Tree rings reveal globally coherent signature of cosmogenic radiocarbon events in 774 and 993 CE

Ulf Büntgen et al.*

Though tree-ring chronologies are annually resolved, their dating has never been independently validated at the global scale. Moreover, it is unknown if atmospheric radiocarbon enrichment events of cosmogenic origin leave spatiotemporally consistent fingerprints. Here we measure the $^{14}$C content in 484 individual tree rings formed in the periods 770–780 and 990–1000 CE. Distinct $^{14}$C excursions starting in the boreal summer of 774 and the boreal spring of 993 ensure the precise dating of 44 tree-ring records from five continents. We also identify a meridional decline of 11-year mean atmospheric radiocarbon concentrations across both hemispheres. Corroborated by historical eye-witness accounts of red auroras, our results suggest a global exposure to strong solar proton radiation. To improve understanding of the return frequency and intensity of past cosmic events, which is particularly important for assessing the potential threat of space weather on our society, further annually resolved $^{14}$C measurements are needed.
The precise dating of high-precision proxy archives is essential for climate reconstructions, as well as for their comparison with climate forcing agents, climate model simulations, historical sources and archaeological evidence. Extratropical wood formation usually generates distinct annual stem growth increments. Consecutive patterns of tree-ring width therefore allow continuous and often well-replicated records of multi-centennial to millennial length to be developed if suitable measurements from living trees are successfully cross-dated against relict wood from historical timbers, archaeological excavations and/or subfossil remains. The annual dating accuracy of such composite chronologies is not only crucial for (paleo-) climatology and ecology, but also for advancing interdisciplinary research that engages archaeology, history and the environmental sciences. Although intercontinental assessments reveal a high level of growth coherency between individual ring width chronologies from different parts of the world, their dating precision has never been independently corroborated at the global scale. Even a 1-year dating offset would prevent any straightforward comparison of tree-growth anomalies with climate forcing agents, output from climate model simulations, climate-induced environmental responses or documented socio-economic and political changes. A prime example of such interdisciplinary cross-comparison is the cluster of large volcanic eruptions identified from ice-core anomalies in 536, 540 and 547 Common Era (CE), which coincided with rapid cooling at the onset of the Late Antique Little Ice Age (LALIA), as well as the outbreak of the Justinian Plague in 541 CE and large-scale societal transformation and human migration across much of Eurasia.

If of sufficient amplitude, abrupt changes in the Earth’s atmospheric radiocarbon ($^{14}$C) abundance are recorded in tree rings owing to the short mixing time of the atmosphere, including stratosphere-troposphere exchanges. Often attributed to extreme fluxes of high-energy solar particles, distinct $^{14}$C anomalies in 774/5 and 992-4 CE, as well as possibly much earlier in 660 and 3372/1 BCE have been identified in local proxy archives. These so-called Cosmic Events also yield anomalies in records of other cosmogenic radionuclides, such as $^{10}$Be and $^{36}$Cl that are measured in ice cores. Though proposed as a “paradigm for chronology”, the extra-terrestrial origin, spatial variation and time-transgressive evolution of cosmogenic tie-points are still unknown because a spatially extensive, well-replicated network of isotopic markers across continents and hemispheres has not hitherto been available.

In an unprecedented voluntary collaboration of the international tree-ring community, the COSMIC initiative gathered wood samples from the majority of the world’s longest tree-ring records, spanning the decades 770–780 and 990–1000 CE. The resulting COSMIC network includes data from 44 disjunct tree-ring width measurement series (Supplementary Note 1), with sampling locations on five continents (Fig. 1; Supplementary Fig. 1). With the individual sites being distributed between 42° S and 72° N, and ranging from around 40 to 4000 m a.s.l., COSMIC represents most of the world’s extra-tropical forest biomes. Covering four atmospheric radiocarbon zones, our dataset is composed of 13 genera, including 25 coniferous and two broadleaf species (Supplementary Tables 1–2). Wood fibres from each tree ring, dendrochronologically cross-dated to the period 770–780 CE, or, if not reaching that far back in time, to the interval 990–1000 CE, were manually separated, chemically extracted and automatically graphitized (Methods; Supplementary Table 3). Modern compact tandem accelerator mass spectrometry (AMS) requires 1000-times less material and operates as precisely as some traditional decay counters. Developed and based at ETH-Zurich, the “Mini Radiocarbon Dating System” (MICADAS) was used to measure the $^{14}$C content of 30–50 mg bulk cellulose for a total of 484 tree rings. A subset of 374 rings in the 770s CE interval originates from 27 records on the Northern Hemisphere (NH) and seven records on the Southern Hemisphere (SH). Another 110 rings that did not reach back into the 8th century CE represent eight NH and two SH records in the 990s CE.

**Fig. 1** COSMIC network. Distribution of 44 tree-ring records from which cellulose was extracted for annual $^{14}$C measurements during the intervals 770–780 and 990–1000 CE (circles and rectangles) (Supplementary Fig. 1; Supplementary Tables 1-2). Independent $^{14}$C evidence from two floating tree-ring chronologies (green), and five (quasi) annually resolved ice-core $^{10}$Be records (yellow). White dashed lines refer to atmospheric radiocarbon zones. The map reflects knowledge from the authors and was created via software ArcGIS 10.1 SP1 for Desktop by Esri.
Results
Cosmogenic radiocarbon signature in 774 CE. The coherent, rapid increase of $^{14}$C concentration in NH and SH tree rings reveals the global extent of the cosmogenic signature of extreme fluxes of high-energy solar energetic particles (SEP) in 774 (Fig. 2a). The lower $\Delta^{14}$C values in the SH most likely reflect different ocean circulation, wind and land–ocean–atmosphere exchanges\(^6\)\(^,\)\(^9\). For the NH, the individual $^{14}$C site values, as well as their corresponding hemispheric range, show low levels in 773 ($\Delta^{14}$C = −0.1%), higher concentrations in 774 (0.4%), a further increase in 775 (0.95%), a relatively small increase in 776 (0.2%), and decreasing concentrations thereafter. Although the overall shape of the $^{14}$C time-series through the event is similar for both hemispheres, its amplitude is lower in the SH, and, in contrast to the NH signal, the $^{14}$C increase in 774 (0.7%) is comparable to the increase in 775 (0.6%) (Fig. 2a). Collating results from both hemispheres into four meridional bands reveals a similar time-transgressive pattern (Supplementary Fig. 2). The tree ring-based $^{14}$C concentrations predominantly reflect tropospheric conditions during wood formation, rather than concentrations of radiocarbon in the stratosphere where it is mostly produced. We therefore employ a global carbon box model to generate mechanistic understanding of the intra-annual course of the radiocarbon cycle (Supplementary Fig. 3). With 95% confidence, the model times the event, presumed to have been ephemeral, within the boreal growing season (June to August) of 774 CE (Supplementary Fig. 4a; Supplementary Table 4). Importantly, this seasonal timing is consistent with the observed ~10% relative difference in radiocarbon amplitude between the NH and SH.

Cosmogenic radiocarbon signature in 993 CE. Similar in shape to the 8th century event is a significant, but smaller $^{14}$C excursion in 993 (Fig. 2b). The best model/data agreement at the 95% confidence interval suggests it occurred between February and June 993 (Supplementary Fig. 4b; Supplementary Table 4). In contrast to the 8th century excursion, the sharp radiocarbon enrichment in 993, found in both hemispheres, is followed by a moderate increase from 993 to 994 CE. This behaviour is indicative of a late boreal spring event. Although associated with uncertainties, our monthly resolved model assumes that about 2/3 of the total annual wood biomass is produced within 1–2 months in the middle of the vegetation period (Supplementary Fig. 3). Since this rather short window of cell formation and cell wall thickening is synchronized between all sites in each hemisphere, phenological changes in growing season length have no influence on the model outcome. Moreover, only a very small impact is expected from so-called carry-over effects, because <10% of stored carbohydrates from previous year(s) is typically used for cell growth. The model also accounts for seasonal differences in stratosphere–troposphere $^{14}$C exchange, and thus simulates the occurrence of both radiocarbon enrichment spikes in the boreal summer (July ± 1 month) of 774 and the boreal spring (April ± 2 months) of 993 (Supplementary Fig. 4) with great confidence. The intra-annual timing of the $^{14}$C event in 993 CE translates into a coherent signature across both hemispheres. While the global extent and time-transgressive evolution of the 774 and 993 events are similar, the amplitude of the latter event is about half that of the former. With our box model, an additional 5.3 ± 0.5 (9.6 ± 0.5) $10^{26}$ atoms, i.e. 1.8 ± 0.2 (3.2 ± 0.2) times the annual production, are needed to produce the 993 (774) anomaly (Supplementary Fig. 4). Although our findings demonstrate accurate cross-dating of well-replicated tree-ring chronologies from around the world, they still cannot guarantee the annual precision of individual measurements from single trees (Methods). The independent replication of tree-ring width measurement series therefore remains an essential element in dendrochronology, which further distinguishes our discipline from most other proxy archives for which sample size is much more restricted.

Fig. 2 COSMIC signature. a Annual $^{14}$C content of 374 tree rings formed between 770 and 780 CE at 27 and seven sites across the NH and SH (light blue and red lines), respectively (Supplementary Fig. 2). b $^{14}$C content of 110 tree rings from 990–1000 CE at eight and two sites in the NH and SH (blue and red lines), respectively. Thick lines bracket standard uncertainties around hemispheric means, lower box plots reveal year-to-year $^{14}$C differences (median, 25th and 75th percentiles), and SH data have been shifted relative to the earlier NH data.
Discussion

Following the LALIA, the boreal summer of 774 over most of the NH was ~0.7 °C colder than the 1961–90 reference period\(^{20}\), whereas 993 coincided with medieval summer warmth of ~0.6 °C (relative to the 1961–90 mean climatology). Although speculative, slightly lower mean temperatures in the 770s (compared to the 990s) may have contributed to a larger, though insignificant (4.0‰ ± 0.4 in 774 versus 3.5‰ ± 0.7 in 993), hemispheric offset in the radiocarbon concentration (Fig. 2). In contrast to previous, model-based assumptions\(^{19}\), we hypothesize that an overall warmer climate in the 990s might explain the smaller inter-hemispheric 14C difference during high medieval times via reduced atmospheric mixing and/or ocean upwelling in the SH. Our limited understanding of how, if at all, climate change affects the amount of outgassing 14C-depleted CO\(_2\) from the proportionally larger SH oceans, however, calls for more research. Moreover, different ecological site conditions and species-specific plant physiological processes, including xyleogenesis, may further impact the timing and intensity of cellulose-based 14C anomalies through varying rates of cell formation and carbon sequestration\(^{12}\).

Such influences are expected to be particularly strong in multi-biome, global scale tree-ring compilations\(^2\), such as the COSMIC network, which contains wood from living trees, historical timbers, archaeological excavations and subfossil remains of 27 species.

Of greater significance than the ~3–4‰ 14C inter-hemispheric offset (Fig. 2), we identify a meridional north–south gradient of declining average 14C values in each 11-year tree-ring record (Fig. 3). Independently of the two cosmogenic events in the 770s and 990s, the mean atmospheric radiocarbon concentration is generally higher at northern latitudes >60° N. The 14C transport to lower latitudes where the growing season of trees is usually lengthening, however, might be altered by stratosphere–troposphere exchanges\(^6\). Complex ocean circulations, climate gradients and different growing season lengths are expected to alter further the large-scale distribution of the Earth’s radiocarbon zones. Since the high 14C values at the most northern sites cannot be explained by these processes alone, further research into the role of ocean extent and winds\(^6,19\), ocean–atmosphere circulation and coupling, terrestrial and solar magnetism, and the combined effects on the global 14C dispersal, is needed.

The global signature of the two cosmogenic excursions independently validates the precise dating of well-replicated tree-ring chronologies from five continents. Moreover, it offers a unique opportunity for assessing and/or correcting records within and between proxy archives, akin to the nuclear Bomb Peak of the 1960s (Methods). This study further emphasizes the accuracy and relevance of using high-resolution 14C measurements in determining the age of floating tree-ring series that have been used to date the eruptions of Katla (Iceland)\(^{21}\) and Changbaishan (China and DPR Korea)\(^{22}\) and (Fig. 1). Quasi-independent evidence of the two radiometric time markers in the 770 and 990s is also found in high-resolution 10Be deviations in five ice cores from Greenland and Antarctica\(^{23,24}\) (Fig. 1; Supplementary Table 5).

Given the exceptional nature of these two SEP events, we have examined contemporary medieval texts to see if any references might attest to these cosmic events. We recognize that interpretation of such documents is contested and acknowledge the potential for misinterpreting these narratives. The prominent Japanese Buddhist priest Kūkai (Kôbô Dashi), born in 774, was given the official name Henshō Kūkō, often translated as “worldwide shining diamond”\(^{25}\). Moreover, a person from India presented himself before the Caliph al-Mansur in the year 776 who was well versed in the siddhánta method of calculation related to the movement of the heavenly bodies, and in the same year there was a gathering of Mayan mathematicians and astronomers at Copán in Honduras\(^{22}\). Together with other writers, Britton\(^{28}\) refers to an aurora when talking about a red cross that appeared in the heavens after sunset between 773 and 776. Again, the 18th century physicist Thomas Short (1690–1772) repeated a record from Chronicon Magdeburgense\(^{29}\): “993 On the 7th of the Calends of January, at one a Clock in the Night, suddenly Light shined out of the Night like mid-day; it lasted an Hour, but the Sky turning red, the Night returned...”. Some references have been interpreted as aurora\(^{28–30}\) but may, alternatively, suggest point-of-light events, such as a gamma ray burst or supernova. Our data, however, suggest globally homogeneous impacts in 774 and 993 that can be best explained by large energy releases from the Sun\(^7\), such as SEP events. Historical records from Germany, Ireland and the Korean Peninsula suggest the occurrence of red auroras between late-992 and early-993 CE\(^{31}\), which could be interpreted as great magnetic storms from intense solar activity. While preceding previously reported 14C results from local analyses by one year\(^8,14\), the medieval observations are consistent with our findings.

Together with advances in accelerator mass spectrometry and the availability of continuous, multi-millennial tree-ring chronologies from different parts of the world, our results highlight the importance and feasibility of reproducing the decadal-resolved IntCal calibration curve at annual resolution over much of the Holocene and maybe even beyond\(^{32}\). Such an improved high-resolution radiocarbon record would provide unprecedented dating confidence to various fields of the natural sciences and humanities. It would also bring a deeper understanding of the frequency, magnitude and origin of cosmic events, critical to assessments of the threat of space weather to our society\(^{33}\).

Methods

Sample preparation. Although the highest level of caution has been applied in each step throughout the COSMIC project, the final 14C measurements may still contain some degree of uncertainty, because of a wider range of possible biases and errors inherent to such a community wide, voluntary collaboration (Supplementary Note 1).

Once identified, the original data provider, usually an experienced tree-ring researcher either at a university, institute or laboratory, be it private or governmental, delivered the right wood sample that comprises either the 770–780 or 990–1000 interval CE. Although this sounds trivial as individual samples are usually coded after sampling and before archiving, the relevant material often originates from fieldwork campaigns that, in some cases, have been conducted several decades ago. It is important to note, that both samples and scholars may have changed location and workplace throughout the years. A systematic, long-

---

**Fig. 3** COSMIC gradient. The 14C content of individual tree-ring site records averaged over 11-year intervals from 770–780 and 990–1000 CE. Horizontal lines indicate atmospheric radiocarbon zones\(^{17}\). Grey lines are standard errors of the tree-ring site records. Linear trends within the NH and across both hemispheres are R\(^2\) = 0.29 and 0.71, respectively (not shown).
term archiving of wood samples from either extremely long-lived trees, historical timbers, archaeological excavations or subfossil remains, is often complicated because many universities, institutes and laboratories, smaller or larger, simply do not have the appropriate storage capacity. A sustainable archiving of relic wood samples, especially in the case of wet archaeological and subfossil material, poses a serious challenge, and funding for appropriate facilities of such long-term service is generally scarce.

Once the right sample was identified and found in one of the many COSMIC-relevant archives around the world (Supplementary Table 1), an accurate, high-resolution re-measurement of the individual tree-ring widths of the two decades of interest (770–780 and 990–1000 CE) was performed to ensure precise cross-dating. Each of the samples was asked to mark their questions about smaller than 0.1 mm if trees were growing at or near their species-specific distribution limit (see above). The labelled (coded) and marked (stitched) wood samples were then packed and sent to the Swiss Federal Research Institute WSL in Birmensdorf (Switzerland), where all material was quality controlled (e.g. wood composition), and further processing steps were performed (see details below).

At WSL, each individual ring boundary from 770–780 or 990–1000 CE was re-identified to guarantee the correct ring width sequence within the two 11-year intervals. All rings were then manually cut with a scalpel and the corresponding wood material was carefully divided and fragmented into similarly sized fibre flake sections. The fibre flake sections from each processing step. The combination of sample combustion with an elemental analyser graphite sample is then weighed into an OX-II standard typically yielding ~500,000 counts or more (12C-ion currents of 50 μA) (see details below). Radiocarbon dead kaori (Agathis australis) wood from New Zealand and brown coal from Germany, as well as an absolutely dated Scots pine (Pinus sylvestris) sample from the Torneträsk region in northern Sweden suggested a one-year inconsistency. The Torneträsk 14C measurements herein used, however, precisely detected the cosmic signal in either 993 or 774 CE (depending on the material used). A similar, 1-year dating irregularity was found in an individual kauri (Agathis australis) from northern New Zealand. The kauri samples herein used, however, confirm both of the events in 993 and 774 CE. It is important to note at this stage that in the temperate regions of the SH, tree growth starts in the spring of a certain year and ends in the summer of the following year. Following Schulman’s (1996) convention 8, which assigns to each tree-ring the date of the year in which tree growth started, year 774 in our paper refers to the spring-summer of the NH and November 774 until March 775 on the SH.

On top of biological carry-over effects and wood anatomical features, several biotic and abiotic disturbance factors, such as insect outbreaks, fungal diseases and severe defoliation, may affect tree-ring widths. Therefore, a well-replicated core ring width dataset should also be expected to capture the individual climate signal. The 14C measurements herein used, however, precisely detected the cosmic signal in either 993 or 774 CE (depending on the material used). A similar, 1-year dating irregularity was found in an individual kauri (Agathis australis) from northern New Zealand. The kauri samples herein used, however, confirm both of the events in 993 and 774 CE.

Data availability

All data will be freely available via http://www.ams.ethz.ch/research/published-data.html.

Received: 30 May 2018 Accepted: 7 August 2018

Published online: 06 September 2018

Radiocarbon measurements. Wood fibres of each tree ring (Supplementary Tables 1-2), putatively dendrochronologically cross-dated to either the 770–780 or 990–1000 CE interval, were manually separated, chemically extracted and automatically graphitized (Supplementary Table 3). All fibres were soaked in NaOH over night at 70 °C, before being washed for 1 h with HCl and again 1 h in NaOH. All fibres were then bleached in 5% NaClO2 for 2–3 h at 70 °C until they turned white. A total of 2–3 mg of cellulose per individual ring sample was wrapped in tin capsules and graphitized in the automated graphitization line “AGN” (see details below). The resulting graphite was homogenised by a high-precision compact accelerator mass spectrometer (AMS). The graphite samples are then counted on a high-precision compact accelerator mass spectrometer (AMS) (see details below). The labelling (coded) and marked (stitched) wood samples were then packed and sent to the Swiss Federal Research Institute WSL in Birmensdorf (Switzerland), where all material was quality controlled (e.g. wood composition), and further processing steps were performed (see details below).

At WSL, each individual ring boundary from 770–780 or 990–1000 CE was re-identified to guarantee the correct ring width sequence within the two 11-year intervals. All rings were then manually cut with a scalpel and the corresponding wood material was carefully divided and fragmented into similarly sized fibre flake sections. The fibre flake sections from each processing step. The combination of sample combustion with an elemental analyser graphite sample is then weighed into an OX-II standard typically yielding ~500,000 counts or more (12C-ion currents of 50 μA) (see details below). Radiocarbon dead kaori (Agathis australis) wood from New Zealand and brown coal from Germany, as well as an absolutely dated Scots pine (Pinus sylvestris) sample from the Torneträsk region in northern Sweden suggested a one-year inconsistency. The Torneträsk 14C measurements herein used, however, precisely detected the cosmic signal in either 993 or 774 CE (depending on the material used). A similar, 1-year dating irregularity was found in an individual kauri (Agathis australis) from northern New Zealand. The kauri samples herein used, however, confirm both of the events in 993 and 774 CE. It is important to note at this stage that in the temperate regions of the SH, tree growth starts in the spring of a certain year and ends in the summer of the following year. Following Schulman’s (1996) convention 8, which assigns to each tree-ring the date of the year in which tree growth started, year 774 in our paper refers to the spring-summer of the NH and November 774 until March 775 on the SH.

On top of biological carry-over effects and wood anatomical features, several biotic and abiotic disturbance factors, such as insect outbreaks, fungal diseases and severe defoliation, may affect tree-ring widths. Therefore, a well-replicated core ring width dataset should also be expected to capture the individual climate signal. The 14C measurements herein used, however, precisely detected the cosmic signal in either 993 or 774 CE (depending on the material used). A similar, 1-year dating irregularity was found in an individual kauri (Agathis australis) from northern New Zealand. The kauri samples herein used, however, confirm both of the events in 993 and 774 CE.

Data availability

All data will be freely available via http://www.ams.ethz.ch/research/published-data.html.

Received: 30 May 2018 Accepted: 7 August 2018

Published online: 06 September 2018
References

1. Büntgen, U. et al. 2500 years of European climate variability and human susceptibility. Science 331, 578–582 (2011).

2. Esper, J. et al. Ranking of tree-ring based temperature reconstructions of the past millennium. Quat. Sci. Rev. 145, 134–151 (2016).

3. Büntgen, U. et al. Cooling and societal change during the Late Antique Little Ice Age from 536 to around 660 AD. Nat. Geosci. 9, 231–236 (2016).

4. Miyake, F., Nagaya, N., Masuda, K. & Nakamura, T. A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan. Nature 486, 240–242 (2012).

5. Miyake, F., Masuda, K. & Nakamura, T. Another rapid event in the carbon-14 content of tree rings. Nat. Commun. 4, 1748 (2013).

6. Braziunas, T. F., Fung, I. Y. & Stuiver, M. The preindustrial atmospheric 14CO2: latitudinal gradient as related to exchanges among atmospheric, oceanic, and terrestrial reservoirs. Glob. Biogeochem. Cycles 9, 565–584 (1995).

7. Mekhaldi, F. et al. Multiradionuclide evidence for the solar origin of the cosmic-ray events of AD 774/5 and 993/4. Nat. Commun. 6, 8611 (2015).

8. Sukhodolov, T. et al. Atmospheric impacts of the strongest known solar particle storm of 775 AD. Sci. Rep. 7, 45257 (2017).

9. Büntgen, U. et al. Extratropical confirmation of tree-ring dating. Nat. Clim. Change 4, 404–405 (2014).

10. Jull, A. J. T. et al. Excursions in the 14C record at A.D. 774–775. Radiocarbon 52, 2072 (2010).

11. Wacker, L. et al. Radiocarbon dating to a single year by means of rapid AMS. Radiocarbon 52, 2073–2081 (2010).

12. Adolphi, F., Gu, X., Wacker, L., Hajdas, I. & Gäggeler, H. Alternative methods for 14C peaks in AD 775, AD 993, and 660 BC. Radiocarbon 52, 1507–1512 (2010).

13. Hayakawa, H. et al. Historical auroras in the 990s: evidence of great magnetic storms. Nature 486, 240–242 (2012).

14. Braziunas, T. F., Fung, I. Y. & Stuiver, M. The preindustrial atmospheric 14CO2: latitudinal gradient as related to exchanges among atmospheric, oceanic, and terrestrial reservoirs. Glob. Biogeochem. Cycles 9, 565–584 (1995).

15. Wang, F. Y. et al. A rapid cosmic-ray increase in BC 3372. Geology 45, 783–786 (2017).

16. Fogtmann-Schulz, A. et al. Cosmic ray event in 994 C.E. recorded in New Zealand kauri trees indicates short-lived increase in 14C production spanning both hemispheres. Earth. Planet. Sci. Lett. 411, 290–297 (2015).

17. Li, M. H. et al. Responses of leaf nitrogen and mobile carbohydrates in different Quercus species/provenances to moderate climate changes. Plant Biol. 15, 177–184 (2013).

18. Reiners, F. et al. Pulse-labelling trees to study carbon allocation dynamics: a review of methods, current knowledge and future prospects. Tree Physiol. 32, 776–798 (2012).

19. De Micco, V. et al. Intra-annual density fluctuations in tree rings: how, when, where and why? IAWA 37, 232–259 (2016).

20. Fritts, H. C. Tree Rings and Climate p. 567 (Academic Press, London, 1976).

21. Schulman, E. Dendroclimatic changes in Semiarid America p. 142 (University of Arizona Press, Tucson, 1956).

Author contributions

U.B. and L.W. designed the study with input from J.D.G. Radiocarbon measurements and analyses were performed by J.D.G. and L.W., with the involvement of J.W. Additional radiocarbon measurements and analyses were performed by A.J.T., J.P. and F.M.A. Radiocarbon AMS system. Radiocarbon 52, 2073–2081 (2010).

Additional information

Supplementary Information accompanies this paper at https://doi.org/10.1038/s41467-018-06036-0.

Competing interests: The authors declare no competing interests.

Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
