Reply to “Rapid $^{14}$C excursion at 3372-3371 BCE not observed at two different locations”

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The nuclide $^{14}$C can be produced in the atmosphere by high energy particles and $\gamma$-rays from high-energy phenomena. Through the carbon cycle, some of $^{14}$CO$_2$ produced in the atmosphere can be retained in annual tree rings$^{12}$. Four events of rapid increase of the $^{14}$C content occurred in AD 775, AD 994, BC 660 and BC 3371 were found$^{3-6}$. Recently, the data of Jull et al. (2020) was inconsistent with our records around BC 3371. We measured our sample again and found the $^{14}$C records are consistent with the value in Wang et al. (2017). Therefore, our $^{14}$C records are robust. The inconsistency may be caused by the difference of calendar ages for the wood samples, or the physical origin of the event. First, crossdating on ring width can be performed only between trees whose growth has the same environmental conditions. Because the master tree-ring for dendrochronology is lack for Chinese trees. The master tree-ring from California has to be used. Therefore, the calendar ages derived from dendrochronology may be not precise. Second, the $^{14}$C even may be not global. One evidence
is the variation of $^{14}$C content around AD 1006\cite{12,18}. The $^{14}$C contents of Californian trees increase 12‰ in two years\cite{12}, while Japanese trees\cite{7,8} show no $^{14}$C increase.

In order to cross-check the measured result, a new piece of sample was cut from the buried tree used in our 2017 study\cite{6}. We separated annual rings carefully. The new-cut sample was measured using the Accelerator Mass Spectrometry (AMS) method at the Institute of Accelerator Analysis laboratory (IAA). The new measured results are shown as red circles in Figure 1 and also listed in Table 1. This figure also contains the measurement results in Wang et al. (2017)\cite{6}. Considering the measurement error, we can see that the new results are consistent with those in Wang et al. (2017)\cite{6}. Therefore, the $^{14}$C records are robust. The overall variation shows a rapid increase with a gradual decrease over several years due to the carbon cycle. The solid line is the best fit for filled circles using the four-box carbon cycle model with a net $^{14}$C production of $Q = (7.2 \pm 1.2) \times 10^7$ atoms/cm$^2$. The parameters of the four-box carbon cycle model are the same as those used in ref\cite{3,6}.

The calendar ages for our wood sample and Jull’s samples may not be at the same time as also suggested by the author. The calendar age is usually determined by dendrochronology (or tree-ring dating). Dendrochronology is the scientific method of dating tree rings to the exact year they were formed, which is widely used. In dendrochronology, master tree-ring is required. In dendrochronology, crossdating on ring width can be performed only between trees whose growth has the same environmental conditions. However, there is no such master tree-ring for about five thousand years in China. So, we have to use the master tree-ring from other places\cite{9}. Because, the
growth rate (width) of trees is controlled by numerous variables such as climate and atmospheric conditions. The climate and atmospheric conditions in central China and California are dramatically different. Therefore, the age of Chinese wingnut tree can not be precisely determined using the master tree-ring from California. The dpLR (Dendrochronology Program Library) may not suitable for correlation analysis of different tree-ring records\cite{10}, which may cause the unexpected value of correlation. So the calendar ages derived from dendrochronology may contain systematic errors, which is unpredictable. Besides dendrochronology, we also dated the wood sample using the following method in our 2017 paper\cite{6}. From $^{14}$C measurements, the calibrated ages of tree rings are given by IntCal13 curve\cite{11}. If the age of the innermost ring is $x$, the ages of outer rings can be determined by the order of tree rings. The least squares method is used to constrain the value of $x$ by comparing calibrated ages with ages from the order of tree rings. Using this method, we found that the rapid $^{14}$C increase occurs at about BC 3371. However, due to the large error of calibrated ages (i.e., several decades), the derived age has the same error. Therefore, the rapid $^{14}$C increase occurred around BC 3371 with an error of several decades. In order to derive the exact calendar age of the wood sample from dendrochronology, the master tree-ring from central China is needed. We hope it will be built in the future.

The physical origins of $^{14}$C events are still unclear. Although, some works demanded that solar proton events (SPEs) produce the AD 775 event\cite{12,14}, basing on that this event is global and the $^{10}$Be and $^{36}$Cl data in ice cores\cite{15}. However, Sigl et al. (2015) found that the time offset between $^{14}$C peak and peaks of $^{10}$Be and $^{36}$Cl is about 7 years\cite{16}. Mekhaldi et al. (2015) adjusted the $^{10}$Be and $^{36}$Cl ice-core records to fit the tree rings $^{14}$C peaks by hands\cite{12}. The $^{10}$Be is only
2σ above the noise\textsuperscript{13}. In the yearly $^{10}$Be data of the last 400 years, there are more deviations of similar strength (as claimed by Mekhaldi et al. (2015) for AD 775 and 994), e.g. around 1460, 1605, 1865, and 1890 in North Greenland Ice Core Project, are all unrelated to strong $^{14}$C variations\textsuperscript{13}. Therefore, the peaks of $^{14}$C and $^{10}$Be may have different origins, which challenges the SPE origin. Meanwhile, there are also several problems with the interpretation of these $^{14}$C events as SPEs\textsuperscript{13,17,18}, including no definite historic records of strong aurorae or sunspots around AD 775 and AD 994\textsuperscript{19,20}, the inferred solar fluence ($>30$ MeV) value is inconsistent with the occurrence probability distribution for SPEs\textsuperscript{21,22}, and whether the Sun can produce such large proton events is still debated\textsuperscript{23}. Neuhäuser & Hambaryan (2014) calculated the probability for one solar superflare with energy larger than $10^{35}$ erg within 3000 years to be possibly as low as 0.3 to 0.008. For the BC 3371 event, there is no $^{10}$Be and $^{36}$Cl measurement at present. There is no reason to claim that the four events are all caused by SPEs. The Carrington event is the most energetic solar flare observed so far, which implies that upsurges of greater magnitude may require extra-solar explanations. Meanwhile, gamma-ray photons produced by high-energy explosions can also generate $^{14}$C events, such as supernovae\textsuperscript{13}, short gamma-ray bursts\textsuperscript{24,25}, and pulsar outbursts\textsuperscript{18}. A supernova remnant, named Vela Jr., has an age of $t = 2,000 - 13,000$ yr at a distance less than 400 parsecs\textsuperscript{26}, which is a promising candidates to cause the BC 3371 event. It has long been hypothesized that intense bursts of high-energy gamma-ray flux would also be accompanied by ozone depletion, on account of changing the exchanges in the atmosphere\textsuperscript{25,27,28}. The effect on atmosphere by gamma-ray radiation is poorly understood and needed extensive study. This will affect the $^{14}$C absorption rate in different locations. So the tree rings at the same period may have different $^{14}$C contents in
different regions. One possible evidence is the $^{14}$C increase around AD 1006. Damon et al. (1995) measured annual samples of sequoia wood from America between the years AD 995-1020. They found that the $^{14}$C content increases from $-22.2\%\epsilon$ (AD 1009) to $-10.0\%\epsilon$ (AD 1011). The $^{14}$C content increases about 12$\%\epsilon$ in two years. Meanwhile, an increase was also found in the IntCal98 curve in the same period. However, Menjo et al. (2005) measured wood samples from Japan during the same time-period. No rapid $^{14}$C increase was found around AD 1006, and the measured $^{14}$C records are dramatically different for the three wood samples (see table 2 of Dee et al. 2017). The possible reason is the regional effect, which can cause different $^{14}$C variations in different regions. Although, whether the rapid increase around AD 1006 is produced by SN 1006 is unclear. The different $^{14}$C records confirm the regional effect of $^{14}$C contents during the same period.

In conclusion, the $^{14}$C records in Wang et al. (2017) are robust. The difference between Wang et al. (2017) and Jull et al. (2020) may be caused by the difference of calendar ages for the wood samples, or the increase may be not global. The master tree-ring in China is required to determine the age of sample precisely. Meanwhile, study the true origin of $^{14}$C events is important.

Methods

AMS measurement at IAA. The sample was neutralized with pure water, and dried. In the acid treatments, the sample is treated with HCl (1 M). In the standard alkaline treatment, the sample is treated with NaOH, by gradually raising the concentration level from 0.001 M to 1 M. If the alkaline concentration reaches 1 M during the treatment, the treatment is described as Acid-Alkali-Alkali (AAA), while “AaA” if the concentration does not reach 1 M. (3) The sample was
oxidized by heating to produce CO$_2$ gas. (4) The CO$_2$ gas was purified in a vacuum line. (5) The purified CO$_2$ gas was reduced to graphite by hydrogen using iron as a catalyst. (6) The graphite was pressed into a target holder for the AMS $^{14}$C dating. Measurement The graphite sample is measured against a standard of Oxalic acid provided by the National Institute of Standards and Technology, using a $^{14}$C-AMS system based on the tandem accelerator. The background check was also performed.

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**Competing interests statement** The authors declare that they have no competing financial interests.
| Year (BC) | $\Delta^{14}$C(‰) | Error$^a$ |
|----------|------------------|-----------|
| 3375     | 67.02            | 1.90      |
| 3373     | 61.06            | 1.90      |
| 3372     | 63.97            | 2.00      |
| 3371     | 72.60            | 2.00      |
| 3370     | 73.23            | 1.90      |
| 3369     | 71.96            | 1.80      |
| 3368     | 68.22            | 1.90      |
| 3366     | 66.12            | 1.90      |
| 3364     | 65.23            | 1.90      |
| 3361     | 66.99            | 1.80      |

$^a$ The error (s.d.) of $\Delta^{14}$C is calculated from error propagation.

Table 1: Measured results in the Institute of Accelerator Analysis laboratory.
Figure 1: **Measured $^{14}$C content.** Measured results of $\Delta^{14}$C for the tree rings using the AMS method at the Institute of Accelerator Analysis laboratory in 2020 (red circles). The measured results in Wang et al. (2017) are also shown as black circles. The solid line is the best fit for all data using the four-box carbon cycle model with a net $^{14}$C production of $Q = (7.2 \pm 1.2) \times 10^7$ atoms/cm$^2$. 