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ORIGINAL ARTICLE

The isotopic footprint of irrigation in the western Mediterranean basin during the Bronze Age: the settlement of Terlinques, southeast Iberian Peninsula

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Abstract The isotopic composition of the remains of cereals and pine has been studied, from three different chronological phases from 2140 to 1500 cal BC at the Terlinques site, southeast Iberian Peninsula. The $\delta^{13}C$ values range between −24.91 and −21.19 ‰ (V-PDB), with an average of −23.05 ‰ (STD = 0.69). The archaeological cereals show an average isotopic discrimination ($\Delta^{13}C$) with the past atmospheric CO_2 of 16.96 ‰, which is much greater than the average $\Delta^{13}C$ of 13.89 ‰ of the rainfed Triticeae (wheat and barley) in modern times. However, considering the effect of the atmospheric CO_2 concentration, which is included in the WUEi (intrinsic water-use efficiency), this difference is even greater, 77 for archaeological samples versus 144 for present-day rainfed cereals. This could represent some of the earliest evidence of the use of irrigation techniques in Europe. Modern cereals which have been irrigated show a general $\Delta^{13}C$ average of 17.17 ‰, very similar to those of the middle Holocene. However, when the WUEi is calculated, the value of 108 indicates that present-day irrigated cereals are more stressed than the archaeological samples. For comparison, we have included pine trees, since these have an extensive root development which is capable of reaching the water table. In the past, both cereals and pine present similar WUEi values (77 vs. 72), however at present only irrigated cereals show similar WUEi values to pine (108 vs. 107). This again suggests irrigation of cereals in the past. The processes of climatic degradation towards drier conditions which started in the middle Holocene could be responsible for the use of land near water sources, on riverbanks and near shallow lakes. According to the isotopic and plant macrofossil data, irrigation or water management techniques were used at the Terlinques site, located close to the Laguna de Villena, a lake which has now dried out.

Keywords $\delta^{13}C$ · Stable isotopes · WUEi · Early agriculture · Global change · Archaeobotany

Introduction

The use of irrigation could have played an important role during the early stages of agriculture (Wittfogel 1957; Helbæk 1960; Finlayson et al. 2011). Its use has been archaeologically proven for sites in the Near East from the rise of the first states onwards, although there is much debate about the date of the first signs of irrigation (Jacobsen and Adams 1958; Adams 1974, 1981; Hunt 1988; Oleson 2001; Bienert and Hässer 2004; Bourke 2008; Philip 2008; Gillmore et al. 2009). This has promoted important discussions regarding the origin of complex societies and social inequalities (Wittfogel 1957; Chapman 1990; Scarbourough 2003). Considering that the southeast

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Iberian Peninsula is relatively arid, together with the establishment of some of the first complex societies in this area, some authors have considered it predictable that irrigation practices already existed during its prehistory (Gilman and Thornes 1985; Chapman 1990). However, the early use of irrigation for cereals in the western Mediterranean has not yet been demonstrated (Araus et al. 1997). Although it is probable that watering techniques were implemented sooner in very dry areas, this is difficult to prove. This matter has usually been investigated through indirect evidence, such as the presence of structures for water management (Shüle 1967; Helms 1981; Gilman and Thornes 1985; Bienert and Hässer 2004; Kuijt et al. 2007), the size of grains (Helbæk 1960), the characteristics of weeds that appear together with the crops (Jones et al. 1995, 2005) or the analysis of phytoliths (Rosen and Weiner 1994; Jenkins et al. 2011). Nevertheless, none of these methods provide direct quantitative evidence. In contrast, stable isotopes of carbon give a direct approach to solving this problem (Araus et al. 1997; Ferrio Díaz et al. 2005; Wallace et al. 2013; Fiorentino et al. 2015).

Carbon is the most important element in primary production, being the base of the trophic chain of continental and marine ecosystems. Plants with a type C3 photosynthetic cycle show δ^{13}C values between −20 and −35 ‰ (Bender 1971; Peterson and Fry 1987), while the average isotopic composition in modern CO_2 is approximately −8.4 ‰ (−6.5 ‰ before the industrial revolution) (Keeling et al. 1979; Friedli et al. 1986). δ^{13}C represents the ratio of stable carbon isotope ^{13}C to ^{12}C per mil (‰). During the synthesis of organic material through atmospheric CO_2 fixation by photosynthesis, two processes of isotopic fractionation can be observed. The first one is related to the diffusion of CO_2 through the stomata and it is affected by factors such as the size and density of the stomata, atmospheric CO_2 concentrations and the rate of gas exchange; the second one is associated with the activity of the RuBisCO enzyme (Bender 1971; Farquhar et al. 1982, 1989; Farquhar and Lloyd 1993).

In the context of this study, it is important to note that plants, when stressed by lack of water, tend to respond by closing their stomata to prevent water loss through transpiration. This loss of stomata conductivity causes a decrease in the concentration of CO_2 in the intercellular space and, consequently, less discrimination of ^{13}C, which increases the values of δ^{13}C in the synthesized organic material. Some publications have been dedicated to the influence of other factors apart from the available water (Stewart et al. 1995; Arens et al. 2000; Hartman and Danin 2010). But nevertheless, the isotopic composition of plants is affected mainly by the δ^{13}C value of atmospheric CO_2, the concentration of CO_2 in the atmosphere and water availability. Through the Holocene, isotopic composition of atmospheric CO_2 has barely changed (Friedli et al. 1986). So, we can compare directly values of isotopic discrimination of carbon (Δ^{13}C, see below) and/or isotopic composition of carbon (δ^{13}C). However, since the industrial revolution, both the amount and the δ^{13}C of atmospheric CO_2 have changed. Consequently, for comparing past and present conditions we must eliminate this bias. All these parameters are considered by Farquhar et al. (1982) in their famous equation (see "Materials and methods" section). This equation works reasonably well and only minor considerations have been suggested (Farquhar and Cernusak 2012; Cernusak et al. 2013).

The ecophysiological relations between the isotopic composition of carbon (δ^{13}C) in archaeobotanical remains and climate variations have allowed the development of models that help to trace back aspects such as the rainfall regime or the amount of water that plants received during their growth (Araus and Buxó 1993; Araus et al. 1997; Ferrio Díaz et al. 2005; Aguilera et al. 2009, 2011; Araus et al. 2014), the existence of irrigation practices in the past (Araus et al. 1997; Flohr et al. 2011; Wallace et al. 2013), the productivity and evolution of crops (Araus et al. 2003; Aguilera et al. 2008), or the current climate in the Iberian Peninsula (Ferrio Díaz et al. 2006; Aguilera et al. 2009, 2011).

At the site of Terlinques, southeast Iberian Peninsula, abundant cereal remains have been found. Archaeobotanical studies on material from this settlement indicate the existence of weeds and some species such as *Phalaris arundinacia* and *Persicaria maculosa* which are compatible with the use of irrigation (Precioso Arévalo and Rivera 1999). In contrast, the Holocene climatic evolution of the Mediterranean shows an aridity crisis from ≈5,500 to 2,700 cal BP, as shown by changes in vegetation cover and an evolution towards Mediterranean climatic conditions (Morellon et al. 2009; Martin Puertas et al. 2010; Aranbarri et al. 2014). The main goal of the present study is to verify this hypothesis, using the isotopic ratios of ^{13}C to ^{12}C in the cereal remains. These allow us to obtain quantitative data regarding the water use efficiency (WUEi), which can be connected to the use of irrigation (Araus et al. 1997; Flohr et al. 2011; Wallace et al. 2013).

Archaeological and geographical background

Terlinques is located in the municipality of Villena, southeast Spain, at 520 m a.s.l. (UTM 30SXH8028749). The settlement is near a small plain where in the past there was an endorheic basin (with no external drainage), and irrigation is practised there today (Fig. 1). The Alto Vinalopó region is characterised by a Mesomediterranean

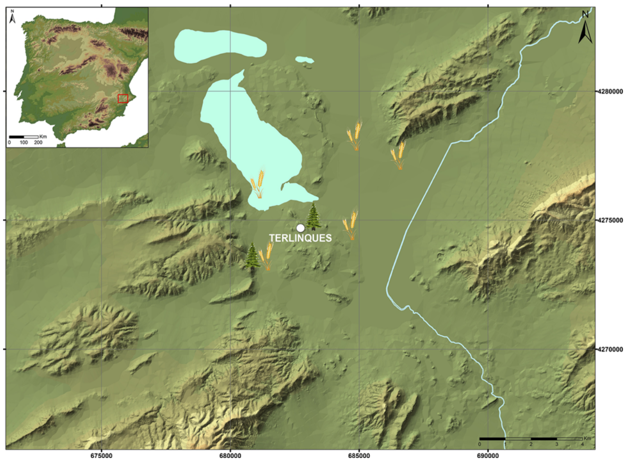

Fig. 1 Map of the Terlinques site. The extent of the old lake and the points of modern sampling are indicated, marked with a *cereal symbol* for barley and wheat and a *tree symbol* for pine

climate of a continental character, with an average yearly temperature between 13 and 17 °C, and a high thermal range (15 °C) (Matarredona 1983). Cold winters with frost in the cold months and hot summers characterise the annual cycle. Nowadays the precipitation corresponds to a semi-arid ombroclimate, with levels of precipitation between 200 and 350 mm, (234 mm for 2014), the rain mostly falling during the springtime, around 169 mm between January and August (68 mm for 2014) and 63 mm during the months of April and May (23 mm for 2014), the data provided by Agencia Estatal de Meteorología, Ministerio de Agricultura, Alimentación y Medio Ambiente, Gobierno de España (Forteza et al. 1995; Alonso 1996). The area is characterised by alluvial-colluvial and dark chalky soils in the flattest areas, while there are calcareous soils of poor agricultural quality in the mountainous area (Forteza et al. 1995; Machado et al. 2009). Finally, the vegetation is dominated by *Pinus halepensis, Quercus ilex, Pistacia lentiscus* and a vegetation layer with maquis scrub (Matarredona 1983; Machado et al. 2009).

Excavations at Terlinques have been carried out throughout the last two decades. Three phases of occupation have been found: Phase I (2140–1930 cal BC), Phase II (1930–1750 cal BC) and Phase III (1750–1500 cal BC) (Jover Maestre et al. 2014). The site of Terlinques was the result of a political project which developed in the late 3rd millennium BC in the Levante area of the Iberian Peninsula, where a transformation of the strategies of land occupation took place. This was supported by an institutionalization of property and also institutionalized land redistribution and the exploitation of local resources (Jover Maestre 1999). Phases I and II are characterised by the presence of two big houses. In Phase I, Housing Unit I stands out, with spaces for various activities, such as textile production or food preparation processes (Jover Maestre et al. 2001; Machado et al. 2009). One of these is delimited by a wooden dividing wall. Four esparto bags were found in this area, three of them used for grain storage and one for manure (Machado et al. 2009), demonstrating the importance of agriculture and land use. Archaeological remains also show an increase in labour investment in the building of more solid structures, which were maintained and transformed over time, about 700 years in this case. There was a restructuring of the space in the settlement following a change in the organization of productive activities after 1750 cal BC. The large housing units were replaced by smaller living spaces in which only evidence of maintenance activities has been found. Parallel to this process, some population growth is also recorded in other settlements (De Pedro 2005).

Materials and methods

We have analyzed archaeobotanical remains from the three phases. Phase I is best represented in terms of quantity and quality of the remains, but they are scarcer in the later phases. In the first period, all samples come from Housing Unit I. In total, 218 remains have been analyzed: 175 remains of Triticeae, of which 50 are *Hordeum vulgare* and 125 are *Triticum aestivum/durum*, 3 fragments of wood charcoal of *Olea europaea* and 40 fragments of *Pinus halepensis* (Table 1).

Apart from this, we have also worked with 95 present day samples from 2014. These consist of 20 samples of *P. halepensis* leaves from two different locations and 75 Triticeae seeds: 15 of *Triticum* sp., 15 of *H. vulgare* var *distichum* and 45 of *H. vulgare* var. *hexastichum*, from five different fields. Of the barley samples, two fields were irrigated (two-row barley) and two were rainfed (six-row and two-row barley) (Table 1).

Each of the samples has been analyzed individually. The modern plants were dried at a temperature of 65 °C for 48 h. Then each seed was milled in a microcontainer with tungsten balls. In order to eliminate any possible remains of carbonates in the archaeological remains, the ground samples were placed in a desiccator containing concentrated 37 % HCl for 12–14 h (Hedges and Stern 1984). After this, two measurements were made on each sample, weighing 0.5 mg each.

Isotope measurements were carried out at the Stable Isotope Laboratory of the Instituto Andaluz de Ciencias de la Tierra (CSIC-UGR, Granada). Samples were analysed for the isotopic composition of carbon using a Carlo Elba NA1500 (Milan, Italy) elemental analyser on line with a Delta Plus XL (ThermoQuest, Bremen,

Table 1 Studied samples, plant taxa, dating, isotopic composition of carbon ($\delta^{13}C$), isotopic discrimination of carbon ($\Delta^{13}C$), water use efficiency (WUEi) and isotopic composition of carbon of the atmospheric CO_2 ($\delta^{13}C$)

Species	Dating		$\delta^{13}C$ ‰ (STD)	$\Delta^{13}C$ ‰ (STD)	WUEi (STD)	δ ^{13}C (CO_2)
Triticum aestivum/durum (*n* = 125)	2140–1930 (cal BC)	Average	−22.86 (0.63)	16.88 (0.66)	78 (5)	−6.36
		Range	−24.67 to −21.19	15.15–18.77	63–91	
Hordeum vulgare (n = 50)	2140–1930 (cal BC)	Average	−23.12 (0.80)	17.16 (0.83)	76 (6)	−6.36
		Range	−24.91 to −21.69	15.67–19.02	61–87	
Pinus halepensis (*n* = 30)	2140–1930 (cal BC)	Average	−23.56 (0.42)	17.61 (0.44)	72 (3)	−6.36
		Range	−24.33 to −22.52	16.53–18.42	66–80	
Olea europaea (*n* = 3)	2140–1930 (cal BC)	Average	−23.02 (0.19)	17.05 (0.20)	76 (2)	−6.36
		Range	−23.19 to −22.81	16.83–17.23	75–78	
Pinus halepensis (*n* = 4)	1930–1750 (cal BC)	Average	−23.34 (0.83)	17.35 (0.86)	74 (7)	−6.40
		Range	−24.09 to −22.60	16.57–18.13	68–80	
Pinus halepensis (*n* = 6)	1750–1500 (cal BC)	Average	−23.73 (0.53)	17.72 (0.55)	71 (4)	−6.43
		Range	−24.27 to −22.82	16.77–18.28	67–79	
Pinus halepensis (*n* = 10)	Present (2014)	Average	−26.27 (1.36)	18.36 (1.42)	95 (16)	−8.4
		Range	−28.62 to −24.65	16.66–20.82	68–113	
Pinus halepensis (*n* = 10)	Present (2014)	Average	−24.19 (0.53)	16.19 (0.55)	118 (6)	−8.4
		Range	−25.00 to −23.33	15.28–17.03	109–128	
H. vulgare var. *distichum* (*n* = 15)	Present (2014)	Average	−24.47 (0.67)	16.48 (0.70)	115 (8)	−8.4
		Range	−25.70 to −23.58	15.54–17.76	101–125	
H. vulgare var. *distichum* (*n* = 15)	Present (2014)	Average	−25.80 (0.92)	17.86 (0.96)	100 (11)	−8.4
		Range	−28.00 to −24.46	16.46–20.16	75–115	
Tritcum sp. (*n* = 15)	Present (2014)	Average	−22.42 (1.06)	14.34 (1.10)	139 (12)	−8.4
		Range	−23.79 to −20.58	12.44–15.77	123–159	
H. vulgare var. *distichum* (*n* = 15)	Present (2014)	Average	−22.07 (0.79)	13.98 (0.82)	143 (9)	−8.4
		Range	−23.80 to −20.81	12.67–15.78	123–157	
H. vulgare var. *hexastichum* (*n* = 15)	Present (2014)	Average	−21.47 (0.33)	13.35 (0.34)	149 (4)	−8.4
		Range	−22.06 to −20.98	12.85–13.97	143–155	

Modern samples are grouped by fields in which they were grown

Germany) mass spectrometer (EA-IRMS). The stable composition is reported as δ values per mil:

$$\delta = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right) * 1000,$$

where R is the $^{13}C/^{12}C$ for $\delta^{13}C$.

For this study, two internal standards of −30.63 and −11.65 ‰ (V-PDB) have been used. The calculated precision, after correction of the mass spectrometer daily drift, from standards systematically interspersed in analytical batches was better than ±0.1 ‰ for $\delta^{13}C$. The standard for reporting carbon measurements is V-PDB (Vienna-PDB).

Various studies have demonstrated that the $\delta^{13}C$ of seeds is not affected by the charring process (Marino and DeNiro 1987; Araus et al. 1997; Nitsch et al. 2015). In contrast, the impact of charring on *P. halepensis* wood $\delta^{13}C$ has been pointed out. We have obtained original wood $\delta^{13}C$ ($\delta^{13}C_w$) following the equation developed by Ferrio Díaz et al. (2006):

$$\delta^{13}Cw = 0.706 * \delta^{13}C_{ch} + 0.031 * \%C_{ch} - 8.07,$$

where $\delta^{13}C_{ch}$ is the isotopic composition of carbon in charcoal and $\%C_{ch}$ is the charcoal carbon concentration.

The isotopic composition of atmospheric CO_2 has changed, principally after the industrial revolution (Keeling et al. 1979; Tans and Mook 1980; McCarrol and Loader 2004). In order to eliminate this bias, we have calculated values of the isotopic discrimination of carbon ($\Delta^{13}C$) using the equation of Farquhar et al. (1982) and Farquhar and Richards (1984):

$$\Delta^{13}C = \frac{\delta^{13}C_{atm} - \delta^{13}C_{sample}}{1 + \delta^{13}C_{sample}/1000}$$

In this equation $\delta^{13}C_{atm}$ is the isotopic composition of carbon in atmospheric CO_2 and $\delta^{13}C_{sample}$ is the isotopic composition of carbon in the sample. $\delta^{13}C_{atm}$ in the archaeological period has been obtained from

AIRCO2_LOESS system (http://web.udl.es/usuaris/x3845331/AIRCO2_LOESS.xls) (Leuenberger et al. 1992; Indermühle et al. 1999; Ferrio Díaz et al. 2005).

Finally, in order to take account of changes in the amount of CO_2, we have calculated the intrinsic water use efficiency (WUEi) (Farquhar et al. 1982, 1989):

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

In this equation A is the net carbon assimilation, g_w is stomatal conductance to water vapour, a is the the fractionation during CO_2 diffusion through the stomata (4.4 ‰), b is the fractionation associated with reactions by the RuBisCO enzyme (27 ‰), $\Delta^{13}C$ is the isotopic 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, www.esrl.noaa.gov/gmd/ccgg/trends/).

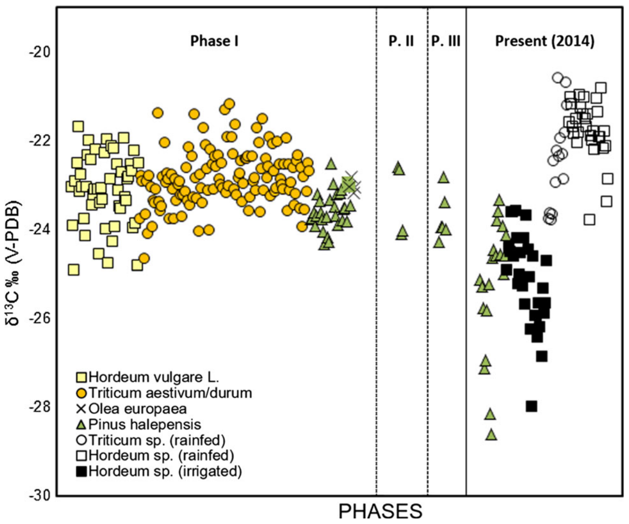

Fig. 2 Scatter plot with the results of the isotopic composition of carbon ($\delta^{13}C$) throughout Phases I, II and III of the settlement and present-day plants (2014). Samples of *Triticum aestivum/durum* (*orange circles*) *Hordeum vulgare* (*yellow squares*), *Pinus halepensis* (*green triangles*), *Olea europaea* (*crosses*), rainfed *Triticum* sp. (*hollow circles*), rainfed *Hordeum* sp. (*hollow squares*) and irrigated *Hordeum* sp. (*filled squares*) are included

Results

Analysis of the isotopic composition of carbon ($\delta^{13}C$)

The results are summarized in Tables 1, 2, and Figs. 2, 3, 4. The 218 archaeological samples ranging between −24.91 and −21.19 ‰ (V-PDB) give an average $\delta^{13}C$ value of the site of −23.05 ‰ (STD = 0.69). For Phase I we obtained a general average of −23.02 ‰ (STD = 0.69), ranging between −24.19 and −21.19 ‰; the average for Phase II is −23.34 ‰ (STD = 0.83), ranging between −24.09 and −22.60 ‰; finally, −23.73 ‰ (STD = 0.53) for Phase III, ranging between −24.47 and −22.82 ‰ (Fig. 2).

The average of $\delta^{13}C$ values of the Triticeae is −22.93 ‰, the *H. vulgare* samples have values of −23.12 ‰, relatively similar to *T. aestivum/durum* (−22.86 ‰). For the charcoal samples, the general signature is −23.52 ‰ (STD = 0.48), ranging between −24.33 and −22.52 ‰; the *P. halepensis* samples show a value of −23.56 ‰ (Table 2) and the *Olea europaea* samples −23.02 ‰.

For the modern samples (year 2014, n = 95), the average is −23.66 ‰ (STD = 1.92), ranging between −28.62 and −20.58 ‰ (V-PDB); for *P. halepensis* leaves −25.23 ‰; for the cereals the signature is −23.25, −22.42 ‰ for wheat samples (N = 15) and −23.45 ‰ (STD = 1.91) for the barley samples (N = 60).

For the seeds from irrigated fields (N = 30), the average isotopic composition of carbon is −25.14 ‰ and for the rainfed barley samples (N = 30) −21.77 ‰ (STD = 0.67), ranging between −20.81 and −23.80 ‰. Generally, for the wheat and barley from rainfed fields, the average is −21.99 ‰ (Table 2).

Table 2 Isotopic composition of carbon ($\delta^{13}C$), isotopic discrimination of carbon ($\Delta^{13}C$) and water use efficiency (WUEi) for archaeological and modern (irrigated and rainfed) cereals and pines analyzed in this study

Plants	Dating		$\delta^{13}C$ ‰ (V-PDB)	$\Delta^{13}C$ ‰	WUEi
Cereal ($n = 175$)	Archaeol.	Average	−22.93 (0.69)	16.96 (0.72)	77 (6)
		Range	−24.91 to −21.19	15.15–19.02	61–91
Pine ($n = 40$)	Archaeol.	Average	−23.56 (0.48)	17.60 (0.50)	72 (4)
		Range	−24.33 to −22.52	16.53–18.42	66–80
Rainfed cereal ($n = 45$)	Present (2014)	Average	−21.99 (0.86)	13.89 (0.90)	144 (10)
		Range	−23.80 to −20.58	12.44–15.78	123–159
Irrigated cereal ($n = 15$)	Present (2014)	Average	−25.14 (1.04)	17.17 (1.09)	108 (12)
		Range	−28 to −23.58	15.54–20.16	75–125
Pine ($n = 20$)	Present (2014)	Average	−25.23 (1.46)	17.27 (1.53)	107 (17)
		Range	−28.62 to −23.33	15.28–20.82	68–128

Note that WUEi integrates $\Delta^{13}C$ and the atmospheric CO_2 concentration (ppm)

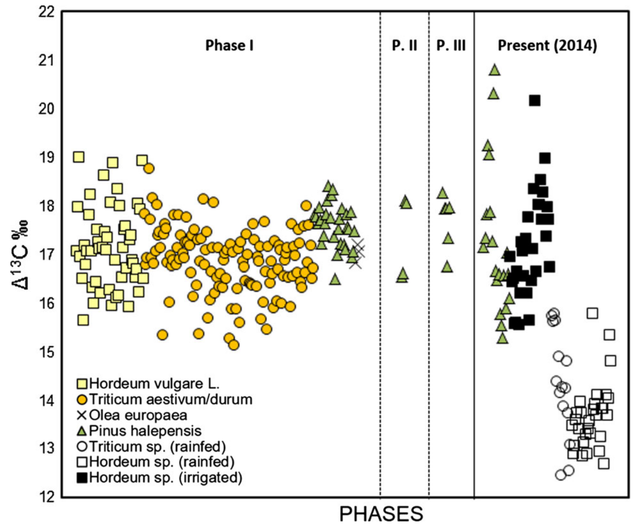

Fig. 3 Scatter plot with the results of the isotopic discrimination of carbon (Δ ^{13}C) throughout Phases I, II and III of the settlement and present-day plants (2014). For symbols, see Fig. 2. Note that the archaeological cereals show Δ^{13}C values that are equivalent to the modern cereals which were irrigated. On the contrary, the rainfed cereals *Triticum* sp. and *Hordeum* sp. show much lower values

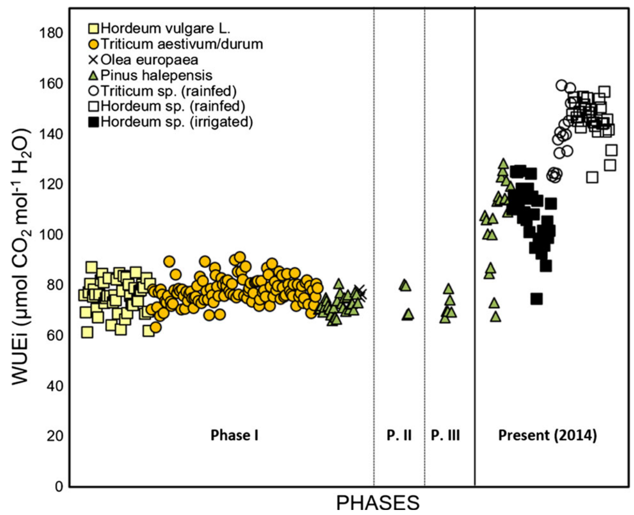

Fig. 4 Scatter plot with the results of water use efficiency (WUEi) throughout Phases I, II and III of the settlement and present-day plants (2014). For symbols, see Fig. 2

Analysis of the isotopic discrimination of carbon (Δ^{13}C)

The general Δ^{13}C average obtained from the site ($n = 218$) was 17.08 ‰ (STD = 0.72), ranging between 15.15 and 19.02 ‰. For Phase I, we obtained a general average of 17.06 ‰ (STD = 0.72), ranging between 15.15 and 19.02 ‰; for Phase II, 17.35 ‰ (STD = 0.86), ranging between 16.57 and 18.13 ‰; and finally, 17.72 ‰ (STD = 0.55) for Phase III, ranging between 16.77 and 18.28 ‰ (Fig. 3).

For the cereal samples we have a general average of 16.96 ‰ (Table 2) and for the *H. vulgare* samples, 17.16 and 16.88 ‰ for *T. aestivum/durum* (Table 1).

As for the charcoal samples, the general signature is 17.56 ‰ (STD = 0.50), ranging between 16.53 and 18.42 ‰. The *P. halepensis* samples show a signature of 17.60 ‰ and the *Olea europaea* samples 17.05 ‰ (Table 1).

The total average for modern samples is 15.64 ‰ (STD = 2), ranging between 12.44 and 20.82 ‰; the *P. halepensis* samples show a value of 17.27 ‰; for all of the cereal samples the signature of isotopic discrimination of carbon is 15.20, 14.34 ‰ for wheat and 15.42 ‰ (STD = 1.98) for barley.

For the irrigated barley samples the average isotopic discrimination is 17.17 ‰ (STD = 1.09), while for the rainfed samples it is 13.67 ‰ (STD = 0.69). Finally, for all rainfed samples (wheat and barley) the average is 13.89 ‰ (Table 2).

Water use efficiency

The water use efficiency (WUEi, μmol CO_2 mol^{-1} H_2O) has been calculated for each of the samples. In total the average was 76 (STD = 6), ranging between 61 and 91; the change through the various phases shows an average of 76 (STD = 5), ranging between 61 and 91; Phase II, 74 (STD = 7), between 68 and 80, and Phase III 71 (STD = 4), between 67 and 79 (Fig. 4).

As for the charcoal samples, the average is 73 (STD = 4), ranging between 66 and 80; having a look at the individual species, *P. halepensis* remains show a value of 72 and *Olea europaea*, 76; as for the cereals, the signature is 77, for the *T. aestivum/durum* samples, 78 and for *H. vulgare* samples, 76.

The average for modern plants is 124 (STD = 22), ranging between 68 and 159; for *P. halepensis* this is 107; for the cereal samples, the average is 129–139 for the wheat and 127 for the barley. For the irrigated barley the WUEi is 108; the rainfed barley shows a WUEi of 146, ranging between 123 and 157. Finally, the average for rainfed cereals (wheat and barley) is 144 (Table 2).

Discussion

Charcoal studies at the Terlinques site show that already at the end of 3rd millennium BC the environment was relatively dry (Machado et al. 2009). This is in agreement with numerous studies indicating a climatic degradation in southwest Europe from the middle Holocene (Carrión et al. 2010a, b; Yanes et al. 2011; Aranbarri et al. 2014). Lake sediments indicate a very dry phase (Gonzalez Samperiz et al. 2008; Morellon et al. 2009), some lakes drying up completely during this period (4–3 ka), but then the lake levels rose, in general, from about 3,000 years BP to the present (Martin Puertas et al. 2010). However, isotopic values obtained from seed remains (≈4,100–3,500 BP) in this study do not indicate arid climatic conditions (Figs. 2, 3, 4). The average Δ^{13}C around 17 ‰ is much greater than of the rainfed Triticeae (≈14 ‰) in modern times (2014). Additionally, Δ^{13}C values of archaeological samples (15–19 ‰) are less variable than values of modern cereals (12.4–20 ‰), but the range is similar to irrigated samples (15.5–20 ‰). This would suggest a greater human influence, due to irrigation-based agriculture, using lake and other water resources. Consequently, the Bronze Age subsistence strategies in this area would have been strongly influenced by a climate that was drier, and compensated by the existence of a lake complex (Fig. 1) and the possible use of irrigation. Precioso Arévalo and Rivera (1999) have already suggested that the seed remains had been cultivated under very favourable moisture conditions. This was related to a high edaphic moisture level in this area, either because of the use of streams and the lake, or thanks to irrigation strategies that were organized, to a greater or lesser extent.

In Phase I relatively similar Δ^{13}C values can be observed for the cereal and *P. halepensis* charcoal samples (Table 1). It is known that grasses and trees from the same location show different Δ^{13}C values, since the grasses show a greater WUEi, that is, less isotopic discrimination of Δ^{13}C, which is related to their lesser root development (Stewart et al. 1995; Kohn 2010). This would indicate that wheat and barley developed under different climatic conditions or especially favourable human-induced conditions, which has been pointed out previously (Precioso Arévalo and Rivera 1999). Moreover, the existence of irrigation practices has been proposed, at least for legumes and perhaps for cereals, for some settlements in the southeast Iberian Peninsula (Araus et al. 1997; Aguilera et al. 2008). Although some studies have suggested a tree ring enrichment in δ^{13}C as compared to leaves (Stewart et al. 1995; Brooks et al. 1997; Klein et al. 2005; Brandes et al. 2006; Barnard et al. 2007; Brandes 2007; Gressler et al. 2009), we can compare values of different taxa in archaeological and modern contexts, looking for the relationship between cultivated and wild plants under similar conditions (Ferrio Díaz et al. 2005). So, taking the modern samples (2014) as a reference, we can verify how *P. halepensis* shows values that are similar to the irrigated barley, but very different from those of the rainfed barley and wheat, which is in agreement with our hypothesis (Figs. 3, 4).

Some authors have proposed various global isotopic limits, not local, to determine the presence of irrigation: Araus et al. (1997) suggested that Δ^{13}C values of 17.5 and 18 ‰ for wheat and barley respectively imply irrigation management; Wallace et al. (2013) indicate a gradient (poorly watered, moderately watered and well-watered), also with different limits for wheat and barley, ranging between 15 and 19 ‰. However, other researchers, such as Stokes et al. (2011) or Flohr et al. (2011) suggest that site-specific parameters must be considered, as various studies have demonstrated (Heaton et al. 2009; Riehl 2012; Riehl et al. 2014). In any case, our values (15–19 ‰) are within the range of irrigated cereals of Wallace et al. (2013), and fall partially in the range of Araus et al. (1997) (Fig. 5). Modern samples from the Terlinques area, both rainfed and irrigated, are at the correct theoretical levels of Wallace et al. (2013). Additionally, for comparison we have collected data from other authors (Fig. 5). In general, these values indicate that the artificially irrigated footprint could be present to a greater degree than previously thought.

On the other hand, we have approximately similar Δ^{13}C values for barley and wheat in the archaeological context (17.16 and 16.88 ‰). It has been pointed out in literature that wheat and barley have different average values of isotopic discrimination of carbon (Araus et al. 1997; Anyia et al. 2007; Flohr et al. 2011). According to the model of

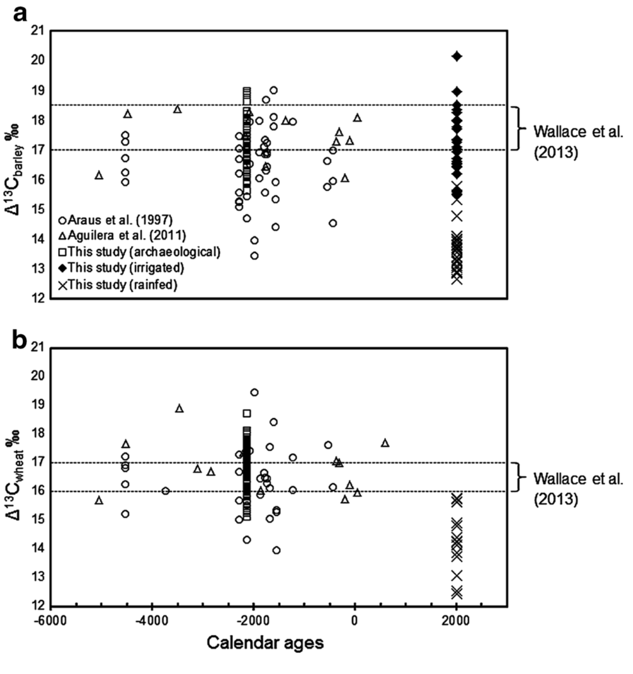

Fig. 5 Scatter plot with the results of the isotopic discrimination of carbon (Δ^{13}C) for samples in the southeast Iberian Peninsula. **a** barley; **b** wheat. The data includes samples from Araus et al. (1997) (empty circles), Aguilera et al. (2011) (*empty triangles*) and from this study: archaeological samples (*empty squares*), modern irrigated cereals (*filled rhomboids*) and modern rainfed cereals (*crosses*). Dotted lines represent the range of the model proposed by Wallace et al. (2013). Limits proposed by Araus et al. (1997) are included. Note that in this study, among the archaeological samples, 18 % of the barley and 90 % of the wheat indicate that they were moderately-watered or well-watered (Wallace et al. 2013)

Wallace et al. (2013), which includes boundaries proposed by Araus et al. (1997), 90 % of wheat grains suggest moderately or well-watered levels, but only 18 % of barley (Fig. 5). The results obtained for both species and the differences pointed out in literature could lead us to believe that moisture gradients were part of a selective strategy in the specific cereals sown, especially with regard to wheat, as has been proposed for settlements in the Near East and western Asia (Masi et al. 2014; Wallace et al. 2015). This is consistent with the possible use of watering practices and of wetter soils. However, it is necessary to take into account local backgrounds and differences between sites in order to compare past and current conditions (Stokes et al. 2011).

Finally, when these isotopic values are transformed into WUEi, it has been possible to confirm that cereals of the Bronze Age are similar to a theoretical slightly stressed plant such as *P. halepensis* (WUE: 77 vs. 72). In contrast, modern rainfed cereals have high WUEi values (144), in agreement with the present dry conditions; only irrigated cereals show similar values to pine (108 vs. 107).

Conclusions

The comparison of isotope values and the calculations derived for the water use efficiency carried out on archaeological and modern samples indicate a lower WUEi in the archaeological samples. This would be compatible with wetter growing conditions or, as seems more probable, it represents direct evidence of the use of irrigation or deliberate water management. Apart from this, the Bronze Age cereals have a WUEi that is similar to the trees (*P. halepensis*) in the same period, with an extensive root system that reaches the ground water. In modern cereals only samples that were cultivated with irrigation techniques come close to the values of pine, which also strengthens this hypothesis. Moreover, our results are consistent with models proposed by other authors (Araus et al. 1997; Wallace et al. 2013), which are compatible with the use of irrigation practices at Terlinques.

Finally, these results confirm the necessity of opening new lines of investigation that focus on integrating multiple plant taxa and present-day samples, while taking into account site-specific conditions and the complexity of environmental and human-related processes. This has allowed us to establish relations between plants that grew in rainfed conditions and with the help of irrigation techniques. In this way it has also been possible to verify the effects of global change in the studied area.

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