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The use of radiocarbon-derived $\Delta^{13}C$ as a paleoclimate indicator: applications in the Lower Alentejo of Portugal

Brandon L. Drake [a,*], David T. Hanson [b], James L. Boone [a]

[a] Department of Anthropology, University of New Mexico, 1 University of New Mexico, Albuquerque, NM 87131, USA
[b] Department of Biology, University of New Mexico, 1 University of New Mexico, Albuquerque, NM 87131, USA

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ABSTRACT

Values of $\delta^{13}C$ are frequently reported with radiocarbon dates from organic materials. In C_3 plants $\delta^{13}C$ values have been linked to changes in water use efficiency as a response to arid conditions. By calculating ^{13}C discrimination ($\Delta^{13}C$) from ^{13}C isotopic composition ($\delta^{13}C$), archaeologists can gain potentially valuable inference into past climate conditions. Values of $\Delta^{13}C$ reflect the process of discrimination against heavier ^{13}C isotopes of carbon by comparing the $\delta^{13}C$ of samples to that of the atmosphere, and can be calculated when records of atmospheric $\delta^{13}CO_2$ are available. The present study examines a 1300 year history of radiocarbon-derived $\Delta^{13}C$ from the Lower Alentejo of Portugal using charcoal recovered from excavations of a series of medieval habitation sites in the study area. To calculate $\Delta^{13}C$, the posterior means generated from Bayesian change-point analysis of $\delta^{13}CO_2$ records were used. Archaeological data were then compared to contemporary ecological studies of $\Delta^{13}C$ of the same taxa against instrumental records of climate. Values of $\Delta^{13}C$ fell within mean ranges for the taxa through a period of population growth between the 7th and 10th centuries AD. During the height of the Medieval Warm Period in the 11th century AD $\Delta^{13}C$ values frequently fell to low levels associated with arid conditions. At this time environmental degradation and erosion were documented. Values of $\Delta^{13}C$ increased for a brief period in the early 12th century AD before the rural Lower Alentejo was largely abandoned for nearly two centuries. Another period of aridity occurred in the 16th and 17th centuries AD. Radiocarbon-derived $\Delta^{13}C$ is a potentially useful paleoclimate proxy for archaeologists provided that results can be paired with observed $\Delta^{13}C$ variation in studies that pair these data with instrumental climate records.

1. Introduction

Climate has played a pivotal role in shaping human societies; increasing social complexity is dependent upon agriculture which is in turn dependent upon variation in climate. Yet determining the influence of local climate patterns at the site level is difficult in many areas. Stable carbon isotope ratios from botanical material can serve as a paleoclimate record that in turn can expand archaeologists' ability to detect significant changes in local environmental conditions. By using $\delta^{13}C$ values, which are regularly reported with radiocarbon dates (Stuiver and Polach, 1977), archaeologists can build on current methods to reconstruct paleoclimatic conditions in sites where other methods are not available. The variation in ^{13}C discrimination ($\Delta^{13}C$) among and within species likely makes direct climate reconstruction using $\delta^{13}C$ values unrealistic. However, extended periods of extreme weather that are likely to impact human migration or range expansion should be detectable given appropriate sampling.

Variation in $\delta^{13}C$ values in plant tissues is caused by preference for $^{12}CO_2$ over $^{13}CO_2$. Under normal conditions, the process of photosynthesis in plants consumes CO_2 from the atmosphere and releases O_2, incorporating carbon into the plant while using light to provide the necessary chemical energy. The majority of the discrimination effect against heavier carbon isotopes in C_3 grasses occurs during carboxylation when Ribulose-1,5-biphosphate carboxylase oxygenase (RuBisCo) fixes the carbon atoms in the first step of the Calvin cycle (Calvin, 1956; Farquhar et al., 1982, 1989). However, changes in the diffusive resistance for CO_2 between the atmosphere and the chloroplast also affect the isotopic composition of plant material (Farquhar et al., 1982). Resistance to CO_2 diffusion increases as stomatal pores close in response to dry conditions, among other factors (Farquhar et al., 1989), and also due to changes in the expression of protein channels in the chloroplast inner membrane that facilitate CO_2 diffusion (Uehlin et al., 2008). Higher resistance causes greater diffusional discrimination, but also reduces the chance that CO_2 will escape fixation by the enzyme

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[*] Corresponding author. Tel.: +1 505 510 1518.
E-mail address: thalesian@gmail.com (B.L. Drake).

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RuBisCo and diffuse back out of the leaf and into the atmosphere and this reduces the ability of RuBisCo to discriminate against $^{13}CO_2$. Since discrimination by RuBisCo is roughly an order of magnitude larger than the diffusional discrimination, the net effect of dry conditions is a decrease in discrimination that makes sugars produced by photosynthesis more enriched in ^{13}C (Farquhar et al., 1982, 1989). These sugars are then distributed throughout the entire plant for growth. For example, tree rings formed during years of drought will be more enriched in ^{13}C relative to rings formed in wet years as will all other tissues. For this reason, the stable carbon isotope ratios of botanical remains in the archaeological record have the potential to record periods of drier and wetter conditions (McCarrol and Loader, 2004). Over the past three decades, studies of the stable carbon isotope ratio in trees, referred to as isotope dendroclimatology, have consistently shown relationships between stable carbon isotope ratios and precipitation and temperature patterns (Robertson et al., 2010). Just as tree ring widths vary in response to precipitation, so too does the stable carbon isotope ratio in the same rings. Drier conditions result in more enriched ^{13}C and pluvial conditions result in more depleted ^{13}C in plant tissues. Unlike traditional dendroclimatology, isotopic dendroclimatology can be extended to infer paleoclimate from archaeological charcoal samples. The data is already regularly gathered as part of radiocarbon dating, and a large body of literature is growing to allow for species-specific interpretations of stable carbon isotope ratios.

Changes in the ratio of ^{13}C and ^{12}C in plants have been shown to have significant relationships with the Palmer Drought Severity Index (Leavitt and Long, 1986, 1988), water use efficiency (Beerling and Woodward, 1995), seasonal variation in precipitation (Hemming et al., 2005), mean annual precipitation in biomes (Diefendorf et al., 2010) and soil moisture content (Dupuoey et al., 1993). The consistency of the effects of water use efficiency and carbon isotope discrimination in plants have led to the proposal that stable carbon isotope ratios can be used as a paleoclimate reconstruction method (February and Van der Merwe, 1992; Winkler, 1994; Vernet et al., 1996; February, 2000; Hall et al., 2008; Aguilera et al., 2009). However, other factors such as variable resistance inside the leaf and leaf shape can affect the stable isotope concentration of plants in ways that are poorly understood, leaving direct attribution of changes in stable carbon isotopes to climate problematic (Seibt et al., 2008). Most plants utilize a photosynthetic pathway termed C_3 (the first stable product is made of 3 carbons), but C_4 plants have a supplemental temporary CO_2 fixation pathway where CO_2 is initially fixed from the atmosphere into a 4 carbon compound and then released right next to RuBisCo for final fixation via the Calvin cycle. These plants effectively have very high levels of CO_2 inside their leaves and allowing them to reduce water loss by closing stomata more than C_3 plants. As a result C_4 plants are less affected by factors such as drought. C_4 plants are also better at consistently limiting CO_2 escape from leaves, which means much more ^{13}C is fixed into sugars (lower discrimination) and with less variation and thus provide a more reliable estimate of atmospheric $\delta^{13}C$. This relationship has been used in the past to model atmospheric $\delta^{13}CO_2$ values (Marino and McElroy, 1991; Marino et al., 1992), in particular documenting the changing ratio of ^{13}C to ^{12}C associated with anthropogenic carbon emissions. Nonetheless there are few studies of stable carbon isotope ratios in archaeological charcoal. Stable carbon isotope ratios have the potential to play a valuable role in paleoclimate reconstruction, but little research has been done to illustrate the strengths and weaknesses of the method to date.

Paleoclimate reconstruction remains difficult at most archaeological sites. Dendroclimatology is the most accurate and precise paleoclimate reconstruction available to archaeologists, but full tree ring sequences are rare in excavations. For either dendrochronological or dendroclimatological analysis to be possible, trees need preserved cutting dates in order to properly place them in a known sequence (Towner, 2002; Nash, 2002). Often dendroclimatological sequences are generated by standardizing and averaging multiple trees to describe paleoclimate in a given region (Fritts, 1971), but vast areas of the globe do not have enough (or any) tree ring chronologies to allow for historical climate records that overlap with archaeological records. Many regions have only floating tree ring sequences, as in the Asian steppes (Panyushkina et al., 2010, 2008). The most extensive North African dendroclimatological sequence only goes back to A.D. 1179 (Touchan et al., 2011). A more widespread source of climate data comes from palynology, where either pollen or phytolith counts can show taxa change over time (Bartlein et al., 1998; Huntley, 1990). However the kind of landscape changes in vegetation that would show an unambiguous signal in pollen or phytolith counts can often be beyond the scope of the smaller climate events that affect human populations (Davis and Botkin, 1985). For most archaeological sites, local paleoclimate reconstruction is beyond reach using these methods.

Stable carbon isotopes have potential to help fill this gap. Macrobotanicals are frequently found as ecofacts and archaeologists already regularly receive $\delta^{13}C$ data with radiocarbon dates (Stuiver and Polach, 1977). Recent articles have begun to look at stable carbon isotopes in the soil as an indicator for broad changes in C_3 and C_4 vegetation (Leavitt et al., 2007a). These have included identifying changes in vegetation associated with the Younger Dryas (Bement and Carter, 2010) and the cultivation of maize, a C_4 plant, in Mesoamerica (Webb et al., 2007). A promising recent archaeological study used stable carbon isotope ratios to identify changes in wheat in Greek sites (Heaton et al., 2009). Reconstructed $\Delta^{13}C$ from barley plants in Anatolia suggested increases in water use efficiency at 2200 and 3100 BC (Riehl, 2008); consistent with known arid periods for the region (Cullen et al., 2000). However variation in $\Delta^{13}C$ of C_3 plants is still rarely applied in reconstructing paleoclimate in archaeology despite the ubiquity of the data.

A key obstacle is the lack of a generalizable approach to the utilization of $\Delta^{13}C$ for paleoclimate reconstruction. In the present study, we recommend pairing $\Delta^{13}C$ approximated from radiocarbon assayed-charcoal with contemporary ecological studies of observed $\Delta^{13}C$-climate variation in related taxa. This approach can establish a threshold for interpreting aridity in the past. The present study uses stable carbon isotope data from the Lower Alentejo to present a test case of paleoclimate reconstruction. This study area is ideal as the time of occupation overlaps with a significant change in climate conditions during the Medieval Warm Period. The study uses isotope data from three genera of plants, including rockrose brushes (*Cistus*), oak trees (*Quercus*) and olive trees (*Olea*). The Mediterranean region lacks dendroclimatological data during most of the Medieval Warm Period. Stable carbon isotope data from Lower Alentejo offer a new approach that may offer new insight into the climate conditions of the period.

2. Study area

2.1. Environmental background

The climate pattern in the study area (Fig. 1) is meso-Mediterranean, with hot, dry summers and wet winters with infrequent freezing temperatures. Rainfall averages 550 mm, most of which falls between October and April based on figures for Beja from 1931 to 1960 (Amorim Ferreira, 1970: 118). The maximum difference in relief within the survey area is about 100 m, although most of the land lies between 150 m and 200 m in elevation. Within