by the ^{14}C method. Depositional events (e.g. the use of a fireplace) and archaeological events (e.g. the time span of use of an archaeological site) do not directly correspond to the moment in which a living being – animal or plant – ceased to interact with the atmosphere and biosphere. Rather, they are composed of a number of single events with specific durations and locations in time. A chronological inference chain was proposed to define these and more complex events (Bogdanović-Barceló-Capuzzo 2012; Barceló-Capuzzo-Bogdanović 2014). This chain is composed of four levels, from the lowest to the highest. The sequence of events can be delineated as follows: *isotopic event*, *depositional event*, *archaeological event*, and *social event*. The *isotopic event* corresponds to a radiocarbon date, therefore it is a single event defined by the interruption of carbon exchange between the organism and the biosphere. The *depositional event* is defined as the specific action that resulted in the placement of an item, such as a fireplace or a floor, at a specific location and time. To ensure the greatest precision and accuracy, the date of the depositional event must be composed of more than one isotopic event. The *archaeological event* is situated above the depositional event. It represents the material consequence of social actions that occurred in the past and it is composed of many different particular depositional events, each with a distinct calendar age and duration. On top of the chain it is located the *social event*, representing the social action that produced the body of material evidence visible in the archaeological record. This structure implies that all the events, with the exception of the isotopic one, are an assemblage of subsets of punctual events with varying durations. Therefore, a single date, which corresponds to the isotopic event in the inference chain, is inadequate for determining the duration of more complex events, such as the archaeological and the social events, whose time span can be reconstructed only using an assemblage of ^{14}C dates. This chain shows, therefore, the necessity of utilising aggregates of radiocarbon dates to accurately date an archaeological site or to reconstruct more complex phenomena. The statistical analysis of these aggregates can assist in providing answers to a diverse range of research questions.

As a consequence, a remarkable growth in the publication of a considerable number of radiocarbon databases has characterised the last decades (see *Appendix: Software and Datasets*). These are often collation of data from site reports (and in some cases from pre-existing databases, or even previous aggregation of multiple databases) and generally contain key metadata such as the sampling location and the specific object being dated. Furthermore, efforts have been made to standardise data entry in accordance with the FAIR (Findable, Accessible, Interoperable, and Reusable) data principles. However, the quality and the detail of the information provided differ significantly. Some databases are limited to terrestrial samples and do not provide much additional information on the stratigraphic context of recovery or references to the original site reports, while others provide a large number of metadata that can dramatically improve research opportunities, particularly when associated with so-called 'data-papers'[1]. Concerns about the interoperability of these datasets have been raised, mainly related to the reusability of archaeological radiocarbon data. Consequently, software packages have been designed to enable exploration and querying of data physically stored in different repositories (Schmid-Seidensticker-Hinz 2019; Bird *et al.* 2022). Radiocarbon databases are an essential tool when large-scale radiocarbon datasets are needed for the study of broad-scale phenomena, such as dispersal processes, socio-cultural changes, and palaeodemographic fluctuations. In parallel to the increase in the number of radiocarbon dates and available datasets, new methods and software have been developed to facilitate the statistical analysis of radiocarbon data (see Section 3).

The objective of the paper is to serve as a primer for navigating an increasingly complex landscape, providing basic users with the fundamental tools to understand the use and potential of working with large radiocarbon datasets, while highlighting the main caveats and methodological biases that may be encountered. The paper is divided into four sections: Part 1 is the introduction; Part 2 represents an overview of the ba-

[1] It is worth noting that the Journal of Open Archaeology Data, one of the leading platforms for archaeological data-papers, has published 14 different radiocarbon databases between 2016 and 2024.

sic principles of radiocarbon dating and the distinction between uncalibrated and calibrated ^{14}C dates. Part 3 is devoted to the transition from individual ^{14}C dates to multiple dates and events, which are employed as proxies for inter- and intra-site modelling (stratigraphic sequences and age depth-models), regional analyses (Bayesian and space-time models) and palaeodemographic inferences. Part 4 presents novel approaches to using radiocarbon dates in human biology and biochemistry, with a particular focus on the potential of integrating radiocarbon data with other data types, such as archaeogenetic and isotope data. This combination has the potential to facilitate new developments within the discipline.

BASIC PRINCIPLES BEHIND RADIOCARBON DATING

Radiocarbon dating technique is founded upon the natural phenomenon of radioactive decay of carbon-14 (^{14}C), which is caused by the higher number of neutrons (8) in the nucleus compared to protons (6). Due to this inherent instability, the atomic nucleus tends to revert to its previous stable state through the emission of □ particles (radioactive decay). Consequently, the initial carbon-14 atom is transformed into a nitrogen-14 atom. The duration of this process is known and corresponds to 5,730 ± 40 years, during which the original percentage of ^{14}C in a carbon sample reduces to half. The carbon-14 isotope is continuously produced in the stratosphere and upper troposphere as a consequence of the interaction between the atoms of nitrogen and the cosmic rays. When a neutron collides with a nitrogen atom, a nitrogen-14 atom (comprising seven protons and seven neutrons) turns into a carbon-14 atom, an unstable isotope that tends to recover its original atomic signature. The processes of generation and degradation of ^{14}C are naturally in equilibrium in the atmosphere. This is because ^{14}C radioactive (unstable) isotopes are mixed with the stable non-radioactive isotopes (^{12}C and ^{13}C) in the carbon dioxide present in the atmosphere. In the lower part of the Earth's atmosphere, the concentration of carbon-14 is approximately one part per trillion (ppt) (Bowman 1990). In comparison to the other carbon isotopes, ^{12}C and ^{13}C, the concentration of the ^{14}C in the atmosphere is notably low, with only one in a trillion carbon atoms being ^{14}C.

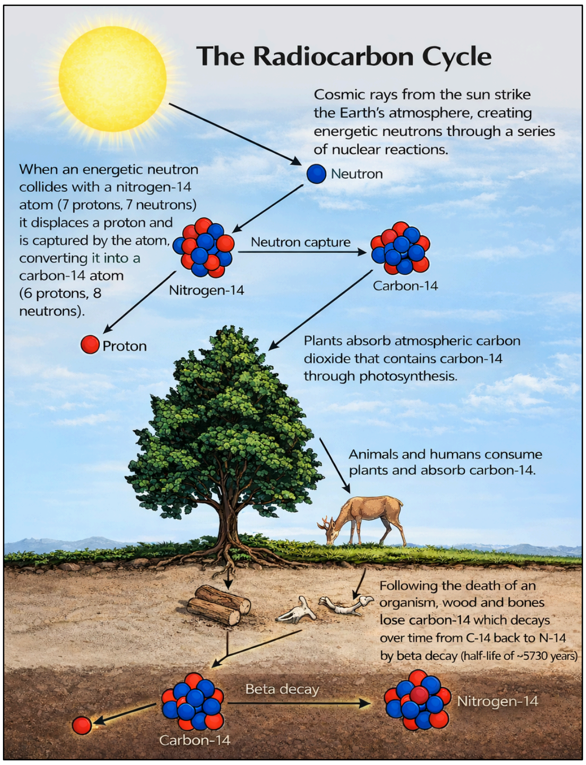

Fig. 1 – Schematic overview of the radiocarbon cycle.

Rappresentazione schematica del ciclo del radiocarbonio.

Through the process of photosynthesis, atmospheric CO_2 is incorporated into the biological cycles, with ^{14}C being absorbed by plants. This results in a decrease in the ^{14}C/^{12}C ratio, due to the phenomenon of isotopic fractionation. Subsequently, ^{14}C is incorporated into human and animal tissues via the food chain (fig. 1). Following the death of a living organism, the exchange process ceases and isotopes of ^{14}C are no longer incorporated by the organism. From this point onwards, the percentage of ^{14}C in the organic sample begins to decrease at a constant rate. After 5,730 years, approximately half of the original amount of ^{14}C has decayed. By knowing the half-life of this isotope and measuring the radiocarbon composition remaining in the sample, a carbon-bearing material can be dated (Bowman 1990). Initially, samples were radiocarbon dated using Gas Proportional Counting (GPC), and from the 1960s onwards, Liquid Scintillation Counting (LSC), both of which involved measuring the amount of radioactivity (□ particles) emitted

(Hogg and Cook 2022). Since the 1980s, advances in Accelerator Mass Spectrometry (AMS) have enabled the direct separation and counting of ^{14}C atoms from other carbon isotopes, on the basis of their atomic mass (Harris-Gove-Damon 1987; Linick *et al*. 1989). This improvement permitted the dating of samples of a much smaller weight and size (only ca. 1 mg of carbon is required for the AMS technique).

Radiocarbon dates are commonly expressed in years before present (BP), with AD 1950 serving as a conventional baseline, and are associated with a standard error related to measurement (Stuiver and Polach 1977). An uncalibrated radiocarbon date can thus be described as a Gaussian distribution formed by a central point and a homogeneously distributed error, i.e. the standard deviation (SD), around it. However, it is important to note that '^{14}C years' are not necessarily equivalent to 'calendar years'. Indeed, the concentration of ^{14}C has not been uniform throughout the large time span of the astronomical scale (Aitken 1990; Bowman 1990). A number of factors have been identified as responsible for variations in the percentage of ^{14}C in the atmosphere. These include variations in the flow of galactic cosmic rays, changes in solar activity and the geomagnetic field of the Earth, climatic changes, volcanic eruptions, and the past century nuclear bomb testing. This implies that radiocarbon dates must be calibrated to be converted into calendar years (BC/AD or BCE/CE or cal BP) (fig. 2).

Calibration curves have been constructed for the purpose of correcting radiocarbon dates, such as the atmospheric curves IntCal20 (Reimer *et al*. 2020) for the northern hemisphere and SHCal20 (Hogg *et al*. 2020) for the southern hemisphere, and the marine-specific calibration curve Marine20 (Heaton *et al*. 2020), all of which extend until 55,000 years cal BP. Such curves are developed by radiocarbon dating materials of known age through the applications of techniques such as dendrochronology, uranium-thorium dating, and geological stratigraphy. The shape of atmospheric calibration curves is complex, exhibiting wiggles and plateaus that reflect ^{14}C variations over time in the atmosphere. Furthermore, the resolution of the calibration curves is also not uniform: some sections have data resolution that enables a more precise representation of atmospheric ^{14}C values, whereas in other sections, interpolated data do not provide the same level of precision and accuracy. Indeed, the principal non-Gaussian error in radiocarbon estimates is related

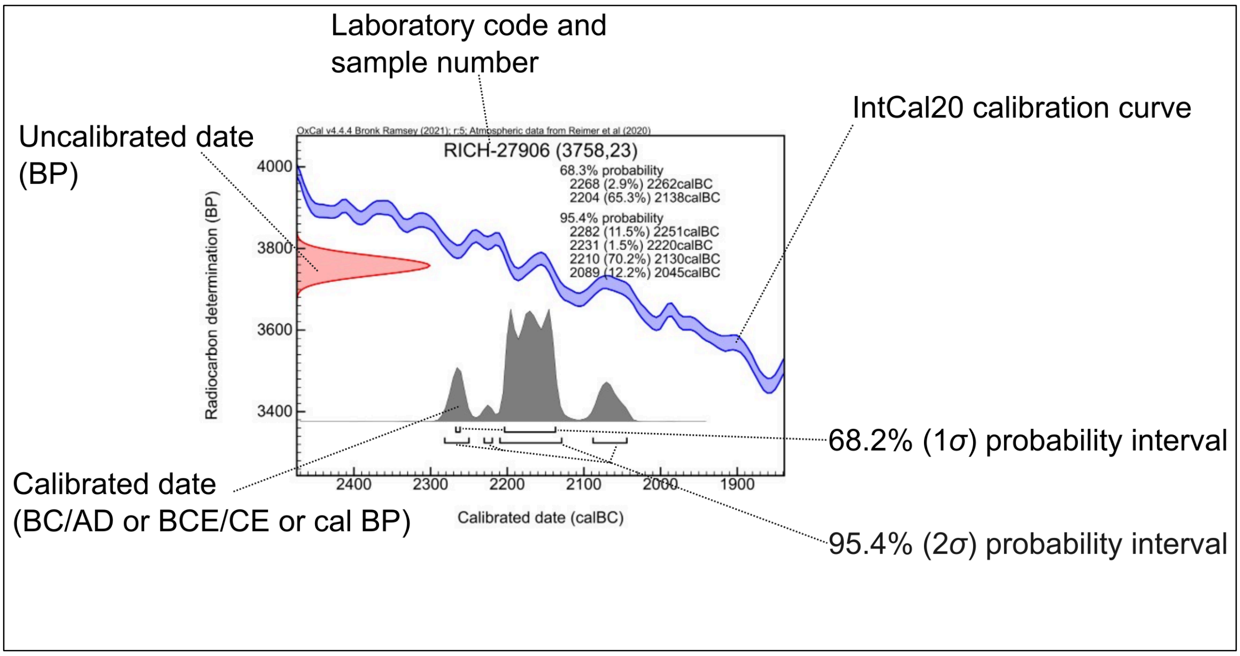

Fig. 2 – OxCal plot of an uncalibrated and calibrated radiocarbon date.

Grafico OxCal di una data radiocarbonica non calibrata e calibrata.

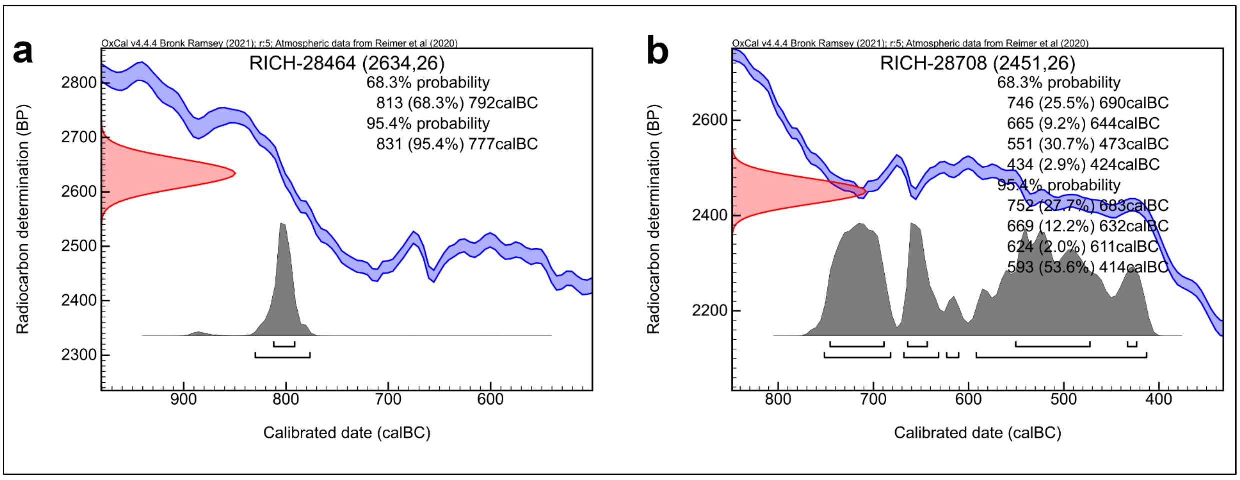

Fig. 3 – OxCal plots showing the impact of calibration on two radiocarbon dates, each with an identical standard deviation. Data from Capuzzo *et al*. (2023). These dates are placed at (a) a steep section of the calibration curve (referred to as a calendar age step) and (b) a flat section of the IntCal20 calibration curve, known as the Hallstatt plateau.

Grafici OxCal che mostrano l'impatto della calibrazione su due date radiocarboniche, ciascuna con identica deviazione standard. Dati da Capuzzo et al. (2023). Le date sono collocate (a) in un intervallo ripido della curva di calibrazione (definito calendar age step) e (b) in un intervallo piatto della curva di calibrazione IntCal20, noto come plateau di Hallstatt.

to the calibration curve and the process of calibration. While the uncertainty of a ^{14}C measurement (standard error of a BP date) can be represented by a symmetrical normal distribution, centred around its mean, a calibrated radiocarbon date is not symmetrical. Consequently, the central tendency is not a straightforwardly interpretable parameter. This implies that the probability of estimating the true date outside the central point of the calibrated interval does not significantly decrease as we move away from that point. It is therefore not possible to consider the mean, median, or any other single value from any part of the calibrated range as representative of a possible meaningful central tendency that does not exist. Consequently, calibrated radiocarbon dates must be expressed in probabilistic terms, using the 95.4% (2σ) and 68.2% (1σ) probability intervals (Millard 2014). The shape of the calibration curve strongly influences the shape of the resulting calibrated probability distribution (fig. 3). More precise confidence intervals are obtained at the points in the calibration curve where the curve steepens, which correspond to the so-called calendar age steps (Williams 2012) (fig. 3-a). Conversely, plateaus are responsible for large calibrated confidence intervals, which frequently span several centuries. One example of this is the well-known Hallstatt plateau, a flat section of the IntCal20 calibration curve located between 750 and 420 BC, which was caused by variations in solar activity (Jacobsson *et al*. 2018; Rose *et al*. 2022) (fig. 3-b).

From individual ^{14}C dates to multiple dates and events

The *quality*, both in terms of precision and accuracy, of individual ^{14}C dates has seen and continues to see dramatic improvement in the last 30 years. The widespread availability of accelerator mass spectrometry (AMS) and the continuous improvement of calibration curves are cornerstones of these achievements. But perhaps the most striking change observed in the last few decades is the exceptional increase in the *quantity* of dated samples, and the associated development of novel statistical approaches. In a review article from 2009, Alex Bayliss (2009) refers to this as the 'third radiocarbon revolution', following the introduction of radiometric dating (the 'first radiocarbon revolution') and the impact of the calibration process (the 'second radiocarbon revolution'). The 15 years that followed Bayliss' review article saw further developments of this 'third' revolution, with an expansion from site-level to regional-scale modelling, partly promoted by the increasing availability of large radiocarbon databases.

Individual ^{14}C dates provide information on when a sampled organism died, but it is often the case that our primary goal is not to date such an event but an event that is *associated* with what is actually being dated. This is an important distinction and effectively leads us to a spectrum of different dating practices. On the one end, we might be just exclusively interested in the sample date. For example, dating the human remains recovered at the presumed site of the Grey Friars friary in Leicester, UK, was a key step in determining whether the individual was King Richard III (King *et al*. 2014). In some cases, the dated sample (i.e. the *isotopic event*) in question might be assumed to be contemporary to another event (e.g. a charcoal sample from a hearth would represent an episode of human occupation and use of fire), although such association can often be problematic (e.g. 'old-wood' effect, (Ward and Wilson 1978)). On the other end of the spectrum, we might be interested in more elusive events, such as *social events*, that are theoretically impossible to date directly. For example, we might be interested in estimating when a domesticated crop was introduced in a particular geographic region (e.g. Leipe *et al*. 2019; Crema-Stevens-Shoda 2022). In such a scenario, the earliest directly dated specimen of such crop would solely provide a *terminus ante quem*, and the proximity to the 'true' arrival date will in part depend on the sample size. The distinction between these two examples is fundamentally a reflection of whether we are carrying out descriptive or inferential statistics. In the former case, we are mainly just interested in the property of our samples alone, while in the latter case, we are interested in some property of the underlying statistical population.

The key objective of any inferential statistic is to relate observed samples to a statistical population that is modelled using a probability distribution model. Thus, if we continue with the example introduced above, one could assume that dates from our charred crop follow a uniform probability distribution, or more formally:

$$P(t) \sim \text{Uniform}(a,b) \quad [1]$$

where $P(t)$ is the probability of the sample being of age t, and a and b are the parameters of our statistical model, in this case defining its chronological boundaries. If we represent time t as BCE/CE using negative and positive values respectively[2], then $P(t)=0$ when $t < a$ or $t > b$, while $P(t) = 1/(b-a)$ when $a < t < b$. If we consider b to be the end of our temporal sampling window, then a represents the moment when the crop appears in our region according to our model. Equation [1] comes with an important assumption: a given sample of a charred crop has the same probability of being from any point between a and b. While this is a simple and perhaps convenient assumption, one could speculate, for example, that is more likely that a random sample of charred crops remain to be from later periods due to the diffusion of farming practices within the particular region (Crema *et al*. 2024a). Thus, one could use alternative probability distribution to [1], which would ultimately entail different estimates of the arrival date. Assumptions matter.

Inferential statistics can be approached in many ways, but the chronological modelling of radiocarbon dates has mostly relied on a Bayesian inferential paradigm. Indeed, the analyses of radiocarbon dates represent one of the first (Buck-Litton-Smith 1992) and undoubtedly the most common sub-field in archaeological science where the use of Bayesian inference has effectively become a norm (Otárola-Castillo and Torquato 2018). There are indeed several intrinsic advantages to this paradigm, but perhaps three aspects are particularly worth highlighting here. First, Bayesian statistics are particularly well suited when the objective is to estimate parameters and report any forms of uncertainty associated with them. P-values are effectively of little use when the goal is to determine the time of a particular event and confidence intervals are not well suited to describing the complex shapes of probability distributions dictated by the idiosyncrasies of the calibration curve. Second, as noted in the section "Basic principles behind radiocarbon dating", individual ^{14}C dates are associated with a measurement error that is often of considerable magnitude in relation to the target event of in-

[2] For simplicity we assume there is a year '0', using astronomical year numbering.

terest. As such, estimations should formally take into account and 'inherit' the uncertainties observed at the level of individual samples. Third, contextual information can greatly improve the inferential process by, for example, adding constraints (e.g. sample A is known to be older than sample B), or other forms of priors to reduce the uncertainty of the estimated parameters. These three aspects are naturally intertwined but can be all expressed as part of a hierarchical Bayesian model. While early applications of Bayesian and other techniques for the analyses of multiple radiocarbon dates were severely limited by the lack of dedicated software packages, the last decade saw a dramatic change. New software packages are continuously being developed, both as stand-alone and as add-on libraries in widely used programming languages such as R and Python (see *Appendix: Software and Datasets*). Crucially, and contrary to some of the earliest stand-alone software packages, many of the most recent developments are open-source, providing the necessary transparency on hidden assumptions of some of these techniques and simultaneously fostering opportunities for further development.

Thanks in part to the development of these new software packages, archaeological case studies involving analyses of multiple radiocarbon dates have become common, particularly in developing intra-site chronologies. Below, we briefly review existing applications focusing on three areas of application: intra-site modelling, regional analyses, and palaeodemography and cultural phenomena. While these do not represent the full range of examples where multiple radiocarbon dates are statistically examined in archaeology, they all provide an overview of the opportunities as well as the challenges of different research agendas.

Intra-site modelling

Intra-site analyses of radiocarbon dates undoubtedly represent the most successful and common area of research where the analyses of multiple radiocarbon dates, particularly via Bayesian analyses, have flourished. Software packages such as *OxCal* (Bronk Ramsey 1995, 2009) have now become a standard tool used by many archaeologists to date specific site contexts combining radiocarbon dates and stratigraphic information. While an extensive review of these applications is outside this paper (interested readers can consult a larger number of review studies, for example (Buck-Cavanagh-Litton 1997; Blaauw and Heegaard 2012; Bayliss 2015; Pettitt and Zilhão 2015; Buck and Meson 2015; Lacourse and Gajewski 2020; Bayliss and Marshall 2022), here we briefly describe two common approaches as they highlight principles that can be extended to applications beyond the analyses within individual sites: *phase modelling* and *age-depth modelling* (fig. 4).

Phase modelling (fig. 4-a) starts by formally integrating stratigraphic context in the inferential process. In practical terms, given a set of *n* radiocarbon-dated samples, we can obtain information on 1) the stratigraphic context of recovery; and potentially 2) the temporal relationship between the contexts. Suppose, for example, that we have four samples from a hypothetical stratigraphic unit X, an additional nine samples from stratigraphic unit Y and that we know that X superimposes Y, i.e. context X is assumed to be younger than Y. If we assume that our samples are from any point in time during the formation of contexts X and Y, we can model our radiocarbon dates as two sets of uniform distributions with start dates a_X and a_Y and end dates b_X and b_Y. This adds some constraints to our inference so that samples from context X will be dated between a_X and b_X, samples from context Y between a_Y and b_Y, and b_X will be assumed to be equal to a_Y. Software applications such as *OxCal* can provide estimates of the four parameters (i.e. a_X, a_Y, b_X, and b_Y) as well as posterior dates of individual ^{14}C samples amongst other things (Bronk Ramsey 2009)[3]. Importantly the posterior dates would often be different from the calibrated probability distribution one would obtain without considering these stratigraphic assumptions: the additional set of

[3] Additional pieces of information include diagnostic tools such as agreement indices (i.e. effectively how much the model assumption modifies the posterior calibrated distribution of each date) and outlier probabilities, offering ways to re-assess the extent to which the assumptions formalised in the model holds.

constraints effectively reduces the range of possible calendar dates for each sample.

Age-depth modelling (fig. 4-b) also incorporates additional information associated with each sample, in this case by simply providing information of relative order (e.g., *Sample-001* being older than sample *Sample-013*) and depth (e.g., *Sample-001* recovered at 195 cm from the surface, *Sample-013* recovered at 99 cm from the

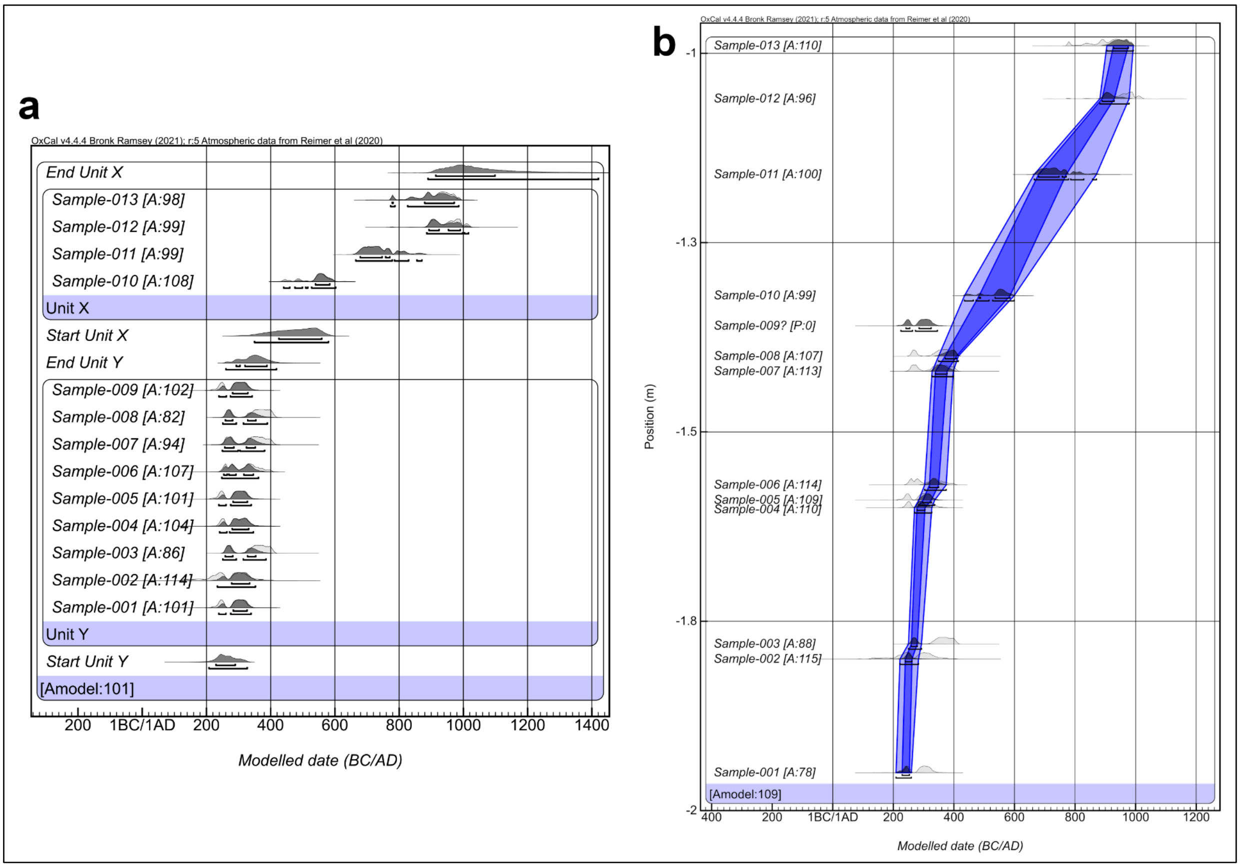

Fig. 4 – An example of (a) a two-phase Bayesian model and (b) an age-depth model implemented by the software package OxCal (Bronk Ramsey 1995, 2009). Data from Cherretté *et al.* (2021). The Bayesian model (a) estimates the start date and the end date of Units X and Y by modelling the calendar dates of thirteen ^{14}C samples (*Sample-001 ~ Sample-013*). The age-depth model (b) constrains the calibrated probability distributions of each date (*Sample-001 ~ Sample-013*) on the basis of the stratigraphic information related to each sample (i.e. the depth). Both models account for the measurement error of each observation, and as such, individual calibrated distributions are 'updated' (light-grey distributions indicate the calibrated distribution without the model for each date whilst the dark grey represents the posterior models) accounting for assumptions of the model and the other observations. The agreement indexes [A] provide an effective means of gauging the extent to which any posterior distribution agrees with the prior distribution (Bronk Ramsey 1995, 2009). A date may be defined as an outlier when the agreement index is less than 60%, as exemplified by *Sample-009* in the age-depth model. In such instances, the confidence interval of the date does not statistically fit into the model. The OxCal codes to generate the figure can be found on https://github.com/ercrema/capuzzo_crema_2024.

Esempio di (a) un modello bayesiano a due fasi e (b) un modello età-profondità implementati dal software OxCal (Bronk Ramsey 1995, 2009). Dati da Cherretté et al. (2021). Il modello bayesiano (a) stima le date di inizio e fine delle Unità X e Y modellando le date di tredici campioni ^{14}C (Campione-001 ~ Campione-013). Il modello età–profondità (b) vincola le distribuzioni di probabilità calibrate di ciascuna data (Campione-001 ~ Campione-013) sulla base delle informazioni stratigrafiche associate a ciascun campione (ovvero la profondità). Entrambi i modelli tengono conto dell'errore di misura di ciascuna osservazione e, di conseguenza, le singole distribuzioni calibrate vengono rese più precise (le distribuzioni in grigio chiaro indicano le distribuzioni calibrate a priori senza il modello, mentre quelle in grigio scuro rappresentano le distribuzioni a posteriori), incorporando le assunzioni del modello e le altre osservazioni. Gli indici di concordanza [A] rappresentano un mezzo efficace per valutare il grado di affinità tra distribuzioni a posteriori e a priori (Bronk Ramsey 1995, 2009). Una data può essere definita outlier quando l'indice di concordanza è inferiore al 60%, come nel caso del Campione-009 nel modello età-profondità. In tali casi, l'intervallo di confidenza della data non si adatta statisticamente al modello. I codici OxCal utilizzati per generare la figura sono disponibili su https://github.com/ercrema/capuzzo_crema_2024.

surface). The object in this case is to formally model the relationship between depth and time on the basis of the observed samples so that one can potentially 'date' a particular phenomenon associated with a particular depth. For example, Parnell and colleagues (2008) examined pollen records from six different sites in northern Europe to determine the synchronicity of particular shifts in vegetation composition (e.g. increase in *Alnus*, decline in *Ulmus*, etc.). These key events can be identified at specific depths in the pollen core but are not directly associated with ^{14}C dates. Hence age-depth models were constructed to estimate *when* abrupt changes in the pollen frequencies were observed. The uncertainty, in this case, is dictated by the distance between a target depth of interest and the closest known dated sample as well as other factors such as the error associated with individual radiocarbon samples, the number of samples, and the rate of deposition.

As mentioned above, both *phase* and *age-depth* models are routinely used in archaeology and palaeoenvironmental studies. Many of these models have also become more complex, integrating multiple contextual information in the form of priors and constraints, enabling scholars to achieve increased precision in their estimates. As we note below, however, these high levels of precision are not necessarily accompanied by an equally high level of accuracy. The flexibility to constrain the model can indeed accidentally promote the inclusion of unwarranted assumptions, and the extent to which diagnostic tools can detect them inevitably differs case by case (for further discussion see: Buck and Meson 2015).

Regional analyses

While intra-site analyses benefited from a strong and coherent three-decade tradition of studies, applications, and pipelines, regional analyses of ^{14}C dates are somewhat a mixture of different approaches reflecting both a wider range of scholarly interests and backgrounds and the breadth of research questions. On the one hand, some of the approaches developed in intra-site contexts have been naturally extended to include multiple sites within a region, effectively employing the same basic principles used for stratigraphic phase models and age-depth models. On the other hand, a plethora of new and independent approaches have been and continue to be developed, tailored to address specific questions that cannot be easily tackled by just modifying slightly the premises of existing approaches developed within inter-site contexts. As we will see below, in some cases this second strand often disregards key issues such as the appropriate handling of chronological uncertainty and sampling error, leading to analytical outcomes that are potentially subject to substantial biases.

An example of a method originally developed for intra-site analyses and adapted to regional context is phase modelling. The intuition in this case is to treat particular phenomena protracting over time as something analogous to a stratigraphic unit. Thus for example, Bayesian phase models have been used to estimate the start and end date of archaeological cultures and regional phases (Ziedler-Buck-Litton 1998; Capuzzo-Boaretto-Barceló 2014; Long and Taylor 2015; Manning *et al*. 2014; Banks *et al*. 2019; Brunner *et al*. 2020; Crema and Kobayashi 2020). A related application is the estimate of arrival times or origination date, where the focus is the inference of the start of one or more distribution, entailing again the use of Phase models (Blackwell and Buck 2003; Leipe *et al*. 2019; Leipe *et al*. 2020; Crema-Stevens-Shoda 2022) and more recently of optimal linear estimation (OLE), a tool original devised in palaeontology and conservation science to estimate extinction dates from sparse observations (Bebber and Key 2022; Djakovic-Key-Soressi 2022; Key-Roberts-Jarić 2021).

Another common range of applications involves the use of regression analyses where radiocarbon samples are either the predictor or the response variable. Examples of these kinds of regional analyses often focus on the study of the origins and diffusion of farming and include analyses of evolutionary rates of plant domestication traits (Purugganan and Fuller 2011), estimates of dispersal rates of farming (Pinhasi-Fort-Ammerman 2005; Bocquet-Appel *et al*. 2012; Fort 2015; van Etten and Hijmans 2010; Mazzucco *et al*. 2018) and identification of putative points of origin of domestication (Silva *et al.* 2015). On the one hand, the level of sophistication of many of these applications goes well beyond what is

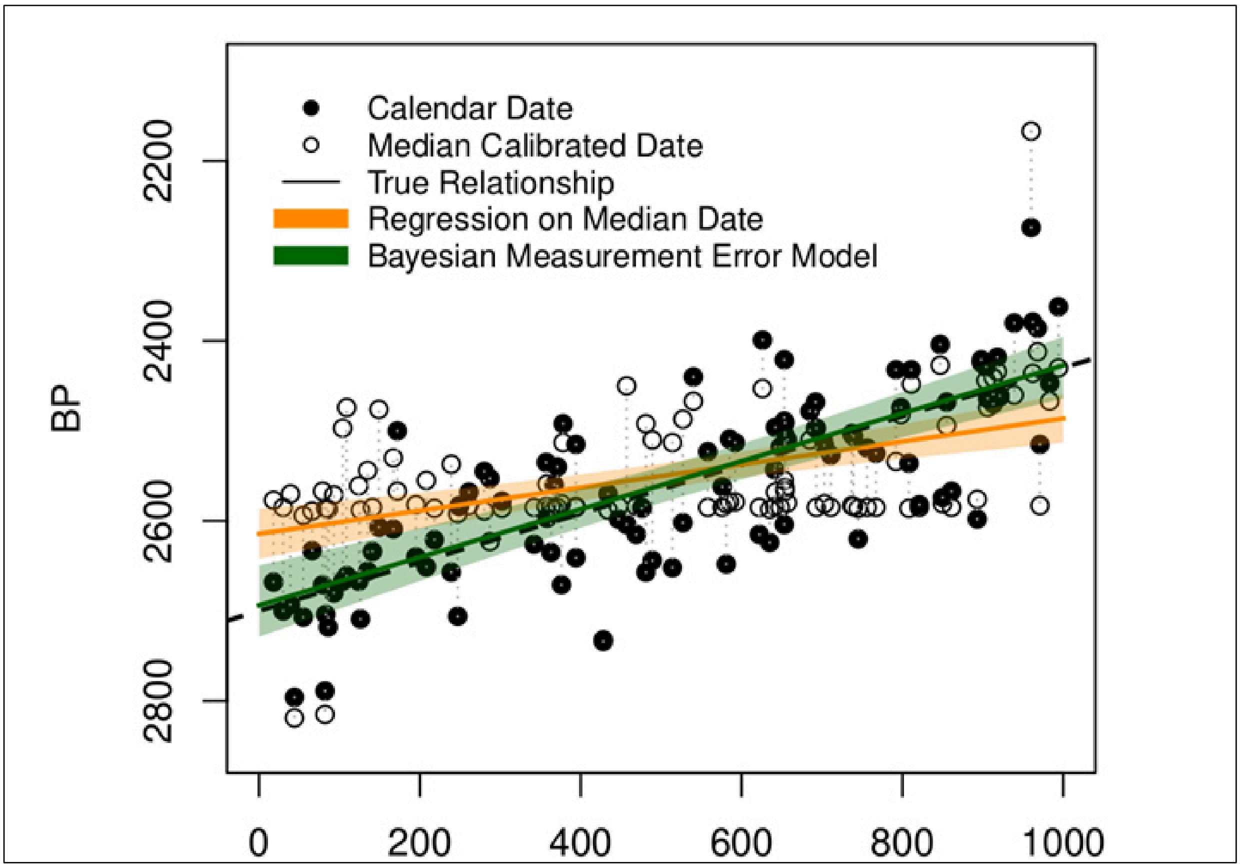

Fig. 5 – Measurement error bias on regression analysis carried out on median calibrated dates. Solid dots are simulated as calendar dates conditional to an independent variable x, more with a mean μ_i of the sample i equivalent to 2700 - 0.27027 * xi and standard deviation equal to σ equal to 70. Circle dots were obtained by: 1) back-calibrating each calendar date to 14C age; 2) assigning an error of 30 years; 3) calibrating into calendar date; and 4) extracting the median calibrated date. The presence of a calibration plateau around 2450 14C age lead samples with different calendar dates to have their median calibrated date 'pulled' towards 2600 cal BP. As a result, regression analyses on median calibrated dates (in orange, with 95% CI shown as an envelope) fail to recover the true relationship (95% CI intercept: 2586 ~ 2641; 95% CI slope: -0.175 ~ -0.08) shown in as dashed lined. In contrast, a Bayesian regression model (in green, with 95% HPDI shown as an envelope) that accounts for the measurement error and structure can successfully recover the true relation between the dates and x (95% HPDI intercept: 2653 ~ 2731; 95% HPDI slope: -0.327 ~ -0.204). Further details and the R script to generate the figure can be found on https://github.com/ercrema/capuzzo_crema_2024.

Effetto del bias da errore di misura su un'analisi di regressione condotta sulle mediane delle date calibrate. I punti pieni rappresentano date di calendario simulate condizionate a una variabile indipendente x, con media μ_i del campione i pari a 2700 - 0,27027·x_i e deviazione standard σ = 70. I punti circolari sono stati ottenuti: (1) retro-calibrando ciascuna data di calendario in età ^{14}C; (2) assegnando un errore di 30 anni; (3) calibrando nuovamente in data di calendario; e (4) estraendo la mediana della data calibrata. La presenza di un plateau di calibrazione attorno a 2450 anni ^{14}C induce campioni con date di calendario differenti ad avere mediane calibrate attorno al ~2600 cal BP. Di conseguenza, le analisi di regressione basate sulle mediane delle date calibrate (in arancione, con IC al 95% mostrato come banda di incertezza) non riescono a recuperare la relazione reale (IC 95% intercetta: 2586 ~ 2641; IC 95% pendenza: -0,175 ~ -0,08), mostrata con linea tratteggiata. Al contrario, un modello di regressione bayesiano (in verde, con HPDI al 95% mostrato come banda di incertezza), che tiene conto dell'errore di misura e della struttura dei dati, riesce a ricostruire correttamente la relazione reale tra le date e x (HPDI 95% intercetta: 2653 ~ 2731; HPDI 95% pendenza: -0,327 ~ -0,204). Ulteriori dettagli e lo script R per generare la figura sono disponibili su https://github.com/ercrema/capuzzo_crema_2024.

offered by simple linear regression analyses, providing exceptionally detailed insights into the origin and diffusion of agriculture. On the other hand, however, chronological uncertainties associated with ^{14}C dates are minimally accounted for or even entirely ignored in many of these applications, with median-calibrated dates typically used to represent the time-stamp of each sample. The consequences of this analytical shortcut are likely to vary depending on the nature and scale of the analyses. Nonetheless, in some cases, the use of median dates can profoundly impact the result of analyses, in particular when used for calibrated dates located on a plateau. Figure 5 illustrates this point with a simple linear regression on a simulated dataset where the response variables are dates conditioned by some hypothetical independent variable *x*. When the analyses are carried out on median calibrated dates, a systematic error determined by the calibration curve can lead to a biased estimate that fails to accurately recover the true relationship between the dates and *x*.

Robust alternatives to the use of median dates do exist. Riris and Silva (Riris and Silva 2021) for example, combine the result of multiple regression analyses carried out by random sampling dates from the calibrated probability distributions, whilst Crema and colleagues (Crema-Stevens-Shoda 2022) employ a Bayesian measurement error that shares the same statistical principles as those underlying phase models. Figure 5 shows how these alternative approaches provide superior accuracy as they fully account for the measurement errors associated with each sample as well as the idiosyncratic nature of calibration curves. While in some instances (e.g. large temporal scales) the use of median calibrated might be acceptable, readers should avoid using them in most cases.

A second major issue in the analyses of regional ^{14}C data concerns sample interdependence and, more broadly, sampling bias. By nature, legacy data contains samples collected for different purposes with different strategies and intensities. As a result, imbalanced data, i.e. datasets with significant variations in the number of observations across particular classes or grouping variables, are very common in the regional analyses of radiocarbon dates. Yet, in many cases, samples are treated *as if* they are independent leading to potentially biassed estimates. For example, regional phase models and estimates of arrival dates often contain multiple samples from the same site or even the same stratigraphic contexts, but analyses are often undertaken ignoring this factor. To use an extreme example, ignoring sample interdependence means that when estimating the origination date of a particular technology we consider 40 ^{14}C dates from 40 different archaeological sites to be the same as 40 ^{14}C dates from one site. Clearly the latter will only provide the origination date at one particular site and does not represent the entire region. Similar problems apply when we estimate changes in the proportion of a particular class of dates over another (e.g. dates on domesticated vs wild plants, cremation vs inhumation, etc.). As for chronometric uncertainty, solutions to this problem require just an extension of the same principles developed within intra-site analyses (see for example Crema *et al.* 2024a). The relative paucity of most suitable solutions such as Bayesian hierarchical models is most likely due to existing software packages either requiring considerable user input and customisation and coding knowledge (e.g. JAGS, Nimble, and Stan) or limited for applications beyond their original scope (e.g. OxCal).

Palaeodemography and cultural phenomena

The use of radiocarbon dates to infer past population changes is perhaps the most representative example showcasing the potential and the success as well as the many problems associated with the analyses of large collections of radiocarbon dates. While John Rick's seminal paper (Rick 1987) is often considered the first example of using the time-frequency of radiocarbon dates as a proxy of population fluctuations in the past, earlier examples of this approach do date back to the early 1970s (Deacon 1974; Bryson-Baerreis-Wendland 1970).

It is worth highlighting here the difference between a central premise shared by a wide variety of methods, often referred to as the 'Dates-as-Data' approach, and the most commonly used technique to examine radiocarbon time-frequency data, i.e. summed probability distribution of radiocarbon dates (hereafter SPD, fig. 6-a). The central premise of 'Dates-as-Data' is to purposely abstain from defining the event associated with each ^{14}C sample beyond a generic reference to an 'anthropic'. As noted by Blackwell and Buck (2003), because the samples do not relate precisely to the same type of event, the interpretation of time frequencies becomes unclear, with multiple confounding factors potentially playing a role. The extent to which this premise holds, and the 'Dates-as-Data' can be considered a sufficiently robust proxy of demographic change is most likely an open question with different answers for different contexts. Still, it is important to highlight that one could arguably be more specific in definitions of what particular event type the radiocarbon frequency refers to. For example, using dates specifically associated with the construction or the use of dwelling structure would make the radiocarbon time-frequency a proxy of house counts, making the inferential connection to demography much more direct.

Perhaps the most emblematic consequence of the 'Dates-as-Data' approach is the treatment of imbalanced data. Because samples are frequently not associated with precisely defined events (e.g. the construction of a household, the burning of a firepit, etc.), it is not possible to differentiate the intensity of anthropic activities from sampling intensity. For example, if we are interested in modelling changes in the number of pit-dwellings over time, a hypothetical sample of 20 dates from the same dwelling can be reduced into a single estimate via Bayesian analyses. However, within a 'dates-as-data' framework, because we do not specify the event of interest, we would effectively treat the 20 dates as 20 distinct samples. As a result, differences in sampling intensity between sites and contexts can greatly influence the time-frequency of radiocarbon dates and ultimately its utility as a demographic proxy. While none of this is new and has been noted and discussed in Rick's original paper (Rick 1987: fig.1), practical solutions to the problem have been comparatively limited, and in many cases, entirely ignored. The current 'go-to' solution involves the 'binning' of multiple samples that are close in time into a unique 'site-phase', thus attempting to solve any bias pertaining to inter-site variations in sampling intensity by loosely specifying the event of interest to be an occupation episode of a particular site. While this offers a practical solution to the problem, analysts are forced to select what constitutes 'close in time'. The selection of differently sized bins can lead to different time-frequency distributions (Crema and Bevan 2021), and whilst sensitivity analyses are recommended (e.g. Prentiss *et al*. 2022), these are rarely implemented. An alternative approach is to combine ^{14}C dates based on the stratigraphic information using a pre-analytic 'binning' procedure, instead of the more common post-analysis 'binning'. However, this method can be more time-consuming since it necessitates a thorough filtering of ^{14}C data and is feasible only when comprehensive metadata on the stratigraphic provenance of the dated samples are available (Capuzzo *et al*. 2018). Following this approach, to ensure an equitable representation between sites with a limited number of few radiocarbon dates and multi-dated archaeological contexts, dates from the same archaeological context and corresponding to the same depositional event (for example, two bones from the same individual in a grave) can be tested following Ward and Wilson (1978). When the test is positive, the uncalibrated dates can be combined using the pooled mean.

It is also worth noting how samples are treated post-binning. In many cases, this involves an arbitrary use of either pooled means (e.g. using OxCal's R_Combine function; which is strictly acceptable for events that are truly contemporary), the summing and normalising of the distribution (which fails to properly model the error structure), or the selection of a random date within the bin (which addresses the two issues above but leads to an additional source of stochasticity for larger bins). None of these are entirely satisfactory.

Not all radiocarbon time-frequency analyses employ the 'Dates-as-Data' premise, and similarly, not all 'Dates-as-Data' approaches involve the use of SPDs. Nonetheless, the practice of summing calibrated probability distributions has become *de facto* the most common statistical approach for palaeodemographic studies based on ^{14}C data. SPDs are, however, highly problematic ways to examine time frequency of ^{14}C dates, as they obscure the structure of the underlying measurement errors and are based on a mathematically dubious way to portray changing densities (see Carleton and Groucutt 2020 for an extended discussion). While the use of SPDs as a quick visualisation tool can be acceptable, its direct use in statistical analyses is unwarranted. It can easily lead to biassed, if not entirely incorrect, conclusions. This is because the spikes and troughs of SPDs are known to be affected by the shape of the calibration curve (Williams 2012; Crema and Bevan 2021) and by sampling error. Simulation of a SPD composed of uniformly distributed radiocarbon dates, under the assumption that the

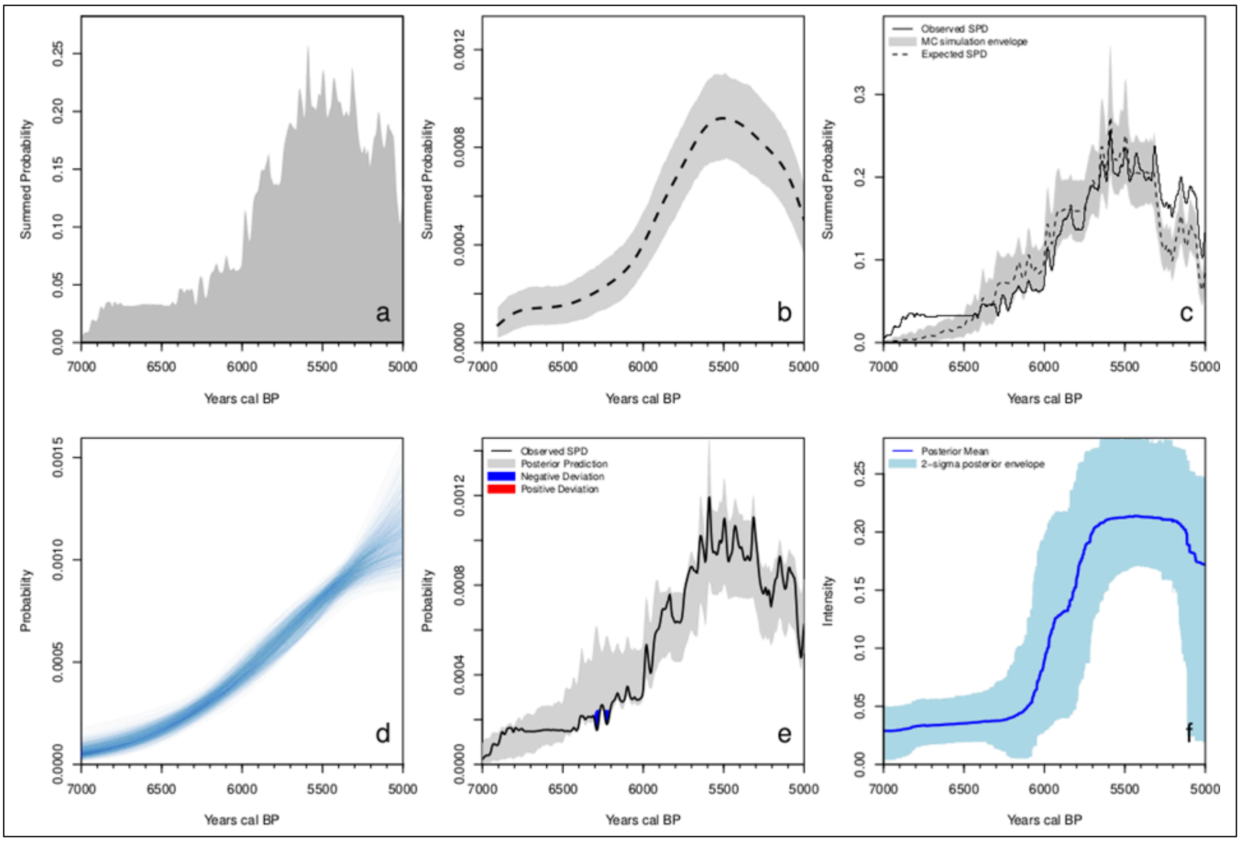

Fig. 6 – Different approaches for examining time-frequencies of radiocarbon dates: a) summed probability distribution of calibrated dates; b) composite Kernel Density Estimates (Brown 2017) on bootstrapped sampled calendar dates; c) Monte-Carlo simulation test against a null hypotheses based on SPD-fitted logistic growth (Timpson *et al*. 2014); d) posterior distribution of a fitted logistic growth model (Crema and Shoda 2021) ; e) posterior predictive check of the model fitted in panel (d); e) Bayesian inhomogeneous Poisson Process model (Heaton 2022). Dates were a subset of Danish dates from the EUROEVOL database (Manning *et al*. 2016). Further details and the R script to generate the figure can be found on https://github.com/ercrema/capuzzo_crema_2024.

Diversi approcci per analizzare le frequenze temporali delle date radiocarboniche: (a) distribuzione di probabilità sommata delle date calibrate; (b) stime di densità Kernel composite (Brown 2017) su date di calendario campionate mediante bootstrap; (c) test di simulazione Monte Carlo rispetto a un'ipotesi nulla basata su una crescita logistica adattata alla SPD (Timpson et al. 2014); (d) distribuzione posteriore di un modello di crescita logistica adattato (Crema e Shoda 2021); (e) posterior predictive check del modello adattato nel pannello (d); (f) modello bayesiano di processo di Poisson non omogeneo (Heaton 2022). Le date costituiscono un sottoinsieme dei dati danesi del database EUROEVOL (Manning et al. 2016). Ulteriori dettagli e lo script R per generare la figura sono disponibili su https://github.com/ercrema/capuzzo_crema_2024.

number of dated archaeological context was the same for each year, does not yield a flat curve but a curve with peaks and troughs that mirror the wiggles and plateaus of the calibration curve (Capuzzo *et al.* 2018, 2023). Yet, unfortunately, SPDs are routinely used directly as the basis of subsequent analyses, often involving complex approaches that nonetheless ignore these fundamental issues.

Robust alternatives to SPDs that can overcome these two core issues (sampling error and non-random measurement error), however, exist. In a recent review article, Crema (2022) classifies these approaches into three categories: 1) null-hypothesis significance testing (NHST), 2) non-parametric reconstructive methods, and 3) model-based fitting. While an extensive discussion on each approach is beyond the scope of this paper, it is worth briefly highlighting some of the benefits and challenges of each.

NHST approaches represent the earliest attempt to provide a more robust alternative to the visual inspection of SPDs. Its core premise consists of comparing *expected* SPDs under a particular null model against the *observed* SPDs, with the former conditioned by the same biases derived from sampling error and calibration curve as the latter. As a result, these biassing factors are cancelled out, and users can determine whether the observed data deviates from a particular null model and identify when and how such a deviation occurred (fig. 6-c). For example, Shennan and colleagues (2013) examined the time-frequency of radiocarbon dates in Western Europe, noting a lower-than-expected density of around 5,500 cal BP. The core principles of the method have been subsequently updated (Timpson *et al.* 2014; Crema and Bevan 2021), while similar efforts have been made to compare the difference in the density of dates between specific points in time (Edinborough *et al.* 2017) or for determining whether two or more SPDs are different from each other (Crema *et al.* 2016). The core limitations of NHST are similar to those found among conventional frequentist hypothesis testing. Firstly, the results of analyses are highly conditional to the null hypotheses used, and whilst practitioners commonly use exponential growth, its choice is not necessarily warranted, nor is there an obvious candidate on what constitutes a sensible set of parameters (e.g. growth rate, temporal window of analyses). Secondly, inevitably, results are going to be conditioned by the available sample size, and interpretation should account for both statistical power (i.e. the ability to detect patterns deviating from the null model) and effect size (i.e. the extent by which the observed pattern is deviating from the null model). As such, a small sample size might not show any deviations from a particular null model (i.e. lead to a false negative), while a large sample size might detect the tiniest deviations that might be statistically significant but not archaeologically relevant.

More recent methodological developments have entirely ditched the use of SPDs and focused on either parametric (fig. 6-d,e) or non-parametric (fig. 6-b,f) model fitting. The former consists of 'fitting' a particular statistical model with a defined set of parameters that are inferred from the observed data. These parameters can define the general shape of the time-frequency distribution (e.g. a logistic growth, fig.6-d) or establish putative relationship between the observed data and some external covariates, while still being able to detect deviations from the fitted model (fig.6-e). Examples of the former often focus specifically on the interpretation of the estimated parameter values themselves. For instance, establishing whether the difference in the growth rates prior to and after the arrival of farming exhibit regional differences (Crema *et al.* 2024b), or determine the temporal relationship between a major shift in the magnitude and sign (i.e. increase vs decrease) of the growth rate and episodes of abrupt climatic changes (Kim-Lee-Crema 2021). Examples typically focus on whether changes in radiocarbon density over time relate to external climatic forces (Stewart-Carleton-Groucutt 2021; DiNapoli *et al.* 2021). Parametric model-fitting has been implemented in different statistical formalisations, ranging from likelihood based approaches (Timpson *et al.* 2021; Crema and Shoda 2021; Carleton 2021) to a more flexible (but limited in precision and coupled by substantial computation cost) simulation-based generative inference (DiNapoli *et al.* 2021).

The strength of parametric approaches lies in the ability to employ specific model(s) to describe the observed data, inferring key parameters that can be used to test particular hypotheses. While this is a desirable feature, it is often the case that the researcher does not have a specific model in mind and wishes simply to 'reconstruct' the shape of the changing density of radiocarbon dates over time, whilst accounting for issues such as sampling error and calibration effects (fig. 6-b,f). This is the case when dates are used as data to model long-term population dynamics, as well as cultural phenomena such as the use of different funerary practices (cremation vs inhumation) and burial types (Brunner *et al.* 2020; Capuzzo *et al.* 2020, 2023; Schmid 2020; Capuzzo and Barceló 2022). The use of different types of grave goods (Gibaja *et al.* 2017; Brownlee 2023) and the visualisation on a time scale of various burial sites (Steuri *et al.* 2023) and settlements (Antolín *et al.* 2022) have also been investigated using ^{14}C data. Furthermore, changes in prehistoric harvesting technology (Mazzucco *et al.* 2020) have also been inferred using the temporal frequency of large ^{14}C datasets. A wide range of approaches

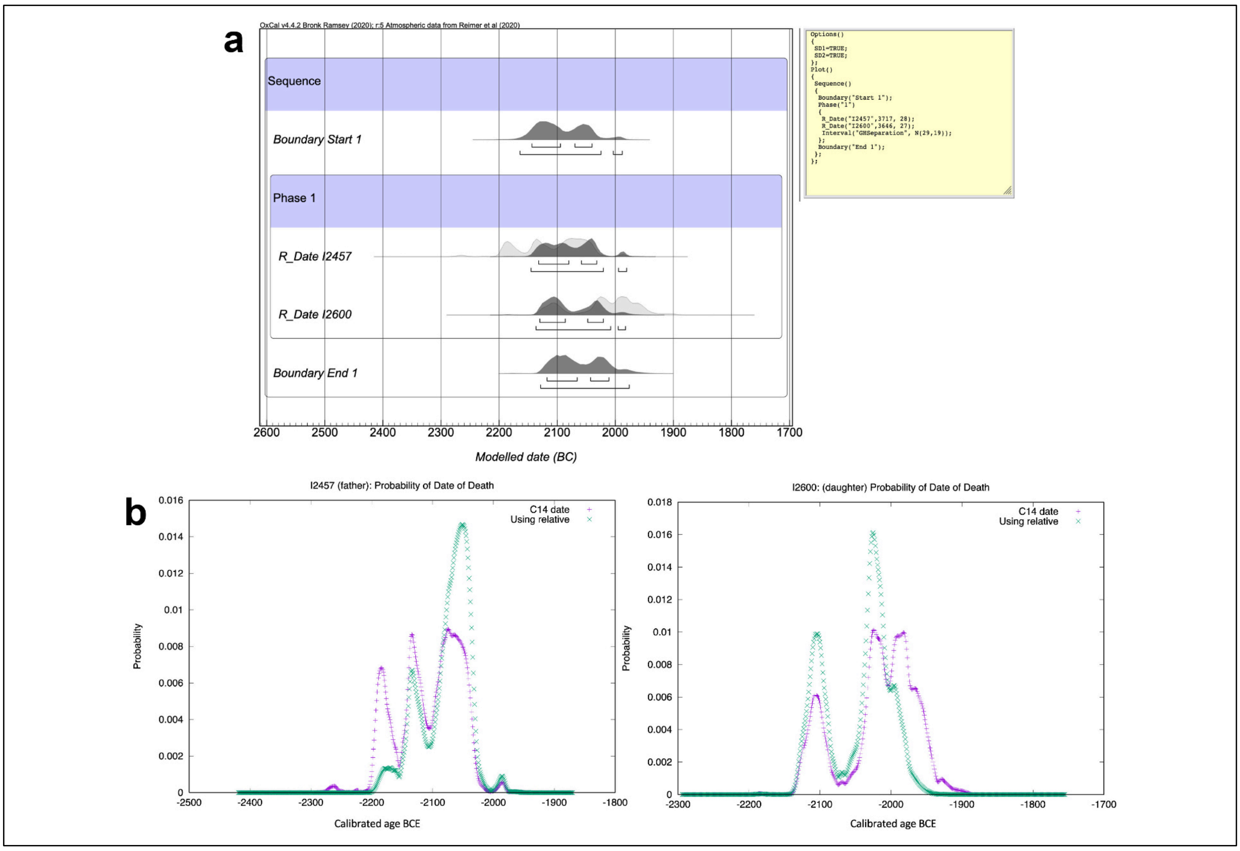

Fig. 7 – Radiocarbon dates constrained using aDNA information from two individuals I2457 (father) and I2600 (daughter) excavated from two Bell Beaker sites, Amesbury Down and Porton Down, in Britain: (a) OxCal interval function analysis of father-daughter pair; (b) Prior and posterior probability distribution for I2457 (left) and I2600 (right). Original calibrated date probability distribution from OxCal in purple, new distribution plotted from results generated by refinedate (SM 6.1) in green. (Source: Sedig *et al*. 2021). The scripts to generate the figure can be found on https://github.com/ercrema/capuzzo_crema_2024.

Date radiocarboniche rese più precise e accurate utilizzando i dati di DNA antico da due individui, I2457 (padre) e I2600 (figlia), provenienti da due siti della cultura del vaso campaniforme, Amesbury Down e Porton Down, in Gran Bretagna: (a) analisi della funzione Interval in OxCal della coppia padre-figlia; (b) distribuzioni di probabilità a priori e a posteriori per I2457 (sinistra) e I2600 (destra). La distribuzione di probabilità originale della data calibrata in OxCal è mostrata in viola, mentre la nuova distribuzione, ottenuta dai risultati generati con refinedate (SM 6.1), è mostrata in verde (fonte: Sedig et al. 2021). Gli script per generare la figura sono disponibili su https://github.com/ercrema/capuzzo_crema_2024

have been proposed to tackle these and similar objectives, from basic bootstrapping (Rick 1987) to various forms of Kernel Density Estimates (Bronk Ramsey 2017; Brown 2017; fig. 6-b) to more advanced non-parametric Bayesian methods (Price *et al*. 2021; Heaton 2022, fig. 6-f). The key advantage of these suites of techniques is the relatively small input required by users and visual outputs that can flexibly 'reconstruct' the underlying shape in the time-frequency of radiocarbon density over time as means for an exploratory data analysis. Their major limitations are the comparatively higher computational cost (often unapproachable with standard laptops) and the fact that they effectively encourage post-hoc explanations rather than explicit modelling and testing.

Another important aspect to take into account in the interpretation of the 'dates-as-data' reconstructions is postdepositional bias. Pedogenetic and taphonomic processes may imply different degrees of preservation of archaeological material suitable for radiocarbon dating (Bailey 2008; Zilhão 2011). For example, poor preservation of unburnt bone (e.g. from inhumations) is common in acidic soils, such as sandy or schist-derived soils. This bias can result in gaps in the archaeological visibility of specific categories and therefore alter the reliability of temporal patters constructed from modelled ^{14}C data. Additionally, taphonomic bias may affect the general trend of temporal series, as many more dated samples are usually available for recent periods compared to the earliest ones (see Surovell and Brantingham 2007; Surovell *et al*. 2009; Bluhm and Surovell 2019). This bias produces an overall positive trend in 'dates-as-data' reconstructions that analyse long time spans of several millennia.

Novel approaches to using radiocarbon dates in human biology and biochemistry

In the last few years, new methods have been developed through the integration of diverse disciplines such as radiocarbon dating, human biology, and isotope biochemistry. These recent advances have opened up new horizons in the study of past populations. In 2021, Sedig *et al*. (2021) have demonstrated that the combination of data from ancient DNA (aDNA) and from radiocarbon dating of past human remains can increase the accuracy and precision of the ^{14}C estimates for dated individuals with available genetic information. The application of ancient DNA to human remains provides information on kinship, enabling the identification of relationships between individuals and the degree of kinship, such as parents-offspring, siblings, grandparent-grandchild, and other second- and third-degree relationships. Related individuals are separated in their date of death, by a maximum number of years known as the biological maximum death separation, which depends on the type of kinship. Sedig *et al*. (2021) managed to quantify such mean years of death separation by consulting ethnographic and historical data from industrialised societies, which are available in large repositories. In the future, an evaluation of such values to assess their reliability in prehistoric societies, and the use of different estimated values for different societies, such as hunter-gatherer communities vs farmer-herders, would be of great relevance. On the basis of such data the authors were able to estimate the limits of the so-called degree of separation that individuals can have on the date of death (relatedness death separation).

Human samples whose aDNA is analysed are usually also radiocarbon-dated to assess their chronology. Knowledge of the date of death (DOD) for two or more genetically related individuals can help refine radiocarbon dates by constraining their confidence intervals, thereby providing more precise and accurate time spans. This indicates that radiocarbon dates can be adjusted based on genetic knowledge. Exploring large datasets of paleogenetic data associated with radiocarbon dates, Sedig *et al*. (2021) statistically modelled several case studies with radiocarbon dates associated with aDNA data. Two distinct methodologies were employed: the Bayesian analysis in OxCal using the Interval function (fig. 7-a), and the refinedate program (fig. 7-b), which was specifically designed to assist in refining the radiocarbon probability distributions of related individuals. The results obtained with both programs were found to be comparable.

Differences in radiocarbon dates on human remains can also be related to other factors, such as the consumption of marine/freshwater resources which implies a reservoir effect in the radiocarbon dates (Stuiver-Reimer-Braziunas 1998; Philippsen 2013; Alves *et al*. 2018) and the various rates of bone-turnover in different human skeletal elements, which implies that old bone is removed and new bone is formed upon osteocyte signalling, thereby regenerating the skeletal tissues (Kenkre and Bassett 2018). The petrous portion of the temporal bone and tooth enamel are the only tissues that do not undergo remodelling after their formation during childhood and early adolescence. In contrast, all the other bones do remodel at varying rates, with the ribs exhibiting the most rapid bone turnover. Consequently, radiocarbon dates on human ribs provide the most accurate results to estimate the date of death of individuals (Johnstone-Belford *et al*. 2022). This highlights the need of meticulous documentation of both data and metadata associated with radiocarbon dates, particularly, in the case of human remains, regarding the specific bone sample used for dating. However, such information is frequently missing in ^{14}C databases.

The importance of having multi-proxy analyses carried out on the same bone fragment is also demonstrated in recent studies that combine osteological data, strontium isotope data, and radiocarbon dates on archaeological calcined human bones. Strontium isotope ratios ($^{87}Sr/^{86}Sr$) are commonly used as a proxy in inhumations and cremation burials to trace the origin, the mobility, and the variations in landscape use of buried individuals (Alexander Bentley 2006; Montgomery 2010; Snoeck *et al*. 2022). In two studies conducted by Sabaux and colleagues (2021, 2024), cremation deposits from the Late Bronze Age-Early Iron Age (ca. 1200-600 BC) from various archaeological sites located in Belgium were analysed. The results revealed non-overlapping radiocarbon dates and different values of $^{87}Sr/^{86}Sr$ on calcined diaphyseal bone fragments from cremation deposits, whose osteological analyses revealed the presence of more than one individual. Non-overlapping radiocarbon dates might be a consequence of an old-wood effect that affected cremated bone due to the carbon exchange between wood fuel and the bone that takes place in the burning environment (Zazzo *et al*. 2009; Van Strydonck-Boudin-De Mulder 2010; Hüls *et al*. 2010; Olsen *et al*. 2013; Snoeck-Brock-Schulting 2014). Nevertheless, this seems unlikely for the analysed sites. Research on the selection of wood used as fuel in Bronze Age pyres in northern Europe indicated the use of mixed timbers based on the availability of wood around the site (Moskal-del Hoyo 2012; O'Donnell 2016). Additionally, the old-wood effect, if present, would have affected the cremated individuals heterogeneously, resulting in a more statistically significantly difference in the ^{14}C content of the cremated bones (Snoeck-Brock-Schulting 2014; Rose-Meadows-Henriksen 2020), with radiocarbon dates not organised in groups but scattered in a time interval. Analysing $^{87}Sr/^{86}Sr$ in long bone diaphyseal fragments from LBA-EIA Belgian cremation cemeteries, the authors (Sabaux *et al*. 2024) identified quite different $^{87}Sr/^{86}Sr$ (>0.0010), indicating that the diaphyseal bone fragments were unlikely to belong to the same individual. Interestingly, such variations were also frequently correlated with differences in the radiocarbon dates, meaning that samples with different $^{87}Sr/^{86}Sr$ also exhibited different ^{14}C estimates. This, in turn, points towards the presence of non-contemporary multiple individuals deposited in the same cremation deposits (fig. 8).

Sabaux *et al*. (2021, 2024) showed that the information obtained from osteological analyses combined with radiocarbon dates and $^{87}Sr/^{86}Sr$ on the same fragments of calcined bone can be used as a proxy to reconstruct the minimum number of individuals (MNI) in cremation deposits. This approach helps in the detection of multiple individuals in cremation deposits, which would otherwise be unfeasible using conventional osteological methods alone.

As shown, the use of state-of-the-art bioarchaeological approaches for analysing human skeletal remains has grown exponentially in the last decade. This was prompted by scientific advances in method developments and the significant decrease in analytical costs for various analyses, enabling and encouraging the application of multiple methods (e.g. aDNA, isotopes analyses, radiocarbon dating, etc.) in one sample. Combining current and emerging methods, we can generate in-depth new knowledge, which helps to understand ancient population lifeways better, answering an extensive range of questions that would not be possible otherwise. The increasing inter- and multidisciplinary archaeological research requires experts with transdisciplinary skills who can integrate knowledge and techniques from different disciplines and fields by merging multiple lines of investigation. Using a multi-proxy approach that combines different methods and techniques can lead to the development of new methods, foster new interpretations, and open new horizons in the archaeological discipline.

Conclusions

Radiocarbon dating has profoundly transformed our understanding of the chronology of past societies, becoming a fundamental tool for placing on a chronological framework a wide range of events and phenomena, from a site scale to a regional scale. Over the past seven decades, the method has evolved significantly, improving in precision and accuracy thanks to advancements in technology and statistical modelling of ^{14}C dates. However, it is essential to recognize the probabilistic nature of radiocarbon dates, which inherently include uncertainties that must be carefully managed. The development of large ra-

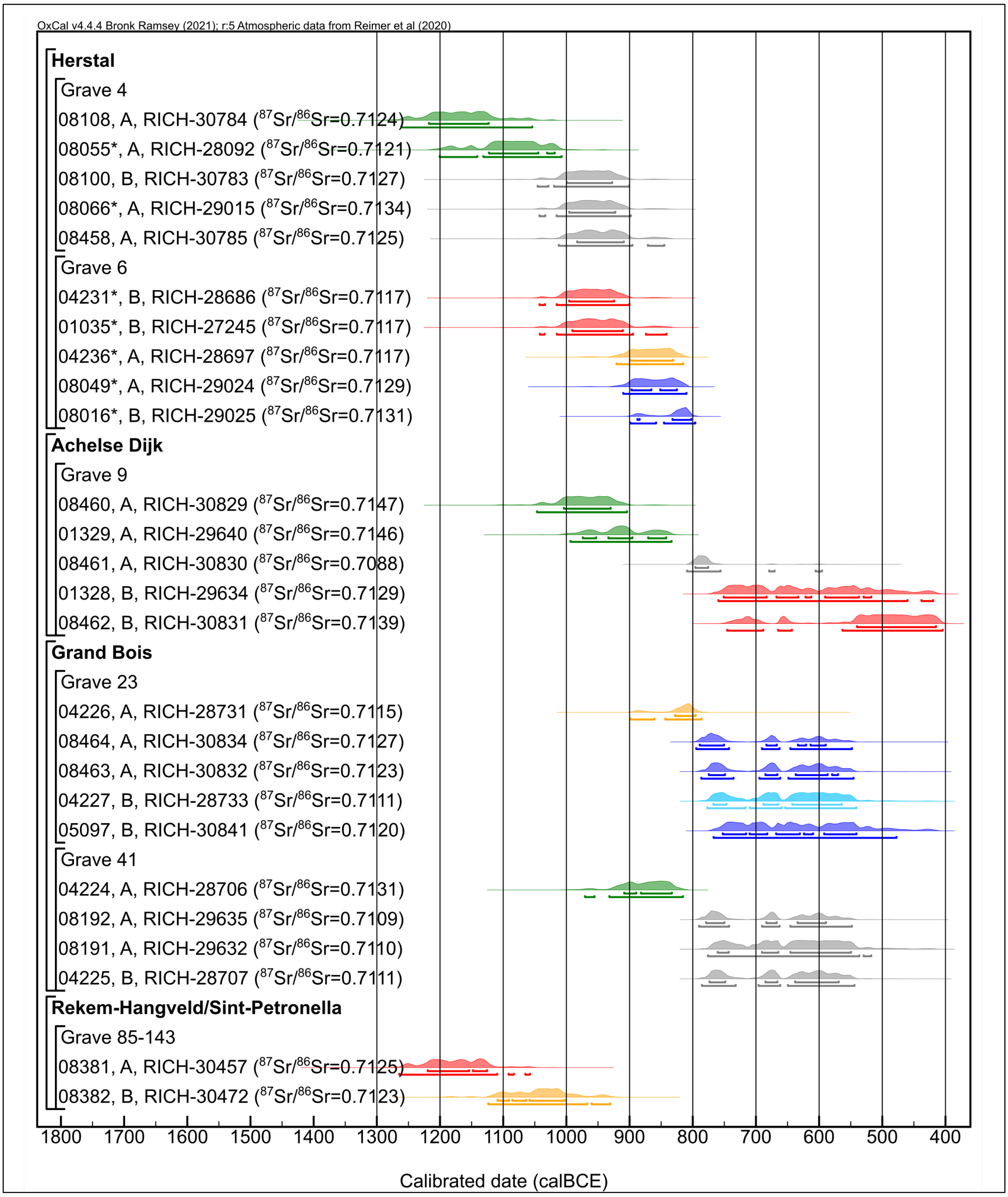

Fig. 8 – Calibrated radiocarbon dates with $^{87}Sr/^{86}Sr$ isotope ratios from fragments of calcined bone originating from cremation deposits in the LBA-EIA cemeteries of Herstal, Achelse Dijk, Grand Bois, and Rekem, located in Belgium. Each colour in each grave corresponds to a different individual based on the combination of osteology, radiocarbon dating and strontium (MNI = 14 or 15) (*data from Sabaux *et al*. 2021). (Source: Sabaux *et al*. 2024). The OxCal code to generate the figure can be found on https://github.com/ercrema/capuzzo_crema_2024.

*Date radiocarboniche calibrate associate ai rapporti isotopici $^{87}Sr/^{86}Sr$ ottenuti da frammenti di osso calcinato provenienti da tombe a cremazione nelle necropoli di Bronzo Finale-Prima Età del Ferro di Herstal, Achelse Dijk, Grand Bois e Rekem, in Belgio. Ogni colore all'interno dei guppi di date di ciascuna sepoltura corrisponde a un individuo distinto, sulla base della combinazione di dati osteologici, radiocarbonici e dello stronzio (MNI = 14 o 15) (*dati da Sabaux et al. 2021). (Fonte: Sabaux et al. 2024). Il codice OxCal utilizzato per generare la figura è disponibile su https://github.com/ercrema/capuzzo_crema_2024.*

diocarbon databases and sophisticated software for statistical analysis has further enhanced our ability to interpret complex archaeological and ecological data. In this paper, we have provided an overview of current methods used for the analysis of radiocarbon data, from intra-site analyses, such as Bayesian and age-depth models, to inter-site studies, including modelling of complex dispersal phenomena, palaeodemography and cultural processes. We have emphasised the need for careful consideration of methodological biases and showed how the integration of radiocarbon dates with other scientific data types can drive future research.

It is often said that 'all models are wrong' (Box 1976), given that they are a simplification of reality. This is particularly the case when models are used to represent complex socio-cultural phenomena, which are identified by the material remains of past societies as documented in the archaeological record. It is therefore crucial to ensure that models as reliable as possible are produced, using reliable data preserved in large-scale radiocarbon datasets. Therefore, a rigorous control of the data introduced into the models is required. This gives rise to certain issues, particularly when working with legacy data, which can be particularly challenging due to their inherent nature. It is frequently overlooked by archaeologists that the process of obtaining a reliable radiocarbon date starts in the field, when the sample for dating is collected. A primary step is therefore to understand what exactly we want to date, identifying which are the events of interest (i.e. the depositional and archaeological events, such as the use of a floor, a destruction layer, the period of activity of a fireplace, the time span of use of a settlement, etc.). Once the objective has been determined, the most appropriate sampling strategy can be implemented. When working with large radiocarbon datasets produced across multiple projects with diverse goals and objectives, dates are used as data to address a range of research questions that may differ from those for which the data were originally generated. To mitigate this bias, it is essential to record, in radiocarbon databases, not only the basic information on the radiocarbon date (lab and sample code, age BP, standard deviation), but also as much metadata as possible. This should include information on the type of dated sample, the archaeological context from which it originates, and references to the original publication. Such information is crucial to evaluate how data were obtained in the first place, which is fundamental to assessing the reliability of past dates. In accordance with the open science principles and practices implemented in the Horizon Europe programme (2024), data and metadata must be freely accessible online and 'as open as possible, as closed as necessary'. As evidenced in this review article, the free access to data and metadata is fundamental when working with large radiocarbon datasets. Open access is not limited to the data, but extends to the software, models, and algorithms used to analyse extensive radiocarbon datasets. To ensure the reproducibility of the obtained results, it is essential to upload the code used to analyse the dataset in public and trusted repositories.

APPENDIX: SOFTWARE AND DATASETS

Standalone software applications

- Calib: Basic calibration (Stuiver and Reimer 1993). http://calib.org/
- BCal: Bayesian Chronological Modelling (Buck *et al*. 1999). https://bcal.shef.ac.uk/
- Chronolog: Provides graphical support for generating complex Bayesian chronological model scripts for OxCal (Levy *et al*. 2021). https://chrono.ulb.be/
- ChronoModel: Hierarchical Bayesian Chronological Modelling (Lanos and Dufresne 2019). https://chronomodel.com/
- OxCal: Bayesian Chronological Modelling, including Age-Depth Models, and several diagnostic tools (Bronk Ramsey 1995, 2009). https://c14.arch.ox.ac.uk/oxcal.html

R Packages

- ADMUR: Analyses time-frequencies of radiocarbon dates using an alternative approach to traditional SPDs. https://cran.r-project.org/web/packages/ADMUR/index.html
- Bchron: Offers a wide range of Bayesian chronological models, including age-depth models and non-parametric phase models. https://cran.r-project.org/web/packages/

Bchron/index.html

- carbondate: Offers alternative to SPDs within a Bayesian framework. https://cran.r-project.org/web/packages/carbondate/index.html
- clam (age-depth models): Age-depth models. https://cran.r-project.org/web/packages/clam/index.html
- oxcAAR: Offers an R-interface to OxCal. https://cran.r-project.org/web/packages/oxcAAR/index.html
- rbacon: Age-depth models. https://cran.r-project.org/web/packages/rbacon/index.html
- rcarbon: Basic calibration, SPDs, spatial analyses, KDE, and several NHST. https://cran.r-project.org/web/packages/rca
- nimbleCarbon: Extension to nimble probabilistic programming language for developing highly customisable Bayesian chronological models. https://cran.r-project.org/web/packages/nimbleCarbon/index.html
- spDates: Spatial Modelling of Radiocarbon dates. https://cran.r-project.org/web/packages/spDates/index.html

Datasets

Africa

aDRAC (Seidensticker and Hubau 2021)
AfriArch (Goldstein *et al.* 2022)
KITE East Africa (Courtney Mustaphi 2016)
MedAfriCarbon (Lucarini *et al.* 2020)
Holocene archaeological dates (Kay *et al.* 2019)
Holocene dates (Manning and Timpson 2014)
SARD (Loftus-Mitchell-Ramsey 2019)

Europe

AgriChange (Martínez-Grau-Morell-Rovira-Antolín 2021)
AIDA (Palmisano *et al.* 2022a)
Arch14CZ (Vondrovský-Demján-Dreslerová 2023)
BANADORA (BAnque NAtionale de DOnnées RAdiocarbone Pour l'Europe et le Proche Orient)
CalPal Archaeological ^{14}C-Database (Weninger 2023)
^{14}Canarias (Pardo-Gordó *et al.* 2023)
C14.sk (Barta *et al.* 2013)
EUBAR (Capuzzo-Boaretto-Barceló 2014)
EUROEVOL (Manning *et al.* 2016)
EVOLPAST (Pardo-Gordó *et al.* 2019)
IDEArq (Uriarte *et al.* 2017)
IRDD (Chapple 2018)
NeoNet Dataset (Huet *et al.* 2022, 2024)
PACEA (d'Errico *et al.* 2011)
Radiocarbon Palaeolithic Europe Database (Vermeersch 2024)
Rado-NB (Rinne *et al.* 2024)
14SEA (Reingruber and Thissen 2017)

Near East and Asia

Archaeological Radiocarbon Database of Japan (Kudo *et al.* 2023)
NERD (Palmisano *et al.* 2022b)
Radiocarbon Dataset China (Wang *et al.* 2014)
TAY (TAY Project 14C sample Database)

North America

CARD (Gajewski *et al.* 2011)
New radiocarbon database for the lower 48 states (Kelly *et al.* 2022)

Central and South America

Andes (Ziólkowski *et al.* 1994)
caribbean-14C (Riris 2021)
MesoRAD (Hoggarth-Ebert-Castelazo-Calva 2021)
rxpand (de Souza 2021)
The Bolivian Radiocarbon Database (Capriles 2023)

Oceania

AustArch (Williams *et al.* 2014)
Aotearoa (Petchey *et al.* 2022)

World

BDA (Perrin 2021)
KIK-IRPA (Van Strydonck and De Roock 2011)
ORAU (Oxford Radiocarbon Accelerator Unit online database)
P3k14c (Bird *et al.* 2022)

References

Aitken MJ. (1990) - *Science-based dating in archaeology*. London; New York: Longman.

Alexander Bentley R. (2006) - Strontium Isotopes from the Earth to the Archaeological Skeleton: A Review, *Journal of Archaeological Method and Theory* 13 (3): 135-187.

Alves E.Q., Macario K., Ascough P, Bronk Ramsey C. (2018) - The Worldwide Marine Radiocarbon Reservoir Effect: Definitions, Mechanisms, and Prospects, *Reviews of Geophysics* 56: 278-305.

Anderson E.C., Libby W.F., Weinhouse S., Reid A.F., Kirshenbaum A.D., Grosse A.V. (1947) - Radiocarbon From Cosmic Radiation, *Science* 105 (2735): 576-577.

Antolín F., Martínez-Grau H., Steiner B. L., Follmann F., Soteras R., Häberle S., Prats G., Schäfer M., Mainberger M., Hajdas I., Banchieri D.G. (2022) - Neolithic Occupations (c. 5200-3400 Cal BC) at Isolino Virginia (Lake Varese, Italy) and the Onset of the Pile-Dwelling Phenomenon around the Alps, *Journal of Archaeological Science: Reports* 42: 103375.

Arnold J. R., Libby W. F. (1949) - Age Determinations by Radiocarbon Content; Checks with Samples of Known Age, *Science* 110 (2869): 678-680.

BANADORA. Banque Nationale de Données Radiocarbone pour l'Europe et le Proche Orient, Centre de Datation par le Radiocarbone. Lyon: CNRS. https://banadora.mom.fr/

Banks W.E., Bertran P, Ducasse S., Klaric L., Lanos P., Renard C., Mesa M. (2019) - An Application of Hierarchical Bayesian Modeling to Better Constrain the Chronologies of Upper Paleolithic Archaeological Cultures in France between Ca. 32,000-21,000 Calibrated Years before Present, *Quaternary Science Reviews* 220:188-214.

Barceló J.A., Capuzzo G., Bogdanović I. (2014) - Modeling Expansive Phenomena in Early Complex Societies: The Transition from Bronze Iron Age in Prehistoric Europe, *Journal of Archaeological Method and Theory* 21 (2): 486-510.

Barta P., Demján P., Hladíková K., Kmeťová P., Piatničková K. (2013) - Database of radiocarbon dates measured on archaeological samples from Slovakia, Czechia, and adjacent regions. Archaeological Chronometry in Slovakia, Slovak Research and Development Agency Project No. APVV-0598-10, 2011 -2014, Dept. of Archaeology, Faculty of Arts, Comenius University in Bratislava. URL: https://www.c14.sk

Bailey G. (2008) - Time perspectivism: origins and consequences, in: Holdaway S., Wandsnider L., eds. - *Time in Archaeology: Time Perspectivism Revisited*. Utah University Press, Utah: 13-30.

Bayliss A. (2009) - Rolling Out Revolution: Using Radiocarbon Dating in Archaeology, *Radiocarbon* 51 (1): 123-147.

Bayliss A. (2015) - Quality in Bayesian Chronological Models in Archaeology, *World Archaeology* 47 (4): 677-700.

Bayliss A., Marshall P. (2022) - *Radiocarbon Dating and Chronological Modelling: Guidelines and Best Practice*. Historic England, London.

Bayliss A., Bronk Ramsey C., van der Plicht J., Whittle A. (2007) - Bradshaw and Bayes: Towards a Timetable for the Neolithic, *Cambridge Archaeological Journal* 17 (S1): 1-28.

Bebber M.R., Key A.J.M. (2022) - Optimal Linear Estimation (OLE) Modeling Supports Early Holocene (9000-8000 RCYBP) Copper Tool Production in North America, *American Antiquity* 87 (2): 267-283.

Bird D., Miranda L, Vander Linden M, Robinson E, Bocinsky R.K., Nicholson C., Capriles J.M., Finley J.B., Gayo E.M., Gil A., d'Alpoim Guedes J., Hoggarth J.A., Kay A., Loftus E., Lombardo U., Mackie M, Palmisano A., Solheim S., Kelly R.L., Freeman J. (2022) - p3k14c, a Synthetic Global Database of Archaeological Radiocarbon Dates, *Scientific Data* 9 (1): 1-19.

Blaauw M., Heegaard E. (2012) - Estimation of Age-Depth Relationships, in Birks H.J.B., Lotter A.F., Juggins S., Smol J.P., eds. - *Tracking Environmental Change Using Lake Sediments: Data Handling and Numerical Techniques*, Dordrecht: 379-413

Blackwell P.G., Buck C.E. (2003) - The Late Glacial Human Reoccupation of North-Western Europe: New Approaches to Space-Time Modelling, *Antiquity* 77 (296): 232-240.

Bluhm L.E., Surovell T.A. (2019) - Validation of a global model of taphonomic bias using geologic radiocarbon ages, *Quaternary Research* 91(1): 325-328.

Bocquet-Appel J.-P., Naji S., Vander Linden M., Kozlowski J. (2012) - Understanding the Rates of Expansion of the Farming System in Europe, *Journal of Archaeological Science* 39 (2): 531-546.

Bogdanović I., Barceló J., Capuzzo G. (2012) - A Database for Radiocarbon Dates. Some Methodological and Theoretical Issues about Its Implementation, in *On-Line Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA), Southampton (UK), 26-29 March 2012*: 457-467.

Bowman S. (1990) - *Radiocarbon dating* (Vol. 1). University of California Press.

Box G.E. (1976) - Science and statistics, *Journal of the American Statistical Association* 71 (356): 791-799.

Bronk Ramsey C. (1995) - Radiocarbon Calibration and Analysis of Stratigraphy: The OxCal Program, *Radiocarbon* 37 (2): 425-430.

Bronk Ramsey C. (2009) - Dealing with Outliers and Offsets in Radiocarbon Dating, *Radiocarbon* 51 (3): 1023-1045.

Bronk Ramsey C. (2017) - Methods for Summarizing Radiocarbon Datasets, *Radiocarbon* 59 (6): 1809-1033.

Brownlee E. (2023) - A radiocarbon-based model of changing burial rites in early medieval England, *Radiocarbon* 65 (6): 1232-1252.

Brown W.A. (2017) - The Past and Future of Growth Rate Estimation in Demographic Temporal Frequency Analysis: Biodemographic Interpretability and the Ascendance of Dynamic Growth Models, *Journal of Archaeological Science* 80: 96-108.

Brunner M., von Felten J., Hinz M., Hafner A. (2020) - Central European Early Bronze Age Chronology Revisited: A Bayesian Examination of Large-Scale Radiocarbon Dating, *PLoS ONE* 15 (12): e0243719.

Bryson R.A., Baerreis D.A., Wendland W.M. (1970) - Character of Late-Glacial and Post-Glacial Climatic Changes, in Wakefield D., Jones J. K., eds. - *Pleistocene and Recent Environments of the Central Great Plain*, University Press of Kansas: 53-74.

Buck C.E., Cavanagh W.G., Litton C.D. (1997) - *Bayesian Approach to Interpreting Archaeological Data*. Chichester, England: J. Wiley and Son.

Buck C.E., Christen J.A. James G.N. (1999) - BCal: an on-line Bayesian radiocarbon calibration tool, *Internet Archaeology* 7. (http://intarch.ac.uk/journal/issue7/buck/).

Buck C.E., Kenworthy J.B., Litton C.D., Smith. A.F.M. (1991) - Combining Archaeological and Radiocarbon Information: A Bayesian Approach to Calibration, *Antiquity* 65 (249): 808-821.

Buck C.E., Litton C.D., Smith A. F. M. (1992) - Calibration of Radiocarbon Results Pertaining to Related

Archaeological Events, *Journal of Archaeological Science* 19 (5): 497-512.

Buck C.E., Meson B. (2015) - On Being a Good Bayesian, *World Archaeology* 47 (4): 567-584.

Capriles J.M. (2023) - The Bolivian Radiocarbon Database: A Countrywide Compilation of Radiocarbon Dates, *Journal of Open Archaeology Data* 11: 6.

Capuzzo G., Barceló J.A. (2022) - Cremation Burials in Central and Southwestern Europe: Quantifying an Adoption of Innovation in the 2nd Millennium BC, *Anthropologica et Præhistorica* 131/2020: 113-160.

Capuzzo G., Boaretto E., Barceló J.A. (2014) - EUBAR: A Database of ^{14}C Measurements for the European Bronze Age. A Bayesian Analysis of ^{14}C-Dated Archaeological Contexts from Northern Italy and Southern France, *Radiocarbon* 56 (2): 851-869.

Capuzzo G., De Mulder G., Sabaux C., Dalle S., Boudin M., Annaert R., Hlad M., Salesse K., Stamataki E., Veselka B., Warmenbol E., Snoeck C., Vercauteren M. (2023) - Final Neolithic and Bronze Age funerary practices and population dynamics in Belgium, the impact of radiocarbon dating cremated bones, *Radiocarbon* 65 (1): 51-80.

Capuzzo G., Snoeck C., Boudin M., Dalle S., Annaert R., Hlad M., Kontopoulos I., Sabaux C., Salesse K., Sengeløv A., Stamataki E., Veselka B., Warmenbol E., De Mulder G., Tys D., Vercauteren M. (2020) - Cremation vs. inhumation: modeling cultural changes in funerary practices from the Mesolithic to the Middle Ages in Belgium using Kernel Density Analysis on ^{14}C data, *Radiocarbon* 62 (6): 1809-1832.

Capuzzo G., Zanon M., Dal Corso M., Kirleis W., Barceló J.A. (2018) - Highly Diverse Bronze Age Population Dynamics in Central-Southern Europe and Their Response to Regional Climatic Patterns, *PLoS ONE* 13 (8): e0200709.

Carleton W.C. (2021) - Evaluating Bayesian Radiocarbon-Dated Event Count (REC) Models for the Study of Long-Term Human and Environmental Processes, *Journal of Quaternary Science* 36 (1): 110-123.

Carleton W.C., Groucutt H.S. (2020) - Sum Things Are Not What They Seem: Problems with Point-Wise Interpretations and Quantitative Analyses of Proxies Based on Aggregated Radiocarbon Dates, *The Holocene* 31 (4): 630-643.

Chapple R.M. (2018) - *Catalogue of Radiocarbon Determinations & Dendrochronology Dates* (March 2018 Release)'. Oculus Obscura Press, Belfast. https://sites.google.com/site/chapplearchaeology/irish-radiocarbon-dendrochronological-dates?pli=1

Cherretté B., van der Meer W., Clement C. (2021) - *Door de bomen het bos zien*. SYNTAR 7. Synthese-onderzoek op archeologisch materiaal uit Vlaanderen. Agentschap Onroerend Erfgoed.

Crema E.R. (2022) - Statistical Inference of Prehistoric Demography from Frequency Distributions of Radiocarbon Dates: A Review and a Guide for the Perplexed, *Journal of Archaeological Method and Theory* 29 (4): 1387-1418.

Crema E.R., Bevan E. (2021) - Inference from Large Sets of Radiocarbon Dates: Software and Methods, *Radiocarbon* 63 (1): 23-39.

Crema E.R., Bloxam A., Stevens C.J., Vander Linden M. (2024a) - Modelling Diffusion of Innovation Curves Using Radiocarbon Data, *Journal of Archaeological Science* 165: 105962.

Crema E.R., Carrignon S., Shoda S., Stevens C.J. (2024b) - Regional variations in the demographic response to the arrival of rice farming in prehistoric Japan, *Antiquity* 98(401): 1290-1305.

Crema E.R., Habu J., Kobayashi K., Madella M. (2016) - Summed Probability Distribution of ^{14}C Dates Suggests Regional Divergences in the Population Dynamics of the Jomon Period in Eastern Japan. *PLoS ONE* 11 (4): e0154809.

Crema E.R., Kobayashi K. (2020) - A Multi-Proxy Inference of Jomon Population Dynamics Using Bayesian Phase Models, Residential Data, and Summed Probability Distribution of ^{14}C Dates, *Journal of Archaeological Science* 117: 105136.

Crema E.R., Shoda S. (2021) - A Bayesian Approach for Fitting and Comparing Demographic Growth Models of Radiocarbon Dates: A Case Study on the Jomon-Yayoi Transition in Kyushu (Japan), *PLoS ONE* 16 (5): e0251695.

Crema E.R., Stevens C.J., Shoda S. (2022) - Bayesian Analyses of Direct Radiocarbon Dates Reveal Geographic Variations in the Rate of Rice Farming Dispersal in Prehistoric Japan, *Science Advances* 8 (38): eadc9171.

Courtney Mustaphi C. (2016) - *Radiocarbon dates from eastern Africa in the CARD2.0 format*, https://doi.org/10.7910/DVN/NJLNRJ, Harvard Dataverse, V5.

Deacon J. (1974) - Patterning in the Radiocarbon Dates for the Wilton/Smithfield Complex in Southern Africa, *The South African Archaeological Bulletin* 29 (113/114): 3-18.

d'Errico F., Banks W.E., Marian Vanhaeren M., Laroulandie V., Langlais M. (2011) - PACEA Geo-Referenced Radiocarbon Database, *PaleoAnthropology* 2011: 1-12.

de Souza J.G. (2021) - *rxpand: Radiocarbon dates for the spread of farming and ceramics in tropical South America*. https://github.com/jgregoriods/rxpand

DiNapoli R.J., Crema E.R., Lipo C.P., Rieth T.M., Hunt T.L. (2021) - Approximate Bayesian Computation of Radiocarbon and Paleoenvironmental Record Shows Population Resilience on Rapa Nui (Easter Island), *Nature Communications* 12 (1): 3939.

Djakovic I., Key A., Soressi M. (2022) - Optimal Linear Estimation Models Predict 1400-2900 Years of Overlap between Homo Sapiens and Neandertals prior to Their Disappearance from France and Northern Spain, *Scientific Reports* 12 (1): 15000.

Edinborough K., Porčić M., Martindale A., Brown T.J., Supernant K., Ames K.M. (2017) - Radiocarbon Test for Demographic Events in Written and Oral History, *Proceedings of the National Academy of Sciences of the United States of America* 114 (47): 12436-12441.

Fort J. (2015) - Demic and Cultural Diffusion Propagated the Neolithic Transition across Different Regions of Europe, *Journal of the Royal Society, Interface* 12 (106): 20150166.

Gajewski K., Munoz S., Peros M., Viau A., Morlan R., Betts M. (2011) - The Canadian Archaeological Radiocarbon Database (Card): Archaeological ^{14}C Dates in North America and Their Paleoenvironmental Context, *Radiocarbon* 53 (2): 371-394.

Gibaja J.F., Morell B., Barceló Álvarez J.A., Duboscq S., Masclans A., Remolins G., Roig J., Martín A., González P., Plasencia J., Coll J.M., Subirà M.E. (2017) - The Chronology of the Neolithic Necropolis Bòbila Madurell-Can Gambús in the Northeast Iberian Peninsula: Dating the Pit Burials Cultural Horizon and Long-Range Raw Material Exchange Networks, *Radiocarbon* 59 (6): 1713-1736.

Goldstein S., Hixon S., Scott E., Wolfhagen J., Iminjili V., Janzen A., Chritz K., Sawchuk E., Ndiema E., Sealy J.C., Stone A., Zoeller G., Phelps L.N., Fernandes R. (2022) - Presenting the AfriArch Isotopic Database, *Journal of Open Archaeology Data* 10: 6.

Hajdas I. (2009) -Applications of Radiocarbon Dating Method, *Radiocarbon* 51 (1): 79-90.

Harris D.R., Gove H.E., Damon P. (1987) - The Impact on Archaeology of Radiocarbon Dating by Accelerator Mass Spectrometry [and Discussion], *Philosophical Transactions of the Royal Society of London. Series A: Mathematical and Physical Sciences* 323 (1569): 23-43.

Heaton T.J. (2022) - Non-Parametric Calibration of Multiple Related Radiocarbon Determinations and Their Calendar Age Summarisation, *Journal of the Royal Statistical Society. Series C, Applied Statistics* 71 (5): 1918-1956.

Heaton T.J., Köhler P., Butzin M., Bard E., Reimer R.W., Austin W.E., Bronk Ramsey C., Grootes P.M., Hughen K.A., Kromer B, Reimer P.J., Adkins J., Burke A., Cook M.S., Olsen J., Skinner, L. C. (2020) - Marine20—the marine radiocarbon age calibration curve (0-55,000 cal BP), *Radiocarbon* 62 (4): 779-820.

Hogg A.G., Cook G.T. (2022) - Liquid Scintillation Counting (LSC) - past, present, and future, *Radiocarbon* 64 (3): 541-554.

Hogg A.G., Heaton T.J., Hua Q., Palmer J.G., Turney C.S.M., Southon J., Bayliss A., Blackwell P.G., Boswijk G., Bronk Ramsey C., Pearson C., Petchey F., Reimer P., Reimer R., Wacker L. (2020) - SHCal20 Southern Hemisphere calibration, 0-55,000 years cal BP, *Radiocarbon* 62 (4): 759-778.

Hoggarth J.A., Ebert C.E., Castelazo-Calva V.E. (2021) - MesoRAD: A New Radiocarbon Data Set for Archaeological Research in Mesoamerica, *Journal of Open Archaeology Data* 9: 10.

Horizon Europe (HORIZON). HE Programme Guide. Version 4.1. 01 May 2024.

Huet T., Basílio A.C., Carvalho A.F., Cubas M., Gibaja J.F., López-Romero E., Oms F.X., Mazzucco N. (2024) - NeoNet Atlantic. Radiocarbon Dates for the Late Mesolithic/Early Neolithic Transition in the Southern European Atlantic Coast, *Journal of Open Archaeology Data* 12: 2.

Huet T., Cubas M., Gibaja J.F., Oms F.X., Mazzucco N. (2022) - NeoNet Dataset. Radiocarbon Dates for the Late Mesolithic/Early Neolithic Transition in the North Central-Western Mediterranean Basin, *Journal of Open Archaeology Data* 10: 3.

Hüls C.M., Erlenkeuser H., Nadeau M.-J., Grootes P.M., Andersen N. (2010) - Experimental Study on the Origin of Cremated Bone Apatite Carbon, *Radiocarbon* 52 (2): 587-599.

Jacobsson P., Hamilton W.D., Cook G., Crone A., Dunbar E., Kinch H., Naysmith P., Tripney B., Xu S. (2018) - Refining the Hallstatt Plateau: Short-Term ^{14}C Variability and Small Scale Offsets in 50 Consecutive Single Tree-Rings from Southwest Scotland Dendro-Dated to 510-460 BC, *Radiocarbon* 60 (1): 219-237.

Johnstone-Belford E., Fallon S.J., Dipnall J.F., Blau S. (2022) - The Importance of Bone Sample Selection When Using Radiocarbon Analysis in Cases of Unidentified Human Remains, *Forensic Science International* 341:111480.

Kay A.U., Fuller D.Q., Neumann K., Eichhorn B., Höhn A., Morin-Rivat J, Champion L., Linseele V., Huysecom E., Ozainne S., Lespez L., Biagetti S., Madella M., Salzmann U., Kaplan J.O. (2019) - Diversification, Intensification and Specialization: Changing Land Use in Western Africa from 1800 BC to AD 1500, *Journal of World Prehistory* 32 (2): 179-228.

Kelly R.L., Mackie M., Robinson E., Meyer J., Berry M., Boulanger M., Codding B.F., Freeman J., Garland C.J., Gingerich J., Hard R., Haug J., Martindale A., Meeks S., Miller M., Miller S., Perttula T., Railey J.A., Reid K., Scharlotta I., Spangler J., Thomas D.H., Thompson V., White A. (2022) - A New Radiocarbon Database for the Lower 48 States, *American Antiquity* 87: 581-590.

Kenkre J.S., Bassett J.H.D. (2018) - The Bone Remodelling Cycle, *Annals of Clinical Biochemistry* 55 (3): 308-327.

Key A., Roberts D, Jarić I. (2021) - Reconstructing the Full Temporal Range of Archaeological Phenomena from Sparse Data, *Journal of Archaeological Science* 135: 105479.

Kim H., Lee G.-A., Crema E.R. (2021) - Bayesian Analyses Question the Role of Climate in Chulmun Demography, *Scientific Reports* 11 (1): 23797.

King T.E., Gonzalez Fortes G., Balaresque P., Thomas M.G., Balding D., Delser P.M., Neumann R., Parson W., Knapp M., Walsh S., Tonasso L., Holt J., Kayser M., Appleby J., Forster P., Ekserdjian D., Michael Hofreiter M., Schürer K. (2014) - Identification of the Remains of King Richard III, *Nature Communications* 5: 5631.

Kudo Y., Sakamoto M., Hakozaki M., Stevens C.J., Crema E.R. (2023) - An Archaeological Radiocarbon Database of Japan, *Journal of Open Archaeology Data* 11: 11.

Lacourse T., Gajewski K. (2020) - Current Practices in Building and Reporting Age-Depth Models, *Quaternary Research* 96: 28-38.

Lanos Ph., Dufresne Ph. (2019) - ChronoModel version 2.0: Software for Chronological Modelling of Archaeological Data using Bayesian Statistics'. Available at https://chronomodel.com/

Leipe C., Long T., Wagner M., Goslar T., Tarasov P.E. (2020) - The Spread of Rice to Japan: Insights from Bayesian Analysis of Direct Radiocarbon Dates and Population Dynamics in East Asia, *Quaternary Science Reviews* 244: 106507.

Leipe C., Long T., Sergusheva E.A., Wagner M., Tarasov P.E. (2019) - Discontinuous Spread of Millet Agriculture in Eastern Asia and Prehistoric Population Dynamics, *Science Advances* 5 (9): eaax6225.

Levy E., Geeraerts G., Pluquet F., Piasetzky E., Fantalkin A. (2021) - Chronological Networks in Archaeology: A Formalised Scheme, *Journal of Archaeological Science* 127: 105225.

Libby W.F., Anderson E.C., Arnold J.R. (1949) - Age Determination by Radiocarbon Content: World-Wide Assay of Natural Radiocarbon, *Science* 109 (2827): 227-228.

Linick T.W., Damon P.E., Donahue D.J., Jull A.J.T. (1989) - Accelerator Mass Spectrometry: The New Revolution in Radiocarbon Dating, *Quaternary International: The Journal of the International Union for Quaternary Research* 1: 1-6.

Loftus E., Mitchell P.J., Bronk Ramsey C. (2019) - An Archaeological Radiocarbon Database for Southern Africa, *Antiquity* 93 (370): 870-885.

Long T., Taylor D. (2015) - A Revised Chronology for the Archaeology of the Lower Yangtze, China, Based on Bayesian Statistical Modelling, *Journal of Archaeological Science* 63:115-121.

Lucarini G., Wilkinson T., Crema E.R., Palombini A., Bevan A., Broodbank C. (2020) - The MedAfriCarbon Radiocarbon Database and Web Application. Archaeological Dynamics in Mediterranean Africa, Ca. 9600-700 BC, *Journal of Open Archaeology Data* 8: 1.

Manning K., Colledge S., Crema E.R., Shennan S., Timpson A. (2016) - The Cultural Evolution of Neolithic Europe. EUROEVOL Dataset 1: Sites, Phases and Radiocarbon Data, *Journal of Open Archaeology Data* 5: e2.

Manning K., Timpson A. (2014) - The Demographic Response to Holocene Climate Change in the Sahara, *Quaternary Science Reviews* 101: 28-35.

Manning K., Timpson A., Colledge S., Crema E.R., Edinborough K., Kerig T., Shennan S. (2014) - The Chronology of Culture: A Comparative Assessment of European Neolithic Dating Approaches, *Antiquity* 88 (342): 1065-1080.

Martindale A., Morlan R., Betts M., Blake M., Gajewski K., Chaput M., Mason A., Vermeersch P. (2016) - *Canadian Archaeological Radiocarbon Database (CARD 2.1)*.

Martínez-Grau H., Morell-Rovira B., Antolín F. (2021) - Radiocarbon Dates Associated to Neolithic Contexts (ca. 5900 - 2000 Cal BC) from the Northwestern Mediterranean Arch to the High Rhine Area, *Journal of Open Archaeology Data* 9: 1.

Mazzucco N., Capuzzo G., Petrinelli Pannocchia C., Ibáñez J.J., Gibaja J.F. (2018) - Harvesting Tools and the Spread of the Neolithic into the Central-Western Mediterranean Area, *Quaternary International* 470 (B): 511-528.

Mazzucco N., Ibáñez J.J., Capuzzo G., Gassin B., Mineo M., Gibaja J.F. (2020) - Migration, Adaptation, Innovation: The Spread of Neolithic Harvesting Technologies in the Mediterranean, *PLoS ONE* 15 (4): e0232455.

Millard A.R. (2014) - Conventions for Reporting Radiocarbon Determinations, *Radiocarbon* 56 (2): 555-559.

Montgomery J. (2010) - Passports from the Past: Investigating Human Dispersals Using Strontium Isotope Analysis of Tooth Enamel, *Annals of Human Biology* 37 (3): 325-346.

Moskal-del Hoyo M. (2012) - The Use of Wood in Funerary Pyres: Random Gathering or Special Selection of Species? Case Study of Three Necropolises from Poland, *Journal of Archaeological Science* 39 (11): 3386-3395.

O'Donnell L. (2016) - The Power of the Pyre - A Holistic Study of Cremation Focusing on Charcoal Remains, *Journal of Archaeological Science* 65: 161-171.

Olsen J, Heinemeier J., Hornstrup K.M., Bennike P., Thrane H. (2013) - Old Wood' Effect in Radiocarbon Dating of Prehistoric Cremated Bones?, *Journal of Archaeological Science* 40 (1): 30-34.

ORAU. Oxford Radiocarbon Accelerator Unit online database. Oxford: University of Oxford. https://c14.arch.ox.ac.uk/database/db.php

Otárola-Castillo E., Torquato M.G. (2018) - Bayesian Statistics in Archaeology, *Annual Review of Anthropology* 47: 435-453.

Palmisano A., Bevan A., Kabelindde A., Roberts N., Shennan S. (2022a) - AIDA: Archive of Italian radiocarbon DAtes, version 5.0 (9 April 2022): https://github.com/apalmisano82/AIDA

Palmisano A., Bevan A., Lawrence D., Shennan S. (2022b) - The NERD Dataset: Near East Radiocarbon Dates between 15,000 and 1,500 Cal. Yr. BP, *Journal of Open Archaeology Data* 10: 2.

Pardo-Gordó S., García Puchol O., Bernabeu Aubán J., Diez Castillo A. (2019) - Timing the Mesolithic-Neolithic Transition in the Iberian Peninsula: The Radiocarbon Dataset, *Journal of Open Archaeology Data* 7: 4.

Pardo-Gordó S, Vidal-Matutano P., González-Marrero M.d.C., Chávez-Álvarez M.E. (2023) - The 14Canarias Web Application. An Interactive Radiocarbon Database for the Canary Islands, *Journal of Open Archaeology Data* 11:4.

Parnell A.C., Haslett J., Allen J.R.M., Buck C.E., Huntley B. (2008) - A Flexible Approach to Assessing Synchroneity of Past Events Using Bayesian Reconstructions of Sedimentation History, *Quaternary Science Reviews* 27 (19-20): 1872-1885.

Perrin T. (2021) - *BDA – Base de Données Archéologiques [Dataset] NAKALA*. https://doi.org/10.34847/nkl.dde9fnm8

Petchey F., Bickler S.H., Hughes L., Bunbury M. (2022) - The Aotearoa New Zealand Radiocarbon Database Upgrade, *Archaeology in New Zealand* 65 (3): 32-40.

Pettitt P., Zilhão J. (2015) - Problematizing Bayesian Approaches to Prehistoric Chronologies, *World Archaeology* 47 (4): 525-542.

Philippsen B. (2013) - The Freshwater Reservoir Effect in Radiocarbon Dating, *Heritage Science* 1: 24.

Pinhasi R., Fort J., Ammerman A.J. (2005) - Tracing the Origin and Spread of Agriculture in Europe, *PLoS Biology* 3 (12): e410.

Prentiss A.M., Edinborough K., Crema E.R., Kuijt I., Goodale N., Ryan E., Edwards A., Foor T.A. (2022) - Divergent Population Dynamics in the Middle to Late Holocene Lower Fraser Valley and Mid-Fraser Canyon, British Columbia, *Journal of Archaeological Science: Reports* 44: 103512.

Price M.H., Capriles J.M., Hoggarth J.A., Bocinsky R.K., Ebert C.E., Jones J.H. (2021) - End-to-End Bayesian Analysis for Summarizing Sets of Radiocarbon Dates, *Journal of Archaeological Science* 135: 105473.

Purugganan M.D., Fuller D.Q. (2011) - Archaeological Data Reveal Slow Rates of Evolution during Plant Domestication, *Evolution; International Journal of Organic Evolution* 65 (1): 171-183.

Reingruber A., Thissen L. (2017) - *14SEA*. http://www.14sea.org/.

Rick J.W. (1987) - Dates as Data: An Examination of the Peruvian Radiocarbon Record, *American Antiquity* 52: 55-73.

Rinne C., Kneisel J., Hinz M., Furholt M., Krischke N., Müller J., Raetzel-Fabian D., Rodens M., Sjögren K.-G., Vandkilde H., Wotzka H.-P. (2024) - *Rado.NB*. In: https://radonb.ufg.uni-kiel.de.

Riris P. (2021) - *carribean-14C: A compilation of 2147 anthropogenic radiocarbon (^{14}C) dates for the Caribbean region from 504 sites across 57 islands*. https://github.com/philriris/caribbean-14C/

Riris P., Silva F. (2021) - Resolution and the Detection of Cultural Dispersals: Development and Application of Spatiotemporal Methods in Lowland South America, *Humanities and Social Sciences Communications* 8 (1): 1-13.

Rose H.A., Meadows J., Henriksen M.B. (2020) - Bayesian Modeling of Wood-Age Offsets in Cremated Bone, *Radiocarbon* 62 (2): 379-401.

Rose H.A., Müller-Scheeßel N., Meadows J., Hamann C. (2022) - Radiocarbon Dating and Hallstatt

Chronology: A Bayesian Chronological Model for the Burial Sequence at Dietfurt an Der Altmühl 'Tennisplatz', Bavaria, Germany, *Archaeological and Anthropological Sciences* 14 (4): 72.

Sabaux C., Veselka B., Capuzzo G., Snoeck C., Sengeløv A., Hlad M., Warmenbol E., Stamataki E., Boudin M., Annaert R., Dalle S., Salesse K., Debaille V., Tys D., Vercauteren M., De Mulder G. (2021) - Multi-Proxy Analyses Reveal Regional Cremation Practices and Social Status at the Late Bronze Age Site of Herstal, Belgium, *Journal of Archaeological Science* 132: 105437.

Sabaux C., Snoeck C., Capuzzo G., Veselka B., Dalle S., Warmenbol E., Stamataki E., Hlad M., Sengeløv A., Debaille V., Boudin M., Salesse K., Annaert R., Vercauteren M., De Mulder G. (2024). Novel multidisciplinary approach detects multiple individuals within the same Late Bronze-Early Iron Age cremation graves, *Radiocarbon* 66 (4): 761-773.

Schmid C. (2020) - Evaluating Cultural Transmission in Bronze Age Burial Rites of Central, Northern and Northwestern Europe Using Radiocarbon Data, *Adaptive Behavior* 28 (5): 359-376.

Schmid C., Seidensticker D., Hinz M. (2019) - c14bazAAR: An R Package for Downloading and Preparing C14 Dates from Different Source Databases, *Journal of Open Source Software* 4 (43): 1914.

Sedig J.W., Olalde I., Patterson N., Harney É., Reich D. (2021) - Combining Ancient DNA and Radiocarbon Dating Data to Increase Chronological Accuracy, *Journal of Archaeological Science* 133: 105452.

Seidensticker D., Hubau W. (2021) - *aDRAC. Archive des datations radiocarbones d'Afrique centrale, Version 2.0.* https://github.com/dirkseidensticker/aDRAC

Shennan S., Downey S.S., Timpson A., Edinborough K., Colledge S., Kerig T., Manning K., Thomas M.G. (2013) - Regional Population Collapse Followed Initial Agriculture Booms in Mid-Holocene Europe, *Nature Communications* 4: 2486.

Silva F., Stevens C.J., Weisskopf A., Castillo C., Qin L., Bevan A., Fuller D.Q. (2015) - Modelling the Geographical Origin of Rice Cultivation in Asia Using the Rice Archaeological Database, *PLoS ONE* 10 (9): e0137024.

Snoeck C., Brock F., Schulting R.J. (2014) - Carbon Exchanges between Bone Apatite and Fuels during Cremation: Impact on Radiocarbon Dates, *Radiocarbon* 56 (2): 591-602.

Snoeck C., Cheung C., Griffith J.I., James H.F., Salesse K. (2022) - Strontium Isotope Analyses of Archaeological Cremated Remains – New Data and Perspectives, *Data in Brief* 42:108115.

Steuri N., Milella M., Martinet F., Raiteri L., Szidat S., Lösch S., Hafner A. (2023) - First radiocarbon dating of Neolithic stone cist graves from the Aosta valley (Italy): insights into the chronology and burial rites of the western Alpine region, *Radiocarbon* 65 (2): 521-538.

Stewart M., Carleton W.C., Groucutt H.S. (2021) - Climate Change, Not Human Population Growth, Correlates with Late Quaternary Megafauna Declines in North America, *Nature Communications* 12 (1): 965.

Stuiver M., Polach H.A. (1977) - Discussion Reporting of ^{14}C Data, *Radiocarbon* 19 (3): 355-363.

Stuiver M., Reimer P.J. (1993) - Extended ^{14}C Data Base and Revised CALIB 3.0 ^{14}C Age Calibration Program, *Radiocarbon* 35 (1): 215-230.

Stuiver M., Reimer P.J., Braziunas T.F. (1998) - High-Precision Radiocarbon Age Calibration for Terrestrial and Marine Samples, *Radiocarbon* 40 (3): 1127-1151.

Surovell T.A., Brantingham P.J. (2007) - A note on the use of temporal frequency distributions in studies of prehistoric demography, *Journal of Archaeological Science* 34 (11): 1868-1877.

Surovell T.A., Byrd Finley J., Smith G.M., Brantingham P.J., Kelly R. (2009) - Correcting temporal frequency distributions for taphonomic bias, *Journal of Archaeological Science* 36 (8): 1715-1724.

TAY Project 14C sample Database. http://tayproject.org/C14searcheng.html

Timpson A., Barberena R., Thomas M.G., Méndez C., Manning K. (2021) - Directly Modelling Population Dynamics in the South American Arid Diagonal Using ^{14}C Dates, *Philosophical Transactions of the Royal Society B* 376: 20190723.

Timpson A., Colledge S., Crema E., Edinborough K., Kerig T., Manning K., Thomas M.G., Shennan S. (2014) - Reconstructing Regional Population Fluctuations in the European Neolithic Using Radiocarbon Dates: A New Case-Study Using an Improved Method, *Journal of Archaeological Science* 52: 549-557.

Uriarte González A., Fernández Freire C., Fraguas Bravo A., Castañeda Clemente N., Capdevila Montes E., Salas Tovar E., Gilman A., del Bosque González I., Vicent Gárcia J.M. (2017) - IDEArq-C14: Una infraestructura de datos espaciales para la cronología radiocarbónica de la Prehistoria Reciente ibérica, in Barceló J.A., Bogdanovic I., Morell B., eds. - *Cronometrías para la historia de la Península Ibérica. Actas del congreso de cronometrías para la Historia de la Península Ibérica, Barcelona, Spain, September 17-19, 2016*, CEUR 2024: 209-225.

van Etten J., Hijmans R.J. (2010) - A Geospatial Modelling Approach Integrating Archaeobotany and Genetics to Trace the Origin and Dispersal of Domesticated Plants, *PLoS ONE* 5 (8): e12060.

Van Strydonck M., Boudin M., De Mulder G. (2010) - The Carbon Origin of Structural Carbonate in Bone Apatite of Cremated Bones, *Radiocarbon* 52 (2): 578-586.

Van Strydonck M., De Roock E. (2011) - Royal Institute for Cultural Heritage Web-Based Radiocarbon Database, *Radiocarbon* 53 (2): 367-370.

Van Strydonck M., Nelson D.E., Crombé P., Bronk Ramsey C., Scott E.M., van der Plicht J., Hedges R.E.M. (1999) - Rapport Du Groupe de Travail: Les Limites de Methode Du Carbone 14 Applicquée a L'archéologie, What's in a ^{14}C Date?, in: Evin J., Oberlin C., Daugas J.-P., Salles J.-F., eds. - *Acte Du Colloque "C14 and Archaeology." Revue d'Archéometrie. 1998. GMCPA*, 433-448.

Vermeersch P.M. (2024) - *Radiocarbon Palaeolithic Europe Database, Version 31*. Available at: https://ees.kuleuven.be/en/geography/projects/14c-palaeolithic/index.html.

Vondrovský V., Demján P., Dreslerová D. (2023) - Arch14CZ: A New Open Database of Radiocarbon Dates from the Czech Republic Released, *Archeologické Rozhledy* 75 (1): 99-101.

Wang C., Houyuan L., Jianping Z., Zhaoyan G., Keyang H. (2014) - Prehistoric Demographic Fluctuations in China Inferred from Radiocarbon Data and Their Linkage with Climate Change over the Past 50,000 Years, *Quaternary Science Reviews* 98: 45-59.

Ward G.K., Wilson S.R. (1978) - Procedures for Comparing and Combining Radiocarbon Age Determinations: A Critique, *Archaeometry* 20 (1): 19-31.

Weninger B. (2023) - *CalPal Archaeological 14C-Database*. https://www.academia.edu/28534389/CalPal_Archaeological_14C_Database_Europe_xls_Dec_2014.

Weninger B., Edinborough K., Clare L., Jöris O. (2011) - Concepts of Probability in Radiocarbon Analysis, *Documenta Praehistorica* 38:1-20.

Williams A.N. (2012) - The Use of Summed Radiocarbon Probability Distributions in Archaeology: A Review of Methods, *Journal of Archaeological Science* 39 (3): 578-589.

Williams A.N., Ulm S., Smith M., Reid J. (2014) - AustArch: A Database of ^{14}C and Non-^{14}C Ages from Archaeological Sites in Australia - Composition, Compilation and Review (Data Paper), *Internet Archaeology* 36.

Zazzo A., Saliège J.-F., Person A., Boucher H. (2009) - Radiocarbon Dating of Calcined Bones: Where Does the Carbon Come From?, *Radiocarbon* 51 (2): 601-611.

Ziedler J.A., Buck C.E., Litton C.D. (1998) - Integration of Archaeological Phase Information and Radiocarbon Results from the Jama River Valley, Ecuador: A Bayesian Approach, *Latin American Antiquity* 9 (2): 160-179.

Zilhão J. (2011) - Time is on my side, in: Hadjikoumis A., Ronbison E., Viner S., eds. - *The Dynamics of Neolithisation in Europe. Studies in Honour of Andrew Sherratt*. Oxbow Books, Barnsley: 46–65.

Ziółkowski M.S., Pazdur Mieczyslaw F., Krzanowski A., Michczynski A. (1994) - *Andes: Radiocarbon Database for Bolivia, Ecuador, and Peru.* Warsaw: Andean Archaeological Mission of the Institute for Archaeology, Warsaw University; Gliwice: Gliwice Radiocarbon Laboratory, Institute of Physics, Silesian Technical University.