Resond letter to the reviewer 1#

Dear reviewer:

We would like to express our feelings of appreciations to you for your kindly help and professional comments to our manuscript entitled “Summer precipitation reconstructed quantitatively using a Mid Holocene δ^{13}C common millet record from Guanzhong Basin, China”. We have tried our best to modify the weakness and flaws pointing out by you. Now, we believe that we made a better work which would probably satisfy the reviewer and suitable to be published. The answer to the comments is listing in the following paragraph.

Thanks again for your help.
Best wishes!

Sincerely,

Yang Qing and Xiaoqiang Li

Reviewer 1:

General comments

The paper intends to demonstrate the suitability, accuracy and usefulness of d^{13}C of millet seed as proxy of paleoprecipitation. Application is performed for late Holocene in northern China. This study is innovative and definitively deserves to be published in Climate of the Past. I do not have any irremediable concerns: raw data should be provided and I have some propositions 1- to tone down a little bit the writing to make it closer to the reality, 2- to be more precise in the text when talking about general concepts, 3- to be more accurate when reporting data by e.g. including uncertainty ranges and by propagating them and 4- to re-organize a little bit the manuscript. See details for these specific comments.

Details

* line 16: please replace "are highly suited" by "are suited", this is enough

Thanks for the reviewer’s suggestion. We have removed “highly” from the sentence.

*Line 40: "modern records", do you mean "instrumental records"? Please correct.

Thanks for the reviewer’s suggestion. We have corrected “modern records” into “instrumental records” following the suggestion.

* Lines 52-54: this better suits to late Holocene, even the newly acknowledged Anthropocene. Please be specific

Thanks for the reviewer’s suggestion. According to the two reviewers’ suggestions, we have shorten the first three paragraphs and this sentence have been removed.

* Lines 55-58: this is clearly overstatement. Megathermal was under quite different external forcings (insolation, CO2, ..) and can not be considered analog of future climate. This even for impacts as the warming recorded at mid Holocene was not global and the present global

warming. This sentence does not furthermore have any added-value. Please remove

Thanks for the reviewer's suggestion. According to the two reviewers' suggestions, we have shorten the first three paragraphs and this sentence have been removed.

*Line 73: please correct Hetté into Hatté

Thanks for the reviewer's kind remind. We have corrected Hetté into Hatté.

* Line 74: please decline EASM

Thanks for the reviewer's suggestion. Considering the integrity and coherence of the manuscript, we have revised the paragraph, adding the research significance of precipitation in the CLP rather than declined EASM, hoping EASM appears in the appropriate place.

*Lines 101-102: This has led [: : :] results. Aggressive and useless. Please remove.

Thanks for the reviewer's suggestion. We have removed the sentence following the suggestion.

* Line 103: ": : : a continuous distribution.." I don't know here if you're talking "in general" or if you already focus on millet. Pollen records are continuous, that's not the case for millet records. They might be numerous in a sedimentary record, they remain discrete and their absence can be interpreted as both i- too dry to allow millet to growth and to produce seed" or ii- bad luck

Thanks for the reviewer's suggestion. According to the suggestion, we have removed "a continuous distribution" from the sentence to avoid confusion.

* Lines 109-110: " : : : agricultural rain-fed crop: : :": how can you deal with irrigation? I guess this bias your signal towards more humid condition. How do you statistically deal with that issue?

Thanks for the reviewer's question. First, common millet is a typical agricultural rain-fed crop. Irrigation in favor of plant growth but the yield of seed will decrease. Secondly, the exploring model to distinguish carbon isotope composition of crops derived from natural precipitation or irrigation has been put forward by *Ferrio et al.* (2005). According to the references *Yang and Li (2015)* and *Ferrio et al(2005)*, we inferred the abnormal high value probably indicate more water supply. So we excluded the abnormal high value according to the Boxplot using SPSS statistical software.

References:

Ferrio J P, Araus J L, Buxò R, et al. Water management practices and climate in ancient agriculture: inference from the stable isotope composition of archaeobotanical remains, 2005, 14: 510-517.

Yang, Q., and Li, X. Q. Investigation of the controlled factors influencing carbon isotope composition of foxtail and common millet on the Chinese Loess Plateau, Sci. China Ser D, 58(12), 2296-2308, 2015.

* Lines 132 and everywhere else: acronyms are OK on figure but please avoid them in the manuscript or restric them to DNA and USA. Nobody will remain what HDP is putting for.

Keep the extended name in the manuscript. You don’t have words limit!

Thanks for the reviewer’s suggestion. According to the suggestion, we have extended all the acronyms for the full names in the manuscript.

* Line 145: please precise "continuous" sampling if you did slice sampling (I understand you did).

Thanks for the reviewer’s suggestion. We really did slice sampling, so following the suggestion, the sentence was changed into “The slice sampling were applied to continuously sampling and the interval was ……”.

* Line 155: the total in table 1 is 66 not 67 seeds

Thanks for the reviewer’s attention. The total samples for $\delta^{13}C$ analysis is really 67 seeds here, but there is one abnormal value which was excluded in the subsequent table.

* Line 159: what do you mean with "distilled water". I don’t know any lab that still distills water. is it ultra-pure water? reverse osmosis purified water? deionized water?

Thanks for the reviewer’s question. It was deionized water. To be more specific, we have corrected “distilled water” into “deionized water” in the manuscript.

* §2.2.: please complete the table 1 with the following information: how many measurements per site, did you run standard (even home reference) to evaluate the fractionation that can occur all along the different steps? please provide us with the values and variability on reference (is it the 0.2‰ you mention at the end of the §?).

Thanks for the reviewer’s suggestion. The column of *n* means the number of measurements per site. We have revised the table and note the meaning of *n*. The fractionation that can occur all along the steps is the 0.2‰ as we mentioned at the end of the paragraph.

* Line 172: only to let me know, why did not you split the millet derived gas into 2 aliquots: one for d13C and one for 14C measurements? you would have had both data on a very homogeneous samples.

Thanks for the reviewer’s question. Because the millet individuals are very tiny and a single millet is even not enough for the $\delta^{13}C$ measurement, three to five grains were composed for $\delta^{13}C$ analysis. That’s why we cannot split the millet derived gas into 2 aliquots: one for $\delta^{13}C$ and one for $\delta^{14}C$ measurement.

* §2.3: please provide us with more information on chemical treatment and reduction prior the 14C physical measurement as you did for 13C.

Thanks for the reviewer’s suggestion. We have added the brief introduction on chemical treatment and reduction prior the ^{14}C physical measurement in the manuscript.

* lines 181-186: - please separate these lines from the preceding, they should be in a §entitled "processing data" or something like that. - please provide us with raw data -> add a figure with all d13C and 14C versus depth and the group you built. - please show us in a figure where are the raw data and what the group you created we really need to understand what you

did and what is the rationale behind this ANOVA that allowed you to do so.

Thanks for the reviewer's suggestion. We have separated the lines as another section entitled "processing data of age model" and added a figure (Figure 3a) with all δ^{13}C and calibrated age range versus depth as well as the groups we built following your suggestion, hoping the readers can understand what we have done and why we did so.

* lines 193-204: these lines seem to be the result of hard time for authors. It seems they had to fight a lot to impose this SMA. Your choice was acknowledged by the publication of the Yang and Li, 2015 's paper. No need to demonstrate, here again, the appropriatnessb of the methodological approach. Please remove.

Thanks for the reviewer's suggestion. We have removed the related content according to the suggestion.

* line 207 ": : : Neolithic .." do you mean "all seeds" or do you restrict to some of them. Please specify. That's the first time , you're talking about neolithic

Thanks for the reviewer's suggestion. To be more specific, we have modified the sentence into "Common millet remains sampled from cultural layers of Guanzhong Basin in our study……".

* lines 208 and everywhere else: ": : : from -11.11‰ to -9.26‰ : : :". If analytical error is 0.2‰ one digit is enough. The second does not have any signification.

Thanks for the reviewer's suggestion. We have modified the related content and kept all per mil numerical value one digit left.

* line 209: you eliminated the -8.8‰ value based on statistics. Did you cross with the lab book to check if there is a physical (lab) reason for that?

Thanks for the reviewer's question. We did cross with the lab book to check this abnormal value, but no runtime exception occurred and the sample was not contaminated. According to the references *Yang and Li (2015)* and *Ferrio et al(2005),* we inferred the plant of sample probably grew in a good ground upon many waters. In this situation, it cannot be included for precipitation reconstruction.

References:

Ferrio J P, Araus J L, Buxò R, et al. Water management practices and climate in ancient agriculture: inference from the stable isotope composition of archaeobotanical remains, 2005, 14: 510-517.

Yang, Q., and Li, X. Q. Investigation of the controlled factors influencing carbon isotope composition of foxtail and common millet on the Chinese Loess Plateau, Sci. China Ser D, 58(12), 2296-2308, 2015.

* line 218: "(Araus and Buxo, 1993)", please also refer to original work of Farquhar or O'Leary. They are the real pioneers.

Thanks for the reviewer's suggestion. We have added the references of Farquhar (1989) and O'Leary (1988).

* line 222: the 2015 values in Mauna Loa is -8.5‰ (http://www.esrl.noaa.gov/gmd/obop/mlo/summary.html) please adapt your calculation. Mauna loa is an island, bare and far from any human activities. It was chosen to reflect the global CO2 free from any local impact (human, vegetation). You are not is this configuration and should include the local effect within your estimation. Your database was designed and completed in 2015 in agricultural regions fully impacted by vegetation and human CO2 emission. You were not in a free zone as Mauna Lo and likely your modern millet did growth in a much more negative atmospheric CO2 that you think. Please discuss this point and (if possible) add d13C measured on modern atmospheric CO2 sampled in locations you collected modern seeds to evaluate the modern shift between Mauna Loa and the CO2 modern millet used for photosynthesis.

Thanks for the reviewer's suggestion. Here, authors would like to say: the modern millet was sampled in 2008 rather than in 2015. Although we don't have data of $\delta^{13}C$ measured on modern atmospheric CO_2 sampled in locations where we collected modern seeds, considering our atmosphere is a perfect blender, we adopted the global mean value of three years after sampling, just as we used the mean value for the past period, from 11 ka BP to the pre-industrial age. So, we consider that the value -8.2‰ which published by Cuntz in 2011 should be more appropriate, even though the samples grew in agricultural regions but not in a free zone. If we adopt the value -8.5‰ to calculate, the reconstructed results would be amplified and bias the environment towards more humid. Based on the above consideration, we didn't adopt the reviewer's suggestion on this issue and hope the reviewer understanding.

* line 228 ": : : growing season : : : " should be defined.. but will be defined if you follow my proposition to move up a part you presently have in discussion (see lines 302-310)

Thanks for the reviewer's suggestion. We have moved up the lines 302-310 to just after the introduction and "growing season" has been defined in this section as follow: The growing season of modern common millet in the Guanzhong Basin lasts from June to September.

* line 229 : - what is the subscript "gp" for?

Thanks for the reviewer's carefulness. "gp" is short for "growing period", but to keep the internally consistent within the manuscript, we have changed "gp" into "gs".

- can you provide us with error margin on a (0.0077) and b (-14.56)?

Thanks for the reviewer's question. But we are sorry to say we cannot provide error margin on a (0.0077) and b (-14.56) since the SMATR software doesn't provide the margin. However, the regression coefficient of data samples are optimized which were solved by optimizing statistical responses in accordance with logical optimization criteria.

* line 238 "-10.55_0.16‰¨ , the very low value of uncertainty clear seems to show that you didn't propagate analytical uncertainties to the mean d13C of each group

Thanks for the reviewer's enquiry. The values are close to each other in each individual group, so the uncertainty is assuredly the very low value in the group.

* line 246: what is the subscript "re" for?

Thanks for the reviewer's question. It means corrected value for precipitation reconstruction. To avoid confusion, we change "$\delta^{13}C_{re}$" into "corrected $\delta^{13}C$".

* §4.1 should be better just after the introduction, it is not part of the discussion but part of rationale behind the approach. This can be part of a "rationale" §with lines 302-310.

Thanks for the reviewer's suggestion. According to your suggestion, we have moved up the lines 302-310 to just after the introduction and entitled "2 The rationale behind using common millet $\delta^{13}C$ for precipitation reconstruction".

* line 259: what is the biblio reference that attests that archeo combustion was performed at temperature of about 250_C? please add.

Thanks for the reviewer's question. The reference is *Yang et al. 2011a*, which were there in the manuscript.

* line 263-265: only accusations that do not bring any added value to the paper. Please remove and only keep "The d13C signatures conserved in carbonized common millet are thus reflective of the true environment".

Thanks for the reviewer's suggestion. We have removed the value and changed the sentence following the suggestion.

* line 266: carbon without capital letter

Thanks for the reviewer's kind remind. We have changed carbon without capital letter.

* line 273: do you mean concentration of CO2 and HCO3-? please correct

Thanks for the reviewer's question. Here "how much CO2 and HCO3-" expresses more accurate than concentration, and we consider it is more appropriate. So we didn't change it, hoping the reviewer understanding.

* line 282: instead of IPCC reference, consider the vegetal physiology original bibliography

Thanks for the suggestion. We have instead the reference by "Hadley and Szarek, 1981; Ehleringer and Mooney, 1983; Murphy and Bowman, 2009".

* line 289: corect stamatal into stomatal

Thanks for the reviewer's kind remind. We have corrected it.

* line 296-301: already stated in results, no need to repeat. remove

Thanks for the reviewer's suggestion. We have removed them.

* line 302-310: move up in a "rationale" §between intro and methodology

Thanks for the reviewer's suggestion. We have moved up them after the introduction and entitled "2 The rationale behind using common millet $\delta^{13}C$ for precipitation reconstruction".

* line 311-314: should better belong to methodology, in site description

Thanks for the reviewer’s suggestion. We have added site description in the section of sampling and moved line 311-314 to this section.

* line 323 and following: as the absolute value is highly dependent of the d13C value of the atmospheric CO2 you had for the reference equation, please consider to discuss relative values: this period of Holocene was wetter or drier than the other part of Holocene

Thanks for the reviewer’s suggestion. We have removed the absolute value and added discussion about the increasing variability of summer precipitation from early Holocene to late Holocene and provided the markedly humid periods in the manuscript.

* line 338: please provide references for ".. other global records".

Thanks for the reviewer’s suggestion. We have added references Cullen and DeMenocal, (2000), Mayewski et al. (2004) and Wu and Liu (2004) for “.. other global records”.

* lines 357-358: no interest, remove

Thanks for the reviewer’s suggestion. We have moved the sentence following the suggestion.

* line 361: please be more specific, you don’t have here the wettest climate but the wettest millet growth season.

Thanks for the reviewer’s suggestion. We have changed the wettest climate into the wettest millet growth seasons.

* line 377: please add a reference for PMIP2 and this specific result

Thanks for the reviewer’s suggestion. The reference for PMIP2 is Zhang and Liu (2009) and the specific result is demonstrated in the following sentence. To avoid confusion, we have adjust the sentence as follow: ……throughout most of China ~6 ka BP and the greatest increases in precipitation seen in the region,…… (Zhang and Liu, 2009). According to the result, it can be inferred……”.

* tables: legends are much too short. please extend them. Table and associated legend should have a stand-alone value.

Thanks for the reviewer’s suggestion. We have extended legends and given them stand-alone value in each table.

* table 1: what do you mean with "sources"? please replace "N_" by "number of grains", replace accronyms by extended names (or define in legend)

Thanks for the reviewer’s question and suggestion. The “sources” means “sample source” and we have added “sample” before “sources”. We replaced “No.” by “*n*” and gave a footnote “n means number of remnant common millet samples derived from the section.” We also replaced accronyms by extended names.

* table 2: - replace accronyms by extended names (or define in legend), - I guess what you call "AMS 14C age (cal yr BP)" is conventional 14C age, thus replace the column title by

"conv. 14C age (yr BP) – 1sigma", - calibrated age range can not be presented as mean value of range extrema _ the half-distance between range extrema. This only because the mid point of the interval is not associated to the maximum of probability. Please follow the 14C convention and provide us with the range(s) and the associated probabilty density (yes, for this period of time you might have several intervals that share the 100% of the 2-sigma probability density. You might consider to add the age with the maximum of probability (last column of the IntCal output table) if it better suits to you.

Thanks for the reviewer's suggestion. We have defined the accronyms in the title, changed "AMS 14C age (cal yr BP)" to "Radiocarbon age (^{14}C yr BP)" and changed calibrated age range (cal yr BP, 2σ) into the age interval.

* table 3: - replace accronyms by extended names (or define in legend), - in legend, please specify what N and d13Cre are for. - instead of mean d13C provide us with d13C range or add another column - please respect the significance of digits and provide d13C with only one digit

Thanks for the reviewer's suggestion. We have replaced accronyms by extended names, replaced "N" and "δ^{13}Cre" by "*n*" and "corrected δ^{13}C" respectively, which were defined in footnote. We also provided δ^{13}C range in the column of corrected δ^{13}C.

* Figure 1: - make sure sites are visible and add their names (or acronyms) on the figure. - if possible add also the sites you mention in Figure 6 (if not possible, add a map with sites in Figure 6 itself) - please add a sign (star, point, arrow, ..) to show depths the seeds were extracted from (entlarge the figure if required) - this question is maybe more for publisher: is it require to provide references for CorelDraw or others Word or Excel?

Thanks for the reviewer's suggestion. We have added all sites names as well as the sites we mentioned in Figure 6 to Figure 1. We also added signs for sampling depths with triangle in the description of all sampling sections of Figure 1.

* Figure 6: the sites mentioned here should be geographically visible in a map, here or on the Figure 1 map. It would be great to locate them within a meteorological context, can you consider to add a limit of monsoon influenced zone?

Thanks for the reviewer's suggestion. We have added a China map with a limit of monsoon influenced zone. The modern Asian summer monsoon limit is shown by a dashed line in the map, where Qinghai Lake, Gonghai Lake and Guanzhong Basin are signed with red dot.

Resond letter to the reviewer 2#

Dear reviewer:

We would like to express our feelings of appreciations to you for your kindly help and professional comments to our manuscript entitled “Summer precipitation reconstructed quantitatively using a Mid Holocene δ^{13}C common millet record from Guanzhong Basin, China”. We have tried our best to modify the weakness and flaws pointing out by you. Now, we believe that we made a better work which would probably satisfy the reviewer and suitable to be published. The answer to the comments is listing in the following paragraph.

Thanks again for your help.
Best wishes!

Sincerely,

Yang Qing and Xiaoqiang Li

Reviewer 2:

The authors presented carbon isotope data from fossilized common millet seeds collected from archeological sites in northern China. The carbon isotope record was then used to reconstruct summer precipitation during the mid-Holocene, on the basis of the relationship between millet C isotopes and summer precipitation established in a modern process study by the same group (Yang and Li 2015). The authors then used the reconstructed summer precipitation to discuss East Asian summer monsoon dynamics.

I find the idea is intriguing and potentially promotes the use of abundantly available millet seeds as a paleoclimate archive in this part of the world. The modern process investigation as presented in Yang and Li (2015) is an excellent study that shows a robust relationship between d13C and summer precipitation, despite that I don’t fully understand the mechanism (it is counterintuitive that lower summer precipitation correlates with lower d13C values).

However, I have issues with both presentation and interpretation of the results.

1. I find that the “conventional” climate reconstruction and interpretation as presented in Figure 4 are unsupported, mostly due to the high variability of the record (including the instrumental climate data!), low resolution, and short, snapshot nature of the record (only cover 8-3.5 ka). The high precipitation variability at present in the study region suggests that 3-5 seeds used in each analysis just captured at most 3 to 5 years of precipitation – too small a sample size to capture mean precipitation. As a result, I don’t think the correlation as presented in Figure 6 and monsoon discussion is supported.

However, I wonder if that the data set (especially an expanded data set form the region) can be used to document and understand the summer precipitation variability during the Holocene or part of the Holocene. The science question could be: is there increasing summer precipitation variability from the early Holocene to late Holocene, when the summer monsoon and precipitation decline during that time period? Is it possible that not only summer

precipitation decreases during the Holocene but also becomes more and more variable and less and less predictable? The data as presented in Fig. 2a seem to suggest that, though the number of analysis is still low. I wonder if a future expanded study can analyze a larger number of samples per sample (say 30-40 seeds, preferably single seed analysis) to capture the decadal/centennial (depending time resolution) variability in summer precipitation, even just in a few time intervals (early Holocene, mid-Holocene, and late Holocene). Each individual seed is a product of a single season/year – as clearly argued and implemented during 2008 in Yang and Li (2015). This is similar to a study on oxygen isotope analysis of individual foraminifera from deep marine sediments to document ENSO variability (and annual seasonal cycle) at a few time intervals during the Holocene.
I suggest that the authors should focus on the variability rather than mean climate (precipitation).

Thanks for the reviewer's comment and suggestion. Your comment affirms that $\delta^{13}C$ of millet can be used as a new proxy to document variability of summer precipitation for the future study, giving us confidence to analyze a larger number of samples per sample at a few time intervals during the Holocene in the future.

It is worth noting the variability of summer precipitation as the reviewer's suggestion. The summer precipitation indeed becomes more and more variable especially after ~5.2 ka BP, which we have added in the discussion of the manuscript.

Since 3-5 millets of a sample from the cultural layer probably formed in the interval of several decades rather than 3 to 5 years, the reconstructed results can indicate the mean precipitation as we careful consideration. Although it is hard to conclude the summer monsoon and precipitation decreases during the Holocene, the reconstructed precipitation during the Holocene exhibits the characteristics of a systemic increase with significant fluctuations. We have discussed precipitation fluctuated significantly and captured three markedly humid periods, showing the mean precipitation as well as variability in the manuscript, hoping the reviewer's agreement.

2. The writing in general is clear – I commend the authors' effort to make it an easy read. However, I find there are many superlative words to describe the results, and some of these are overstatement. I will provide examples below in my specific comments.
Specific comments:
Title: -focus on precipitation variability? -change "China" to "northern China", for international readership?

Thanks for the reviewer's suggestion. We have changed "China" to "northern China". We also consider carefully the precipitation variability in the manuscript but didn't show it in the title.

Abstract -add latitude (34.5 N) and perhaps rounded longitude as well, for international readership?

Thanks for the reviewer's suggestion. We have added rounded latitude and longitude on Guanzhong Basin in the abstract.

-there are many superlative descriptors here in the abstract, such as "accurate" (line 17), "robust" (line 19), "reliably" (line 26), "precise" (line 28). It seems to me none of these is needed and justified. Most of similar words should be deleted throughout the text.

Thanks for the reviewer's suggestion. To be more justified, we have removed all the mentioned words above in the abstract as well as some similar words throughout the text.

-the abstract needs to refocus if the authors accept my suggestion above.

Thanks for the reviewer's suggestion. We partly accepted your suggestion above, that the increasing summer precipitation variability from the early Holocene to late Holocene, and have refocused the abstract.

Introduction -It is unnecessarily too long. In particular, the general discussion on Holocene climate in the first 3 paragraphs on page 1-2 is not really needed. Delete or shorten.

Thanks for the reviewer's suggestion. We have shortened the first 3 paragraphs following the reviewer's suggestion.

-superlative word examples: "accurate" (l 41), "more completely and accurately" (l 60), "robust" (l 135).

Thanks for the reviewer's suggestion. We have removed the words referred above from the manuscript.

Line 91: change "between 5.2-4.3 ka BP", to either "between 5.2 AND 4,3 ka BP", or "at 5.2-4.3 ka BP" (there are other cases of matching "between: : :and: : :" in the text) Methods This section reads well.

Thanks for the reviewer's suggestion. We have changed "between 5.2-4.3 ka BP" to "at 5.2-4.3 ka BP" following the suggestion.

Line 156: I wonder if a single seed is large enough for C isotope analysis, but multiple seed analysis still can be used for the variability study as suggested above (but it will be "conservative" reconstruction of precipitation variability, due to averaging of multiple years growth in one sample).

Thanks for the reviewer's question. The millet individuals are very tiny and single millet is not enough for C isotope analysis. Therefore, multiple millets were used as a sample for $\delta^{13}C$ measurement, which averaging the multiple years growth. So we consider that the reconstruction result can indicate a decadal averaging precipitation. However, the variability can also be concluded from comparison of series of results at different intervals.

L 169: "1r" = 1 sigma? (67% probability?)

Thanks for the reviewer's kind remind. Yes, it should be 1 sigma (67% probability) and it's our error writing. So, we have corrected "1r" into "1σ".

L 179: change to "the sampled culture layers" ("section's" is awkward usage)

Thanks for the reviewer's suggestion. We have changed to "the sampled culture layers" following your suggestion.

L 181-186: unclear how it was done.

Thanks for the reviewer's expression. To make the readers understand, we have separated the lines as another section entitled "processing data" and added a figure (Figure 3) with all δ^{13}C and calibrated age range versus depth as well as the groups we built, hoping it helps.

L 189: delete "ref."

Thanks for the reviewer's suggestion. We have deleted "ref" following your suggestion.

L 190: delete "," before "demonstrated"

Thanks for the reviewer's suggestion. We have deleted "," before "demonstrated" as you suggestion.

Results L 209: change "eliminating" to "without considering"

Thanks for the reviewer's suggestion. We have change "eliminating" to "without considering".

Line 207-214: I'm confused here. You describe carbonized Neolithic seed remains and modern common millet, but you compare "modern seeds" in the last sentence. Also, millet is more negative than seeds, rather than "positive" as described. Check.

Thanks for the reviewer's kind remind. It should be millets remains and modern millet in the paragraph. To avoid confusion, we have rewrite the sentence as follow: Common millet remains sampled from cultural layers of Guanzhong Basin in our study……It can thus be seen that the δ^{13}C values of common millet remains are more positive than those of modern millet by ～2.9‰.

L 233-235: "slightly higher" and "a much more humid" is contradictory. Overstatement/ over-interpretation?

Thanks for the reviewer's kind remind. To avoid contradictory, we have removed "slightly" and "much" from the sentence and the sentence is as follow: The δ^{13}C values yielded by ancient common millets are higher than those of modern common millet seeds, suggesting that these ancient plants grew in a more humid environment than today's.

Discussion As I commented above, the mean precipitation reconstruction doesn't allow for much comparison and discussion on summer monsoon, while precipitation variability is potentially a novel aspect of paleoclimate research. Although your current data are not robust enough, it seems to me that it holds great promise for the future project: even just 3 or 4 horizons, with large analysis per horizon.

Thanks for the reviewer's suggestion. As we answered above, we consider that δ^{13}C of millet can reconstruct mean precipitation although the resolution of current data is low. However, we also accept the reviewer' viewpoint that variability becomes higher from the early Holocene to late Holocene. So we removed the absolute value of the mean precipitation reconstruction and added discussion about the increasing variability of summer precipitation as well as provided the markedly humid periods.

L 341: change “1961-2011” to “1951-2011”? which makes 60 years and also is consistent from description earlier.

Thanks for the reviewer’s kind remind. It should be 1951 and we have corrected it to “1951-2011”.

Conclusions L 392-393: “low resolution” and “convincing” are contradictory.

Thanks for the reviewer’s kind remind. To avoid contradictory, we have changed “convincing” to “innovative”.

Tables Table 1 -move latitudes and longitudes from Figure 1 to new columns here.
-what “source” means here? “12” here means “12 culture layers”? if so, spell out.
-change “No.” to lower case and italic “n” (to indicate number of analyses or samples)

Thanks for the reviewer’s suggestions.

-We have added latitudes and longitudes in a new column.

-The “sources” means “sample source” and we have added “sample” before “sources”. “12” here was placed in an error box and we have moved it to the right box.

-We replaced “No.” by “*n*” and gave a footnote “n means number of samples for δ^{13}C analysis.”

Table 2 -Change heading to “ AMS 14C dates” (“dating data” is unusual”)
-why does a 250-cm-long section (such as BN) have the same or reversed ages? Very rapid accumulation of these layers? I hope it is discussed elsewhere in archeological literature.
-change the heading of column 4 to “AMS 14C date (yr BP)” – it is wrong to say 14C date as “cal yr BP”
-maybe a footnote to indicate the dating lab for OZM

Thanks for the reviewer’s suggestions.

-We have changed heading to “Accelerator mass spectrometry (AMS) dates from Baijia (BJ), Huiduipo (HDP), Manan (MN), Beiniu (BN), and Nansha (NS)”.

-Since all sections selected were cultural layers and deeply affected by human activities, the sections accumulate rapidly and have reverse layer due to human activities. The thickness of the sections and the cultural types were discussed in the archeological literature “Atlas of Chinese Cultural Relics: Shannxi Municipality”, which was edited by State Cultural Relics Bureau in 1998, in Chinese. However, the 14C dates was not adopt to exact age in the literature. They think the cultural layer are different from the natural layer. That is why we cannot apply linear interpolation and extension for age verse depth as which usually applied to the natural section.

-We have changed the heading of column 4 to “Radiocarbon age (^{14}C yr BP)”.

-We have added a footnote for the dating lab of OZM in the manuscript as follow: All assays were run on the STAR Accelerator, ANSTO, Australia.

Table 3 -maybe indicate ages as “calibrated ages” to avoid confusion
-add footnote to indicate “d13Cre” and “Ps”

Thanks for the reviewer's suggestions.

-We have changed "^{14}C age" to "calibrated ages" following your suggestion.

-We have changed "$\delta^{13}C_{re}$" to "corrected δ^{13}C" and also added footnote to indicate corrected δ^{13}C and Ps.

Figure 1. -move latitude and longitude to Table 1

-CorelDRAW12 is not needed to mention, as it is just a map.

Thanks for the reviewer's kind remind. We have move latitude and longitude to table 1 and removed the sentence mentioned CorelDRAW12 from the footnote.

Figure 2. -need more explanation about panel a (raw data points) and b (box plot) in figure caption

-again Fig. 2a kind of shows increase in precipitation variability from 8 ka to 3 ka. Have you tried a regression of all the data to see if there is a significant decline (in precipitation) during that period as well? (perhaps the number of data points are still low)

Thanks for the reviewer's suggestion.

-We have added more explanation about panel a and panel b in figure caption in the manuscript following your suggestion.

-To be more specific, we redrew the figure 2a, showing all raw data points including δ^{13}C and calibrated age range versus depth. However, it does not exhibit a significant decline in δ^{13}C or precipitation from 8 ka BP to 3 ka BP. But the increasing variability of precipitation is visible, which we have discussed in the manuscript.

Figure 3 -indicate reference in figure caption "Modified or data from Yang and Li (2015)"

Thanks for the reviewer's suggestion. We have added "which data from Yang and Li (2015)" in the figure caption.

Figure 4 -Again, I don't think it is a good way to present the data as groups to get mean climate/precipitation – considering the large variability almost nothing can be concluded here (a.k.a. the pattern is not robust/convincing, because of uncertainty).

Thanks for the reviewer's suggestion. To better present, we have added another panel as figure 5a to display all reconstructed precipitation data, hoping it is helpful to understand the mean precipitation and variability. It can be seen from the panel a that there are three markedly humid periods, which have the mean precipitation higher than the other periods, and the variability of precipitation from 8 ka BP to 3 ka BP becomes increasing obviously. We also kept the original figure as panel b to compare with modern summer precipitation.

Summer precipitation reconstructed quantitatively using a Mid Holocene $\delta^{13}C$ common millet record from Guanzhong Basin, northern China

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Abstract

In order to produce quantitative Holocene precipitation reconstructions for particular geographical areas, explicit proxies and accurate dating controls are required. The fossilized seeds of common millet (*Panicum miliaceum*) are found throughout the sedimentary strata of northern China, and are suited to the production of quantitative Holocene precipitation reconstructions: their isotopic carbon composition ($\delta^{13}C$) gives a measure of the precipitation required during the growing season, and allows these seeds to be dated. We therefore used a regression function, as part of a systematic study of the $\delta^{13}C$ of common millet, to produce a quantitative reconstruction of Mid Holocene summer precipitation in the Guanzhong Basin (107°40′～107°49′N, 33°39′～34°45′N). Our results showed that mean summer precipitation at 7.7-3.4 ka BP was 353 mm, ～50 mm or 17% higher than present levels and the variability becomes increasing, especially after 5.2 ka BP. Maximum mean summer precipitation peaked at 414 mm during the period 6.1-5.5 ka BP, ~109 mm (or 36%) higher than today, indicating that the EASM peaked at this time. This work can provide an innovative proxy for further research into continuous paleoprecipitation sequences and the variability of summer precipitation.

Keywords: summer precipitation; quantitative reconstruction; Holocene; Chinese Loess Plateau; common millet; stable carbon isotope

Sect.

1 Introduction

The reconstruction of global climate changes through history is an important part of the Past Global Changes (PAGES) project. The Holocene, as the most recent geological period, has the closest relation to human survival and development. Quantitatively reconstructing climatic factors such as temperature and precipitation provides an understanding of agricultural development and the human impact upon the landscape and environment. However, instrumental records are insufficient for the documenting of the drivers of climate change, since they cover only the past century or so (DeMenocal, 2001). The quantitative reconstruction of temperature and precipitation using high resolution climatic proxy records has therefore become the principal thrust of PAGES research. To date, most continental paleoclimate studies have focused on temperature (Porter and An, 1995; Guo et al., 1996; Genty et al., 2003; Wang et al., 2008; Sun et al., 2012). However, the increase in global surface temperatures has tended to cause changes in precipitation and atmospheric moisture through changes in atmospheric circulation, a more active hydrological cycle and an increasing water holding capacity throughout the atmosphere (Dore, 2005). The availability of water, one of the major challenges for the future, cannot be ignored, due to its significant role in the hydrological cycle (Hatté and Guiot, 2005). To this end, we chose an area key to the warm period of the Holocene to produce a quantitative precipitation reconstruction for that geological time.

The Chinese Loess Plateau (CLP), located in a transition zone between a semi-arid and semi-humid climate, is highly sensitive to changes in precipitation and has thus long been a key area for precipitation reconstruction research. The precipitation of the CLP, is, and has been, deeply impacted by the EASM. The EASM, an important component of the Asian Summer Monsoon (ASM), plays an indispensable role in the hydrological cycle over southern China. Various proxies have been adopted in studies of the EASM during the Holocene. Due to their reliable chronology and relatively easy dating, oxygen isotopes ($\delta^{18}O$) in speleothems from Chinese caves have been taken as a robust measure of summer monsoon precipitation values (Wang *et al.*, 2005a; Cheng *et al.*, 2009). However, the interpretation of these changes in the m $\delta^{18}O$ values of precipitation remains highly controversial; some scientists have contended that the stalagmite δ18O record from the EASM region may not record EASM variability (Le Grande and Schmidt, 2009; Maher and Thompson, 2012; Tan, 2012; Caley et al., 2014; Liu et al., 2015). Fortunately, the precipitation in the CLP can effectively reflect the intensity of the EASM variability due to its special location (Liu et al., 2015).

The quantitative precipitation reconstruction results obtained have been based exclusively on climatic proxies derived from geological and biological records in the CLP. In the western CLP, fossil charcoal records in the Tianshui Basin have demonstrated that the mean annual precipitation (MAP) was 688-778 mm at 5.2-4.3 ka BP (Sun and Li, 2012). In the CLP's hinterland, magnetic susceptibility records from the Luochuan profile have provided estimates of Holocene MAP varying between 600 and 750 mm, with a mean value of 701±74 mm (Lu *et al.*, 1994). In the southern CLP, Guanzhong Basin MAP, as revealed by plant phytolith assemblies, was 700–800 mm during the Holocene, indicating a much more humid climate than today's (Lu *et al.*, 1996). Further evidence from the transfer functions of geological records and the intensity of pedogenesis has shown that Guanzhong Basin MAP was >700 mm during the Holocene Optimum (Sun *et al.*, 1999; Zhao, 2003), supporting the aforementioned results. However, due to their intrinsic limitations, such as discontinuity and an indefinite response mechanism between the proxies and climate change, these tentative proxies have not been extensively applied. Selecting an effective proxy which evinces a reliable dating and an unambiguous implication is crucial for the quantitative reconstruction of paleoprecipitation. High-resolution pollen-based quantitative precipitation results indicating EASM evolution have recently been obtained from an alpine lake in northern China (Chen *et al.*, 2015). However, because these are attributable solely to this unique environment, a regional quantitative precipitation reconstruction, and therefore a new proxy, is still required.

Common millet (*Panicum miliaceum*), as the most representative agricultural rain-fed crop of northern China, contains $\delta^{13}C$; this is sensitive to precipitation and can thus effectively record precipitation during the growing season (Yang and Li, 2015). Rain-fed agriculture originated in the CLP, giving rise to the first recognizably Chinese civilization. Many archeological relics from an unbroken historical continuum are therefore found throughout the region (An, 1988). Quantities of the fossilized seeds of common millet are well-preserved in the cultural layers of these archeological sites (Zhao and Xu, 2004; Liu *et al.*, 2008; Lu *et al.*, 2009). Their stable $\delta^{13}C$ compositions, which remain little change because of the low temperatures associated with carbonization, contain valuable information about paleoclimate change and early agricultural activities (Yang *et al.*, 2011a, 2011b). Common millet remains are therefore perfect for quantitatively reconstructing Holocene precipitation in the CLP.

The Guanzhong Basin (Figure 1), in the southern CLP, was the cradle of Neolithic culture and China's ancient civilization, and fostered the Laoguantai (~7.8-6.9 ka BP), Yangshao (~6.9-5.0 ka BP) and Longshan (~5.0-4.0 ka BP) cultures (Ren and Wu, 2010), the pre-Zhou culture (~3.5-3.0 ka BP) (Lei, 2010), and the Zhou dynasties. Due to the intensity of early agricultural activity, huge quantities of common millet remains have been preserved in numerous, continuously-occupied cultural sites. Carbonized common millet seeds are the most abundant resource found in the samples collected in this study from these cultural layers.

In this study, common millet remains, from five sections characterized by continuous and well-developed sedimentation at typical archeological sites, including the Baijia, Huiduipo, Manan, Beiniu and Nansha sites (Figure 1), were sampled as part of a systematic study of $\delta^{13}C$ records; quantitative precipitation reconstructions for the Holocene were then based upon a transfer function between the $\delta^{13}C$ of modern common millet and precipitation, providing a scientific basis for predicting future climate change and its possible impact.

2 The rationale behind using common millet $\delta^{13}C$ for precipitation reconstruction

The $\delta^{13}C$ values of common millet seeds reflect the ^{13}C of photosynthetic materials during not only their formative and mature stages, but also their vegetative stage. The growing season of modern common millet in the Guanzhong Basin lasts from June to September. The seed kernel's formative and mature stages occur soon after pollination of the blossom. With an increase in kernel size, photosynthetic material as well as pre-accumulated organic material is transferred to kernels from stems, leaves and spikes (Chai, 1999). Therefore, millet $\delta^{13}C$ reflects the environmental conditions extant during the growing season from mid-June to the end of September, or 110 days in total.

Carbon isotope composition of fossilized plant remains is a useful proxy for the reconstruction of local paleoclimatic changes, especially when using $\delta^{13}C$ values from plants which experience a single mode of photosynthesis. Common millet grains have been widely and continuously preserved throughout the Holocene in northern China. Fossilized millet seeds were generally formed by baking at low temperatures (~250℃) (Yang *et al*., 2011a), and deposited in strata over long time periods with limited interaction with the buried environment. The observed $\delta^{13}C$ values of charred common millet formed at ~250℃ were 0.2‰ lower than those of the source samples, and much less than the natural variation typically found in wood (Yang *et al*., 2011b). The $\delta^{13}C$ signatures conserved in carbonized common millet are thus reflective of the true environment.

The carbon isotope composition of plants ($\delta^{13}C_p$) is affected by both physiological characteristics and environmental factors. The $\delta^{13}C$ of C_3 plants responds to environmental factors, such as atmospheric CO_2 pressure, O_2 partial pressure, temperature, light and precipitation, by dominating the ratio of the intercellular and ambient partial pressure of CO_2 (c_i/c_a) with the opening and closing of leaf stomata (Körner and Diemer, 1987; Körner and Larcher, 1988; Körner *et al*., 1989; Farquhar *et al*., 1989; Dawson *et al*., 2002). However, the $\delta^{13}C$ of C_4 plants depends not only on c_i/c_a but also on how much CO_2 and HCO_3^- in bundle sheath cells leaks into the mesophyll cells (called leakiness φ), which is determined by its physiological characteristics (Hubick *et al*., 1990). When φ is larger/smaller than 0.37, there is a positive/negative correlation between $\delta^{13}C_p$ and c_i/c_a (Ubierna *et al*., 2011). Under water stress, the φ of the common millet, belonging to the NADP-ME subgroup of C_4 plants, is likely larger than 0.37 (Schulze *et al*., 1996; Yang and Li, 2015). This may account for the significantly positive relation between the $\delta^{13}C$ of common millet and precipitation (Yang and Li, 2015).

Limited precipitation and soil humidity are the most important environmental factors affecting the growth of plants in arid and semi-arid areas (Hadley and Szarek, 1981; Ehleringer and Mooney, 1983; Murphy and Bowman, 2009). For C_4 species in the arid regions of northwestern China, $\delta^{13}C_p$ tends to decrease with decreasing soil water availability (Wang *et al*., 2005b). For common millet, although altitude, precipitation and water availability have a significant correlation with $\delta^{13}C$ according to correlation analysis, precipitation was the critical control of $\delta^{13}C$, based on functional mechanism analysis (Yang and Li, 2015). The plants' physiological characteristics and morphological adaptability showed that the stomatal, and some non-stomatal, factors of common millet are sensitive to water status, causing the $\delta^{13}C$ of the organic material to change with precipitation. This rationale establishes an important theoretical foundation whereby the $\delta^{13}C$ of common millet can serve as an effective indicator of paleoprecipitation.

3 Methods

3.1 Sampling

All the ancient common millet remains used in this study were found at five archeological sites in the Guanzhong Basin, *i.e.* the Baijia, Huiduipo, Manan Beiniu and Nansha sites (State Cultural Relics Bureau, 1998).

The Guanzhong Basin is located southern of the CLP and is bordered on the south by the Qinling Mountains and the north by the Beishan Mountain and spanned 30-80 km; from Baoji Valley at the west end to Tongguan at the east end, spanning 360 km. The topography is flat and the landscape consists mostly of river terraces and loess table land at an altitude of 326-600 m. The present-day Guanzhong Basin is characterized by semi-humid and semi-arid climatic conditions strongly influenced by the monsoon. Summer monsoon rainfall accounts for most of the annual precipitation and falls primarily in June-August; the climate is therefore characterized by cold, dry winters and moist, warm summers. Mean annual temperature (MAT) in the Guanzhong area is ca. 13℃, MAP is ~575 mm and mean annual relative humidity (MARH) is 70%. Precipitation data from the Guanzhong Basin for the period 1951-2011 were analyzed (Figure 2). The results showed that the precipitation for mid-June to September was between 110-526 mm, with a mean of 305 mm. The 95% confidence interval for this mean is between 279-332 mm, ruling out the extreme values of abnormal years.

The Baijia site, located on the secondary river terrace of the northern bank of River Wei, contains early Laoguantai cultural remains. The area is ca. 120,000 m^2 and the thickness of the cultural layer is between 0.4 m and 1.2 m. The Huiduipo site includes Banpo-type remains from the Yangshao culture. The area is ca. 60,000 m^2, the thickness of the cultural layer is ca. 2 m, and there is partial exposure of ash pits, residential areas and graves. The Manan site, located on tableland at the intersection of the Jinghe and Weihe rivers, exhibits Yangshao cultural remains. MN is ca. 16,000 m^2 in area, and the thickness of the cultural layer is between 2 m and 5 m, with a dense distribution of ash pits. The Beiniu site partly contains Longshan cultural remains. Its area is 200,000 m^2, and the thickness of its cultural layer is ca. 1m. The Nansha site is mainly characterized by Shang Dynasty remains. It is ca. 300,000 m^2 in area and the thickness of its cultural layer is between 1.9 m and 2.7 m (State Cultural Relics Bureau, 1998). All sampling sections are described in Figure 1.

Five sections characterized by continuous and well-developed sedimentation were selected for sampling at the Baijia, Beiniu, Huiduipo, Manan and Nansha sites. The slice sampling were applied to continuously sampling and the interval was 10 cm for the Baijia and Nansha sections, and 20 cm for the Beiniu, Huiduipo and Manan sections (Figure 1). Forty litre sample bags were filled with sufficient quantities of sedimentary material to screen through a 50-mesh sieve to obtain samples using flotation (Tsuyuzaki, 1994). Different archeological remains were separated in the laboratory after air-drying. Agricultural seeds were identified and picked out under the stereomicroscope, then marked in order according to sampling depth. The number of remnant common millet samples derived from all five sections are listed in Table 1.

3.2 Stable $\delta^{13}C$ analysis

Stable $\delta^{13}C$ composition analyses were carried out on all 67 serial and bulk common millet samples from the five sections, each composed of three to five grains, without lemma. Each sample portion was placed in a beaker and covered with a 1% hydrochloric acid solution to remove any carbonates. The samples were then washed with deionized water to pH >5 and oven dried at 40 ℃ for 24 h. The dried samples were ground in an agate mortar and homogenized, then vacuum-sealed in a quartz tube with copper oxide and silver foil and combusted for at least 4 h at 850 ℃. The CO_2 gas from the combustion tube was extracted and cryogenically purified. The isotopic ratio of the extracted CO_2 gas was determined using a MAT-251 gas source mass spectrometer with a dual inlet system at the Institute of Earth Environment, Chinese Academy of Sciences. All isotope ratios were expressed using the following δ notation:

$$\delta^{13}C(‰) = [(R_{sample} - R_{std})/R_{std}] \times 1000 \qquad \text{Eq. (1)}$$

The isotopic standard used was Vienna Pee Dee Belemnite (VPDB); analytical precision at the 1σ level was reported as 0.2‰.

3.3 Radiocarbon dating

AMS ^{14}C dating was conducted on one charcoal fragment and one charred seed of common millet from the Baijia section, five charred seeds each from the Huiduipo and Beiniu sections, one charred seed from the Manan section, and three charred seeds from the Nansha section.

The charcoal and seed samples were pretreated by washing in 10% NaOH and 10% HCl and reduced to neutral pH. They were then converted to graphite and radiocarbon ages were calculated after measurement in the STAR Accelerator at the Australian Nuclear Science and Technology Organisation (ANSTO). AMS ^{14}C dates were calibrated using Calib Rev 7.0.4 software and the INTCAL13 dataset (Reimer *et al.*, 2013).

3.4 Processing data of age model

On the basis that the depth-based linear interpolation method was not fit for the dating of cultural layers because of potential disturbance, all common millet remnant samples were divided into several groups to guarantee at least one dating dataset for each group (Figure 3a), as follows: samples from adjacent depths with close $\delta^{13}C$ values were placed in the same group, allowing a greater difference between each group (One-factor Analysis of Variance (one-way ANOVA), $P<0.05$).

3.5 Quantitative modeling method and data analysis

The results for $\delta^{13}C$ values in the seeds of modern millet grown on the CLP (Yang and Li, 2015) demonstrated that the $\delta^{13}C$ of common millet has a significant positive correlation with precipitation. In this study, standard major axis regression analysis (SMA) was applied to establish a regression model between the $\delta^{13}C$ of modern common millet and precipitation during growing seasons. Statistical analyses were conducted using SMATR software (Version 2.0) (Falster *et al.*, 2006). Other statistical analyses used SPSS 15.0 for Windows and OriginPro 8.0 software. Unless otherwise stated, differences were considered statistically significant when $P<0.05$.

4 Results

The radiocarbon results (Table 2) show that the ages of the sampled cultural layers were usually correspondent with archeological periodization. Common millet remains sampled from cultural layers of Guanzhong Basin in our study have $\delta^{13}C$ values ranging from -11.1‰ to -9.3‰ (Figure 3a), with a mean of -10.2±0.4‰ (n＝66, SD=±1 σ), without considering the anomaly value of -8.8‰ analyzed by Boxplot using SPSS statistical software (Figure 3b), which may be affected by the local environment. The $\delta^{13}C$ composition of modern common millet from the central and western CLP measured in 2008 ranged from -13.9‰ to -12.5‰, with a mean of -13.2±0.5‰ (n＝15, SD= ±1σ) (Yang and Li, 2015). It can thus be seen that the $\delta^{13}C$ values of common millet remains are more positive than those of modern millet by ～2.9‰.

The ^{13}C composition of plants results from a combination of carbon isotope fractionation and source carbon isotope composition. Therefore, $\delta^{13}C$ changes in the atmosphere, as a part of total CO_2, are an important factor impacting upon the $\delta^{13}C$ values in plants (O'Leary, 1988; Farquhar, 1989; Araus and Buxo, 1993). Considering our atmosphere is a perfect blender, we adopted the global mean $\delta^{13}C$ value of atmospheric CO_2, -8.2%, in 2011 (Cuntz, 2011), which was three years after sampling. The $\delta^{13}C$ values of atmospheric CO_2 in the Holocene, from 11 ka BP to the pre-industrial age, show only a slight change, usually ranging between -6.1‰ and -6.6‰, with a mean value of -6.4± 0.15‰ (Marino *et al.*, 1992; Leuenberger *et al.*, 1992). ～1.8‰ higher than present-day atmospheric CO_2 $\delta^{13}C$ values of -8.2‰ (Farquhar *et al.*, 1989; Keeling and Whorf, 1992). After correcting for the change in atmospheric CO_2 $\delta^{13}C$ (1.8‰), the millet $\delta^{13}C$ values for Holocene millet from the Guanzhong Basin are equivalent to modern caryopsis values of -12.0±0.4‰, and are therefore ～1.2‰ less depleted in $\delta^{13}C$ than modern caryopsis (for the t test, t=21.39).

The regression function between $\delta^{13}C$ and precipitation for the common millet growing season was established using SMA as follows (Figure 4):

$$\delta^{13}C\text{（‰）} = 0.0077P_{gs}-14.76\text{，} r^2 = 0.56\text{，} P<0.001 \qquad \text{Eq.(2)}$$

Where P_{gs} denotes the precipitation of millet growth seasons. The function’s gradient indicated that the precipitation coefficient was 0.77‰/100 mm, implying that, within physiological adaptation parameters, there would be a ~0.77‰ increase in $\delta^{13}C$ with a 100 mm increase in precipitation. The $\delta^{13}C$ values yielded by ancient common millets are higher than those of modern common millet seeds, suggesting that these ancient plants grew in a more humid environment than today’s.

Common millet remains from archeological sites were divided into a total of 11 groups (Table 3). Mean $\delta^{13}C$ values for common millet remains were calculated for each group. Results showed that the minimum value was -10.6±0.2‰, and the maximum value -9.6±0.1‰, for common millet growing between 7.7 ka BP and 3.4 ka BP. After correcting for the change in the atmospheric CO_2 $\delta^{13}C$ (1.8‰), the range of mean $\delta^{13}C$ values for ancient millet *vis-à-vis* modern plants was between -12.4±0.2‰ and -11.4±0.1‰. By applying the regression model based on the $\delta^{13}C$ and precipitation values for modern common millet during its growing season, we were able to extract paleoprecipitation values for the growing seasons of ancient crops for certain time periods.

These paleoprecipitation values were reconstructed by applying the corrected $\delta^{13}C$ values for the ancient millet to the regression equation (Eq. 2) which expresses the relation between the $\delta^{13}C$ of common millet and precipitation. The results showed that the precipitation for the growing seasons of ancient millet during the period 7.7-3.4 ka BP varied from 240 mm to 477 mm, with a mean of 354 mm (Table 3).

5 Discussion

5.1 Comparison between the mid-Holocene and modern precipitation

Ancient equivalent-seed δ^{13}C values, ranging from -12.4±0.2‰ to -11.4±0.1‰, are ～1–2‰ higher than those for modern millet in the area. Paleoprecipitation reconstructed from the regression function shows that precipitation of millet growth seasons at 7.7-3.4 ka BP was between 242 and 475 mm, with a mean of 353 mm. Summer paleoprecipitation values show that the climate was much more humid than it is today, which was 305 mm on average during 1951-2011, with mean precipitation ~50 mm, or 17%, higher. A peak mean summer precipitation of 442 mm was reached at ~5.7 ka BP; even the lowest value of 311 mm ~6.5 ka BP was higher than today's mean value. Summer precipitation during the Mid Holocene (7.7-3.4 ka BP) in the Guanzhong Basin exhibited a systemic increase.

The reconstructed summer precipitation also fluctuates significantly and becomes more and more variable, especially after 5.2 ka BP. However, there were three markedly humid periods, i.e. 6.1-5.5 ka BP, ~4.2 ka BP, and ~3.6 ka BP (Figure 5). The period 6.1-5.5 ka BP had the most abundant summer precipitation, which was 414 mm, i.e. 109 mm, or 36%, higher than today. At ~4.1 ka BP, the precipitation was 397±11 mm, 92 mm or 30% higher than at present; at ~3.6 ka BP, the precipitation was 414±45 mm, 36% higher than at present.

The period 6.1-5.5 ka BP, being the most markedly humid period, probably marks the Holocene Climate Optimum in the Guanzhong Basin; this was also when the Yangshao Culture flourished, with archeological finds indicating that there were as many villages in the area as there are today. It is worth noting that the anomalous high value at ~4.1 ka BP and ~3.6 ka BP, may indicate rapidly-developing climatic events, correspondent with other global records (Cullen and DeMenocal, 2000; Mayewski et al., 2004; Wu and Liu, 2004).

5.2 Validating the reliability of quantitative precipitation reconstructions

The instrumental data for the last 61 years (1951-2011) indicate that precipitation in the Guanzhong Basin occurs mainly in the summer (Figure 2). The current inland flow of warm/humid air dominated by the EASM during the summer (June through September) delivers ~58% of the total annual precipitation. The area is a typical monsoon precipitation area, and summer precipitation here is therefore sensitive to variations in the EASM.

Previous studies of various climatic proxies including stalagmite δ^{18}O, lacustrine sediments and loess-paleosols all indicate that the CLP had plenty of rain in the Holocene and was much more humid during the Mid Holocene (Shen *et al*., 2005; Wang *et al*., 2005a; Wang *et al*., 2008; Wang *et al*., 2014; Chen *et al*., 2015). The frequency of paleosol development increased during ~8.6-3.2 ka in the CLP (Wang *et al*., 2014). The eolian-sand activities in the sandlands located to the north of the CLP decreased from ~8.6-3.2 ka BP (Wang *et al*., 2014; Yang *et al*., 2012), whilst the vegetation coverage of the desert/loess transitional zone increased in this interval (Yang *et al*., 2015). These various proxy records infer that the EASM was stronger during the Mid Holocene, but the amplitude of any variations in the EASM remains difficult to assess.

Our quantitative reconstructions of summer precipitation based on millet $\delta^{13}C$ indicate that EASM intensity peaked during 6.1-5.5 ka BP. The strongest summer monsoon brought the wettest millet growth seasons, with 36% higher precipitation than today's. More evidence supporting our contention comes from the tree pollen records from lake sediments around the CLP, which respond more directly to changes in the EASM than the other records because trees on the margins of monsoonal regions are sensitive to variations in monsoonal precipitation. Pollen records from Qinghai Lake, located to the west of the Guanzhong Basin and on the modern monsoon margins, indicate a wet interval during 7.4-4.5 ka BP, culminating in a peak at 6.5 ka BP (Figure 6a) (Shen *et al*., 2005). Although the increase in precipitation cannot be assessed, the general trend is comparable with our $\delta^{13}C$-based precipitation reconstruction results. The percentage of broadleaf trees from pollen record in the Gonghai Lake (on the northeastern margins of the CLP; Figure 6b), indicate that the peak monsoonal period occurred during ~7.8-5.3 ka BP, with an average annual precipitation of 574 mm (Figure 6c), ~30% higher than the modern value (Chen *et al*., 2015). The increase in precipitation is highly consistent with our reconstruction results. More evidence from PMIP2 (the second phase of the Paleoclimate Modeling Intercomparison Project) coupled with Mid Holocene simulations showed that the summer precipitation associated with the EASM increased throughout most of China ~6 ka BP and the greatest increases in precipitation seen in the region, *i.e.* the southern margins of the Tibetan Plateau, and southeastern coastal area of China, which experienced precipitation increases of >1.5 mm/day and 0.7 mm/day (or 547.5 mm/yr and 255.5 mm/yr), respectively (Zhang and Liu, 2009). According to the result, it can be inferred the increase in precipitation in the Guanzhong Basin was lower than 255.5 mm/yr at that time. These multiple lines of evidence corroborate our reconstructions, not only *vis-à-vis* changes in precipitation during the Holocene, but also their quantitative accuracy.

5 Conclusions

Summer precipitation at 7.7-3.4 ka BP reconstructed using the δ13C values of common millet was 242-475 mm, with a mean of 353 mm, ～50 mm, or 17%, higher than at present. The increasing variability of summer precipitation was visible, especially after 5.2 ka BP. Maximum mean summer precipitation peaked at 414 mm during the period 6.1-5.5 ka BP, ~109 mm (or 36%) higher than today, indicating that the EASM peaked at this time.

Although the δ13C-based precipitation record in this study has a low-resolution, the work provides an innovative method and proxy for establishing the paleoprecipitation record. Carbonized common millet remains from the Neolithic Age onward can provide a reliable dating framework and aid the reconstruction of continuous paleoprecipitation sequences and the variability of summer precipitation. This, in turn, can allow regional comparisons, providing a scientific foundation for promoting further research into the quantitative reconstruction of regional paleoclimates, and helping to understand the detailed processes and precise mechanisms of the EASM, as well as the relation between early human activity and environmental change.

Authorial contributions

X. Q. L.: overall coordination of writing, sampling, ^{14}C dating and paleoprecipitation reconstruction; Q. Y.: writing, sampling, data processing and paleoprecipitation reconstruction; X. Y. Z. and K. L. Z.: sampling and data processing; N. S.: sampling and ^{14}C dating. All authors reviewed the manuscript.

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Tables

Table 1 Sampling sites and the number of common millet samples

Sites	Location	Cultural types	Sample source	*n*
Baijia	34°33′7.53″N 109°24′38.6″E	Early Laoguantai Culture	Cultural layer	12
Huiduipo	34°34′4.1″N 109°01′41.8″E	Banpo type, Yangshao Culture	Cultural layer	9
Manan	34°28′23.7″N 109°05′17.5″E	Miaodigou type, Yangshao Culture	Cultural layer	11
Beiniu	109°19′2.6″E	Longshan Culture	Cultural layer	15
Nansha	34°29′30.1″N 109°42′47.9″E	Erlitou Culture, Shang Dynasty	Cultural layer	20

n means the number of remnant common millet samples derived from the section.

Table 2 Accelerator mass spectrometry (AMS) dates from Baijia (BJ), Huiduipo (HDP), Manan (MN), Beiniu (BN), and Nansha (NS)

Sample code	Depth (cm)	Sample type	Radiocarbon age (^{14}C yr BP)	Calibrated age range (cal yr BP, 2σ)	Lab code
BJ-15	180-190	Common millet	6,705±40	7,504-7,657	OZM447
BJ-2	50-60	Charcoal	6,675±40	7,476-7,612	OZM446
HDP-13	235-250	Common millet	5,720±50	6,408-6,639	OZM473
HDP-9	160-180	Rice seed	5,015±45	5,655-5,896	OZM472
HDP-5	80-100	Rice seed	5,120±35	5,750-5,831	OZM471
HDP-3	40-60	Foxtail millet	5,185±40	5,891-6,009	OZM470
MN-8	140-160	Foxtail millet	4,550±35	5,053-5,191	OZM452
BN-13	280-300	Foxtail millet	5,450±70	6,172-6,400	OZM481
BN-10	220-240	Foxtail millet	3,820±45	4,138-4,360	OZM480
BN-8	180-200	Rice seed	3,770±35	4,073-4,244	OZM479
BN-5	120-140	Foxtail millet	4,540±50	5,040-5,323	OZM478
BN-1	40-60	Common millet	4,110±40	4,521-4,730	OZM477
NS-15	230-240	Wheat seed	3,300±30	3,454-3,593	OZM460
NS-11	200-210	Wheat seed	3,280±35	3,445-3,587	OZM459
NS-5	140-150	Wheat seed	3,300±30	3,454-3,593	OZM458

All assays were run on the STAR Accelerator, ANSTO, Australia. Calibrations refer to the Radiocarbon Calibration Program (Reimer et al., 2013).

Table 3 Information for grouped common millet remains, by section

Section	Cultural age	Depth（cm）	*n*	Calibrated ages (cal yr BP)	Mean δ^{13}C(‰)	Corrected δ^{13}C (‰)	P$_{gS}$ (mm)

Baijia	Laoguantai Culture	50-190	12	7,476-7,657	-10.4 ±0.2	-12.2 ±0.2	336 ±30
Huiduipo	Banpo type, Yangshao Culture	200-250	3	6,408-6,639	-10.6 ±0.3	-12.4 ±0.3	311 ±37
	Banpo type, Yangshao Culture	120-200	2	5,655-5,896	-9.6 ±0.1	-11.4 ±0.1	442 ±9
	Banpo type, Yangshao Culture	0-120	5	5,750-6,009	-9.9 ±0.1	-11.7 ±0.1	402 ±12
Manan	Miaodigou type, Yangshao Culture	0-260	11	5,053-5,191	-10.3 ±0.4	-12.1 ±0.4	346 ±47
Beiniu	Yangshao Culture	260-300	3	6,172-6400	-10.3 ±0.1	-12.1 ±0.1	349 ±8
	Longshan Culture	180-240	3	4,073-4,360	-9.9 ±0.1	-11.7 ±0.1	397 ±13
	Longshan Culture	80-180	4	5,040-5,323	-10.3 ±0.2	-12.1 ±0.2	352 ±27
	Longshan Culture	40-80	4	4,521-4,730	-10.6 ±0.2	-12.4 ±0.2	313 ±22
Nansha	Erlitou Culture, Shang Dynasty	50-300	20	3,445-3,593	-10.2 ±0.4	-12.0 ±0.4	346 ±47

n means the number of samples for δ^{13}C analysis. Corrected δ^{13}C means δ^{13}C value of millet being corrected the δ^{13}C difference of atmospheric CO_2 between modern and Holocene for precipitation reconstruction. P_{gs} means reconstructed precipitation of millet growth seasons.

Figures

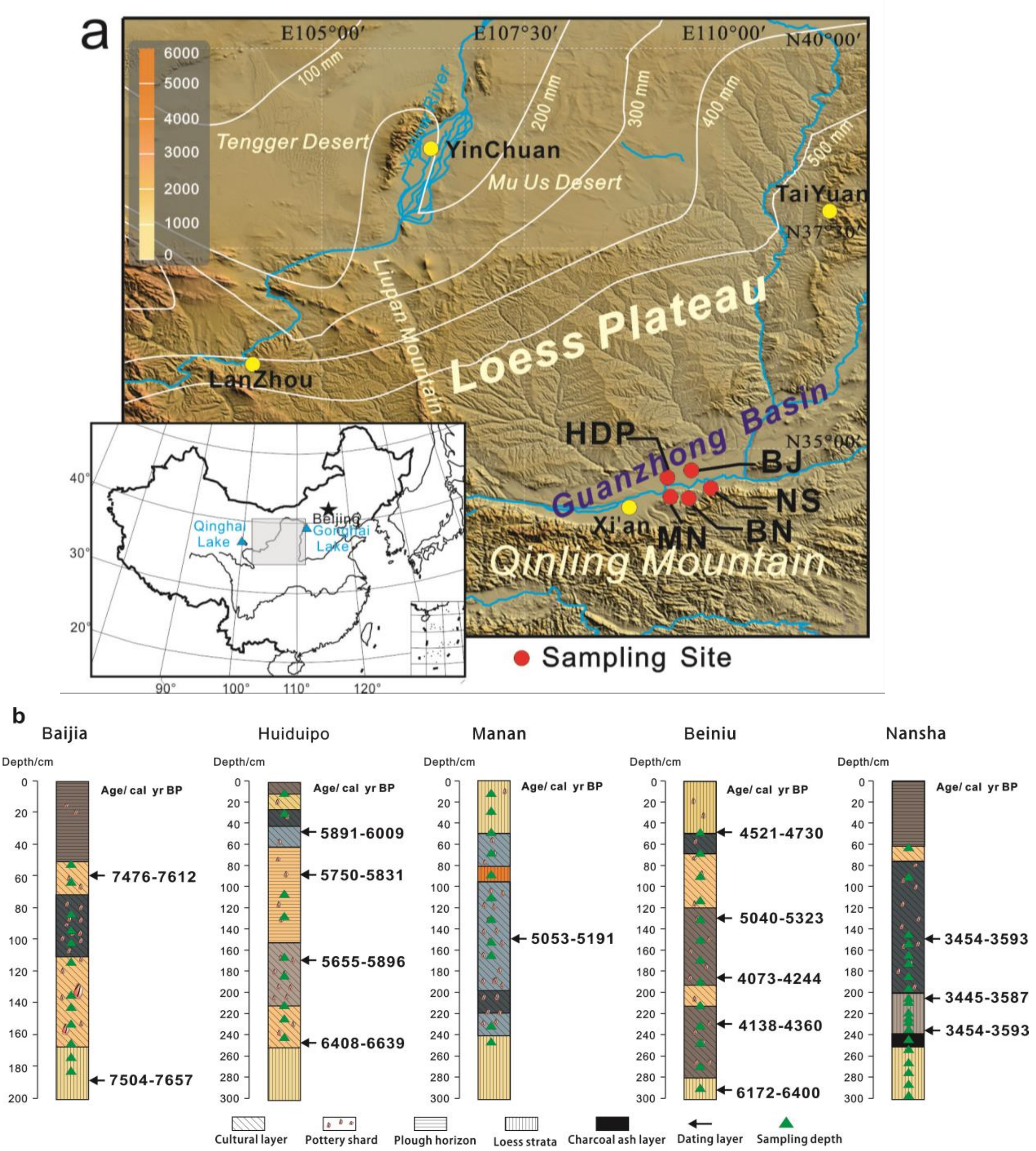


Figure 1. Location of sampling sites (Panel a) and description of all sampling sections (Panel b). Red solid circles indicate sampling sites: Baijia(BJ), Huiduipo (HDP), Manan (MN), Beiniu (BN), Nansha (NS).

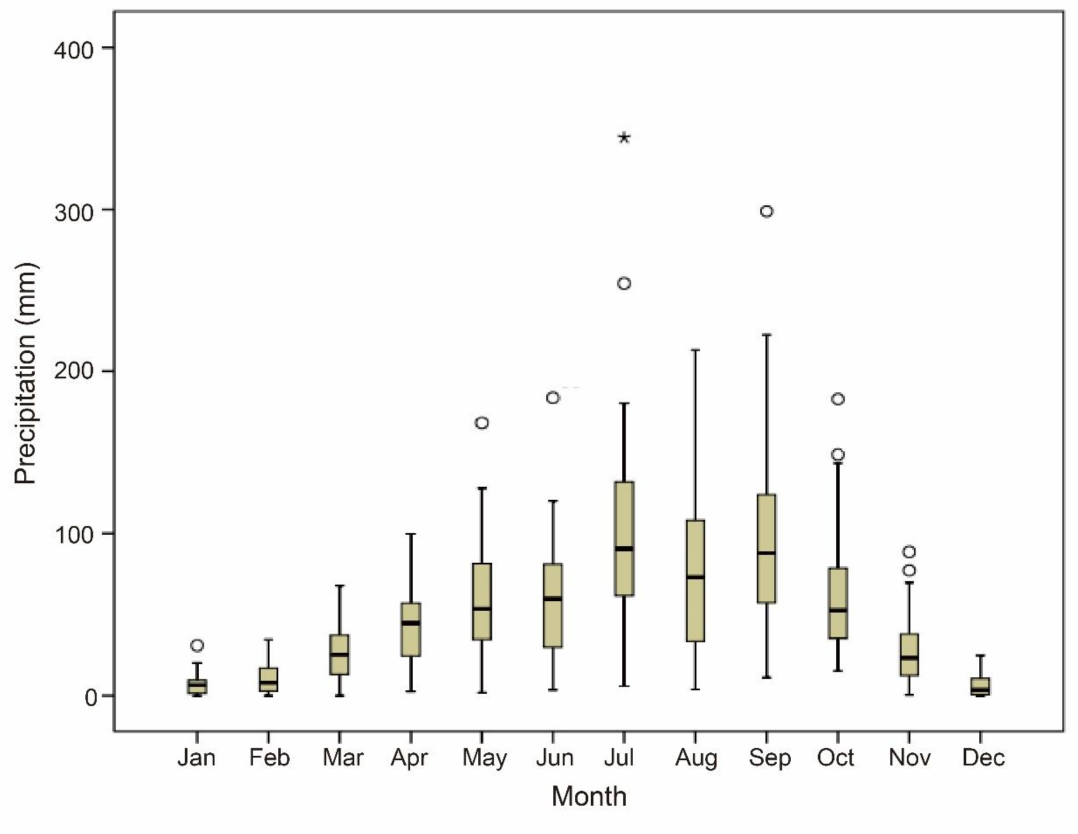
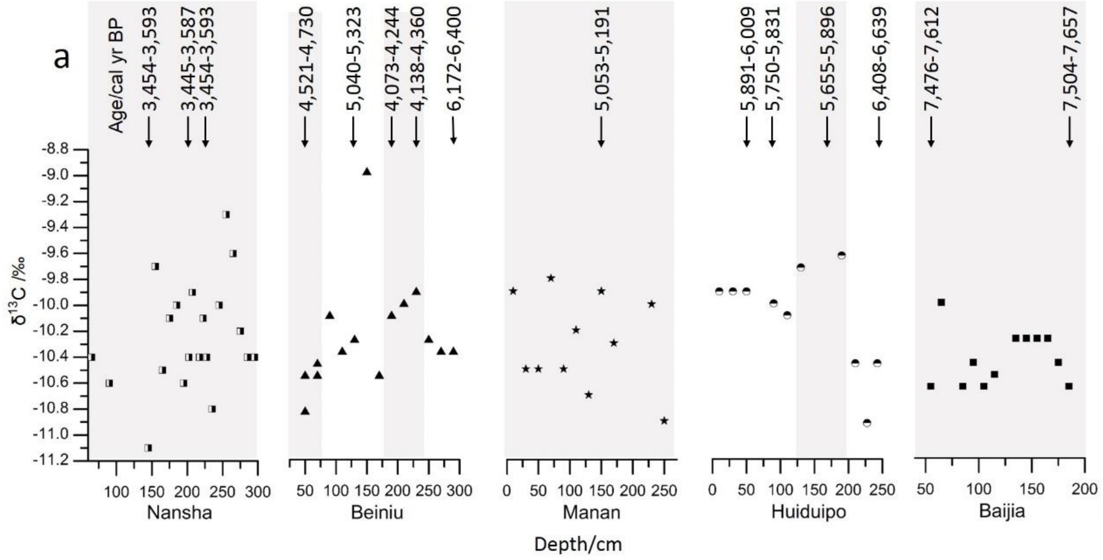


Figure 2. Instrumental precipitation data for 1951-2011 from Xi'an Station, Shaanxi, China (original data, Data Sharing Platform, China Meteorological Administration). The empty circle (○) indicates an abnormal value; the asterisk (*) indicates an extremely abnormal value.



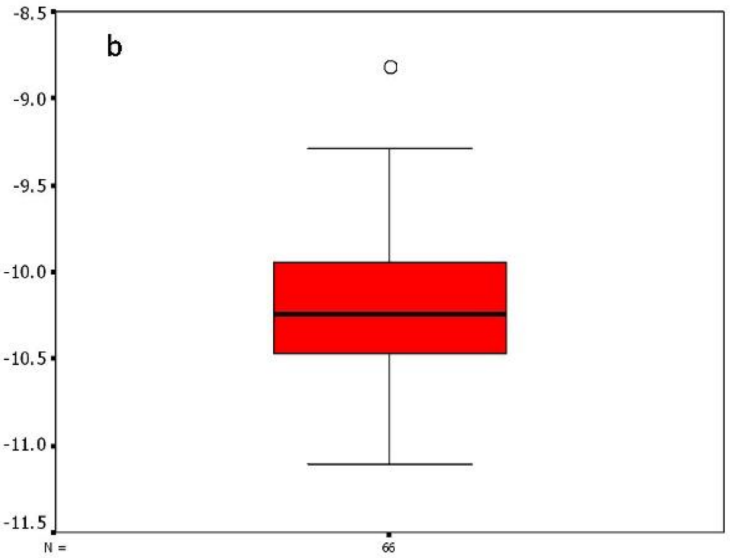


Figure 3. $\delta^{13}C$ of common millet from archeological sites, Guanzhong Basin. Panel a shows raw data points including all $\delta^{13}C$ and calibrated age range versus depth. The group division were expressed in gray or white color. Panel b shows Boxplot of all $\delta^{13}C$ of common millet, with the mean value 10.2±0.4‰ (n＝66, SD=±1 σ) and the anomaly value of -8.8‰ excluded.

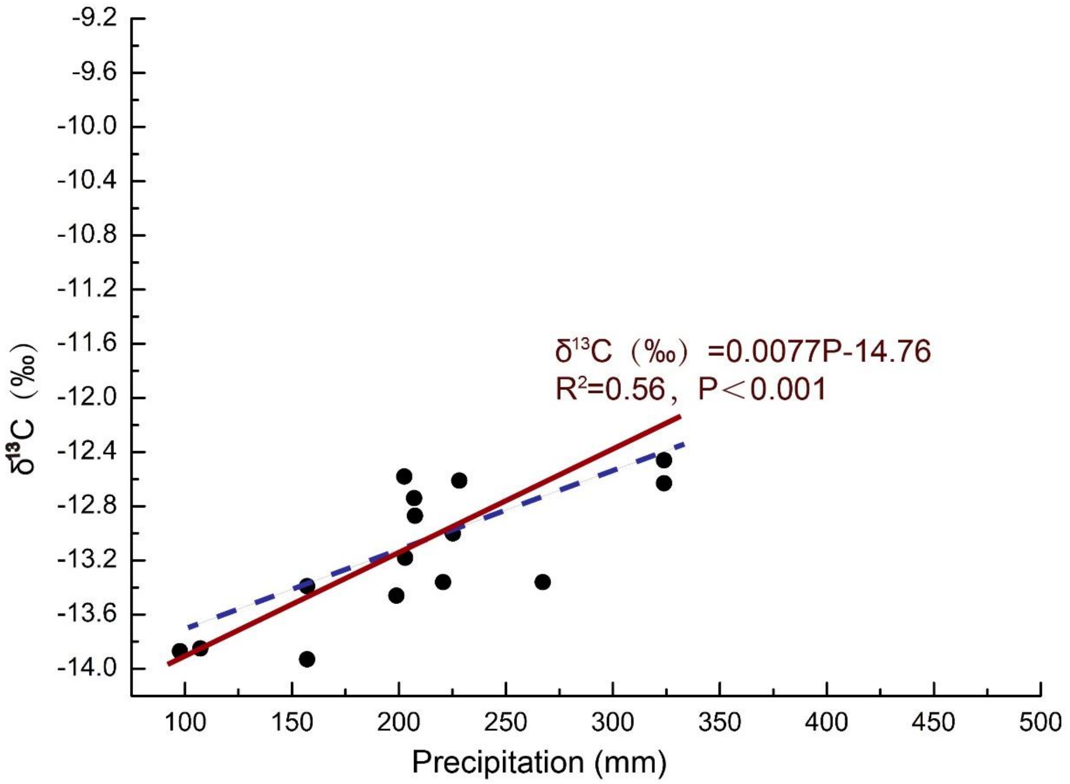


Figure 4. The regression model of the $\delta^{13}C$ of modern common millet and summer precipitation, which data from Yang and Li (2015). Dark red line denotes the line of best fit established using SMA; the blue dotted line denotes the line of best fit established using OLS.

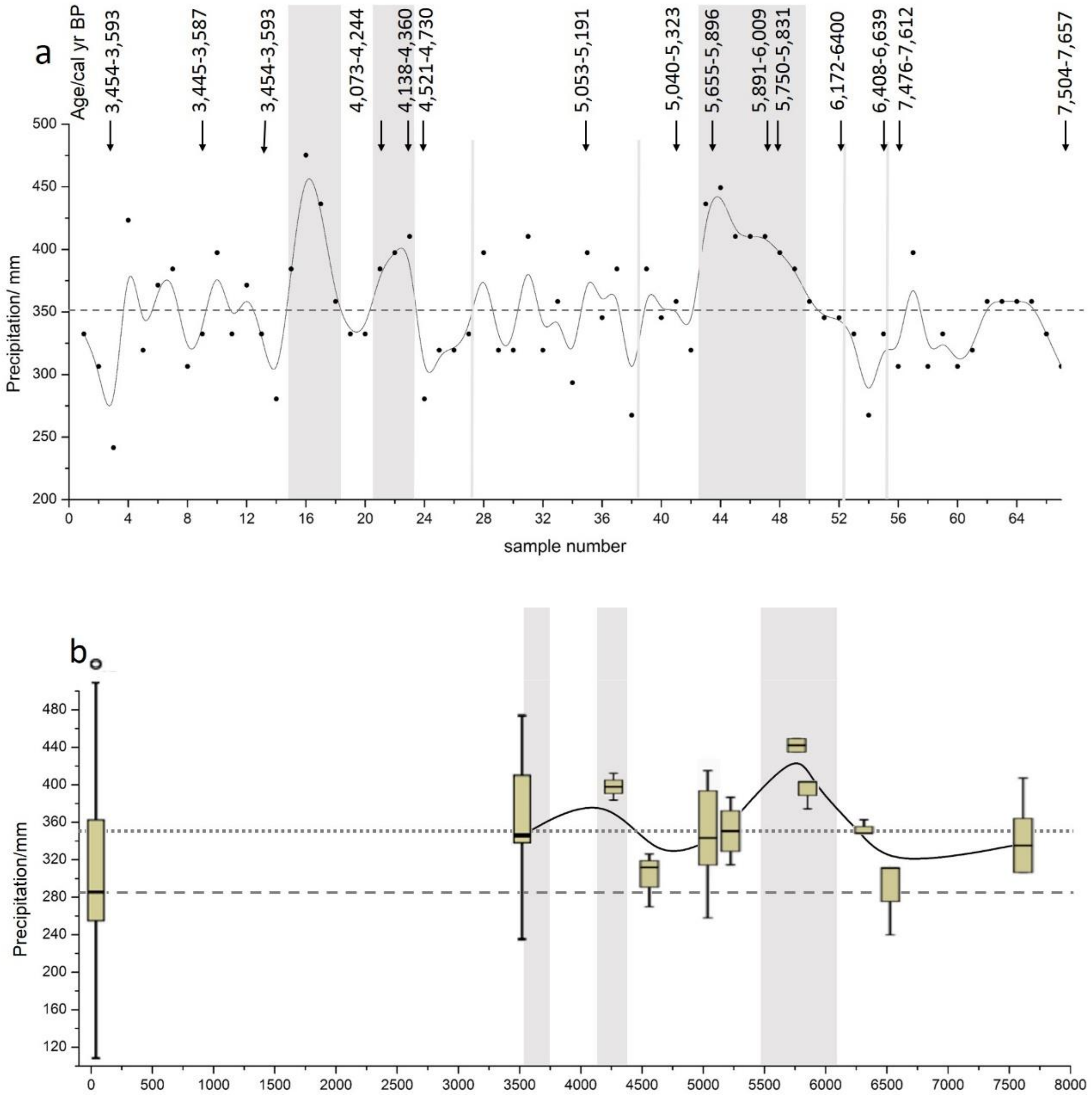


Figure 5. Reconstructed summer precipitation during 7.7-3.4 ka BP, Guanzhong Basin (Panel a) and comparison the reconstructed precipitation during the Holocene to precipitation for mid-June to September for a modern period in Xi’an city (original data for 1951–2011, from the China Meteorological Administration). The gray color in both panel a and b indicates the markedly humid periods during the Holocene. The gray line in panel a means the group division. The dot line in panel b indicates the mean precipitation of millet growth season at 7.7-3.4 ka BP; the dash line in panel b indicates the mean precipitation for mid-June to September during 1951-2011.

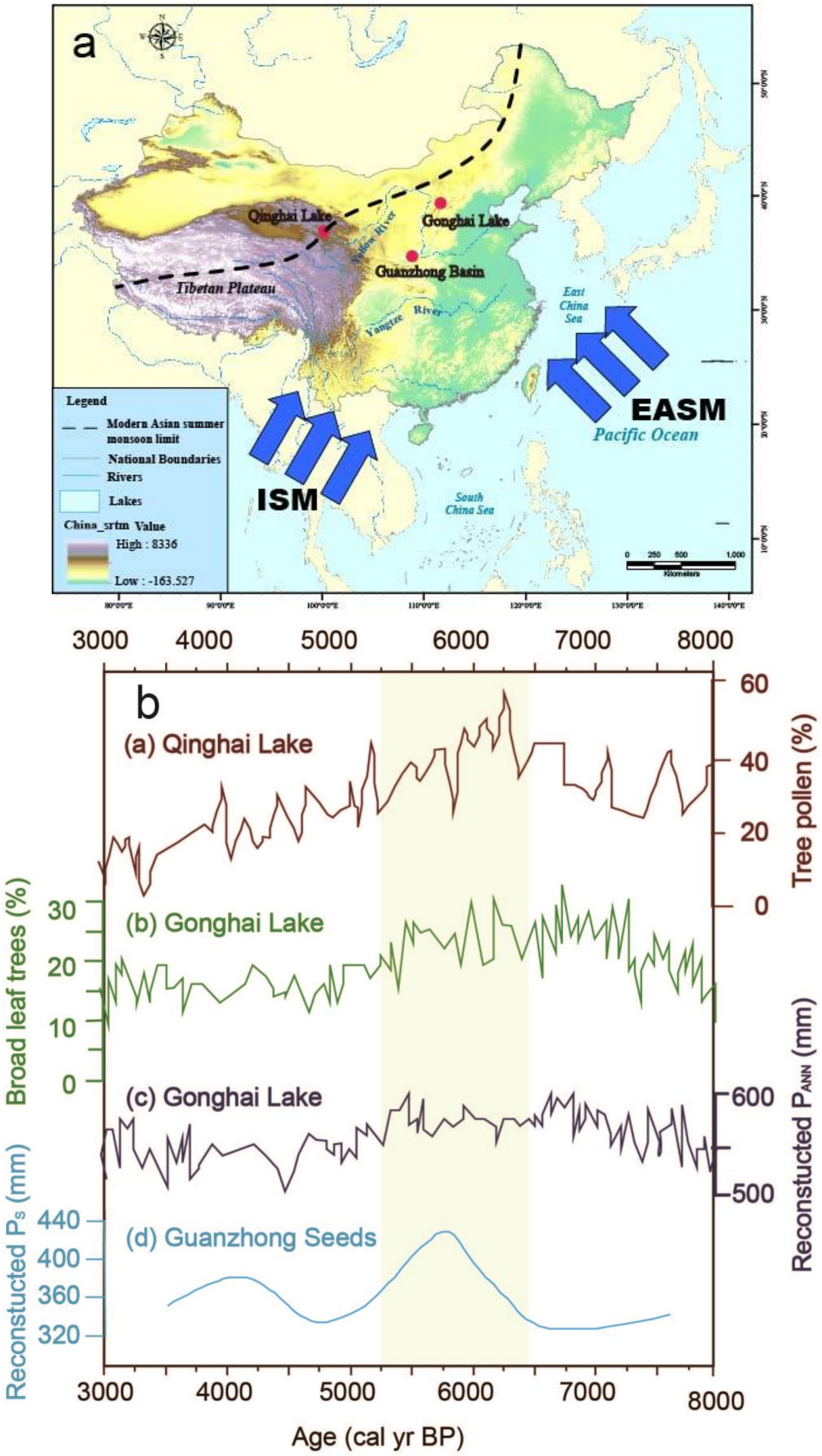


Figure 6. The modern Asian summer monsoon limit is shown by a dashed line in the map (panel a). The red dots signed in the map are the locations of Qinghai Lake, Gonghai Lake and

Guanzhong Basin, whose precipitation were carried out comparison. Comparison of reconstructed summer precipitation for 7.7-3.4 ka BP, Guanzhong Basin, with the pollen records of lakes sediments from around the CLP. (**a**) Tree pollen percentages from Qinghai Lake (Shen *et al*., 2005). (**b**) Broadleaf tree pollen percentages from Gonghai Lake (Chen *et al*., 2015). (**c**) Reconstructed annual precipitation from the pollen records of Gonghai Lake (Chen *et al*., 2015). (**d**) Reconstructed summer precipitation from the $\delta^{13}C$ values of common millet, Guanzhong Basin.