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Complex agriculture during the second millennium BC: isotope composition of carbon studies ($\delta^{13}\text{C}$) in archaeological plants of the settlement Cerro del Castillo de Alange (SW Iberian Peninsula, Spain)

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Abstract The isotope composition of fruits and seeds of *Hordeum vulgare* L. (barley), *Triticum aestivum/durum* (wheat) and *Vicia faba* var. *minor* (faba bean) from three chronological phases between 2200 and 1321 cal BC of the settlement Cerro del Castillo de Alange (SW Iberian Peninsula) have been studied. The $\delta^{13}\text{C}$ values for cereals were between -24.40 and -20.39‰ (V-PDB), with a mean of -22.01‰ , the discrimination (Δ) being 15.96‰ . The legumes registered similar values, between -26.25 and -20.49‰ (mean = -22.59‰), with a differential for the period of 16.51‰ . In both cases, a change was noted from the first phase, where water availability is clearly a limiting factor for plant development. In subsequent phases the growing conditions appear to be wetter. By comparison, we measured samples of *Quercus ilex-coccifera* (oak) charcoal, which shows similar values throughout the series. This suggests that there was no significant climate shift to moister conditions that could explain the above results, but rather they were the consequence of a change in crop management.

In addition, we measured samples of a current rainfed *Triticum* sp. (year 2014), which averaged $\Delta^{13}\text{C}$ 15.56‰ . The changes between the three phases could indicate the development of mixed models of exploitation that combine strategies based on the use of rainfed and potentially irrigated areas during the 2nd millennium BC. The implementation of such a cropping technique, taking advantage of the river banks, could be a response to the processes of climatic degradation that begin in the Middle Holocene. The situation of the Cerro del Castillo reservoir between the rivers of the Guadiana and Matagorda rivers is consistent with the development of this type of practice indicated by the isotopic and archaeobotanical data.

Keywords Agriculture · Archaeobotany · Bronze Age · Stable isotopes · $\delta^{13}\text{C}$ · Irrigation

Introduction

Human societies affect the natural environment, transforming it beyond the limits of nature through the development of technological innovations and changes in environmental exploitation. The literature has emphasized the relationships between changes in climate, technical developments, and expansion of agriculture (Woodbury 1961; Richerson et al. 2001; Munro 2003; Gupta 2004; Weninger et al. 2006; Turney and Brown 2007; Berger and Guilaine 2009). The development of irrigation methods is one example of how human societies intervene in a changing environment to ensure crops in an environment, which is more arid or has irregular rainfall. In this way, the impact of irrigation, the use of more suitable land for cultivation, and the division of space for a differential use of resources are issues that in the Mediterranean basin have received

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special interest in archaeological research (Wittfogel 1957; Adams 1974; Jacobsen 1982; Hunt 1988; Chapman 1990; Price 1994; Purdue and Berger 2015). This interest, especially regarding the development of irrigation, arises for two reasons: first, because the first states developed in environments characterized today by arid or semi-arid climates and, second, because the complexity inherent in organizing irrigation systems helps explain the origin of social hierarchy (Wittfogel 1957; Gilman and Thornes 1985; Chapman 1990).

However, a link between social complexity and the development of irrigation should not be mechanically established. Irrigation as a technique is no more than a manner of controlling nature that does not differ essentially from agriculture as a way of life and relationship with the environment. This, as a substantial change in the relationship between human societies and the environment, evolved with social, political, economic, and cultural transformations (Cohen 1977; Hubbard 1980; Jarman et al. 1982; Rindos 1984; Gebauer and Price 1992; Smith 1994; Price 1995; Harris 1996). On the other hand, irrigation does not involve a substantial change either in the relations of production or in the conception of nature, being a result of the development of agriculture. Irrigation is not only a means of adaptation to the environment, but is a mechanism to encourage crop survival, to increase the amount of food, and to reach a surplus. Although it may appear in a context of adaptation to a changing environment, it can also be developed in a complementary way to rainfed agriculture.

The use of irrigation systems is known from the Prehistory of the Mediterranean. To verify this, different indicators of the archaeological record have been used: hydraulic structures (Shüle 1967; Helms 1981; Bienert and Hässer 2004; Kuijt et al. 2007), phytolith aspects (Rosen and Weiner 1994; Jenkins et al. 2011, 2016), characteristics of plant remains (Helbaek 1960; Jones et al. 1995; Jones 2005) or the study of the isotope composition of carbon ($\delta^{13}\text{C}$) (Araus and Buxó 1993; Araus et al. 1997, 2014; Ferrío Díaz et al. 2005; Wallace et al. 2013; Riehl et al. 2014; Mora-González et al. 2016). Studies have correlated isotopic composition of carbon (ratio between ^{13}C : ^{12}C) and water conditions of plants in their development (Farquhar et al. 1982, 1988, 1989; Farquhar and Richards 1984; Diefendorf et al. 2010; Kohn 2010). During photosynthesis, two fractionation processes occur in the plants of the C3 cycle: one is due to the diffusion of CO_2 through the stomatal ducts, and another to the activity of RuBisCO. The first one is a variable parameter, used by the plant to defend itself against water loss by transpiration. That is, under stress, plants close their stomata, decreasing the amount of CO_2 in the intercellular space and thus $\delta^{13}\text{C}$ values increase. Water conditions correlate with the isotope composition, this being determined by factors such as the $\delta^{13}\text{C}$ from the atmosphere and the concentration

of atmospheric CO_2 (Farquhar et al. 1982, 1989; Farquhar and Lloyd 1993; Cernusak et al. 2013).

These types of studies have been applied to the NE, E and SE of the Iberian Peninsula (Araus et al. 1997; Ferrío Díaz et al. 2005; Aguilera et al. 2008; Mora-González et al. 2016). However, agricultural practices and irrigation development have attracted less attention in areas having higher precipitation and where rainfed agriculture is presumed to be sufficient, as is the case of Northern and Central Europe (Bogaard et al. 2013). This could also be true of the SW Iberian Peninsula, where research is needed on this subject. In this context, charcoal (Grau Almero et al. 1998; Duque Espino 2004) and pollen (Hernández Carretero et al. 2003) has been studied in the middle basin of the Guadiana river, revealing three anthracological phases related to environmental shifts from 7,500 to 2,000 BP due to climate change and anthropic pressure (Duque Espino 2004). Anthracological Phase I, roughly between 7,500 and 4,500 BP (5500–2500 BC), correlates with a wetter environment and lower temperatures, related to the Atlantic Phase of the Holocene of the SW Iberian Peninsula (Duque Espino 2004). Around 4,500 BP (Anthracological Phase II) the tree cover sharply declined, with a predominance of evergreen *Quercus*, a prevalence of thermophilic taxa such as *Olea europaea*, and a reduced amount of riparian woodland species. Regionally, this has been related to the sub-boreal phase of the Holocene of the SW, characterized by a drier climate and higher temperatures, which in turn matches the data for the SE Iberia Peninsula and the Mediterranean basin (Jalut et al. 2000, 2009; Pérez-Obiol et al. 2011). Also, open spaces developed in relation to intensified agriculture and grazing (Duque Espino 2004). Finally, Anthracological Phase III (2,800–2,000 BP, 800–1 BC) had a wetter climate, reflected in recession of *Olea europaea* and an expansion in riparian woodland species, especially in environmentally demanding species such as the walnut. This has been related to the Holocene Sub-Atlantic Phase in the SW, where the changes recorded prove consistent with the anthracological record. This dates to around the 5th century BC, when rainfall appears to have increased (Duque Espino 2004).

Accompanying this natural process human influence gradually grew in relation to the development of cultivation and livestock, activities that later intensified in the Roman era (Castaños Ugarte 1998a; Grau Almero et al. 1998). In this context, there was a tendency towards a greater pressure on cultivation. This implies taking advantage of fluvial soils in the plains of the Guadiana and Matachel rivers. In the Cerro del Castillo de Alange settlement, this process would be dominated by species such as *Triticum aestivum / durum* and legumes, with the possibility of even developing irrigation systems (Grau Almero et al. 1998). In turn, this would result in more vigorous clearing of the climax forest, to establish more abundant pastures for the livestock (Grau

Almero et al. 1998; Duque Espino 2004; Pavón Soldevila and Duque Espino 2014).

The goal of this study is to verify whether the seed remains found at the site were originally cultivated under irrigation. For this, we use the isotope composition of the carbon ($\delta^{13}\text{C}$) from remains of *Triticum aestivum* / *durum* (wheat) (Mora-González et al. 2015), *Hordeum vulgare* L. (barley), *Vicia faba* var. *minor* (faba bean) and *Quercus ilex-coccifera* (oak) at the second millennium BC settlement of the Cerro del Castillo de Alange (SW Iberian Peninsula).

Archaeological and geographical background

The settlement Cerro del Castillo de Alange is located between the high and low *vega* (cultivated plains) of the Guadiana River. Overall, the environment has a flattish profile with a gradual slope, giving rise to two well-differentiated areas: one above 400 m a.s.l., where the Sierra de Peñas Blancas (655 m a.s.l.) is located; and the other at 485 m a.s.l., the site of Castillo de Alange (485 m a.s.l.), with gentle slopes and small open rivers used for cultivation.

Geologically, the territory is composed of basic sediments, with Miocene and carboniferous limestones and calcareous Miocene sediments, in contrast to a general lithology of more acidic soils, in a granite environment. The settlement is located in a contact zone between three metamorphic areas: Tierra de Barros, with loamy-clayey soils, suitable for rainfed agriculture; Guadiana, with loamy soils, well suited to cultivation with irrigation; and the Emeritense Granite Group, with loamy sandy soils, suitable for pastures (Pavón Soldevila 1998).

The area is located in the mesomediterranean bioclimatic belt, where annual temperatures range between 13 and 17 °C, with a minimum of between −1 and −4 °C, and a maximum between 9 and 14 °C. Frost can occur between the months of October and April, with a rainfall typical of an ombroclimate, with average annual precipitation between 350 and 600 mm (Grau Almero et al. 1998). During the year 2014 the rainfall was 452 mm in the weather stations closest to the sampling points (Alange 5 km), with 45.6 mm in April and 14.1 mm in May (the data provided by Agencia Estatal de Meteorología, Ministerio de Agricultura, Alimentación y Medio Ambiente, Spanish Government, <http://www.aemet.es/es/portada>).

The settlement lies in the Marian-Manchique biogeographic sector, in the subsector of Tierra de Barros. The vegetation is characterized by *Quercus ilex* ssp. *rotundifolia*, being close to the silica subsector of the Serena-Pedroches (Rivas Martínez 1987; Grau Almero et al. 1998).

Archaeologically, the settlement has three well-differentiated levels of occupation, defined from the excavations in different areas of the site: Section 5 of Solana and in

Sections 2 and 3 of Umbria: the epi-Chalcolithic Horizon, the Middle Bronze Horizon, and the Late Bronze Horizon I (Pavón Soldevila 1998; Pavón Soldevila and Duque Espino 2014).

The epi-Chalcolithic Horizon corresponds to the Solana Phase I and the transition between Solana Phase I and II, towards the Middle Bronze Age. The Middle Bronze Horizon is defined by the Solana Phases IIA and IIB. The latter corresponds to the Umbria Phases IA and IB, coinciding with the so-called Bronze Age of the Southwest II. Finally, the Late-End Bronze I Horizon is characterized by the Umbria Phase II (Pavón Soldevila 1998; Pavón Soldevila and Duque Espino 2014).

The archaeobotanical studies show a palaeolandscape with a flora that can be divided into three groups: forest species, riparian woodland species, and wild species related to meadows and crops (Grau Almero et al. 1998). This flora reflects the presence of an oak woodland, already degraded, that has been replaced by scrub from the epi-Chalcolithic onwards. This process appears to be a consequence of increased grazing, which would favour the formation of *dehesa*-type pastures (Grau Almero et al. 1998).

In terms of agricultural production, cereals predominate, with some legumes. Naked wheat predominates over naked and hulled barley in a proportion of 62 to 38% in the epi-Chalcolithic levels. Chronologically, wheat continues to appear, with a remarkable finding of a structure containing large quantities of clean and stored wheat, identified as a barn and dating to 1650 cal BC (Pavón Soldevila et al. 2010; Pavón Soldevila and Duque Espino 2014). Wheat is the only cereal preserved in the Late Bronze Age levels (Grau Almero et al. 1998). The plough, although no direct evidence of its use has been found, could have facilitated extensive cereal agriculture to complement crops that thrive on the wetter land nearby, where irrigation systems could even have been implemented (Grau Almero et al. 1998).

Materials and methods

The material used in this study ($n=202$) was recovered from levels III, V, VI and VII of Trench 5 at la Solana (Solana I and Solana I–II phases, 2200–2000 BC, without ^{14}C dates); levels II (Umbría II phase, 1381–1321 cal BC, Beta-68667—3,080 \pm 90 BP), III, IV and IVb (Umbría IB phase, 1875–1785 cal BC, Beta-68668—3,520 \pm 70 BP), and V and VI (Umbría IA phase, 1936 cal BC, Beta-68669—3,600 \pm 80 BP) of Trench 3 at la Umbría (Pavón Soldevila 1995; Pavón Soldevila and Duque Espino 2014); and from Trench 9, where a structure has been identified as a granary that was abandoned around 1650 cal BC (Beta-228897—3,360 \pm 50 BP) (Pavón Soldevila et al. 2010) (Table 1). In addition, *Triticum* sp. cultivated in the year 2014 was sampled from two

Table 1 Mean values for the archaeological samples analysed in this study

Species (n)	Chronology (BC)	$\delta^{13}\text{C}_{\text{‰}}$ (SD) [range]	$\Delta^{13}\text{C}$ (SD) [range]	WUE (SD) [range]	CO_2 ($\delta^{13}\text{C}_{\text{atm}} \text{‰}$)
<i>Triticum aestivum/durum</i> (25)	2200–2000	−21.58 (0.43) [−23.02 to −20.84]	15.57 (0.44) [14.79–17.06]	88 (3) [76–94]	−6.35
<i>Hordeum vulgare</i> L. (24)	2200–2000	−21.35 (0.27) [−21.89 to −20.60]	15.33 (0.28) [14.55–15.89]	90 (2) [85–96]	−6.35
<i>Triticum aestivum/durum</i> (25)	1650 (cal)	−22.93 (0.96) [−24.40 to −20.53]	16.88 (0.99) [14.40–18.42]	78 (8) [66–97]	−6.43
<i>Triticum aestivum/durum</i> (25)	1381–1321 (cal)	−22.15 (1.11) [−24.06 to −20.39]	16.02 (1.16) [14.20–18.02]	84 (9) [69–98]	−6.48
<i>Vicia faba</i> var. <i>minor</i> (6)	2200–2000	−21.36 (0.54) [−22.17 to −20.70]	15.34 (0.56) [14.65–16.18]	90 (4) [83–95]	−6.35
<i>Vicia faba</i> var. <i>minor</i> (25)	1381–1321 (cal)	−22.89 (1.66) [−26.25 to −20.49]	16.80 (1.73) [14.30–20.30]	78 (13) [51–98]	−6.48
<i>Quercus ilex-coccifera</i> (20)	2200–2000	−24.54 (0.58) [−25.72 to −23.49]	18.65 (0.60) [17.55–19.88]	64 (5) [55–73]	−6.35
<i>Quercus ilex-coccifera</i> (20)	1936 (cal)	−25.14 (1.15) [−27.18 to −23.17]	19.24 (1.21) [17.19–21.38]	60 (9) [43–75]	−6.38
<i>Quercus ilex-coccifera</i> (17)	1875–1785 (cal)	−24.67 (0.70) [−26.21 to −23.73]	18.73 (0.73) [17.75–20.34]	64 (6) [51–71]	−6.40
<i>Quercus ilex-coccifera</i> (15)	1381–1321 (cal)	−25.32 (0.59) [−26.01 to −24.04]	19.33 (0.62) [17.99–20.05]	59 (5) [53–69]	−6.48

According to the species (with number of samples), chronology, carbon isotope composition value ($\delta^{13}\text{C}$), carbon isotope discrimination ($\Delta^{13}\text{C}$), WUEi (intrinsic water-use efficiency) and isotopic composition of CO_2 ; for all samples, the CO_2 concentration (ppm) was 278

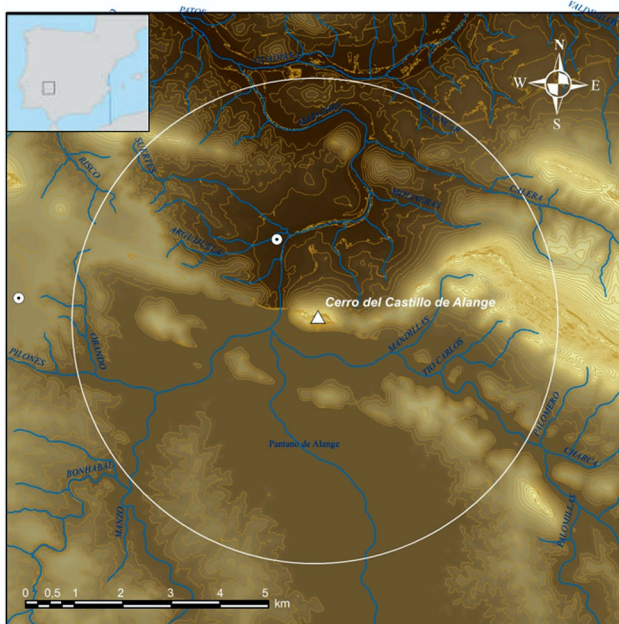


Fig. 1 Map with the location of the settlement Cerro del Castillo de Alange (triangle) and of the sampling of current plants (circles); the circular area delineates an extension of 5 km around the settlement

rained plots (N = 30) located less than 10 km from the settlement (Fig. 1). These plots are in an area characterized by soils with a sandy-clayey matrix and quartzite pebbles,

situated a few 100 m before the clayey Tertiary soils, and which show no major problems of water retention.

All the archaeological samples were in a carbonized state. Different studies have shown that the isotopic carbon signal is not affected by fire in the case of cereal and legume seeds (Marino and DeNiro 1987; Araus et al. 1997; Caracuta et al. 2015; Nitsch et al. 2015). In the case of charcoal remains, it has been pointed out that there may be biases for some species such as pine (Ferrio Díaz et al. 2006) or even for the oak (Turney et al. 2006). However, a more recent study in the eastern Iberian Peninsula has indicated that for this latter species the anthracological remains would not be significantly affected (Aguilera et al. 2009, 2011). Consequently, it is not necessary in the case of the present study to introduce correction factors for the results found.

The modern samples were dried at 65 °C for 48 h and then homogenized with a tungsten ball mill. The archaeological samples, after being homogenized, were treated with 37% hydrochloric acid (HCl) vapours for 12–14 h to dissolve any carbonates that could distort the results (Hedges and Stern 1984).

Although we have analysed a set of seeds for each of the contexts, each of the seeds was analysed individually twice, and were found to weigh an average of 0.5 mg.

Isotope measurements were made at the Stable Isotope Laboratory of the Andalusian Institute of Earth Sciences (CSIC-University of Granada, Granada). Samples were analysed for the carbon isotope composition by means of

a Carlo Elba NA1500 (Milan, Italy) elemental analyser in-line with a Delta Plus XL (Thermoquest, Bremen, Germany) mass spectrometer (EA-IRMS). The stable composition is reported as δ values per thousand:

$$\delta = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1,000$$

where $R = {}^{13}\text{C}/{}^{12}\text{C}$ for $\delta^{13}\text{C}$.

For this study, two internal standards of -30.63 and -11.65% (V-PDB), respectively, were used. Calculated precision, after correction of the mass spectrometer daily drift, with the systematic interspersing of standards in each analytical batch, was better than $\pm 0.1\%$ for $\delta^{13}\text{C}$. The standard for reporting carbon measurements is V-PDB (Vienna-PDB).

To compare current and preindustrial conditions (Keeling et al. 1979; Tans and Mook 1980; McCarroll and Loader 2004), we calculated values of the carbon isotope discrimination ($\Delta^{13}\text{C}$) using the following equation (Farquhar et al. 1982; Farquhar and Richards 1984):

$$\Delta^{13}\text{C} = \frac{(\delta^{13}\text{C}_{\text{atm}} - \delta^{13}\text{C}_{\text{sample}})}{(1 + \delta^{13}\text{C}_{\text{sample}}/1,000)}$$

where $\delta^{13}\text{C}_{\text{atm}}$ is the carbon isotope composition of atmospheric CO_2 and $\delta^{13}\text{C}_{\text{sample}}$ is the carbon isotope composition of sample. For the archaeological period, $\delta^{13}\text{C}_{\text{atm}}$ was determined from AIRCO2_LOESS system (http://web.udl.es/usuarios/x3845331/AIRCO2_LOESS.xls) (Leuenberger et al. 1992; Indermuhle et al. 1999; Ferrio Díaz et al. 2005).

Higher CO_2 concentrations are ultimately beneficial for the plant, allowing similar stomatal conductance, more carbon fixation, and greater carbon isotope fractionation (more negative values in the $\delta^{13}\text{C}$ tissue) under the same water conditions. At the same time, the increase in CO_2 is associated with higher ambient temperatures, which encourage stomatal closure. Therefore, some increasingly negative atmospheric values and a higher concentration of CO_2 results in a trend towards more negative values in plant $\delta^{13}\text{C}$. The second trend has the opposite effect, since stomatal closure due to drought and rising temperatures promotes less negative

values. To take into account changes in CO_2 concentrations, we calculated the intrinsic water-use efficiency (WUEi) (Farquhar et al. 1982, 1989):

$$WUEi = \frac{A}{g_w} = \frac{C_a (b - \Delta^{13}\text{C})}{1.6 (b-a)}$$

where A is the net carbon assimilation, g_w is the stomatal conductance to water vapour, a is the fractionation during CO_2 diffusion through the stomata (4.4%), b is the fractionation associated with reactions by RuBisCO enzyme (27%), $\Delta^{13}\text{C}$ is the isotope composition of carbon, and C_a is the atmospheric CO_2 concentration (≈ 278 ppm in the past vs. ≈ 397 ppm at present; Dlugokencky and Tans, NOAA/ESRL, <http://www.esrl.noaa.gov/gmd/ccgg/trends/>).

Results

The results (mean values) of the analyses of carbon isotope composition ($\delta^{13}\text{C}$), carbon isotope discrimination ($\Delta^{13}\text{C}$) and water-use efficiency (WUEi, $\mu\text{mol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$) for the archaeological samples from the Cerro del Castillo de Alange settlement and modern samples are shown in Tables 1 and 2 and Fig. 2 ($\delta^{13}\text{C}$), Figs. 3 and 5 ($\Delta^{13}\text{C}$) and Fig. 4 (WUEi). For measurements in modern *Triticum* specimens see ESM.

Discussion

The values found for the cereal samples studied in the archaeological settlement of Cerro del Castillo de Alange indicate a trend from a higher WUEi at the end of the third millennium BC (89) to moister conditions in the middle and late second millennium BC (78 and 84). This is also confirmed in the case of legumes (90 vs. 78). The maintenance and even improvement of the water conditions of the cereals could be due to an improved climatic situation, to changes

Table 2 Mean values for the samples analysed in this study (archaeological and modern—according to the field identification): carbon isotope composition value ($\delta^{13}\text{C}$), carbon isotope discrimination

Samples (n)	$\delta^{13}\text{C}\%$ (SD) [range]	$\Delta^{13}\text{C}$ (SD) [range]	WUEi (SD) [range]
Cereals (99)	-22.01 (0.98) [-24.40 to -20.39]	15.96 (1.00) [14.20 – 18.42]	85 (8) [66 – 98]
<i>Vicia faba</i> var. <i>minor</i> (31)	-22.59 (1.62) [-26.25 to -20.49]	16.51 (1.67) [14.30 – 20.30]	81 (13) [51 – 98]
<i>Quercus ilex-coccifera</i> (72)	-24.90 (0.85) [-27.18 to -23.17]	18.97 (0.88) [17.19 – 21.38]	62 (7) [43 – 75]
<i>Triticum</i> sp. (2014, field 1) (15)	-24.21 (0.50) [-24.86 to -23.16]	15.99 (0.52) [14.91 – 16.67]	121 (6) [113 – 133]
<i>Triticum</i> sp. (2014, field 2) (15)	-23.37 (0.56) [-24.41 to -22.52]	15.12 (0.59) [14.24 – 16.21]	130 (6) [119 – 140]
Total <i>Triticum</i> sp. (2014) (30)	-23.79 (0.68) [-24.86 to -22.52]	15.56 (0.70) [14.24 – 16.67]	126 (8) [113 – 140]

($\Delta^{13}\text{C}$), WUEi (intrinsic water-use efficiency); CO_2 concentration (ppm) was 298 (archaeological) and 397 (modern), the isotopic composition of CO_2 ($\delta^{13}\text{C}_{\text{atm}}\%$) was -8.6

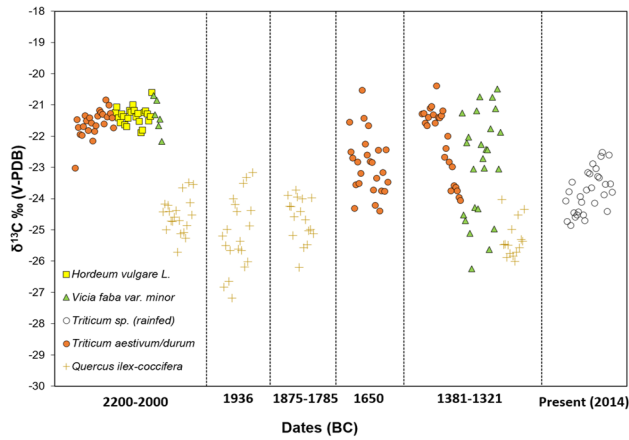


Fig. 2 Scatterplot of the carbon isotope composition ($\delta^{13}\text{C}$) in the samples analysed: the yellow squares represent the *Hordeum vulgare* L. samples, the green triangles *Vicia faba* var. *minor*, the red circles *Triticum aestivum/durum*, the orange cross *Quercus ilex-coccifera*, and the empty squares the samples of present-day cereals (year 2014)

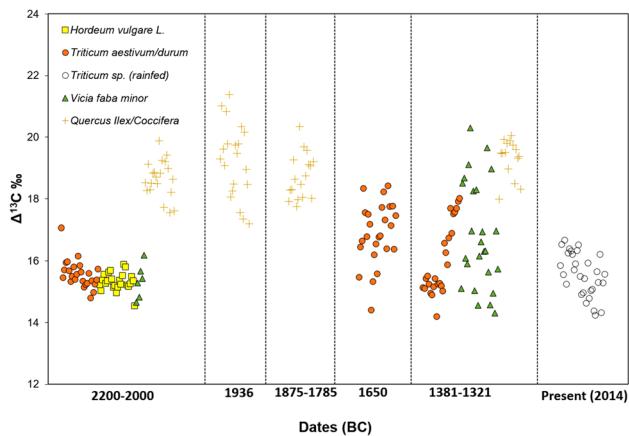


Fig. 3 Scatterplot of carbon isotope discrimination of ($\Delta^{13}\text{C}$) in the samples analysed; for symbols, see Fig. 2

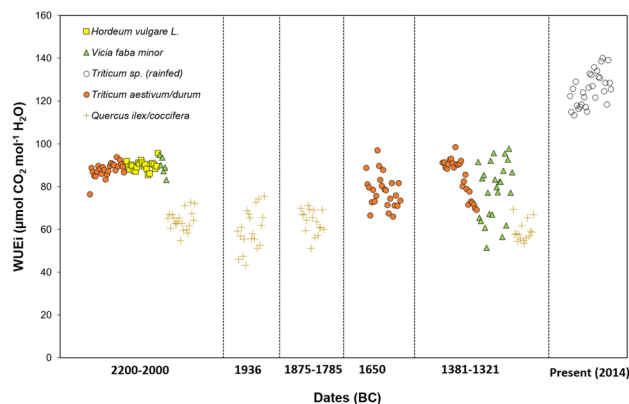


Fig. 4 Scatterplot of water-use efficiency (WUEi) in the samples analysed; for symbols, see Fig. 2

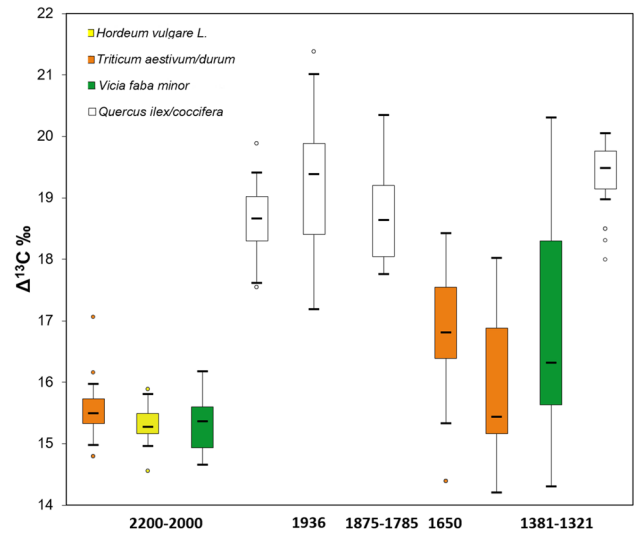


Fig. 5 Boxplot diagram with minimum, maximum, and median values for the different species studied in the Cerro del Castillo de Alange, according to the chronological period: *Hordeum vulgare* L. (yellow), *Triticum aestivum/durum* (orange), *Vicia faba* var. *minor* (green) and *Quercus ilex-coccifera* (white)

in the production methods in the zone (including possible irrigation) or to a combination of the two factors.

The marked trend of improvement in cultivation conditions during the second millennium BC contrasts with existing palaeoclimatic and archaeological data, suggesting a degradation of climatic conditions from 4,500 BP (2500 BC) in the Mediterranean as a whole, as confirmed by the studies made in the settlement (Duque Espino 2004; Pérez-Obiol et al. 2011). This degradation process appears to be verified in the ranges found for the oak samples, the lowest values of which exceed the aridity limit proposed by Drake et al. (2012) in a study of archaeological settlements of the SW Iberian Peninsula: $\Delta^{13}\text{C}$ 18.5‰. However, the mean values registered for oak remain above this level and relatively constant throughout the series studied. This indicates that this degradation process was possibly accompanied by a change in the pattern of rains throughout the year, which would benefit plants such as oak or simply the deeper roots of this species, which can reach the water table and thus enable better adaptation to the changes that occurred. The relationship between wild plants has been explored in other studies (Ferrio Díaz et al. 2005; Aguilera et al. 2011; Mora-González et al. 2016). In our case, although in the older phase, the differences proved greater. That is, in later times the ranges of the cultivated plants overlap in part with the results found for the charcoal remains of *Quercus ilex-coccifera*. Therefore, the values of cultivated plants, despite their meagre root system, tended towards a lower WUEi, while *Quercus* remained relatively constant. Consequently, these results

cannot be explained by greater precipitation but rather by the development of production strategies to ensure bountiful harvests.

The results of the cereals of the first phase studied are characterized by a lower $\Delta^{13}\text{C}$ (15.33 for *Hordeum* and 15.57 for *Triticum*), by a lower standard deviation (0.28 and 0.44), and by a lower range (≈ 1.5 and ≈ 2.5). The same was true for *Vicia faba*. In both cases, the results show conditions of greater water stress than at later time periods of the settlement (Fig. 5). In addition, these averages are lower than the values published for contemporary settlements in areas with similar or lower rainfall ranges: e.g. in the case of Terlinques average $\Delta^{13}\text{C}$ values were 16.88 and 17.16‰ (Mora-González et al. 2016) and in Castellón Alto 16.40 and 16.67‰ (Araus et al. 1997) for *Triticum* and *Hordeum*; in Levant, Riehl et al. (2008) reported results for Mozan (16.3 and 17.6‰, *Triticum* and *Hordeum*) and Qatna (16.7‰, *Hordeum*); Riehl et al. (2014) describe *Hordeum* remains for Emar (16.15‰), Dilkaya Höyük (16.29‰), Kinet Höyük (17.98‰), Tell Teweini (16.91‰) and Tell Mozan (16.84‰).

Finally, although the use of current plants can be mediated by genetic variations and new varieties, all these findings indicate that, for a rainfed crop, precipitation would act as a limiting factor, in agreement with the literature. Araus et al. (1997) proposed limits of 17.5–18‰ for *Triticum* and *Hordeum*. Wallace et al. (2013) suggested values of between 15.5 and 17‰ for low and medium watering levels in the case of *Triticum*, and 17–18.5‰ for *Hordeum*. Consequently, our values are at the limits of water deficiency, with all samples (except one) being below 17‰. Moreover, if we compare the archaeological results with the values found in the current plants grown in the same area, under rainfed conditions (15.56‰), we find similar values both in *Triticum* and *Hordeum* in this archaeological period (15.33 vs. 15.57‰, respectively).

For later periods, in addition to higher averages, a greater dispersion appears in cereal samples for both 1650 cal BC (0.99) and for 1381–1321 cal BC (1.16), as also verified for *Vicia faba* (0.56 vs. 1.73). This greater dispersion also exceeds that found in the samples from the year 2014 (0.70). Furthermore, an analysis of the ranges found for the phases Solana IIb (1650 cal BC) and Umbria II (1381–1321 cal BC) (≈ 4), both in comparison with the modern and phase samples Solana I and Solana I–II (2200–2000 BC), could indicate harvests of different annual cycles, cultivation in different areas, and a differential use of water resources, as suggested in the literature (Bogaard et al. 2007; Heaton et al. 2009; Flohr et al. 2011; Stokes et al. 2011; Riehl et al. 2014). Even when the possibility of finding surpluses from previous harvests is taken into account (Heaton et al. 2009), the values would be consistent with the implementation of exploitation strategies that use the territorial framework.

The case of *Vicia faba* reinforces the idea of a change in agricultural practices throughout the second millennium BC. When comparing our data with those of the literature, we see that the published data for the SE Iberian Peninsula are within the proposed range (4.38–18.92‰) (Araus et al. 1997). In this case, the values of *Vicia faba* were interpreted as a result of the possible use of irrigation, due to its relation to the cereals and the water requirements of these species, in an exploitation model based on garden-vegetable strategies. In our study, the results set a similar pattern for cereals and *Vicia faba*: in the first phase studied, both crops were grown in a rainfed and water-limiting environment or, in the case of *Vicia faba*, under less water availability, even in the case of irrigation practices for this species (Araus et al. 1997; Wallace et al. 2013), while in the last phase rainfed and irrigated samples were taken together, values being higher for *Vicia faba* than for cereals (Figs. 2, 3, 4). On this basis, we deduce once again that the crop strategies used combined the different species, taking into account the physiological characteristics of each of these plants.

The values found and the possibilities offered by the soils etc. (areas of the river very close to the settlement) suggest the development of a mixed model throughout the second millennium BC, where the cultivation of the dry land and irrigated land (or at least the exploitation of wetter soils) would coexist, as has been suggested for other settlements (Riehl et al. 2014; Wallace et al. 2015; Mora-González et al. 2016). Also, the cultivation could have taken place in the nearest areas instead of being based on long-distance exchange, given good conditions in the surrounding areas. This type of exploitation of the territory could be based on the use of the riverbanks, compatible with a possible use of floods or water diversion through more or less simple structures. Such a choice would be consistent with the lower presence of riparian woodland in the area and with the corresponding documented clearing of vegetation, a finding that also recurs in the archaeological record for these periods (Grau Almero et al. 1998; Duque Espino 2004). In addition, this is consistent with the increase in *Quercus ilex-coccifera*/*Q. ilex* throughout the three occupation phases, with the rest of taxa declining and appearing correspondingly towards the end of the second millennium BC (Duque Espino 2004). Similarly, the pollen (Hernández Carretero 1999), seeds (Grau Almero et al. 1998; Pavón Soldevila et al. 2010), and faunal studies (Castaños Ugarte 1994, 1998a, b) reflect this tendency towards a greater human pressure on the environment. In addition, the livestock herd was growing, potentially draft animals for agricultural work (Castaños Ugarte 1998a; Duque Espino 2004). Thus, there could have been exploitation of different areas within a broad and diverse territorial framework, as indicated above (Lightfoot and Stevens 2012). This would be characteristic of a political, social and economic model based on the control of a territory and

the centralization of agricultural production, as the existence of the barn seems to indicate (Pavón Soldevila et al. 2010; Fiorentino et al. 2012; Lightfoot and Stevens 2012; Pavón Soldevila and Duque Espino 2014).

Finally, a comparison of the WUEi results for current and archaeological plants verifies higher stress today, with generally better water conditions in the past, although the botanical remains indicate a climate that tended towards degradation at the end of the third millennium BC. Faced with this trend, human communities would have responded by developing production strategies that would exert pressure on the cultivation areas, and an environment that would continue to be transformed over time, in line with the approaches proposed above.

Conclusions

The carbon isotope ratios ($^{13}\text{C}:^{12}\text{C}$) found and the calculations derived from $\Delta^{13}\text{C}$ and WUEi imply an evolution towards lower intrinsic water-use efficiency in the archaeological samples towards the middle of the second millennium BC, in agreement with wetter conditions for the development of plants. This, in the context of a gradual degradation of the environment for climatic and anthropogenic reasons and a similar rainfall regime throughout the sequence (according to *Quercus* remains), offers evidence of the implementation of territorial management strategies that would combine possible irrigation practices or the use of wetter land with rainfed crops, and possibly with a mixture of different harvests. This is consistent with the opening of the Mediterranean forest recorded by botanical studies, as well as with the results found for modern rainfed plants, showing ranges and results similar to those of the third millennium BC.

Methodologically, the results show the need to develop analytical techniques combining archaeological samples (wild and cultivated plants) and current crops grown in the study areas, in order to know the relationships between the isotope signals, the climatic conditions and the effects of human influence.

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References

- Adams R (1974) Historic patterns of Mesopotamian agriculture. In: Downing TE, Gibson M (eds) *Irrigation's impact on society*. University of Arizona Press, Tucson
- Aguilera M, Arous JL, Voltas J, Rodríguez Ariza MO, Molina F, Rovira N, Buxó R, Ferrio Díaz JP (2008) Stable carbon and nitrogen isotopes and quality traits of fossil cereal grains provide clues on sustainability at the beginnings of Mediterranean agriculture. *Rapid Commun Mass Spectrom* 22:1,653–1,663
- Aguilera M, Espinar C, Ferrio Díaz JP, Pérez G, Voltas J (2009) A map of autumn precipitation for the third millennium BP in the Eastern Iberian Peninsula from charcoal carbon isotopes. *J Geochem Explor* 102:157–165
- Aguilera M, Ferrio Díaz JP, Pérez G, Arous JL, Voltas J (2011) Holocene changes in precipitation seasonality in the western Mediterranean Basin: a multi-species approach using $\delta^{13}\text{C}$ of archaeological remains. *J Quat Sci* 27:192–202
- Arous JL, Buxó R (1993) Changes in carbon isotope discrimination in grain cereals from the North-western Mediterranean Basin during the past seven millennia. *Aust J Plant Physiol* 20:117–128
- Arous JL, Buxó R, Febrero A, Camalich MD, Martín D, Molina F, Rodríguez-Ariza MO, Voltas J (1997) Identification of ancient irrigation practices based on the carbon isotope discrimination of plant seeds: a case study from South–East Iberian Peninsula. *J Archaeol Sci* 24:729–740
- Arous JL, Ferrio Díaz JP, Voltas J, Aguilera M, Buxó R (2014) Agronomic conditions and crop evolution in ancient Near East agriculture. *Nat Commun*. doi:10.1038/ncomms4953
- Berger J-F, Guilaine J (2009) The 8200 cal BP abrupt environmental change and the Neolithic transition: a Mediterranean perspective. *Quat Int* 200:31–49
- Bienert H-D, Hässler J (eds) (2004) *Men of Dikes and Canals: the archaeology of water in the Middle East*. Leidorf, Rahden
- Bogaard A, Heaton THE, Poulton P, Merbach I (2007) The impact of manuring on nitrogen isotope ratios in cereals: archaeological implications for reconstruction of diet and crop management practices. *J Archaeol Sci* 34:335–343
- Bogaard A, Fraser R, Heaton THE, Wallace M, Vaiglova P, Charles M, Jones G, Evershed RP, Styring AK, Andersen NH, Arbogast RM, Bartosiewicz L, Gardeisen A, Kanstrup M, Maier U, Marinova E, Ninov L, Schäfer M, Stephan E (2013) Crop manuring and intensive land management by Europe's first farmers. *Proc Natl Acad Sci* 110:12,589–12,594
- Caracuta V, Barzilai O, Khalaily H, Milevski I, Paz Y, Vardi J, Regev L, Boaretto E (2015) The onset of faba bean farming in the Southern Levant. *Sci Rep* 5:14370. doi:10.1038/srep14370
- Castaños Ugarte PM (1994) Resumen del estudio de los restos óseos del yacimiento de la Solana del Castillo de Alange. In: Pavón Soldevila I (ed) *Aproximación al estudio de la Edad del Bronce en la Cuenca Media del Guadiana: la Solana del Castillo de Alange* (1987). Institución Cultural El Brocense, Diputación de Cáceres, Cáceres, pp 163–167
- Castaños Ugarte PM (1998a) Estudio arqueozoológico de la fauna del Cerro del Castillo de Alange. In: Pavón Soldevila I (ed) *El Cerro del Castillo de Alange (Badajoz): Intervenciones Arqueológicas* (1993). Memorias de Arqueología Extremeña 1. Mérida Junta de Extremadura, Consejería de Cultura y Patrimonio, Mérida, pp 167–177
- Castaños Ugarte PM (1998b) Evolución de las faunas protohistóricas en Extremadura. In: Rodríguez Días A (ed) *Extremadura*

- Protohistórica: Paleoambiente, economía y poblamiento. Universidad de Extremadura, Cáceres, pp 63–72
- Cernusak LA, Ubierna N, Winter K, Holtum JAM, Marshall JD, Farquhar GD (2013) Environmental and physiological determinants of carbon isotope discrimination in terrestrial plants. *New Phytol* 200:950–965
- Chapman R (1990) Emerging complexity: The later prehistory of south-east Spain, Iberia and the west Mediterranean. Cambridge University Press, Cambridge
- Cohen MN (1977) The food crisis in prehistory: overpopulation and the origins of agriculture. Yale University Press, New Haven
- Diefendorf AF, Mueller KE, Wing SL, Koch PL, Freeman KH (2010) Global patterns in leaf ^{13}C discrimination and implications for studies of past and future climate. *Proc Natl Acad Sci USA* 107:5,738–5,743
- Drake BL, Hanson DT, Boone JL (2012) The use of radiocarbon-derived $\Delta^{13}\text{C}$ as a paleoclimate indicator: applications in the Lower Alentejo of Portugal. *JAS* 39(9):2888–2896. doi:10.1016/j.jas.2012.04.027
- Duque Espino DM (2004) La gestión del paisaje vegetal en la Prehistoria Reciente y Protohistoria en la Cuenca Media del Guadiana a partir de la Antracología. PhD Thesis, Universidad de Extremadura, Cáceres
- Farquhar GD, Lloyd J (1993) Carbon and oxygen isotope effects in the exchange of carbon dioxide between terrestrial plants and the atmosphere. In: Ehleringer JR, Hall AE, Farquhar GD (eds) Stable isotopes and plant carbon-water relations. Academic Press, New York, pp 47–70
- Farquhar GD, Richards R (1984) Isotopic composition of plant carbon correlates with water-use efficiency of wheat genotypes. *Funct Plant Biol* 11:539–552
- Farquhar GD, O'Leary MH, Berry JA (1982) On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. *Aust J Plant Physiol* 9:121–137
- Farquhar GD, Hubick KT, Condon AG, Richards RA (1988) Carbon isotope fractionation and plant water-use efficiency. In: Rundel PW, Ehleringer JR, Nagy KA (eds) Stable isotopes in ecological research. Springer, New York, pp 21–40
- Farquhar GD, Ehleringer JR, Hubick KT (1989) Carbon isotope discrimination and photosynthesis. *Annu Rev Plant Physiol Plant Mol Biol* 40:503–537
- Ferrio Díaz JP, Araus JL, Buxó R, Voltas J, Bort J (2005) Water management practices and climate in ancient agriculture: inference from the stable isotope composition of archaeobotanical remains. *Veget Hist Archaeobot* 14:510–517
- Ferrio Díaz JP, Alonso N, López JB, Araus JL, Voltas J (2006) Carbon isotope composition of fossil charcoal reveals aridity changes in the NW Mediterranean Basin. *Glob Chang Biol* 12:1,253–1,266
- Fiorentino G, Caracuta V, Casiello G, Longobardi F, Sacco A (2012) Studying ancient crop provenance: implications from $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of charred barley in a Middle Bronze Age Silo at Ebla (NW Syria). *Rapid Commun Mass Spectrom* 26:327–335
- Flohr P, Müldner G, Jenkins E (2011) Carbon stable isotope analysis of cereal remains as a way to reconstruct water availability: preliminary results. *Water Hist* 3:121–144
- Gebauer AB, Price TD (1992) Transitions to agriculture in prehistory. Monographs in world archaeology 4. Prehistory Press, Madison
- Gilman A, Thornes JB (1985) Land-use and prehistory in South-East Spain. George Allen & Unwin, London
- Grau Almero E, Pérez Jordá G, Hernández Carretero AM (1998) El estudio arqueobotánico del Cerro del Castillo de Alange (Badajoz). In: Pavón Soldevila I (ed) El Cerro del Castillo de Alange (Badajoz): Intervenciones Arqueológicas (1993). Memorias de Arqueología Extremeña 1. Mérida Junta de Extremadura, Consejería de Cultura y Patrimonio, Mérida
- Gupta AK (2004) Origin of agriculture and domestication of plants and animals linked to early Holocene climate amelioration. *Curr Sci* 87:54–59
- Harris D (1996) The origins and spread of agriculture and pastoralism in Eurasia. University College London Press, London
- Heaton THE, Jones G, Halstead P, Tsipropoulos T (2009) Variations in the $^{13}\text{C}/^{12}\text{C}$ ratios of modern wheat grain, and implications for interpreting data from Bronze Age Assiros Toumba, Greece. *J Archaeol Sci* 36:2,224–2,233
- Hedges JI, Stern JH (1984) Carbon and nitrogen determinations of carbonate-containing solids. *Limnol Oceanogr* 29:657–663
- Helbaek H (1960) Cereal weed grasses in Phase A. In: Braidwood RJ, Braidwood LS (eds) Excavations in the plain of Antioch I. University of Chicago Press, Chicago, pp 540–543
- Helms SW (1981) Jawa: lost city of the Black Desert. Methuen, London
- Hernández Carretero AM (1999) Paleoambiente y Paleoeconomía durante el 1er milenio a.C. en Extremadura. Universidad de Extremadura, Cáceres
- Hernández Carretero AM, López García P, López Sáez JA (2003) Estudio paleoambiental y paleoeconómico de la cuenca media del Guadiana durante el I milenio BC: el Cerro del Castillo de Alange y el Cerro de la Muela de Badajoz. *Rev Prehist Arqueol Univ Sevilla* 12:259–282
- Hubbard RNLB (1980) Development of agriculture in Europe and the Near East: evidence from quantitative studies. *Econ Bot* 34:51–67
- Hunt RC (1988) Management in Southern Mesopotamia in Sumerian Times. In: Postgate JN, Powell MA (eds) Irrigation and cultivation in Mesopotamia. Sumerian Agriculture Group, Cambridge, pp 189–206
- Indermuhle A, Stocker TF, Joos F, Fischer H, Smith HJ, Wahlen M, Deck B, Mastroianni D, Tschumi J, Blunier T, Meyer R, Stauffer B (1999) Holocene carbon-cycle dynamics based on CO_2 trapped in ice at Taylor Dome. *Antarct Nat* 398:121–126
- Jacobsen T (1982) Salinity and irrigation agriculture in antiquity Diyala Basin archaeological projects: report on the essential results, 1957–1958. Bibliotheca Mesopotamia 14. Udena Publications, Malibu
- Jalut G, Amat AE, Bonnet L, Gauquelin T, Fontugne M (2000) Holocene climatic changes in the Western Mediterranean from south-east France to south-east Spain. *Palaeogeogr Palaeoclimatol Palaeoecol* 160:255–290
- Jalut G, Dedoubat JJ, Fontugne M, Otto T (2009) Holocene circum-Mediterranean vegetation changes: climate forcing and human impact. *Quat Int* 200:4–18
- Jarman MR, Bailey GN, Jarman HN (1982) Early European agriculture: its foundation and development. Cambridge University Press, Cambridge
- Jenkins E, Jamjoum K, Nuimat S (2011) Irrigation and phytolith formation: an experimental study. In: Mithen S, Black E (eds) Water, life and civilisation: climate, environment and society in the Jordan Valley. Cambridge University Press, Cambridge, pp 347–372
- Jenkins E, Jamjoum K, Nuimat S, Stafford R, Nortcliff S, Mithen S (2016) Identifying ancient water availability through phytolith analysis: an experimental approach. *J Archaeol Sci* 73:82–93
- Jones G (2005) Garden cultivation of staple crops and its implications for settlement location and continuity. *World Arch* 37:164–176
- Jones GEM, Charles M, Colledge S, Halstead P (1995) Towards the archaeological recognition of winter-cereal irrigation: an investigation of modern weed ecology in northern Spain. In: Kroll H, Pasternak R (eds) *Res Archaeobotanicae*. Oetker-Voges, Kiel, pp 49–68
- Keeling CD, Mook WG, Tans PP (1979) Recent trends in the $^{13}\text{C}/^{12}\text{C}$ ratio of atmospheric carbon dioxide. *Nature* 277:121–123
- Kohn MJ (2010) Carbon isotope compositions of terrestrial C3 plants as indicators of (paleo)ecology and (paleo)climate. *Proc Natl Acad Sci USA* 107:19,691–19,695

- Kuijt I, Finlayson B, MacKay J (2007) Pottery neolithic landscape modification at Dhra'. *Antiquity* 81:106–118
- Leuenberger M, Siegenthaler U, Langway C (1992) Carbon isotope composition of atmospheric CO₂ during the last ice age from an Antarctic ice core. *Nature* 357:488–490
- Lightfoot E, Stevens RE (2012) Stable isotope investigations of charred barley (*Hordeum vulgare*) and wheat (*Triticum spelta*) grains from Danebury Hillfort: implications for palaeodietary reconstructions. *J Archaeol Sci* 39:656–662
- Marino BD, DeNiro MJ (1987) Isotopic analysis of archaeobotanicals to reconstruct past climates: effects of activities associated with food preparation on carbon, hydrogen and oxygen isotope ratios of plant cellulose. *J Archaeol Sci* 14:537–548
- McCarroll D, Loader NJ (2004) Stable isotopes in tree rings. *Quat Sci Rev* 23:771–801
- Mora-González A, Delgado-Huertas A, Granados-Torres A, Pavón Soldevila I, Duque Espino DM (2015) Isotopic footprint in carpological remains: preliminary results from the site of Cerro del Castillo de Alange (Badajoz, Spain). *MetroArcheo. 1st International Conference on Metrology for Archaeology, Benevento*
- Mora-González A, Delgado-Huertas A, Granados-Torres A, Contreras Cortés F, Jover Maestre FJ, López Padilla JA (2016) The isotopic footprint of irrigation in the western Mediterranean basin during the Bronze Age: the settlement of Terlinques, southeast Iberian Peninsula. *Veget Hist Archaeobot* 25:459–468
- Munro ND (2003) Small game, the Younger Dryas, and the transition to agriculture in the southern Levant. *Mitt Ges Urgesch* 12:47–71
- Nitsch E, Charles M, Bogaard A (2015) Calculating a statistically robust $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ offset for charred cereal and pulse seeds. *Sci Technol Archaeol Res* 1:1–14
- Pavón Soldevila I (1995) La Solana del Castillo de Alange: un yacimiento de la Edad del Bronce en la Cuenca Media del Guadiana. *Rev Prehist Arqueol Univ Sevilla* 2:147–168
- Pavón Soldevila I (1998) El Cerro del Castillo de Alange (Badajoz): Intervenciones Arqueológicas (1993). *Memorias de Arqueología Extremeña 1*. Mérida Junta de Extremadura, Consejería de Cultura y Patrimonio, Mérida
- Pavón Soldevila I, Duque Espino DM (2014) El Cerro del Castillo de Alange (Extremadura, España): un paisaje de la Edad del Bronce. In: Vilaça R, Serra M (eds) *Idade do Bronze do Sudoeste. Novas perspectivas sobre uma velha problemática*. Instituto de Arqueologia. Secção de Arqueologia. FLUC, Coimbra
- Pavón Soldevila I, Duque Espino DM, Pérez Jordá G, Márquez Gallardo JM (2010) Novedades en la Edad del Bronce del Guadiana Medio. Intervención en el Cerro del Castillo de Alange (2005–2006). In: Macías J (coord) *Actas del IV Encuentro de Arqueología del Suroeste Peninsular*. Universidad de Huelva, Huelva
- Pérez-Obiol RP, Jalut G, Julià R, Pèlachs A, Iriarte MJ, Otto T, Hernández-Beloqui B (2011) Mid-Holocene vegetation and climatic history of the Iberian Peninsula. *Holocene* 21:75–93
- Price DH (1994) Wittfogel's neglected hydraulic/hydroagricultural distinction. *J Anthropol Res* 50:187–204
- Price DT (1995) Social inequality at the origins of agriculture. In: Price TD, Feinman GM (eds) *Foundations of social inequality*. Plenum Press, New York, pp 129–151
- Purdue LE, Berger L-F (2015) An integrated socio-environmental approach to the study of ancient water systems: the case of pre-historic Hohokam irrigation systems in semi-arid central Arizona, USA. *J Archaeol Sci* 53:586–603
- Richerson PJ, Boyd R, Bettinger RL (2001) Was agriculture impossible during the Pleistocene but mandatory during the Holocene? A climate change hypothesis. *Am Antiqu* 66:387–411
- Riehl S, Bryson R, Pustovoytov K (2008) Changing growing conditions for crops during the near Eastern Bronze Age (3000–1200 BC): the stable carbon isotope evidence. *JAS* 35:1,011–1,022
- Riehl S, Pustovoytov K, Weippert H, Klett S, Hole F (2014) Drought stress variability in ancient Near Eastern agricultural systems evidenced by $\delta^{13}\text{C}$ in barley grain. *Proc Natl Acad Sci USA* 111:12,348–12,353
- Rindos D (1984) *The origins of agriculture: an evolutionary perspective*. Academic Press, New York
- Rivas Martínez S (1987) *Memoria del mapa de series de vegetación de España 1:400.000*. ICONA. Ministerio de Agricultura, Pesca y Alimentación, Madrid
- Rosen AM, Weiner S (1994) Identifying ancient irrigation: a new method using opaline phytoliths from emmer wheat. *J Archaeol Sci* 21:125–132
- Shüle W (1967) *Feldbewässerung in Alt-Europa*. *Madr Mitt* 8:79–99
- Smith BD (1994) *The emergence of agriculture*. Scientific American Library, New York
- Stokes H, Müldner G, Jenkins E (2011) An investigation into the archaeological application of carbon stable isotope analysis used to establish crop water availability: solutions and ways forwards. In: Mithen S, Black E (eds) *Water, life and civilisation: climate, environment, and society in the Jordan Valley*. Cambridge University Press, Cambridge, pp 373–380
- Tans PP, Mook WG (1980) Past atmospheric CO₂ levels and the $^{13}\text{C}/^{12}\text{C}$ ratios in tree rings. *Tellus* 32:268–283
- Turney CSM, Brown H (2007) Catastrophic early Holocene sea level rise, human migration and the Neolithic transition in Europe. *Quat Sci Rev* 26:2,036–2,041
- Turney CSM, Wheeler D, Chivas AR (2006) Carbon isotope fractionation in wood during carbonization. *Geochim Cosmochim Acta* 70:960–964
- Wallace M, Jones GEM, Charles M, Fraser R, Halstead P, Heaton THE, Bogaard A (2013) Stable carbon isotope analysis as a direct means of inferring crop water status and water management practices. *World Arch* 45:388–409
- Wallace MP, Jones G, Charles M, Fraser R, Heaton THE, Bogaard A (2015) Stable carbon isotope evidence for Neolithic and Bronze Age crop water management in the Eastern Mediterranean and Southwest Asia. *PLoS One* 10:e0127085. doi:10.1371/journal.pone.0127085
- Weninger B, Alram-Stern E, Bauer E et al (2006) Climate forcing due to the 8200 cal yr BP event observed at Early Neolithic sites in the eastern Mediterranean. *Quat Res* 66:401–420
- Wittfogel KA (1957) *Oriental despotism: a comparative study of total power*. Yale University Press, New Haven
- Woodbury RB (1961) Climatic changes and prehistoric agriculture in the Southwestern United States. *Ann N Y Acad Sci* 95:705–709