δ^{13}Cp VALUES FROM RADIOCARBON-DATED PLANT MATTER AS AN IMPORTANT BUT UNDEREXPLOITED RESOURCE FOR TERRESTRIAL PALEOCLIMATE ANALYSIS AND ARCHAEOLOGY

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ABSTRACT. Variation in stable carbon isotope ratios in C_3 plants can be influenced by climatic and environmental factors. For archaeologists, who regularly collect the measured values of these data as a part of the radiocarbon date reporting process, there is promise in using these data to create a local record of paleoclimatic change relevant to their study areas. Plant δ^{13}C can be expressed as Δ^{13}C values (carbon isotopic discrimination) that can be used in modern experimental studies for stronger paleoclimatic/paleoenvironmental interpretations. As values of Δ^{13}C vary in different species, taxonomic information is necessary for interpretation. In the present study, a record of Irish oak δ^{13}C data are used to construct a local climate history for Ireland. Wetter periods in Ireland inferred from δ^{13}C data correspond to warmer Northern Hemisphere temperatures, in agreement with climate models. Values of δ^{13}C from other species are used to illustrate the importance of using data from taxa with known relationships between climate and stable carbon isotope fractionation.

INTRODUCTION

The primary source of variation in C_3 plants is the ratio of internal to external CO_2 partial pressure, c_i/c_a. Decreasing c_i/c_a results in lower net discrimination against heavier isotopes of carbon, and higher c_i/c_a results in more discrimination due to the strengthened role of Ribulose-1,5-biphosphate carboxylase oxygenase (Rubisco) during fractionation (Farquhar et al. 1982). During periods of water shortage, C_3 plants close their stomata to reduce water vapor loss during respiration. As plants continue to carboxylize remaining CO_2 in the intercellular leaf cavity, the internal partial pressure, c_i, drops relative to the external partial pressure outside the leaf, c_a. This results in a decrease in discrimination against heavier isotopes of carbon, ^{13}C and ^{14}C. The resulting ^{13}C- and ^{14}C-enriched photosynthate produced is passed to product tissues such as wood, seeds, and roots. When δ^{13}C is used to calculate Δ^{13}C, a potentially useful approximation of this plant response to water availability is obtained. Importantly, Δ^{13}C provides highly local climatic information relative to other paleoclimatic reconstruction techniques available to archaeologists.

In an early application of this metric, Leavitt and Long (1986, 1988) found that δ^{13}C values in piñon pine trees across the southwestern US correlated with the Palmer Hydrological Drought Index (PHDI) from 1895 to 1985. Correlation coefficients (r) of PHDI and δ^{13}C ranged widely among sites in strength and significance from 0.09 to 0.93. The δ^{13}C values correlated moderately with tree-ring width in the same trees. Plant tissues tended to be enriched in ^{13}C and ring widths tended to be narrow during the droughts of the 1950s and 1930s. McCarroll and Pawellek (2001) found that while many trees in Finland showed a consistent relationship between δ^{13}C and precipitation, there was enough variation in response that it was less reliable than more traditional measures of tree-ring width. In a study of biome-wide δ^{13}C, Diefendorf et al. (2010) found a relationship with mean annual precipitation ($r^2 = 0.55$, $p < 0.001$). Leavitt (2008) suggested that averaging stable carbon isotope ratios from multiple plants will produce more reliable regional records of paleoclimate; pollen-derived Δ^{13}C values in Greece supported this argument (Drake 2012). Values of δ^{13}C increased by over 1‰ during the Younger Dryas among *Quercus robur* and *Quercus petraea* (Becker et al. 1991). Dupouey et al. (1993) found a significant correlation coefficient ($r = -0.59$, $p < 0.001$) between variation in δ^{13}C in *Fagus sylvatica* L. and relative extractable soil water in the month of July for the years between 1950 and 1990. A 3-yr study in Oregon found strong correlations in

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respired $\delta^{13}C$ in conifer forests and antecedent precipitation, leaf predawn potential, and soil water content (Bowling et al. 2002). Wheat had a strong relationship between $\Delta^{13}C$ and water-use efficiency (Farquhar and Richards 1984). Stable carbon isotope studies in wheat have led to debate as to whether $\Delta^{13}C$ is an accurate predictor of grain yields (Farquhar and Richards 1984; Ehdaie and Waines 1994; Monneveux et al. 2005; Mohammady et al. 2009).

APPLICATIONS IN ARCHAEOLOGY

One important advantage of $\delta^{13}C$ values is its potential use in archaeological studies. Macrobotanicals are commonly found in the course of archaeological excavations, which most often include the remains of charcoal/wood but can also include seeds and other portions of the plant. Typically, these are the non-photosynthetic portions of a plant, the same tissues that are typically used in paleoclimatic reconstruction (Leavitt and Long 1988; Hall et al. 2008). The measured values of $\delta^{13}C$ taken during the course of radiocarbon dating (Stuiver and Polach 1977) can potentially be used for climatic and environmental inference. The process of firing used to produce charcoal does not affect the relative relationship between seasonal and interannual isotopic relationships with climatic indicators (Hall et al. 2008).

Analysis of paleoclimatic/paleoenvironmental proxy data sources can support archaeologists in understanding the conditions in which past human societies exist and change. While archaeology is typified by multiple theoretical approaches to viewing the past (Trigger 2007), many studies benefit from understanding environmental conditions. In processual archaeology, advocated by Louis Binford (1962, 1965), culture is viewed as an adaptation to the environment. Thus, understanding environment is a critical window in developing insight into cultural practices in the past. In human behavioral ecology research, understanding environmental variation helps establish critical variables for models of human behavior and decision making (Sheenan 2002). The use of $\delta^{13}C$ data has much potential to enrich our understanding of the human past in the context of these theoretical approaches.

The application of $\Delta^{13}C$ values in archaeological and paleoenvironmental contexts has been diverse in the past 2 decades. Heaton et al. (2009) found that $\Delta^{13}C$ values in wheat were 2.5‰ higher in a Bronze Age Greek site relative to modern wheat samples, potentially indicating the ancient climate was wetter or irrigation was used. Aguilera et al. (2009) followed a similar direct comparison using archaeological and modern *Quercus ilex* and *Q. coccifera* in eastern Iberia, finding increased $\Delta^{13}C$ values that they interpreted as evidence for more humid conditions during the Late Bronze Age. In western Iberia, Drake et al. (2012) identified aridity in the Lower Alentejo of Portugal during the first half of the Medieval Warm Period using $\Delta^{13}C$ values from taxa with known drought responses in the region. Riehl (2008) looked at $\Delta^{13}C$ in ^{14}C-dated barley and identified 2 periods of lower $\Delta^{13}C$ that corresponded with known arid periods at 5100 and 4200 BP. The 2 arid periods were first identified by Cullen et al. (2000) through pronounced increases in calcium carbonate and dolomite in the Gulf of Oman. Drake (2012) used bulk pollen $\Delta^{13}C$ values to identify aridity in the eastern Mediterranean during the Late Bronze Age collapse, a period of urban abandonment. Beerling (1994) employed values of $\delta^{13}C$ to look at climatic variation over the past 30,000 yr. There are different approaches to utilizing $\Delta^{13}C$ in these studies. In some, it is used to identify differences between modern and ancient values (Aguilera et al. 2009; Heaton et al. 2009), potentially indicating relative differences of water availability for the same region in 2 different times. In other studies, $\Delta^{13}C$ is used as a general climate indicator (Beerling 1994; Riehl 2008; Drake 2012). Another approach uses $\Delta^{13}C$ as a taxon-specific indicator of paleoclimatic change (Drake et al. 2012). While there is no single correct approach to the analysis of $\Delta^{13}C$ data, the robustness of conclusions regarding past human societies drawn from such analysis is dependent upon the way the data are used. In the present manuscript, it is argued that taxon-specific interpretation of Δ^{13}C values makes the most robust use of the data as a localized climate proxy.

As a paleoclimate indicator, values of Δ^{13}C have advantages over traditional techniques such as conventional dendroclimatology. First, they provide local records of climate change centered at the archaeological site, whereas dendroclimatological records provide more regional records that may or may not overlap with conditions at the archaeological site. For example, a near 50-yr drought from AD 1135 to 1180 is inferred from ponderosa pine and Douglas-fir trees used in the construction of great houses in Chaco Canyon (Robinson and Rose 1979). However, those wood construction beams may have originated as far as 60 km from the sites themselves (English et al. 2001), adding uncertainty to understanding local climatic conditions that may have precipitated abandonment of the region. The use of Δ^{13}C values, particularly on local-growing plants used for firewood, can provide a much more local record of climate change.

The second advantage to using Δ^{13}C values is that when they are derived from measured δ^{13}C values used in ^{14}C corrections, they provide a paleoclimate record at the same spatial and temporal scales as the human societies and/or environmental changes that are being studied. Values of Δ^{13}C may be a highly useful paleoclimate proxy record that can enable much higher-resolution studies of the effects of climate impacts upon human societies.

The third advantage is the ubiquity of the source data. Charcoal is a common occurrence in archaeological sites worldwide. In some regions, other paleoclimate proxy records are unavailable or rare. In these cases, as was the case in the Lower Alentejo, Portugal (Drake et al. 2012), measured δ^{13}C values reported with ^{14}C dates were an important record that gave insight into the hydrological system that influenced human settlement patterns.

However, it is critical to note that the potential to misinterpret Δ^{13}C data is always present. Variation in Δ^{13}C values can be driven by changes in the physical features of a plant as well as stochastic variation in mesophyll conductance (Seibt et al. 2008). Perhaps more importantly, different plants have different ranges of Δ^{13}C, which means that simple interpretations about lower Δ^{13}C values and climate are meaningless without an understanding of the range for a given taxon (Figure 2). Secondly, not all taxa respond to arid conditions with a detectable shift in stomatal conductance. Werner and Máguas (2010) studied Δ^{13}C across multiple taxa in the Parque Natural da Serra da Arrábida in southwestern Portugal. They found some taxa had a significant relationship between water potential and Δ^{13}C, including *Cistus albidus* L. ($r^2 = 0.54$), *Cistus monspeliensis* L. ($r^2 = 0.30$), *Olea europeae* Brot. ($r^2 = 28$), and *Quercus coccifera* L. ($r^2 = 0.25$). Other taxa, including a member of *Juniperus*, had no significant relationship. The ranges of taxa drought response were different as well. For example, *C. albidus* had a mean Δ^{13}C of ~19.5‰, while the average value of Δ^{13}C for a drought year in *C. monspeliensis* was also 19.5‰. In a mixed-species sample of Δ^{13}C, Drake et al. (2012) suggested taking the conservative threshold of observed Δ^{13}C values in a drought year for analysis of older charcoal samples. In the case of Portugal, values of Δ^{13}C below 18.5‰ were used to identify drought. Comparing Δ^{13}C values from archaeological or paleoenvironmental contexts with modern experimental data allows for the best control of uncertainty in a highly variable data set.

^{13}C Fractionation in C_3 Plants

Stable carbon isotopes are used in ^{14}C corrections and are frequently reported with ^{14}C dates following the recomendations of Stuiver and Polach (1977). The isotopic composition (δ) of a given sample is expressed with respect to the conventional standard as follows:

$$\delta^{13}C = [(^{13}C/^{12}C - {}^{13}C/^{12}C_{VPDB})/^{13}C/^{12}C_{VPDB}] \times 1000 \qquad (1)$$

C_3 plants are characterized by highly variable $\delta^{13}C$ values in photosynthate and product tissues. Part of this variation emerges due to the reduction of stomatal conductance in response to water shortage, which results in increased $\delta^{13}C$ (Farquhar et al. 1989). These increases in $\delta^{13}C$ can be an important indicator for past aridity, of interest to archaeologists and other researchers interested in reconstructing past climatic conditions. The present paper reviews the current state of these methods and employs them on the Irish oak chronology (McCormac et al. 1994) to test for the presence of climatic events in that record's $\delta^{13}C$ values. Additional $\delta^{13}C$ values will be drawn from other taxa to illustrate the potential pitfalls of uncritical use of stable carbon isotope data. Farquhar et al. (1982) developed an expression for carbon isotopic fractionation in C_3 plants:

$$\Delta^{13}C = a + (b - a)\, c_i/c_a = (\delta^{13}CO_2 - \delta^{13}C)/(1 + \delta^{13}C/1000) \tag{2}$$

where $\delta^{13}CO_2$ is atmospheric carbon dioxide $\delta^{13}C$, $\delta^{13}C$ represents the isotopic carbon product of photosynthesis, a is change brought by diffusion of $\delta^{13}C$ (4.4‰), b is the effect of Rubisco (25–30‰), and c_i/c_a the ratio between the CO_2 partial pressure in the intercellular leaf space and atmosphere, respectively. The fractionation process is driven in part by changes of the carbon source ($\delta^{13}C_a$) and limitations in water availability. When a plant has sufficient water, carbon is more likely to flow freely through the plant and discrimination is dominated by carboxylation. When water is limited, the water-use efficiency of the plant goes up as stomatal conductance is reduced. This limits the flow of carbon and the plant's discrimination against carbon approaches the fractionation due to stomatal diffusion. The resulting discrimination value ($\Delta^{13}C$) directly expresses the influence of plant photosynthesis alone, whereas raw $\delta^{13}C$ records both source (atmospheric) and plant biological processes. These measures of stable carbon isotope composition are often used interchangeably in the current literature when assessing plant responses to environmental change. Other factors within a plant can influence $\Delta^{13}C$ values, including variation in mesophyll conductance between taxa and over time (Seibt et al. 2008). Eamus et al. (1999) found that the photosynthetic rate and c_i/c_a declined on a diurnal basis in some savanna species, but not in others. In some cases, the relationship between photosynthetic rate and c_i/c_a changed between wet and dry seasons within the same taxa. Moreover, $\Delta^{13}C$ can be highly variable from location to location in its relationship with climate (Leavitt and Long 1988). Interpretations of $\Delta^{13}C$ should include multiple samples and experimental evidence that can demonstrate a relationship between carbon isotope discrimination and water availability.

A further effect worth consideration are fractionation effects that occur during the development of different plant tissues. Typically, photosynthetic tissue tends to be more depleted in $\delta^{13}C$ than heterotrophic (non-photosynthetic) tissue (Cernusak et al. 2009). The effect varies from species to species. Hypothesized causes of this include diurnal, seasonal, and developmental changes in photosynthate production and use (Cernusak et al. 2009). Archaeologists typically use charcoal for ^{14}C dating, which typically comes from heterotrophic tissue such as cellulose; these tissues will likely have a systematically enriched $\delta^{13}C$ relative to the photosynthetic tissue that is more likely to be used in experimental studies. There is no evidence that this change is not systematic; multiple studies on tree-ring cellulose have identified clear correlations with climatic records despite the systematic shift in $\delta^{13}C$ (Leavitt and Long 1988; Dupuoey et al. 1993). Hall et al. (2008) identified substantial variation in $\delta^{13}C$ from different cores of *Podocarpus latifolus* indicating different partitioning of photosynthate within the same tree. Nonetheless, the isotopic values from 1 core had statistically significant relationships with temperature and humidity, while that of the other had statistically significant relationships with rainfall and humidity. If modern, experimental results are compared to archaeological data, the threshold for interpreting drought may not be sufficiently conservative (e.g. high $\delta^{13}C$/low $\Delta^{13}C$ for a leaf may be systematically higher than for non-photosynthetic tissue). Drake et al. (2012) proposed using a constant offset to create a more conservative interpretation of drought conditions for Δ^{13}C to address changes in photosynthate distribution in non-photosynthetic plant tissues such as cellulose.

METHODS

Values of Δ^{13}C were calculated following the approximation provided in Equation 2 from the δ^{13}C values in the Irish Oak chronology obtained on a VG Micromas 602E mass spectrometer, originating from Quercus robur and Q. petraea (McCormac et al. 1994). The record of variation in atmospheric $\delta^{13}CO_2$ was derived from ice-core data from Taylor Dome, European Project for Ice Coring in Antarctica (EPICA) Dome C, and Law Dome in Antarctica. Bayesian change-point analysis was run on the combined $\delta^{13}CO_2$ record using the Barry and Hartigan (1993) algorithm. The model had a burn-in of 10,000 iterations and posterior probabilities were generated from 10,000 Markov chain Monte Carlo simulations. These simulations were run in R (2.15.2) using the bcp (3.0.0) package with hyper-parameter defaults recommended by Erdman and Emerson (2007).

To assess the relationship between Δ^{13}C calculated from the Irish oak chronology and climate, the GISP2 ice-core record was used. All values of δ^{13}C and GISP2 temperature reconstructions that fell within the same 10-yr period were used to create a record for a simple linear model. An 11-point running mean of the Δ^{13}C was employed, following the methods of McCormac et al. (1994). After this treatment, the range of Δ^{13}C values from the Irish oak chronology was compared to the range of Δ^{13}C from a contemporary study on piñon pine (Leavitt and Long 1988) to demonstrate the species-specific requirement for interpreting Δ^{13}C data for a local area.

RESULTS

Atmospheric background values of $\delta^{13}CO_2$ have fluctuated from –7.54‰ to –6.24‰, representing variation of ±1.30‰ since 25,000 cal yr BP. At the end of the Last Glacial Maximum and beginning of deglaciation, a short but significant increase in atmospheric $\delta^{13}CO_2$ can be observed. A steady increase in atmospheric $\delta^{13}CO_2$ took place from 12,000 to 7500 cal BP. Up until the industrial era, no significant variation in atmospheric $\delta^{13}CO_2$ is evident in available records. Modern values are close to –8.1‰ due to anthropogenic carbon emissions whose $\delta^{13}CO_2$ was –29.4‰ between 1981 and 2004 in the continental US (Blasing et al. 2004). Recent variation in atmospheric (source) $\delta^{13}CO_2$ will result in depleted δ^{13}C values in plants.

Variation in Δ^{13}C among *Q. robur* and *Q. petraea* in the Irish oak chronology largely matches long-term changes in Northern Hemisphere temperature reconstructions in the GISP2 ice-core record (Figure 2). These include a portion of the Altithermal (a), the Bronze Age Warm Period (b), the Roman Warm Period (c), and Medieval Warm Period (d), though the latter appears to extend for a longer period in the Irish oak chronology. A simple linear regression demonstrates a highly statistically significant but weak positive correlation coefficient ($r = 0.17$, $p < 0.001$) with a sample size of 355 observations used for both records.

While both the Irish oak chronology (Figure 2) and piñon pine (Leavitt and Long 1988) Δ^{13}C records vary to a degree with climatic records, interpretation of low Δ^{13}C values as being indicative of drought can still be potentially problematic. The range of variation in Δ^{13}C in both records do not overlap (Figure 3). Thus, the lowest recorded value in the Irish oak chronology (McCormac et al. 1994) is still higher than the highest recorded value in the piñon pine chronology (Leavitt and Long 1988). All results reported in this manuscript can be replicated and/or adapted for use with other data sets using the R code provided as online Supplementary material.

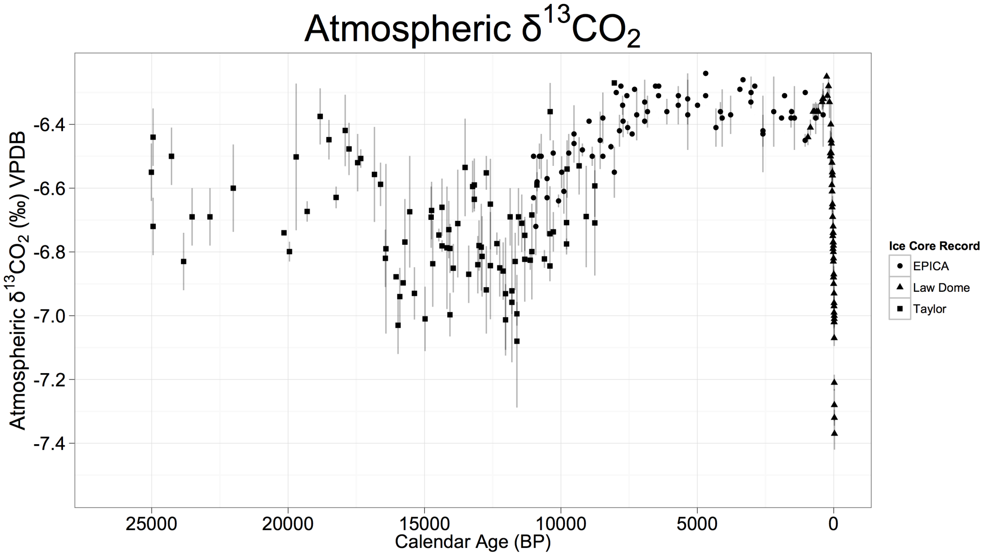

Figure 1 Composite $\delta^{13}CO_2$ record since the Last Glacial Maximum, consisting of records from EPICA Dome C (Elsig et al. 2009; Lourantou et al. 2010), Taylor Dome (Indermühle et al. 1999; Smith et al. 1999), and Law Dome (Francey et al. 1999). Error bars represent measurement error. The rapid depletion at the end of the Holocene (~0 BP) represents the effects of anthropogenic carbon emissions; modern values have surpassed –8‰ (Farquhar et al. 1989).

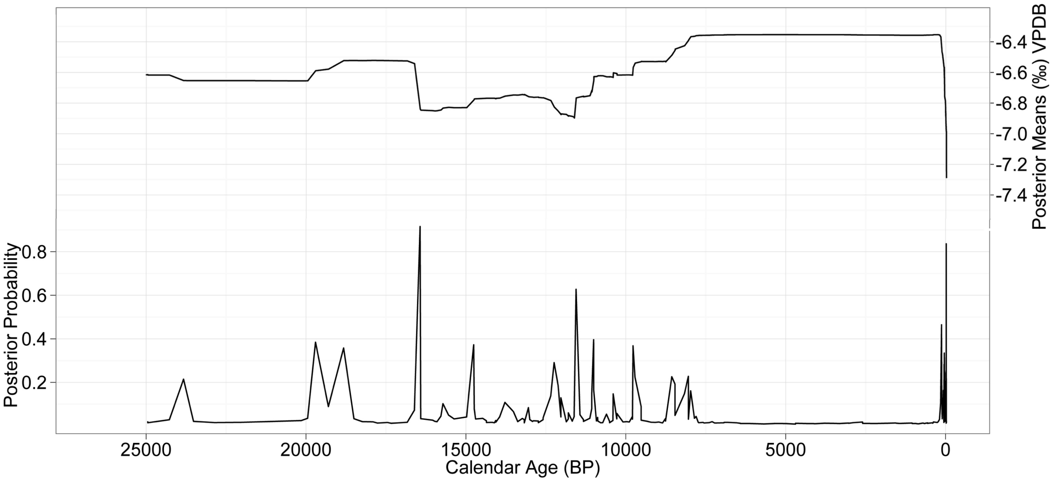

Figure 2 Bayesian change point analysis on the composite atmospheric $\delta^{13}CO_2$ record. High posterior probabilities reflect potential change points in the record, the largest of which occur near 17,000 and 100 cal yr BP (anthropogenic carbon emissions). Pre-industrial values appear to have had little variation in the past 7700 yr based on this analysis.

DISCUSSION

Higher temperatures in Greenland tend to correspond to periods of higher ^{13}C discrimination among *Quercus* trees in Ireland with a weak but statistically significant correlation coefficient ($r = 0.17$, $p < 0.001$). Quantitative analysis of these 2 records is difficult due to the different timescales used in each; a 10-yr interval was used in this analysis, with a standard deviation of 3.77 yr. Secondly, the 2 data sources represent different phenomena. GISP2 represents temperatures in Greenland whereas

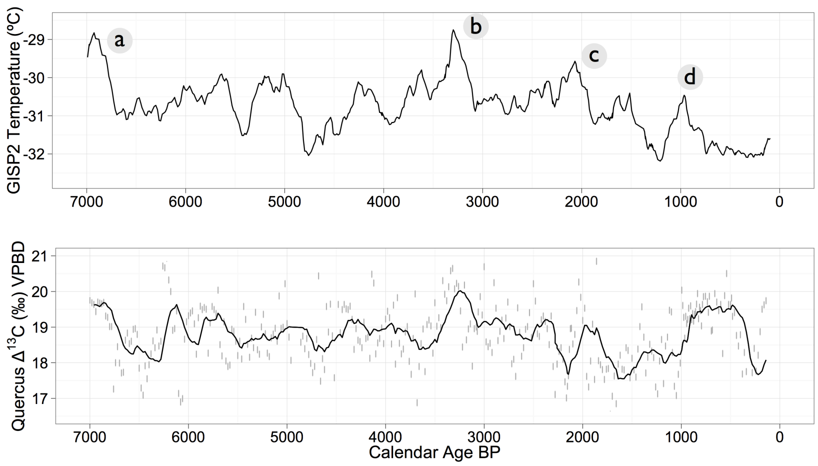

Figure 3 Northern Hemisphere temperature reconstructions from GISP2 (above; Alley 2004) and an 11-point moving average of Δ^{13}C in *Q. robur* and *Q. petreus* (below; McCormac et al. 1994). Periods of higher temperature correspond to periods of increased Δ^{13}C in Irish tree-ring records, including the Altithermal (a), the Bronze Age Warm Period (b), the Roman Warm Period (c), and Medieval Warm Period (d). The 2 records have a weak but statistically significant correlation coefficient ($r = 0.17$, $p < 0.001$).

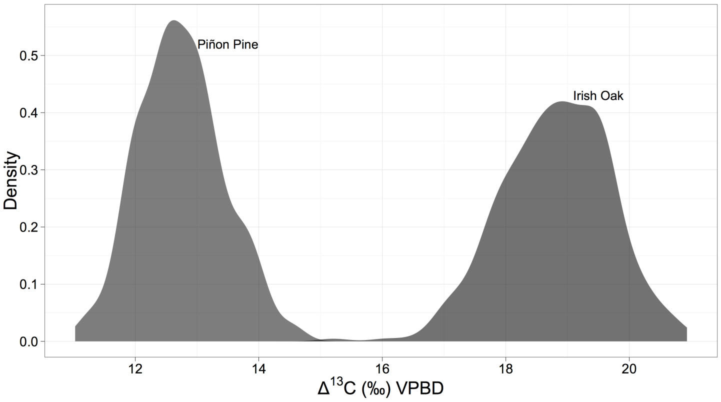

Figure 4 Kernel density plots of piñon pine (Leavitt and Long 1988) and Irish oak (McCormac et al. 1994) Δ^{13}C. Values of Δ^{13}C from the 2 taxa are distinct, underlying why a species-specific approach is critical before interpreting Δ^{13}C values as indicative of paleoclimatic changes.

the Irish oak chronology Δ^{13}C represents variation in stomatal conductance. Thirdly, while GISP2 is a general statement of Northern Hemisphere temperatures, any climatic information in the Irish oak chronology Δ^{13}C is highly specific to the locations sampled. Thus, the GISP2 record explains relatively little variation in Δ^{13}C ($r^2 = 0.03$, $p < 0.001$). The significance of this relationship is likely best interpreted as the climatic influence behind the temperature reconstructions from GISP2 being one of many influences on the hydrological systems that impacted the environment of *Q. robur* and *Q. petraea* in Ireland. Shared features of both records include peaks at 7000 BP, the Late Bronze Age Warm Period at 3300 BP, the Roman Warm Period at 2000 BP, and the Medieval Warm Period at 1000 BP. The Medieval Warm Period, based on global circulation models, may have been relatively wetter for northern Europe (Trouet et al. 2009). While some aspects of the record are similar, there are nonetheless important differences. The Medieval Warm Period begins a little later in the Irish oak Δ^{13}C record, and shows evidence of above-average Δ^{13}C continuing through the 15th century AD. A study by Becker et al. (1991) identified higher δ^{13}C values (corresponding to lower Δ^{13}C in the plant) during the Younger Dryas, 12,800–11,500 cal yr BP. This is consistent with an interpretation of aridity. At most, 0.3‰ of the total 1.5‰ increase in δ^{13}C can be explained be explained by the increase in $\delta^{13}CO_2$ (Figure 1). An important further consideration for δ^{13}C records from oak trees is that they grow in wetter environments, where light can play an increasingly important role in carbon isotope variation.

The interpretation of Δ^{13}C in a combined record of *Q. robur* and *Q. petraea* is complicated by the different patterns of Δ^{13}C in each species. Ponton et al. (2001) found a roughly ~1.0‰ difference in mean Δ^{13}C between *Q. robur* and *Q. patraea*. Despite the difference in mean Δ^{13}C, Δ^{13}C from both species is correlated with intrinsic water-use efficiency (Ponton et al. 2001). For *Q. robur* in particular, the relationship between Δ^{13}C and intrinsic water-use efficiency is genetically controlled (Roussel et al. 2009). This further underlines the importance of using species-specific criteria for using Δ^{13}C as a paleoclimate proxy as the relationship between stable carbon isotope fractionation and climate can be difficult to isolate from interspecific variation.

An extreme case of this relationship can be observed when contrasting Δ^{13}C from the Irish oak chronology with piñon pine Δ^{13}C (Figure 3) gathered from studies by Leavitt and Long (1986, 1988). There is no overlap in Δ^{13}C between the respective distributions of the 2 taxa. Both *Q. robur* and *Q. petraea* have demonstrated relationships between Δ^{13}C and climate, based on both modern (Ponton et al. 2001) and ancient (Becker et al. 1991) samples. Piñon pine Δ^{13}C also has a documented relationship with climate (Leavitt and Long 1988). In both cases, higher values of Δ^{13}C correspond to lower rainfall and relatively arid conditions. However, the minimum Δ^{13}C value from the Irish oak chronology (15.21‰) is almost 0.5‰ higher than the maximum Δ^{13}C value from Leavitt and Long's (1988) piñon pine sample (14.74‰). The strong differentiation in ^{13}C discrimination values between these 2 taxa likely have multiple causes, including different evolutionary adaptations to different environments. In the arid southwest US, water availability is a strong limiting factor while in Europe, more consistent water availability may result in other factors such as light irradiance having a greater role (Farquhar et al. 1989). In the absence of taxonomic information for C_3 plants contributing isotope data, climatic interpretations from Δ^{13}C are in turn subject to uncertainty. In some cases, the specific taxonomic affiliation of a Δ^{13}C value may not be known, which may be frequent in archaeological samples, but the range of taxa found at the site may have been documented. In these cases, as detailed in Drake et al. (2012), the lowest Δ^{13}C value associated with arid conditions from experimental studies could be used as a "threshold" for interpreting aridity once a constant was added to correct for enrichment of δ^{13}C in non-photosynthetic tissues. However, such an approach does not make the most of the data provided by Δ^{13}C, which can ultimately include a detailed analysis of environmental response to changing climate conditions.

The ability to infer climatic change through the use of Δ^{13}C can be an important source of highly local paleoclimatic data in archaeology. The climatic/environmental conditions that surround social development, stability, and collapse can potentially be inferred from this ubiquitous data source. However, greater attention to the limitations of Δ^{13}C, particularly in its species-specific information, is critical for conclusions to be valid.

CONCLUSIONS

Values of $\Delta^{13}C$ from C_3 plants in archaeological or paleoenvironmental contexts have the potential to be a highly useful paleoclimate indicator. In addition, $\Delta^{13}C$ values have key advantages over existing paleoclimate records, including ubiquity of occurrence and easy comparison with modern experimental data. The data have the disadvantage of being highly variable, requiring careful consideration of modern data to provide context to interpretations. As measured $\delta^{13}C$ values are frequently reported in reported ^{14}C assays, they have the potential to be used in paleoclimatic and/or paleoenvironmental studies when the taxa are known.

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