Natural History Sciences

https://sisn.pagepress.org/nhs

eISSN 2385-0922

Publisher's Disclaimer. E-publishing ahead of print is increasingly important for the rapid dissemination of science. The Early Access service lets users access peer-reviewed articles well before print/regular issue publication, significantly reducing the time it takes for critical findings to reach the research community.
These articles are searchable and citable by their DOI (Digital Object Identifier).

Natural History Sciences is, therefore, E-publishing PDF files of an early version of manuscripts that have undergone a regular peer review and have been accepted for publication, but have not been through the copyediting, typesetting, pagination, and proofreading processes, which may lead to differences between this version and the final one.

The final version of the manuscript will then appear in a regular issue of the journal.

The E-publishing of this PDF file has been approved by the authors.

Natural History Sciences 2026 [Online ahead of print]

Please cite this article as:

Helama S. **An overview of the calendar year timelines used in quaternary science and human history, with special reference to sub-annual dating**. *Natural History Sciences* doi: 10.4081/nhs.2026.919

Submitted: 15-05-2025
Accepted: 19-11-2025

An overview of the calendar year timelines used in quaternary science and human history, with special reference to sub-annual dating

Samuli Helama
Natural Resources Institute Finland, Rovaniemi, Finland
samuli.helama@luke.fi

Abstract - The year 2025 celebrates the 1500th anniversary of the way we count years since and before the incarnation of Christ. The BC/AD timeline is used in natural and human sciences, with conversions to cal BP and b2k timelines, the latter two representing ages before AD 1950 and AD 2000. Though the timelines may seem established, there are more ways than one to count the calendar years, especially "before Christ" and "before present". If not correctly addressed, the disparities may impair comparisons between sub-annually and annually resolved records available from tree rings and ice cores, in addition to those from historical documents. The offsets between the timelines range from 0.5 to 2.5 years, which may already be detrimental to determining the cause-effect relationships of short-term events such as volcanic eruptions; however, it is possible that the errors may accumulate if different labs and re-users of data repeat the misconceptions. For example, a tree-ring event dated to 1627.5 BC using one timeline might be misassigned to 1626.5 BC or 1625.5 BC using other timelines. Such confusion may arise due to a "year zero" that is missing from the historical timeline, when the AD and BC years are replaced by positive and negative decimal numbers and when the timelines are converted to the Cartesian coordinate system, and/or due to the timelines used for boreal and austral growing seasons. A previously published formula to convert calendar dates to cal BP dates should be replaced by modified formulae tailored to sub-annual dating in this paper. Similar formulae are also provided for converting b2k ages. Developments in the Quaternary dating methods suggest that the number of disciplines topical to this discussion is likely to increase in the near future. It is emphasized that a clear reference to the particular timeline employed must be clarified in every single individual geoscientific/interdisciplinary study.
Keywords: chronology, dating, Holocene Epoch, Quaternary Period, radiocarbon.

Riassunto - Una panoramica delle cronologie basate sull'anno solare utilizzate nelle scienze del Quaternario e nella storia umana, con particolare riferimento alla datazione sub-annuale.
L'anno 2025 celebra il 1500º anniversario del sistema con cui contiamo gli anni prima e dopo l'incarnazione di Cristo. La cronologia a.C./d.C. è utilizzata nelle scienze naturali e umane, con

conversioni alle scale cal BP e b2k, che rappresentano rispettivamente età anteriori al 1950 d.C. e al 2000 d.C. Benché queste cronologie possano sembrare assodate, esistono più modi per conteggiare gli anni solari, soprattutto "prima di Cristo" e "prima del presente". Se non affrontate correttamente, tali discrepanze possono compromettere il confronto tra dati con risoluzione sub-annuale e annuale ottenute dagli anelli degli alberi e dalle carote di ghiaccio, oltre che dai documenti storici. Gli scarti tra le diverse cronologie variano da 0,5 a 2,5 anni, un margine che può già risultare problematico per determinare le relazioni causa–effetto di eventi di breve durata, come le eruzioni vulcaniche; è inoltre possibile che gli errori si cumulino se diversi laboratori e riutilizzatori di dati riproducono gli stessi fraintendimenti. Ad esempio, un evento dendrocronologico datato al 1627,5 a.C. secondo una cronologia potrebbe essere erroneamente assegnato al 1626,5 a.C. o al 1625,5 a.C. usando altre scale temporali. Questa confusione può emergere a causa dell'assenza dell'"anno zero" nella cronologia storica, quando gli anni d.C. e a.C. vengono sostituiti da numeri decimali positivi e negativi e quando le cronologie sono convertite in un sistema di coordinate cartesiane e/o in relazione all'uso di cronologie basate sulle stagioni di crescita boreali o australi. Una formula precedentemente pubblicata per convertire le date del calendario in date cal BP dovrebbe essere sostituita da formule modificate, adattate alla datazione sub-annuale, presentate in questo articolo. Sono inoltre fornite formule analoghe per convertire le età b2k. Gli sviluppi nei metodi di datazione del Quaternario suggeriscono che il numero di discipline coinvolte in questa discussione è destinato ad aumentare nel prossimo futuro. Si sottolinea la necessità di chiarire esplicitamente, in ogni singolo studio geoscientifico o interdisciplinare, la specifica cronologia di riferimento adottata.
Parole chiave: cronologia, datazione, Olocene, Quaternario, radiocarbonio.

"*All time measurements are performed*
with respect to some reference datum"
Holden *et al.* (2011)

A brief history of our calendric time

Ideally, we would be able to count years since the beginning of the Hadean. This is far from reality, and the years must be numbered from some intermediate event. The timeline we are using today was created by a Scythian monk Dionysius Exiguus who, exactly 1500 years ago, decided on the incarnation of Christ to start our Anno Domini era. In so doing, he dated the first year of our Lord (AD 1) to year 754 *ab urbe condita*, that is since the foundation of Rome (Declercq, 2002). This meant that the work of Dionysius Exiguus was accomplished in AD 525, but it was not until AD 731 when Bede, the Anglo-Saxon historian, introduced the years before the supernatural event, and not until the 17th century that the actual phrase Before Christ (BC) first appeared in literature (Lambe, 2024). Today, the timeline Dionysius Exiguus initiated is taken for granted and used universally by laymen and researchers as almost the only imaginable way to count calendar years. Yet, the timeline itself has its variants that started to emerge as early as it was employed to illustrate dates prior to the AD calendar.

The way the counting of years has changed can be understood if we compare the numeral systems which we use today to those the ancient chronographers had in their use. First, the number zero was unknown to them, for which reason the BC/AD timeline contains no "year zero". Second, negative numbers were not yet in use, and that is why the AD and BC years increase in opposite directions as they are both described by positive numbers. However, these conventions started to slowly blur over the centuries. Two astronomers are commonly named for initiating this process. Johannes Kepler (1571–1630) is cited for adding a year before AD 1, which he called "Christi", and Jacques Cassini (1677–1756) for introducing the actual number zero in that purpose in his deep-time calendar. As a result, two alternative systems to count the ancient years had been created: one where AD 1 is preceded by 1 BC and one with the year zero (Stange, 2024). In contemporary science the two timelines can be distinguished by calling the one with year zero as astronomical BC and that without zero as historical BC (Reimer *et al.*, 2020). After the days of Kepler and Cassini, the astronomers have also replaced the BC years with negative numbers altogether, in which system the year zero is preceded by a year minus one (-1). It follows that the absolute values of historical and astronomical BC years are offset by one year. Astronomers nevertheless primarily adhere to the latter system as it uses the ordinary rules and notation of arithmetic (Wilkins, 2000). A newcomer to this discussion is the ISO 8601 standard (Lund, 1999) whereby the years before the year [0000] are marked with the leading minus sign, akin to astronomical BC years.

In addition to changes in numeral systems, the ongoing move to rebrand the BC and AD notations as Before Common Era (BCE) and Common Era (CE) should not go unnoticed in this context (Lambe, 2024). Generally, the BC/AD timeline may be regarded as scientifically arbitrary (e.g. Gould, 2011), but the rebranding does not change the ways the calendar years are counted, nor does it solve the temporal offsets between the historical and astronomical BC years. In fact, the BC/AD dates are exactly synonymous to BCE/CE. Hence, the original BC/AD notations are used for historical authenticity and consistency throughout this study. The BC and AD notations were also preferred by the International Union of Geological Sciences in their recommendations to sort out the use of time units and notations in earth sciences (Rose, 2007; Grün, 2008). In what follows the dates with BC and AD notations refer invariably to the timeline with no year zero.

Scientific and historical timelines

In light of the above, it is perhaps no wonder that the BC/AD timeline has puzzled generations of academia. The trouble is demonstrated by accounts that from time to time appear even in scientific journals (e.g. Flickinger, 1931; Winger, 1936; Emiliani, 1995; Kukla, 1995). Compared to earlier decades, however, the problem of the year zero is ever-increasingly becoming relevant to Quaternary science where the annual dating accuracy of new millennia-long proxy records is proliferating. Among annually resolved geoscientific records (Noller *et al.*, 2000; Walker, 2005) relevant to this discussion, tree-ring series are routinely dated to exact calendar years using dendrochronological cross-dating techniques (Fritts, 1976; Baillie, 1995; Speer, 2010). Dating accuracy of ice core chronologies, originally based on layer counting, has also been recently much improved by constraining their timescales by pairwise comparisons between volcanic aerosol anomalies in ice layers and historical volcanic dust veil observations, between those aerosols and records of growing season temperature anomalies reconstructed from tree-ring data, ^{10}Be anomalies in ice and those of ^{14}C in tree rings indicating ancient solar proton events, and between ice core tephra evidence and dates of known volcanic eruptions (Sigl *et al.*, 2015; Sinnl *et al.*, 2022). Topical to this review, rigorously produced ice core chronologies show an estimated overall uncertainty of 1 to 2 years during antiquity (McConnell *et al.*, 2020), which is almost comparable to tree-ring dating accuracy of 1 year.

Moreover, sub-annually sampled tree-ring and ice core records demonstrate that maintaining the chronological accuracy between the datasets is of utmost importance for reporting historical, tree-ring and ice core dates as well as for analysing and storing the sub-annually resolved data (Yang *et al.*, 2014, 2021; Friedrich *et al.*, 2020; Fahrni *et al.*, 2020; McConnell *et al.*, 2020; Pearson *et al.*, 2018, 2020, 2022; Sakurai *et al.*, 2020; Miyake *et al.*, 2021; Brehm *et al.*, 2022; Sano *et al.*, 2023; Maczkowski *et al.*, 2024; Regev *et al.*, 2024). The literature cited above shows that this inter-disciplinary theme holds importance for production of single-year tree-ring and isotope/radiocarbon records and characterising rapid excursions in ^{14}C as indications of solar proton events on seasonal to multi-year scales. The theme is likewise important for assessing ancient societal responses to changes in reconstructed environment, such as explosive volcanic eruptions, of which occurrence and magnitude have been inferred from ice core data, and of which climatic and societal impacts can be reconstructed from tree-ring and historical records.

The need for consistent annually resolved timelines has also been emphasised by the radiometric dating community. Reimer *et al.* (2020) referred to considerable confusion – caused by mixed use of timelines, those with and without year zero – in different laboratories and by different software packages when building the IntCal20 radiocarbon age calibration curve for ^{14}C dating. The observation made in their paper presented by more than 40 authors and a similar number of research institutes demonstrates that the year zero remains an issue that may impair – if not correctly addressed – the exchange of samples and data between laboratories, research teams and individual actors in Quaternary science. In the same context it is important to recall that the samples and data that are correctly dated in the first place may still become incorrectly placed on a timeline if it differs from that used to originally date the materials, which again calls for consistent use of nomenclature and numeral systems to avoid the trouble Reimer *et al.* (2020) highlighted.

Apart from the BC/AD dates (Fig. 1A), the radiometric dating naturally comes with an additional timeline based on years that are counted Before Present (BP), running counterclockwise to an assumed direction of time flow. Compared to the BC/AD timeline, the count of the BP years starts without hesitation from the zero year. The "present", represented by 0 BP, is set to AD 1950 as a six-decades-old decision agreed upon by the Fifth Radiocarbon Dating Conference meeting at Cambridge (Godwin, 1962). While this decision may be obvious to most Quaternary scientists, it may nevertheless remain surprisingly unclear, as van der Plicht and Hogg (2006), Wolff (2007) and Duller (2011) have noted, to which datum the "present" occasionally refers to, particularly when the BP or "before present" notations are used outside of its original (^{14}C) scope, in the case of uranium–thorium or luminescence dating, for example. As for the latter, luminescence dates are presented in years from the year of measurement (Bateman, 2015), but ages reported in years before AD 2017 or 2020, as an example, may still be provided with "before present" or "yr BP" notations (Stavi *et al.*, 2021; Martinez *et al.*, 2023). As Wolff (2007) maintained: "[The] use of BP for anything except uncalibrated radiocarbon has become ambiguous and can be misinterpreted." Most readers of Quaternary literature have probably faced the same problem and can agree with this remark. As recommended by the International Union of Geological Sciences, this datum should be understood precisely as AD 1950.0 (Holden *et al.*, 2011).

Fortunately, the relationships between the cal BP and BC/AD timelines can be solved using frequently cited formulae (Stuiver & Pearson, 1993):

$$\text{cal BP} = 1950 - \text{cal AD} \quad (1)$$

and

$$\text{cal BP} = 1949 + \text{cal BC} \quad (2)$$

Putting aside the challenges to calibrate radiocarbon ages, it follows (Eq. 1) that AD 1949 equals 1 cal BP and (Eq. 1) that 1950 cal BP equals 1 BC (Eq. 2) (see Fig. 1B). As the calendric conversion shows, the BP timeline of ^{14}C ages does not include the year zero at the BC/AD boundary. Following this definition, the expressions cal AD and cal BC (Eq. 1 and 2) stand for calibrated or calendar years AD and BC (van der Plicht & Hogg 2006) and can be understood to thus encompass not only radiometric ages calibrated to calendar years but dendrochronological, ice core and historical dates discussed in this paper. More recently, the increasing use of annual and even sub-annual samples and data in ^{14}C studies has resulted in more sophisticated nomenclature. In order to account for the lag in boreal and austral growing seasons, annual wood samples from northern and southern hemispheres are reported relative to AD 1950.5 and AD 1951.0, respectively (Bronk Ramsey *et al*., 2024).
Yet, the most recent geoscientific timeline (b2k) counts time backwards from AD 2000 (Rasmussen *et al.*, 2006) or more precisely from AD 2000.0 (Holden *et al.*, 2011). Since its original appearance, the use of b2k ages has spread from ice core research (Rasmussen *et al.*, 2006) to a wider range of geosciences, including the rock-time divisions of the Geologic Time Scale (Walker *et al.*, 2018; Gibbard and Head, 2020). It is essential that, in keeping with cal BP timeline, conversions from b2k ages to BC dates are carried out without the year zero between 1 BC and AD 1 (Rasmussen *et al.*, 2022, 2023) (see Fig. 1C). This means that the cal BP and b2k timelines are fully comparable over the BC/AD boundary with no offsets. Hence, the foregoing formula (Stuiver & Pearson, 1993) can be modified to express the relationship between the two systems as follows:

$$\text{b2k} = 50 + \text{cal BP} \quad (3)$$

Moreover, the b2k ages can be converted to calendar years using the formulae:

$$\text{b2k} = 2000 - \text{cal AD} \quad (4)$$

and

$$\text{b2k} = 1999 + \text{cal BC} \quad (5)$$

The equations 1 and 2 have stood against time for over three decades, but it should be noted that they are not to be used to resolve sub-annual dates for which purpose they have not been designed. The same restriction now holds for the equations 3-5. The case of sub-annually resolved dates and ages are outlined in the next section.

Ordinal vs. decimal numbers

The desideratum for improved dating precision has led to increased reporting of decimally expressed sub-annual dates and ages. This development has its ramifications also for the conversions between the timelines that may be more complicated than it would first appear. First, the year of writing this article (AD 2025) is the 2025th since the BC/AD boundary (literally the 2025th year of our Lord), but 2025.0 years since that boundary will not have elapsed until the end of 31 December 2025, for the era is counted from the start of 1 January AD 1. An event taking place at noon 2 July AD 2025 could be called an AD 2025.5 event, although it occurred 2024.5 years since the BC/AD boundary. Simply, the calendar year AD 2025 represents the period between 2024.0 and 2025.0 years since the boundary, that is between the dates AD 2025.0 and AD 2026.0, thus the mid-point of that year is AD 2025.5. The same holds for all other calendar dates[1].

The setting becomes more complex, however, when the dates at both sides of the BC/AD boundary are discussed, which may be controversial even among geoscientist (Emiliani, 1995; Kukla, 1995; Randall 2000; Veronis, 2000a, 2000b). The examination of the dates may start from the mid-point of AD 1, which is AD 1.5 (Emiliani, 1995) (see Fig. 1A). This date is reached when 0.5 years (6 months) have passed since the BC/AD boundary, whereas the moment when 1.5 years have passed since that boundary is dated to AD 2.5. Likewise, the calendar year immediately predating AD 1 is 1 BC. It follows, however, that the moment that took place 1.0 years before AD 1.5 is 1.5 BC. The latter is the mid-point of 1 BC, that is the mid-point of the period between the dates 1.0 BC and AD 1.0 (not between 2.0 BC and 1.0 BC, as these dates bracket the calendar year 2 BC). This means that while an event that occurred 1.0 years before the BC/AD boundary is dated to 1.0 BC, an event taking place 1.0 years after that boundary is dated to AD 2.0. This is logical since the interval from 1 Jan 1 BC to 31 December AD 1 lasts 2.0 years. Thus, the interval between the noon of 2 July 1 BC and noon of 2 July AD 1 lasts 1.0 years, which shows that the difference between AD 1.5 and 1.5 BC is one year in length (Fig. 1A), not two or three years (Emiliani, 1993, 1995).

Second, the dates cited above demonstrate the way the BC and AD years originally refer to their ordinal numbers in the timeline (Winger, 1936), each integral number designating an entire calendar year. Sub-annual date, however, corresponds to an instant of time that can be expressed as a floating-point number, a whole number with a decimal point, for which either the BC/AD boundary, the "present", or AD 2000.0 mark the point of origin, depending on the timeline. The decimally expressed years are of special importance for post-bomb dates (Hua *et al.*, 2013) and calibration (Reimer *et al.*, 2004) and for reporting sub-annually dated tree-ring materials and data with reference to the timing of wood formation (Hua *et al.*, 2012; Uusitalo *et al.*, 2018; Sakurai *et al.*, 2020), as well as for ice

[1] In this study, the presentation of sub-annual dates does not account for the effect of leap years.

core records expressing the dates of aerosol deposition from deep-core ice layers (McConnell *et al.*, 2020). As the AD dates and BP/b2k ages are counted in opposite directions the mid-point of AD 1 is a decimal number AD 1.5, whereas the mid-point of 1999 b2k is 1998.5 cal BP (Fig. 1C). For BP ages the situation is more complex, depending on the point of origin (AD 1950.0, AD 1950.5 or AD 1951.0), in which cases AD 1.5 may correspond to 1948.5 cal BP, 1949.0 cal BP or 1949.5 cal BP (Fig. 1B). These differences are of importance for analyses of well-dated very high-resolution records from natural and historical archives.

Third, the conversions between the sub-annual BC dates and cal BP ages can be attained using a modified formula:

$$\text{cal BP} = t - \text{cal BC} + \lceil \text{cal BC} \rceil + \lfloor \text{cal BC} \rfloor - 2 \qquad (6)$$

where "t" is the point of origin (1950.0, 1950.5 or 1951.0), and $\lceil \text{cal BC} \rceil$ and $\lfloor \text{cal BC} \rfloor$ denote the ceiling and flooring functions, respectively, that return the least integer greater than the decimally expressed year and the greatest integer less than the decimally expressed year. One may need to convert 1.5 BC to cal BP age, as an example, in which case $\lceil 1.5 \rceil = 2$ and $\lfloor 1.5 \rfloor = 1$. For example, a date of an annual tree-ring sample representing boreal growing season, 1.5 BC, can be equally expressed as 1950.0 cal BP (present = AD 1950.5), which can be calculated from the foregoing formula (Eq. 6) as follows: $1950.5 - 1.5 + \lceil 1.5 \rceil + \lfloor 1.5 \rfloor - 2 = 1950.5 - 1.5 + \lceil 2 \rceil + \lfloor 1 \rfloor - 2 = 1950.0$). Similar adjustment needs to be done for Eq. 5 to convert sub-annual BC dates to b2k ages, in which case t = 2000.0. It is important to note that the new formula (Eq. 6) ought to be used only for decimally expressed years.

Calendric timelines vs. Cartesian coordinates

In addition to decimal numbers, there is also a need to consider the change taking place when BC dates are converted to negative numbers. It is generally accepted that adding the year zero between BC 1 and AD 1 and expressing BC years simply with the leading minus sign (Fig. 1D) will result in a sequence of calendar years fully compatible with arithmetic and computers. Indeed, this conversion greatly helps plotting, producing matrices and data storage. In so doing, the timeseries follow the ordinary rules and notation of arithmetic, the issue of the missing year zero is indeed removed, and the BC and AD years increase in same direction on the abscissa. Such timelines may also be justified as they comply with the ISO 8601 standard, that comes with an option to present ancient calendar dates. For example, the ISO 8601 standard (International Organization for Standardization, 2004) states that the twelfth of April in the second year before the year [0000] is expressed as -00020412 (see Fig. 1E for comparisons over the BC/AD boundary).

In the context of negative numbers, however, the calendar years are no longer presented as ordinals, a change that may go unnoticed when the dates are presented as integral numbers only (Winger, 1936). The change introduced by the conversion becomes more obvious when dates and ages are expressed decimally. In this way the timeline becomes consistent with the Cartesian coordinate system as the instants of time can be expressed as negative and positive floating-point numbers on the abscissa.

On such temporal BC/AD-like axis, it is the zero-point (not year zero) that marks the point of origin, and there are two zero years, expressed decimally on both sides of that point (Fig. 1F). These changes naturally affect the calculations and interpretations of the dates, as the direction of decimally expressed fractions over the BC years are switched. That is, the limit of -1.999… is -2 but the limit of 1.999… BC is AD 1 (Emiliani, 1995). While 1.25 BC refers to 2 April 1 BC, its conversion to a decimal number can lead into positions at either side of the zero-point, at -0.75 or 0.25 on the temporal axis, depending on the preferred place of the zero-point (1BC/AD1 or 2BC/1BC). The most logical option for the zero-point is at the BC/AD boundary (Winger, 1936) (see Fig. 1F), which results in one-year offset between the timelines over the AD era (as discussed above); for example AD 1.5 translates into a position at 0.5 on the temporal axis and AD 2025.5 (2 July 2025) is found at 2024.5 on the abscissa.

Placing the zero-point at 2BC/1BC would harmonise the yearly intervals over the AD era, but this choice results in an offset that can be two years over the BC era (Bronk Ramsey, 2009) (see Fig. 1G), which needs to be approached with extra caution. Considering that BC years and negatively numbered years increase in opposite directions, the misunderstanding can be even larger. It seems obvious that the option for the zero-point at the BC/AD boundary (Fig. 1F) might create less confusion. If the zero-point is placed at 2BC/1BC, a temporal position at 0.25 on the abscissa corresponds to a moment 0.75 years before the BC/AD transition, which is 1.25 BC, whereas a coordinate position at -0.25 refers to 2.75 BC. Consequently, the offset between the timelines A, F and G can vary between 0.5 and 2.5 years.

Examples from published studies

Apart from theoretical aspects, the use of timelines is exemplified below using high-resolution data from previously published interdisciplinary studies (McConnell *et al.*, 2020; Sakurai *et al.*, 2020). The purpose of this section is to provide practical examples of how the different timelines (Fig. 1) affect the ways the data can be visualised and comprehended.

As the first example, Sakurai *et al.* (2020) analysed ^{14}C concentrations in tree rings of Japanese cedar for the period 669–633 BC to characterise extreme solar proton event signals around 660 BC. Earlywood and latewood portions of each ring were treated separately. The authors found rapid increase in ^{14}C within 665–663.5 BC. According to Sakurai *et al.* (2020), each of their earlywood and latewood specific $\Delta^{14}C$ value is positioned at 1 June and 1 September, respectively, which represent temporal positions 0.417 and 0.668 years since the beginning of 1 Jan. Here, the $\Delta^{14}C$ values are displayed as a function of both AD and BC years (Fig. 2). The AD timeline is presented on the Cartesian x-axis relative to the BC/AD boundary (Timeline F in Fig. 1) and thus with negatively numbered years. BC years are given as ordinal numbers and therefore using Timeline A in Fig. 1.

In another example, McConnell *et al.* (2020) constructed volcanic fallout records from Greenland ice cores (NGRIP2 and GISP2) and compared them with reconstructed summer temperatures from European tree-ring chronologies representing the land region 35°–70° N/10°W–40° E (Luterbacher *et al.*, 2016). They showed that one of the largest volcanic eruptions of the past 2500 years occurred in early 43 BC, which they linked with evidence that the summers 43 BC and 42 BC could be among the coldest during the recent millennia in the northern hemisphere. These conditions probably lead to crop failures, famine and disease, exacerbating social unrest throughout the Mediterranean region. McConnell *et al.* (2020) stated that the year with strongest anomalies (43 BC) corresponded to "the period between 1,991 and 1,992 y before 1950 (ybp)". Here, the summer temperatures (Fig. 3A) and sub-annually dated ice core data (Fig. 3B) were plotted as a function of BC years (Timeline A in Fig. 1) and cal BP years (not present in Fig. 1) on the Cartesian x-axis with the zero-point at AD 1950.0. The reconstructed summer temperatures represent June through August season (Luterbacher *et al.*, 2016). Here, each temperature estimate was accordingly positioned 0.625 years since the beginning of 1 Jan. McConnell *et al.* (2020) dated the strongest volcanic peak to a temporal position of 42.708 years before the BC/AD boundary (i.e. 43.292 BC ~ February 43 BC) – this volcanic fallout signal thus predating the temperature anomaly recorded in the summer of that same year.

Discussion and Conclusions

How we carry out the conversions between the timelines is critically important for chronological assessments and discussions of the dates and ages of high-resolution Quaternary data. As discussed throughout this paper, the issue of the year zero may be confusing for those not familiar with the history of the timelines. A recent contribution to the discussion suggested that the zero year should be included, not excluded, from the BC/AD timeline, in the case of tree-ring and interdisciplinary studies (Büntgen & Oppenheimer, 2020). However, such a solution can hardly be a unifying approach. Encouraging the use of different calendar year timelines in different sub-disciplines runs counter to the fact that until today the year zero has been traditionally excluded from the BC/AD timeline (perhaps with the exception of astronomers) – this approach being maintained in a high number of studies. It could be suggested that the best strategy to avoid confusion is to raise awareness of the potential misuse of the timelines. This paper aims to fill this gap.

Even so, the issue of the year zero signifies but one potential aberration. Replacing the BC and AD dates by negative and positive decimal numbers and expressing them on the Cartesian coordinate system, represents a potential offset between the timelines that range from 0.5 to 2.5 years. Considering the zero-point of BP timelines either as AD 1950.0, AD 1950.5 or AD 1951.0, adds 1.0 years to the length of the potential misassignment, if all the information is not correctly addressed when converting between the timelines. The worst-case scenario could lead to the cumulation of errors, if different labs and re-users of data repeat the misconceptions of timelines. The issues identified in the present paper highlight the pitfalls which need to be considered with caution when citing the dates representing different types of timelines.

This paper focussed on tree-ring, ice core and historical data as source of information about past Quaternary environments. Other types of records that may in the near future become more topical to this discussion include annually laminated sediments and sclerochronological archives (Noller *et al.*, 2000; Walker, 2005). Apart from ice cores, sedimentary timescales can be constrained by tephrochronology that may help produce late Holocene sequences of annually laminated lacustrine sediments to be dated to exact calendar years (Larsen *et al.*, 2011; Kalliokoski *et al.*, 2023). In addition to dendrochronology, the cross-dating is also used for dating sclerochronological materials and producing chronologies from annual shell growth increments that are dated to exact calendar years and extending over the late Holocene intervals (Butler *et al.*, 2013; Reynolds *et al.*, 2017). These developments will open up new opportunities for Quaternary geochronologies, and also increase the need for consistent use of timelines to allow such data to be processed across the disciplines.

Generally, it is insufficient to hope that authors from various backgrounds from history to physics, from geology to theology, will intuitively grasp the timelines and dating systems in a consistent manner when there is more than one way to count the years. With these regards, it cannot be emphasised enough that clear reference to the particular timeline employed must be clarified in every single individual geoscientific or interdisciplinary study. Ambiguity and misunderstandings may be avoided if simple guidelines, which can be expressed in the form of a checklist below, are followed:

• Always specify whether BC (or BCE) dates use the historical (no year zero) or astronomical (includes year zero) timelines.

• When using the BP or "before present" notations, explicitly state the datum (e.g., "BP relative to AD 1950.5", "present = AD 1951.0", "ages are in years before AD 2020").

• When using decimally expressed sub-annual dates and ages, also define the point of origin accordingly (e.g., "AD 1950.5" or “AD 2000.0”).
• When plotting on a Cartesian axis, indicate the location of the zero-point.

This information is included in the timelines presented in Figure 1 and much ambiguity could be eliminated by simply citing the timelines. Moreover, the provided framework for conversions from one timeline to another (Fig. 1; Eq. 1-6) can help mitigate the confusion that may otherwise surround the high-resolution Quaternary studies.

Funding

Grants 339788 and 355268 from the Research Council of Finland.

Acknowledgements

Two anonymous reviewers are thanked for their valuable comments.

References

Baillie M.G.L., 1995 – A slice through time: Dendrochronology and precision dating. *B.T. Batsford*, London (UK).

Bateman, M.D., 2015 – The application of luminescence dating in sea-level studies. In: Handbook of Sea-Level Research. Shennan I., Long A.J. & Horton B.P. (eds.). *John Wiley & Sons*, Chichester, 404-417. doi: 10.1002/9781118452547.ch27

Brehm N., Christl M., Knowles T.D.J., Casanova E., Evershed R.P., Adolphi F., Muscheler R., Synal H.-A., Mekhaldi F., Paleari C.I., Leuschner H.-H., Bayliss A., Nicolussi K., Pichler T., Schlüchte, C., Pearson C.L., Salzer M.W., Fonti P., Nievergelt D., Hantemirov R., Brown D.M., Usoskin I. & Wacker L., 2022 – Tree-rings reveal two strong solar proton events in 7176 and 5259 BCE. *Nature Communications*, 13: 1-8. doi: 10.1038/s41467-022-28804-9

Bronk Ramsey C., 2009 – Bayesian Analysis of Radiocarbon Dates. *Radiocarbon*, 51: 337-360. doi:10.1017/S0033822200033865

Bronk Ramsey C., Adolphi F., Austin W., Bard E., Bayliss A., Blaauw M., Cheng H., Edwards R.L., Friedrich M., Heaton T., Hogg A., Hua Q., Hughen K., Kromer B., Manning S., Muscheler R., Palmer J., Pearson C., Reimer P., Reimer R., Richards D., Scott M., Southon J., Turney C. & Wacker L., 2024 – Development of the Intcal Database. *Radiocarbon*, 66: 1852–1868. doi:10.1017/RDC.2023.53

Büntgen U. & Oppenheimer C, 2020 – The importance of "year zero" in interdisciplinary studies of climate and history. *Proceedings of the National Academy of Sciences of the United States of America*, 117: 32845–32847. doi: 10.1073/pnas.2018103117

Butler P.G., Wanamaker A.D., Scourse J.D., Richardson C.A. & Reynolds D.J., 2013 – Variability of marine climate on the North Icelandic Shelf in a 1357-year proxy archive based on growth increments in the bivalve *Arctica islandica*. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 373: 141-151. https://doi.org/10.1016/j.palaeo.2012.01.016

Declercq G., 2002 – Dionysius Exiguus and the Introduction of the Christian Era. *Sacris Erudiri*, 41: 165–246. doi: 10.1484/J.SE.2.300491

Duller G.A.T., 2011 – What date is it? Should there be an agreed datum for luminescence ages? *Ancient TL*, 29: 1–3.

Fahrni S.M., Southon J., Fuller B.T., Park J., Friedrich M., Muscheler R., Wacker L. & Taylor R.E., 2020 – Single-Year German oak and Californian Bristlecone Pine ^{14}C Data at the Beginning of the Hallstatt Plateau from 856 BC to 626 BC. *Radiocarbon*, 62: 919–937. doi: 10.1017/RDC.2020.16

Emiliani, C., 1993 – Calendar reform. *Nature* 366: 716. doi: 10.1038/366716b0

Emiliani C, 1995 – Counting time. *Nature* 373: 278. doi: 10.1038/373278c0

Flickinger R.C., 1931 – Who Were the Roman Consuls for the Year Zero? *The Classical Journal* 26: 337-339.

Friedrich R., Kromer B., Wacker L., Olsen J., Remmele S., Lindauer S., Land A. & Pearson C., 2020 – A New Annual ^{14}C Dataset for Calibrating the Thera Eruption. *Radiocarbon,* 62: 953-961. doi: 10.1017/RDC.2020.33

Fritts H.C., 1976 –Tree Rings and Climate. *Academic Press*, New York (NY).

Gibbard P.L. & Head M.J., 2020 – The Quaternary Period. In: Geologic Time Scale 2020. Gradstein F.M., Ogg J.G., Schmitz M.D. & Ogg G.M. (eds.). *Elsevier*, Volume 2: 1217-1255. doi: 10.1016/B978-0-12-824360-2.00030-9

Godwin H., 1962 – Half-life of Radiocarbon. *Nature,* 195: 984. doi: 10.1038/195984a0

Gould S.J., 2011 – Questioning the millennium. *Harvard University Press*, Cambridge (MA).

Grün R., 2008 – Editorial. *Quaternary Geochronology,* 3: 1. doi: 10.1016/j.quageo.2007.09.001

Holden N.E., Bonardi M.L., De Bievre P., Renne P.R. & Villa I.M., 2011 – IUPAC-IUGS Common Definition and Convention on the Use of the Year as a Derived Unit of Time. *Episodes,* 34: 39–40. doi: 10.18814/epiiugs/2011/v34i1/006

Hua Q, Barbetti M, Levchenko VA, D'Arrigo RD, Buckley BM and Smith AM, 2012 – Monsoonal influence on Southern Hemisphere $^{14}CO_2$. *Geophysical Research Letters,* 39: 1-5. doi: 10.1029/2012GL052971

Hua Q., Barbetti M. & Rakowski A.Z., 2013 – Atmospheric Radiocarbon for the Period 1950–2010. *Radiocarbon,* 55: 2059-2072. doi: 10.2458/azu_js_rc.v55i2.16177

International Organization for Standardization, 2004 – International Standard ISO 8601. Data elements and interchange formats. Information interchange. Representation of dates and times. 3rd ed. *ISO copyright office*, Geneva (CH).

Kalliokoski, M., Guðmundsdóttir, E.R., Wastegård, S., Jokinen, S. & Saarinen, T., 2023 – A Holocene tephrochronological framework for Finland. *Quaternary Science Reviews,* 312: 1-18. doi: 10.1016/j.quascirev.2023.108173

Kukla, G., 1994 – Counting time. *Nature,* 372: 124. doi: 10.1038/372124d0

Lambe S., 2024 – Waste of Time? Why do we use BC/AD – and should we keep them? *History Today,* 74: 22-24.

Larsen, D.J., Miller, G.H., Geirsdóttir, Á. & Thordarson, T., 2011 – A 3000-year varved record of glacier activity and climate change from the proglacial lake Hvítárvatn, Iceland. *Quaternary Science Reviews,* 30, 2715-2731. doi: 10.1016/j.quascirev.2011.05.026

Lund K, 1999 – International standard for denotation of calendar time. *Production Planning & Control,* 10: 815-817. doi: 10.1080/095372899232641

Luterbacher J., Werner J.P., Smerdon J.E., Fernandez-Donado L., Gonzalez-Rouco F.J., Barriopedro D., Ljungqvist F.C., Buentgen U., Zorita E., Wagner S., Esper J., Mccarroll D., Toreti A., Frank D., Jungclaus J.H., Barriendos M., Bertolin C., Bothe O., Brazdil R., Camuffo D., Dobrovolny P., Gagen M., Garica-Bustamante E., Ge Q., Gomez-Navarro J.J., Guiot J., Hao Z., Hegerl G.C., Holmgren K., Klimenko V.V., Martin-Chivelet J., Pfister C., Roberts N., Schindler A., Schurer A., Solomina O., Gunten L., Wahl E. Wanner H., Wetter O., Xoplaki E., Yuan N., Zanchettin D., Zhang H & Zerefos C., 2016 – European summer temperatures since Roman times. *Environmental Research Letters,* 11: 1-12. doi: 10.1088/1748-9326/11/2/024001

Maczkowski A., Pearson C., Francuz J., Giagkoulis T., Szidat S., Wacker L., Bolliger M., Kotsakis K. & Hafner A., 2024 – Absolute dating of the European Neolithic using the 5259 BC rapid ^{14}C excursion. *Nature Communications*, 15: 1-12. doi: 10.1038/s41467-024-48402-1

Martínez G., Martínez G.A. & Owen L.A., 2023 – Human occupation, site formation, and chronostratigraphy of a mid-Holocene archaeological site at the eastern Pampa-

Patagonia transition, Argentina. *Quaternary Research*, 114: 52-68. doi:10.1017/qua.2023.8

McConnell J.R., Sigl M., Plunkett G., Burke A., Kim W.M., Raible C.C., Wilson A.I., Manning J.G., Ludlow F., Chellman N.J., Innes H.M., Yang Z., Larsen J.F., Schaefer J.R., Kipfstuhl S., Mojtabavi S., Wilhelms F., Opel T., Meyer H. & Steffensen J.P., 2020 – Extreme climate after massive eruption of Alaska's Okmok volcano in 43 BCE and effects on the late Roman Republic and Ptolemaic Kingdom. *Proceedings of the National Academy of Sciences of the United States of America,* 117: 15443-15449. doi: 10.1073/pnas.2002722117

Miyake F., Panyushkina I.P., Jull A.J.T., Adolphi F., Brehm N., Helama S., Kanzawa K., Moriya T., Muscheler R., Nicolussi K., Oinonen M., Salzer M., Takeyama M., Tokanai F. & Wacker L., 2021 – A single-year cosmic ray event at 5410 BCE registered in ^{14}C of tree rings. *Geophysical Research Letters,* 48: 1-8. doi: 10.1029/2021GL093419

Noller J.S., Sowers J., Colman S. & Pierce K., 2000 – Introduction to Quaternary geochronology. In: Quaternary Geochronology; Methods and Applications. Noller J.S., Sowers J.M. & Lettis, W.R. (eds.). *AGU Reference Shelf*, Washington DC, USA, 4: 1-10.

Pearson C.L., Brewer P.W., Brown D., Heaton T.J., Hodgins G.W.L., Jull A.J.T., Lange T. & Salzer M.W., 2018 – Annual radiocarbon record indicates 16th century BCE date for the Thera eruption. *Science Advances,* 4: 1-7. doi: 10.1126/sciadv.aar8241.

Pearson C., Salzer M., Wacker L., Brewer P., Sookdeo A. & Kuniholm P., 2020 – Securing timelines in the ancient Mediterranean using multiproxy annual tree-ring data. *Proceedings of the National Academy of Sciences of the United States of America,* 117: 8410-8415. doi: 10.1073/pnas.1917445117

Pearson C., Sigl M., Burke A., Davies S., Kurbatov A., Severi M., Cole-Dai J., Innes H., Albert P.G. & Helmick M., 2022 – Geochemical ice-core constraints on the timing and climatic impact of Aniakchak II (1628 BCE) and Thera (Minoan) volcanic eruptions. *PNAS Nexus,* 1: 1-12. doi: 10.1093/pnasnexus/pgac048

Randall J, 2000 – Comment on "Which one is correct, 2000 or 2001? How about 1995?" *Eos,* 81: 532. doi: 10.1029/EO081i045p00532-02

Rasmussen S.O., Andersen K.K., Svensson A.M., Steffensen J.P., Vinther B.M., Clausen H.B., Siggaard-Andersen M.-L., Johnsen S.J., Larsen L.B., Dahl-Jensen D., Bigler M., Röthlisberger R., Fischer H., Goto-Azuma K., Hansson M.E. & Ruthon U., 2006 – A new Greenland ice core chronology for the last glacial termination. *Journal of Geophysical Research,* 111: 1-16. doi: 10.1029/2005JD006079.

Rasmussen S.O., Dahl-Jensen D., Fischer H., Fuhrer K., Hansen S.B., Hansson M., Hvidberg C.S., Jonsell U., Kipfstuhl S., Ruth U., Schwander J., Siggaard-Andersen M.-L., Sinnl G., Steffensen J.P., Svensson A.M. & Vinther B.M., 2023 – Ice-core data used for the construction of the Greenland Ice-Core Chronology 2005 and 2021 (GICC05 and GICC21). *Earth System Science Data,* 15: 3351-3364. doi: 10.5194/essd-15-3351-2023

Rasmussen S.O., Svensson A.M. & Vinther B.M., 2022 – Greenland Ice-Core Chronology 2005 (GICC05) annual layer depths for various Greenland ice cores [dataset bundled publication]. *PANGAEA* <https://doi.org/10.1594/PANGAEA.943195> (retrieved in March 3, 2025).

Regev J., Gadot Y., Uziel J., Chalaf O., Shalev Y., Roth H., Shalom N., Szanton N., Bocher E., Pearson C.L., Brown D.M., Mintz E., Regev L. & Boaretto E., 2024 – Radiocarbon chronology of Iron Age Jerusalem reveals calibration offsets and architectural developments. *Proceedings of the National Academy of Sciences of the United States of America,* 121: 1-12. doi: 10.1073/pnas.2321024121

Reimer P., Austin W., Bard E., Bayliss A., Blackwell P., Bronk Ramsey C., Butzin M., Cheng H., Edwards R., Friedrich M., Grootes P., Guilderson T., Hajdas I., Heaton T., Hogg A., Hughen K., Kromer B., Manning S., Muscheler R., Palmer J., Pearson C., van der Plicht J., Reimer R., Richards D., Scott E., Southon J., Turney C., Wacker L., Adolphi F., Büntgen U., Capano M., Fahrni S., Fogtmann-Schulz A., Friedrich R., Köhler P., Kudsk S., Miyake F., Olsen J., Reinig F., Sakamoto M., Sookdeo A. & Talamo S., 2020 – The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0-55 kcal BP). *Radiocarbon*, 62: 725-757. doi: 10.1017/RDC.2020.41

Reimer P.J., Brown T.A. & Reimer R.W., 2004 – Discussion: Reporting and Calibration of Post-Bomb ^{14}C Data. *Radiocarbon,* 46: 1299-1304. doi: 10.1017/S0033822200033154

Reynolds D.J., Richardson C.A., Scourse J.D., Butler P.G., Hollyman P., Román-González A. & Hall I.R., 2017 – Reconstructing North Atlantic marine climate variability using an absolutely-dated sclerochronological network. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 465B: 333-346. doi: 10.1016/j.palaeo.2016.08.006.

Rose J, 2007 – The use of time units in Quaternary Science Reviews. *Quaternary Science Reviews* 26: 1193. doi: 10.1016/j.quascirev.2007.04.002

Sakurai H., Tokanai F., Miyake F., Horiuchi K., Masuda K., Miyahara H., Ohyama M., Sakamoto M., Mitsutani T. & Moriya T., 2020 – Prolonged production of ^{14}C during the ~660 BCE solar proton event from Japanese tree rings. *Scientific Reports,* 10: 1-7. doi: 10.1038/s41598-019-57273-2

Sano M., Kimura K., Miyake F., Tokanai F. & Nakatsuka T., 2023 – Two new millennium-long tree-ring oxygen isotope chronologies (2349–1009 BCE and 1412–466 BCE) from Japan. *Radiocarbon,* 65: 721-732. doi: 10.1017/RDC.2023.29

Schulman E., 1956 – Dendroclimatic changes in Semiarid America. *University of Arizona Press*, Tucson (AZ).

Sigl M., Winstrup M., McConnell J.R., Welten K.C., Plunkett G., Ludlow F., Büntgen U., Caffee M., Chellman N., Dahl-Jensen D., Fischer H., Kipfstuhl S., Kostick C., Maselli O.J., Mekhaldi F., Mulvaney R., Muscheler R., Pasteris D.R., Pilcher J.R., Salzer M., Schüpbach S., Steffensen J.P., Vinther B.M. & Woodruff T.E., 2015 – Timing and climate forcing of volcanic eruptions for the past 2,500 years. *Nature,* 523: 543-549. doi: 10.1038/nature14565

Sinnl G., Winstrup M., Erhardt T., Cook E., Jensen C. M., Svensson A., Vinther B.M., Muscheler R. & Rasmussen, S.O., 2022 – A multi-ice-core, annual-layer-counted Greenland ice-core chronology for the last 3800 years: GICC21. *Climate of the Past,* 18: 1125-1150. doi: 10.5194/cp-18-1125-2022

Speer J.H., 2010 – Fundamentals of Tree-ring Research. *The University of Arizona Press*, Tucson (AZ).

Stange U., 2024 – The Anthropocene as a civil time unit. *The Anthropocene Review,* 11: 550-569. doi: 10.1177/20530196231204326

Stavi I., Ragolsky G., Haiman M. & Porat N., 2021 – Ancient to recent-past runoff harvesting agriculture in the hyper-arid Arava Valley: OSL dating and insights. *The Holocene*, 31: 1047-1054. doi: 10.1177/0959683621994641

Stuiver M. & Pearson G.W., 1993 – High-precision bidecadal calibration of the radiocarbon time scale, AD 1950-500 BC and 2500-6000 BC. *Radiocarbon,* 35: 1-23. doi: 10.1017/S0033822200013783

Uusitalo J., Arppe L., Hackman T., Helama S., Kovaltsov G., Mielikäinen K., Mäkinen H., Nöjd P., Palonen V., Usoskin I. & Oinonen M., 2018 – Solar superstorm of AD 774 recorded subannually by Arctic tree rings. *Nature Communications,* 9: 1-8. doi: 10.1038/s41467-018-05883-1

van der Plicht J and Hogg A, 2006 – A note on reporting radiocarbon. *Quaternary Geochronology,* 1: 237-240. doi: 10.1016/j.quageo.2006.07.001

Veronis G., 2000a – Which one is correct, 2000 or 2001? How about 1995? *Eos,* 81: 290. doi: 10.1029/00EO00216

Veronis G., 2000b – Reply to "Comments on "Which one is correct, 2000 or 2001? How about 1995?" *Eos,* 81: 532. doi: 10.1029/EO081i045p00532-03

Walker, M.J.C., 2005 – Quaternary Dating Methods. *John Wiley & Sons*, Chichester (UK).

Walker M., Head M.J., Berkelhammer M., Björck S., Cheng H., Cwynar L., Fisher D., Gkinis V., Long A., Lowe J., Newnham R., Rasmussen S.O. & Weiss H., 2018 – Formal ratification of the subdivision of the Holocene Series/ Epoch (Quaternary System/Period): Two new Global Boundary Stratotype Sections and Points (GSSPs) and three new stages/ subseries. *Episodes,* 41: 213-223. doi: 10.18814/epiiugs/2018/018016

Wilkins G.A., 2000 – The year with a name but without a number. *Astronomy & Geophysics,* 41: 6.9. doi: 10.1093/astrog/41.6.6.9-a

Wolff E.W., 2007 – When is the ''present''. *Quaternary Science Reviews,* 26: 3023-3024. doi: 10.1016/j.quascirev.2007.10.008

Winger R.M., 1936 – Zero and the calendar. *The Scientific Monthly,* 43: 363-367.

Yang B., Qin C., Wang J., He M., Melvin T.M., Osborn T.J. & Briffa K.R., 2014 – A 3,500-year tree-ring record of annual precipitation on the northeastern Tibetan Plateau. *Proceedings of the National Academy of Sciences of the United States of America,* 111: 2903-2908. doi: 10.1073/pnas.1319238111

Yang B., Qin C., Bräuning A., Osborn T.J., Trouet V., Ljungqvist F.C., Esper J., Schneider L., Grießinger J., Büntgen U., Rossi S., Dong G., Yan M., Ning L., Wang J., Wang X., Wang S., Luterbacher J., Cook E.R. & Stenseth N.C., 2021 – Long-term decrease in Asian monsoon rainfall and abrupt climate change events over the past 6,700 years. *Proceedings of the National Academy of Sciences of the United States of America,* 118: 1-7. doi: 10.1073/pnas.2102007118

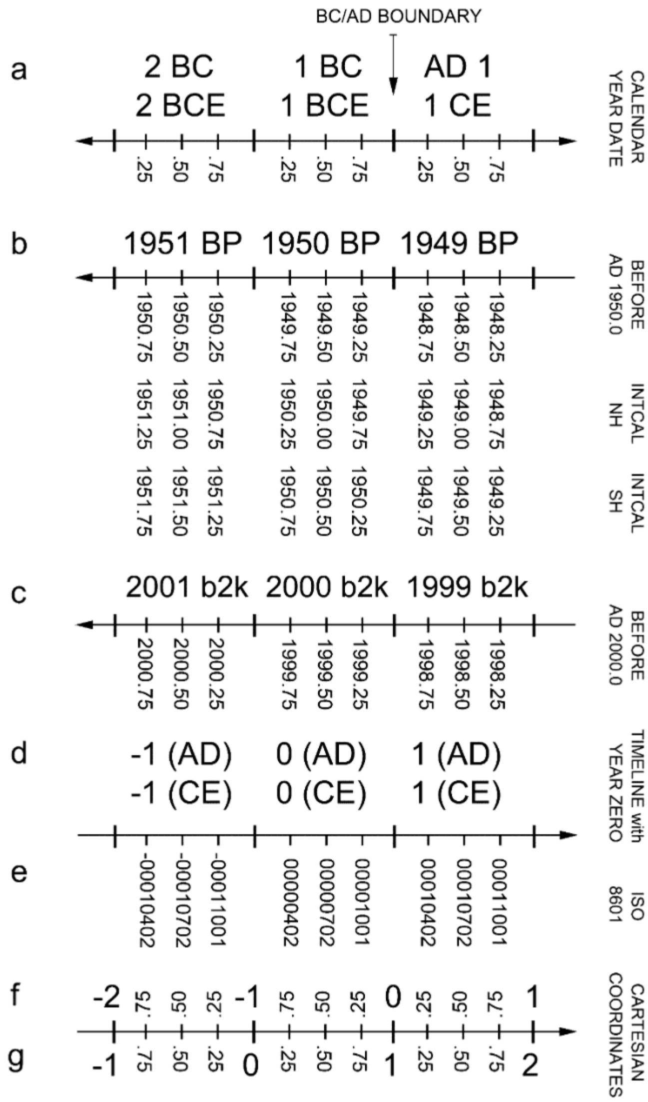

Fig. 1 – A comparison of timelines and notations. a) Calendric dates as ordinal numbers, each integral number designating an entire calendar year, with associated decimally expressed sub-annual dates. b) Before Present (BP) age as integral numbers relative to AD 1950 and with associated decimally expressed sub-annual ages, where 0.0 cal BP equals either AD 1950.0 (Holden *et al.*, 2011), AD 1950.5 (IntCal Northern Hemisphere (NH)), or AD 1951.0 (Intcal Southern Hemisphere (SH)). c) Before AD 2000 (b2k) ages as integral numbers and with associated decimally expressed sub-annual ages relative to AD 2000.0. d) Calendar years as negative and positive numbers relative to AD (and CE) timescale, following Schulman (1956). e) Calendar dates using the ISO 8601 standard. f) Dates plotted as floating-point numbers on Cartesian coordinates where the zero-point is placed at 1BC/AD1 (that is the BC/AD boundary). g) Same as F but the zero-point is placed at 2BC/1BC. The BC/AD boundary is marked with a downward arrow. BP ages refer to cal BP timeline. / Confronto tra cronologie e notazioni. a) Date calendariali come numeri ordinali, in cui ciascun numero intero designa un intero anno del calendario, con associate date sub-annuali espresse in forma decimale. b) Età *Before Present* (BP) come numeri interi riferiti al 1950 d.C., con età sub-annuali espresse in formato decimale; 0,0 cal BP corrisponde infatti a 1950,0 d.C. (Holden *et al*., 2011), 1950,5 d.C. (IntCal Northern Emisphere (NH)) oppure 1951,0 d.C. (IntCal Southern Emisphere (SH)). c) Età *Before AD 2000* (b2k) come numeri interi, con età sub-annuali espresse in formato decimale rispetto al 2000,0 d.C. d) Anni del calendario espressi come numeri negativi e positivi rispetto alla scala temporale d.C. (e C.E.), secondo Schulman (1956). e) Date calendariali secondo lo standard ISO 8601. f) Date rappresentate come numeri in virgola mobile su coordinate cartesiane, con il punto zero posto a 1 a.C./1 d.C. (ossia il limite a.C./d.C.). g) Come in f), ma con il punto zero posto a 2 a.C./1 a.C. Il limite a.C./d.C. è indicato con una freccia rivolta verso il basso. Le età BP si riferiscono alla cronologia cal BP.

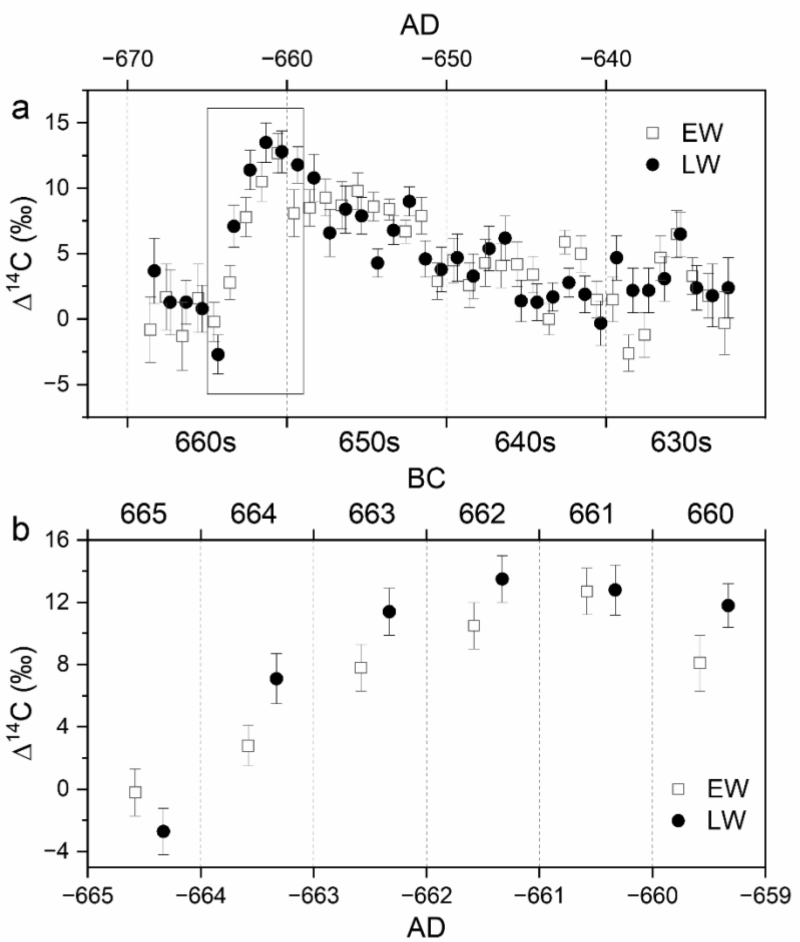

Fig. 2 – A sub-annually sampled ^{14}C archive from tree rings of Japanese cedar *Cryptomeria japonica* (Thunb. ex L.f.) D.Don. Earlywood (EW) and latewood (LW) ^{14}C concentrations of each annual ring are presented a) for 669-633 BC period and b) detailed for 665-660 BC period. The BC and AD years represent the timelines A and F, respectively (see Fig. 1). The ^{14}C data originate from Sakurai *et al.* (2020). / Un archivio di 14C campionato con risoluzione sub-annuale dagli anelli di crescita di cedro giapponese *Cryptomeria japonica* (Thunb. ex L.f.) D.Don. Le concentrazioni di 14C del legno precoce (EW) e del legno tardivo (LW) di ciascun anello annuale sono presentate: a) per il periodo 669–633 a.C., e b) in dettaglio per il periodo 665–660 a.C.. Gli anni a.C. e d.C. rappresentano rispettivamente le cronologie A e F (vedi Fig. 1). I dati del 14C provengono da Sakurai *et al*. (2020).

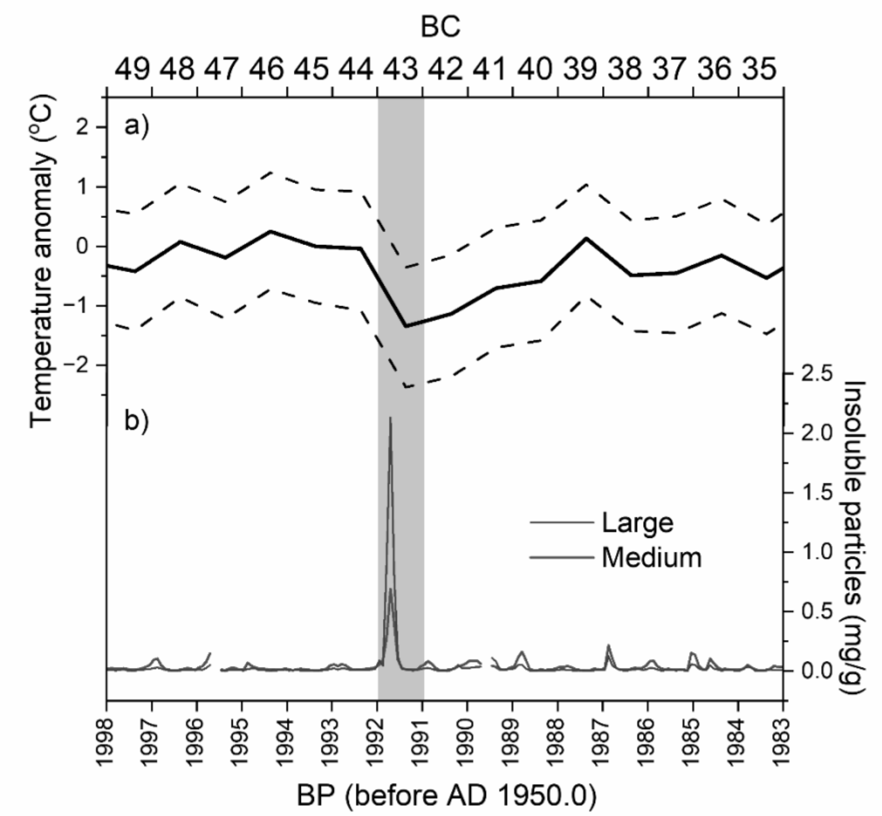

Fig. 3 – Tree-ring and ice core evidence. a) Reconstructed European summer (June-August) temperatures (thick line) inferred from tree-ring data (Luterbacher *et al.*, 2016) with associated 95% uncertainty range outlined by dashed lines. b) Ice core (NGRIP2) records of volcanic fallout indicated by sub-annually measured size-resolved insoluble particle concentrations, shown separately for large (5-10 µm) and medium (2.5-5 µm) particles. The BC years represent the timeline A (see Fig. 1). The cal BP years are presented on the Cartesian x-axis relative to AD 1950.0. The tree-ring and ice core data originate from Luterbacher *et al.* (2016) and McConnell *et al.* (2020). / Evidenze da anelli di accrescimento degli alberi e carote di ghiaccio. a) Temperature estive europee (giugno–agosto) ricostruite (linea spessa) sulla base dei dati dendrocronologici (Luterbacher *et al.*, 2016), con l'intervallo di incertezza al 95% indicato dalle linee tratteggiate. b) Registrazioni di una carota di ghiaccio (NGRIP2) del fallout vulcanico, evidenziate tramite concentrazioni sub-annuali di particelle insolubili, misurate per classi dimensionali e presentate separatamente per particelle grandi (5–10 µm) e medie (2,5–5 µm). Gli anni a.C. rappresentano la cronologia A (vedi Fig. 1). Gli anni cal BP sono riportati sull'asse cartesiano delle x rispetto al 1950,0 d.C.. I dati dendrocronologici e delle carote di ghiaccio provengono da Luterbacher *et al.* (2016) e McConnell *et al.* (2020).