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Juan P. Ferrio · José Luis Araus · Ramon Buxó · Jordi Voltas · Jordi Bort

Water management practices and climate in ancient agriculture: inferences from the stable isotope composition of archaeobotanical remains

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Abstract Carbon isotope discrimination ($\Delta^{13}C$) in charred grains from archaeological sites provides reliable information about water availability of ancient crops. However, as cereals are cultivated plants, they may reflect not only climatic fluctuations, but also the effect on water status of certain agronomic practices, such as sowing in naturally wet soils or irrigation. In this work, we propose a methodological approach to combine $\Delta^{13}C$ data from different plant species, in order to discriminate between climate-derived and anthropogenic effects on ancient crops. We updated previous models for estimating water inputs from $\Delta^{13}C$ of cereal grains of *Hordeum vulgare* and *Triticum aestivum/durum*, and we applied them to published data from several archaeological sites, including samples from the Neolithic to the present day in northeast and southeast Spain, as well as from the Neolithic site of Tell Halula (northwest Syria). We found an important decrease in water availability from the Neolithic to the present time in the three areas of study, especially clear for the two driest areas (southeast Spain and northwest Syria). Potential differences in water management practices between wheat and barley, as well as between cereal and legume crops (*Vicia faba* and *Lens culinaris*), are also discussed on the basis of the comparison of $\Delta^{13}C$ values across several archaeological sites.

J. P. Ferrio · J. Voltas
Departament de Producció Vegetal i Ciencia Forestal, E.T.S.E.A, Universitat de Lleida,
Av. Rovira Roure, 191, E-25198 Lleida, Spain
e-mail: jaraus@ub.edu

J. L. Araus · J. Bort
Unitat de Fisiologia Vegetal, Departament de Biologia Vegetal, Facultat de Biologia,
Universitat de Barcelona,
Av. Diagonal, 645, E-08028 Barcelona, Spain

R. Buxó
Museu d'Arqueologia de Catalunya,
C. Pedret, 95, E-17007 Girona, Spain

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Introduction

Improving our knowledge about the way early farmers reacted to environmental changes might assist us in facing current conflicts resulting from water shortage in different areas of the world. Up to now, the most evident way to obtain insight into ancient water management methods is the study of archaeological structures related to water uptake or distribution. However this methodology is limited to relatively advanced societies, and does not give any information about the actual results of such management on the performance of the crops. Several indirect methods have been proposed to determine the water status of ancient crops, such as the size of charred seeds (Ferrio et al. 2004; Helbæk 1960), the analysis of phytoliths (Rosen and Weiner 1994), as well as the study of weed floras (Jones et al. 1995). However, none of these methods is conclusive, and some of them, such as phytolith analyses, are only applicable to certain crops.

Carbon isotope composition ($\delta^{13}C$) in C_3 plant tissues constitutes an integrated record of the ratio of intercellular to atmospheric concentration of CO_2 during the period in which the carbon was fixed, and thus reflects the balance between carbon fixation and stomatal conductance. Plants typically react to a decrease in water availability through stomatal closure, and thus $\delta^{13}C$ from plant tissues is a good indicator of the water status during the time these tissues were formed (see Farquhar et al. 1989 for further details on carbon isotope theory). Many studies under growth chamber and field conditions have shown that plants grown under water stress produce leaves with higher (that is, less negative) $\delta^{13}C$ values (see references in Ferrio et al. 2003b; Hubick et al. 1993). According to these findings, a significant relationship would be expected between $\delta^{13}C$ and environmental parameters related to water availability. Although most of the basic studies on δ^{13}C and plant water relations have been performed on leaf material (as this is the tissue directly involved in photosynthesis), further works have shown that similar relationships can be established using other plant tissues, such as seeds or wood.

Wood δ^{13}C has been related to changes in various climatic variables, including humidity (Saurer and Siegenthaler 1989; Stuiver and Braziunas 1987), precipitation (Ferrio et al. 2003a; Warren et al. 2001) and water pressure deficit (Ferrio and Voltas 2005; Korol et al. 1999), among others. Although most of these works were limited to the last 100 or 200 years, such relationships have been recently extended over longer tree-ring chronologies, allowing high resolution climatic reconstructions back to ca. 11000 B.P. (see references in Heaton 1999). However, these studies are limited to a few world regions where such long-term chronologies are available. Even though they provide important keys to the understanding of global climate changes, it would be helpful to find alternative sources of information to refine climatic reconstructions at the local scale. In this context, Araus and Buxó (1993) proposed the use of δ^{13}C in charred grains from archaeological sites to gain insight into the environmental conditions in early agriculture. This approach has been subsequently improved to allow the quantification of cereal water inputs (Araus et al. 1997a, 1999a) and crop yields (Araus et al. 1999b, 2003a). These works are based on a comparison with modern reference material, since δ^{13}C of seeds shows negligible changes during carbonisation, and thus the original isotopic signal is well preserved in charred remains (Araus et al. 1997b; Marino and DeNiro 1987). The impact of carbonisation on the δ^{13}C of wood has not yet been fully described, but indirect evidence shows that δ^{13}C in fossil charcoal also retains the original climatic signature of wood (February 2000; Van-Klinken et al. 1994; Vernet et al. 1996).

In this context, it is necessary to find some additional clues to interpret the evidence of ancient crop conditions derived from δ^{13}C analyses. Indeed, crop water availability, and thus δ^{13}C values in cereal crops, may be affected not only by climatic variations, but also by changes in crop management, such as irrigation practices (Araus et al. 1997b). To solve this question, one possibility is to compare δ^{13}C values found in cultivated plants with those from wild plants, for example trees, which are not directly affected by agricultural practices. On the other hand, comparing the results from different crops can provide evidence about selective water management. In this work, we propose the use of combined δ^{13}C analyses of different plants as a way of obtaining further information from isotope data, with the aim of discriminating between climate-derived and anthropogenic effects on crop water status, as well as distinguishing different strategies of water management.

Materials and methods

Review on δ^{13}C data from archaeological grains

We collected published δ^{13}C values from several archaeological sites in northeast and southeast Spain (Araus et al. 1997b, Araus and Buxó 1993) and from the Neolithic site of Tell Halula, in northwest Syria (Araus et al. 1999a; Ferrio et al. 2003b). The dataset (see Table 1) includes δ^{13}C values from the cereals *Hordeum vulgare* (hulled barley), *Triticum durum/aestivum* (naked wheat) and the legumes *Vicia faba* var *minor* (faba bean) and *Lens culinaris* (lentil).

Determination of Δ^{13}C values

To account for changes in δ^{13}C of atmospheric CO_2 ($\delta^{13}C_{air}$) during the Holocene, we calculated plant Δ^{13}C from $\delta^{13}C_{air}$ and plant carbon isotope composition ($\delta^{13}C_p$), as described by Farquhar et al. 1982):

$$\Delta^{13}C = \frac{\delta^{13}C_{air} - \delta^{13}Cp}{\left(1 + \frac{\delta^{13}Cp}{1000}\right)} \tag{1}$$

$\delta^{13}C_{air}$ was inferred by interpolating a range of data from ice-core records covering the whole Holocene (Eyer et al. 2004; Francey et al. 1999; Indermühle et al. 1999; Leuenberger et al. 1992). We recalculated Δ^{13}C for all the archaeological data compiled, using these updated estimates of past $\delta^{13}C_{air}$.

Reference Δ^{13}C values in present crops

Average values of Δ^{13}C in modern cereals and legumes were compiled from the literature (Araus et al. 1997b, 2003b; Ferrio et al. 2001; Voltas et al. 1999). The dataset includes data from *Hordeum vulgare* (barley), *Triticum aestivum* and *T. durum* combined (wheat) and *Vicia faba* (faba bean) grown in northeast Spain, southeast Spain and northwest Syria, either under irrigated or rainfed conditions (see Table 2). We took advantage of the additional compiled data to update the model developed by Araus et al. (1999a) to estimate crop water inputs from Δ^{13}C in wheat grains.

Meteorological data

In order to enable comparisons among data from different geographical origins, we used as reference values total precipitation from the second half of April to the end of May, coinciding approximately with the average grain filling period across the studied areas. Meteorological data was supplied by the *Instituto Nacional de Meteorología*, the *International Center for Agricultural Research in Dry Areas* (ICARDA) and the *Confederación Hidrográfica del Ebro*.

Statistical analysis

Heterogeneity of slopes ANOVA was performed to determine the differences between barley and wheat in their relationship between Δ^{13}C and water inputs. $\delta^{13}C_{air}$ data from different sources was interpolated by fitting locally weighted least squares (LOESS) regression curves (Cleveland 1979). Due to the far greater time resolution of $\delta^{13}C_{air}$ data available since ca. A.D. 1800, we performed two separate LOESS regressions, one including data from 16100 B.C. to A.D. 1800 (span = 0.1) and the other for the period A.D. 1798–1996 (span = 0.4). The resulting curves were then used as a single one, since they gave nearly identical estimations at the point where they join, around A.D. 1800 (end of the first curve: $\delta^{13}C_{air}(1800)=-6.402$; beginning of the second curve: $\delta^{13}C_{air}(1798)=-6.406$). A linear regression between Δ^{13}C of ar-

Table 1 Ages, chronological date, carbon isotope discrimination ($\Delta^{13}C$) of grains and estimated water inputs (WI) during grain filling for the samples analysed. Mean plus standard error are indicated, as well as the number of samples, between parentheses. Average values of accumulated rainfall from the second half of April to the end of May (P 1/2 A + M) are included, as a reference for present WI during grain filling in the studied sites. $\Delta^{13}C$ values are recalculated from original $\delta^{13}C$ data reported by Araus and Buxó (1993), Araus et al. (1997b, 1999a) and Ferrio et al. (2003b), and updated estimations of air $\delta^{13}C$ (Eyer et al. 2004; Francey et al. 1999; Indermühle et al. 1999; Leuenberger et al. 1992)

Archaeological site	Cultural period	Age (cal B.P.)	Air $\delta^{13}C$ (%)	$\Delta^{13}C$ (%)				*WI* (mm)		P 1/2 A + M (mm)
				H. vulgare	*T. aest/durum*	*V. faba*	*L. culinaris*	*H.vulgare*	*T.aest/durum*	
NE Spain										
L'Esquerda	Middle Ages	700–800	−6.4		17.7±0.4 (3)				143±18	115
St.Vicenç Enclar*	Middle Ages	800–900	−6.4	15.9±0.1 (2)	17.0 (1)			68±3	108	105
C.Mediona	Middle Ages	800–900	−6.4	16.9±0.8 (2)	16.4 (1)			103±32	88	88
Empúries	Iron	2300–2400	−6.5	16.9±1.2 (2)	16.8±0.2 (2)			112±48	103±7	83
Ullastret	Iron	2300–2400	−6.5	17.3±0.6 (2)	17.0±0.3 (3)			120±25	110±12	80
Bòbila Madurell	Iron	2400–2750	−6.5	17.0±0.0 (2)	16.6±0.2 (2)			104±1	94±7	93
Sitges UAB	Iron	2550–2650	−6.5	16.0±0.8 (2)	17.2 (1)			75±22	117	85
Montou*	Late Bronze	2850–3350	−6.5	17.6±0.3 (2)	17.0±0.3 (2)			132±13	108±10	83
Montou	Middle Bronze	3200–3700	−6.5	17.3 (1)	17.5 (1)			116	131	83
Institut de Manlleu	Chalcolithic/Bronze	4450–4850	−6.3	17.3±0.9 (2)	17.2 (1)			124±40	116	115
Cova 120	Neolithic/ Chalcolithic	4690–4910	−6.3		16.9±0.0 (2)				104±1	150
Can Tintorer	Neolithic	4690–5290	−6.3	16.2 (1)				77		75
Montou	Neolithic	5700–6290	−6.4	17.9 (1)	19.3 (1)			143	251	83
Plansallosa	Neolithic	6710–6890	−6.3	18.0 (1)				152		143
Cova 120	Neolithic	6600–7200	−6.4	18.5 (1)	17.4±0.2 (2)			181	127±11	150
La Draga	Neolithic	7200–7750	−6.6	17.5 (1)	17.7 (1)			125	140	135
SE Spain										
Fuente Amarga	Iron	2300–2400	−6.5	16.2±0.8 (3)	16.2 (1)			84±21	81	76
Puente Tablas	Iron	2400–2500	−6.5	16.2±0.4 (2)	17.7 (1)			79±12	139	82
Cuesta del Negro	Bronze	3100–3190	−6.5	18.0 (1)	16.7±0.6 (2)			152	99± 20	53
Los Palacios	Bronze	3240–3520	−6.5	15.3±0.4 (3)	15.0±0.5 (3)			57±9	54±8	75
Peñalosa	Bronze	3340–3570	−6.5	18.1±0.2 (2)	18.5 (1)	17.5 (1)		154±9	191	66
Motilla del Azuer	Bronze	3360–3720	−6.4	16.4 (1)	16.4±0.7 (3)			84	93±25	75
Motilla de las Cañas	Bronze	3350–3750	−6.4	17.2 (1)	16.5 (1)			113	92	75
Castellón Alto	Bronze	3520–3700	−6.4	16.8±0.2 (2)	16.5±0.1 (2)			96±7	91±2	76
Fuente Amarga	Bronze	3530–3730	−6.4	16.6±0.9 (2)	16.6 (1)	15.4 (1)		94±30	96	76
Cerro de la Virgen	Early Bronze	3730–3840	−6.4		16.3±0.3 (2)	18.5 (1)			86±9	76
Las Pilas	Chalcolithic	3840–3940	−6.4		15.1 (1)	19.1 (1)			55	38
Cerro de la Virgen	Campaniform	3900–4040	−6.4	18.2 (1)	17.6 (1)	19.1 (1)		161	138	76
Campos	Chalcolithic	3925–4165	−6.4		15.2±0.6 (2)	17.3 (1)			57±12	38
Cerro de la Virgen	Pre-campaniform	4000–4100	−6.3	17.4 (1)	17.1 (1)	18.8 (1)		120	112	76
Los Millares	Chalcolithic	3880–4240	−6.4	17.3±0.4 (2)	17.5 (1)	16.4±1.2 (3)		117±16	132	42
El Malagón	Chalcolithic	3860–4265	−6.4	15.5 (1)	16.0±0.5 (3)	16.4 (1)		59	78±13	80
Cueva del Toro	Late Neolithic	5200–5700	−6.4		16.2 (1)				83	70
Cueva del Toro	Late Neolithic	5700–6500	−6.3		16.5 (1)				92	70
Cueva del Toro	Middle/ Late Neolithic	5700–6500	−6.3	17.3±0.3 (2)	16.8±0.5 (4)	17.1±0.7 (2)		116±12	106±15	70
NW Syria										
Tell Halula	Late Neolithic	8400–9125	−6.5	16.7±0.4 (4)	16.8±0.5 (3)		18.0±0.5 (6)	96±14	106±18	33
Tell Halula	Late PPNB	9125–9490	−6.5		17.4±0.3 (10)		17.3±0.4 (7)		130±13	33
Tell Halula	Middle PPNB	9600–9840	−6.6	17.3±0.2 (2)	17.2±0.3 (12)		17.0±0.3 (5)	114±10	123±13	33

*St. Vicenç Enclar and Montou are indeed located in Andorra on SE France, respectively, but have been included within "NE Spain" for simplicity

Table 2 Average values of carbon isotope discrimination ($\Delta^{13}C$) of barley, wheat and faba bean grains, grown under rainfed and irrigated conditions, in the three geographical areas studied. Mean plus standard error are indicated, as well as the number of field trials analysed, between parentheses. For the rainfed trials, we include also water inputs (WI) during grain filling (estimated from $\Delta^{13}C$ values) and, for comparison, accumulated rainfall from the second half of April to the end of May (P 1/2 A + M). $\Delta^{13}C$ values compiled from Araus et al. (1997b, 2003b), Ferrio et al. (2001), and Voltas et al. (1999)

Geographic area	Rainfed/irrigated	$\Delta^{13}C$ (‰)			WI (mm)		P 1/2 A + M (mm)
		H. vulgare	*T. aest/durum*	*V. faba*	*H. vulgare*	*T. aest/durum*	
NE Spain	Rainfed	16.4±0.5 (9)	15.4±0.9 (3)		82±14	62±20	70
	Irrigated	19.0±0.4 (5)	17.9±0.5 (3)				
SE Spain	Rainfed	15.1±0.5 (9)	14.9±1.0 (7)	14.9 (1)	51±10	52±15	59
	Irrigated	18.7 (1)	16.9±0.1 (6)	16.7±0.6 (3)			
NW Syria	Rainfed	14.6±0.6 (2)	14.3±0.5 (2)		42±9	41±8	35
	Irrigated		16.8±0.1 (2)				

chaeological grains of wheat and barley across sites was used to determine the degree of agreement between the two species, as well as to find potential outliers, according to the 95% confidence interval of the regression line.

Results and discussion

Modelling water inputs from $\Delta^{13}C$ in grains

The models relating $\Delta^{13}C$ in cereal grains and water inputs during grain filling are plotted in Fig. 1. Araus et al. (1997a, 1999a) already reported strong positive relationships between water inputs and $\Delta^{13}C$ values from *Hordeum vulgare* (barley) and *Triticum durum/aestivum* (wheat) grains across a range of environmental conditions. After adding data from six wheat trials located in the Iberian Peninsula (Araus et al. 2003b), both species provided nearly identical relationships, indicating that despite their differences in growth cycles and ecological preferences, they show similar physiological responses to water availability. Nevertheless, wheat $\Delta^{13}C$ values tended to be smaller than those of barley, especially in the driest environments, in agreement with the greater sensitivity of wheat to water stress. On the other hand, it should be noted that in both cases the observed relationship was not linear, and thus $\Delta^{13}C$ was more sensitive to water availability under harsher conditions. This can be explained by the fact that the main factor relating $\Delta^{13}C$ to water availability is the ratio of intercellular to atmospheric concentration of CO_2 which is supposed to reach its maximum value in non-stressed plants. Thus, under near-optimum crop water status, no further increments in this variable, and thus in $\Delta^{13}C$, would be expected (Farquhar et al. 1989; Lambers et al. 1998).

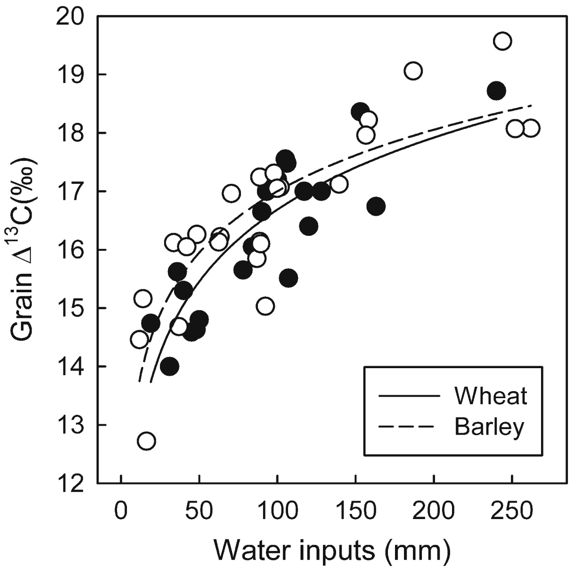

Fig. 1 Relationship between water inputs (WI, rainfall plus irrigation if applied) during grain filling and $\Delta^{13}C$ of barley (*Hordeum vulgare*, empty circles) and wheat (*Triticum aestivum* and *T. durum*, *filled circles*) grains. Data from Araus et al. (1997a) for barley and from Araus et al. (1999a, 2003b) for wheat; Δ_{barley}=9.99+1.52* ln (WI), r^2=0.73, p<0.001, N=25; Δ_{wheat} = 8.50+1.78* ln (WI), r^2=0.73, p<0.001, N=22

Applications of $\Delta^{13}C$ to fossil plant remains

Reconstruction of past climate changes in the Mediterranean Basin

A case study of the application of archaeological plant remains to the analysis of climate fluctuations is shown in Fig. 2. The evolution of $\delta^{13}C_{air}$ during the Holocene, as inferred from ice-core records, is shown at the top of Fig. 2a. Average $\delta^{13}C$ values in cereal grains (wheat and barley combined) are plotted at the bottom of Fig. 2a. The data presented here was compiled from the archaeological sites described in Table 1, as well as from modern agronomic trials (see Table 2). $\Delta^{13}C$ values were then recalculated from the updated estimates of $\delta^{13}C_{air}$ and measured $\delta^{13}C$ in grains, as described in Eq. (1) (Fig. 2b). Finally, by applying the modelled relationship between $\Delta^{13}C$ and water inputs (Fig. 1), it was possible to estimate water availability in the past from $\Delta^{13}C$ of ancient grain samples (Fig. 2c). We observed an important decrease in water availability from the Neolithic to the present time in the three regions of study, which was especially clear for the two driest areas, southeast Spain and northwest Syria. These results indicate that during the period of early agriculture, cereals were cultivated under a much better

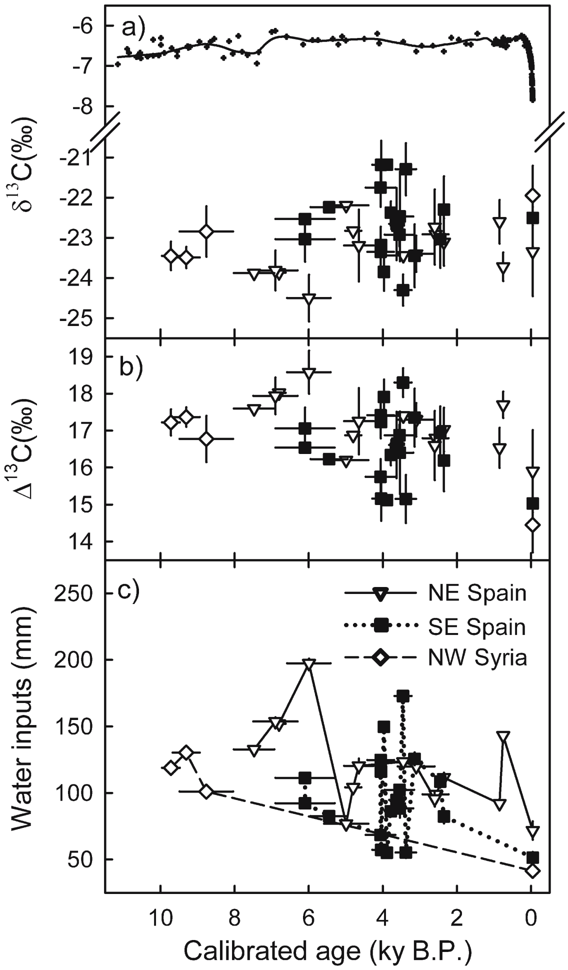

Fig. 2 Estimates of past water inputs from carbon isotope discrimination ($\Delta^{13}C$) of archaeological cereal grains (*Hordeum vulgare* and *Triticum aestivum/durum* combined) collected from archaeological sites located in three areas of the Mediterranean Basin (northeast Spain, southeast Spain and northwest Syria, see Table 1). **a** Evolution of the isotopic composition ($\delta^{13}C$) in atmospheric CO_2 (top) and archaeological cereal grains (*bottom*). Both variables (air and plant $\delta^{13}C$) are required to calculate $\Delta^{13}C$ of grains **b**, as described in Eq. (1). **c** Evolution of cereal water inputs (estimated from $\Delta^{13}C$) from the Neolithic to present times in the areas studied

water status than that expected from present-day (rainfed) conditions in the same areas. This finding is in agreement with archaeobotanical evidence supporting the possibility that environmental conditions during the period of early agriculture were cooler and moister than those of today, both in the Near East (Harlan 1998; Willcox 1996) and the Iberian Peninsula (Vernet 1990). The origin of such an increase in aridity appears to be relatively recent, and has been probably enhanced by human activities. Indeed, several palaeoenvironmental records have shown a considerable decrease in precipitation in the Mediterranean area since the mid 19th century, along with a global rise in temperature (Barriendos and Martín-Vide 1998; Creus et al. 1996; Folland et al. 2001; Riera et al. 2004).

Is it feasible to discriminate between climatic and anthropogenic effects on $\Delta^{13}C$?

As cereals are cultivated plants, they may reflect not only climatic fluctuations, but also the effect on water status of certain agronomic practices, such as sowing in naturally wet soils (Hillman 1996) or irrigation (Helbæk 1960). This might be the case, for example, in some sites from northeast and southeast Spain, where estimated water inputs exceeded the expected values for rainfed cultivation, even considering the wetter climate in the area (for example, Montou and Cova 120, in northeast Spain (and southeast France); Puente Tablas, Peñalosa, Cuesta del Negro, Cerro de la Virgen and Los Millares, in southeast Spain). A possible way to discriminate between natural and anthropogenic changes in plant water status is to compare the carbon isotope signature of cultivated plants with that of wild plants, such as trees. This is shown in Fig. 3, where we compared the estimated water inputs for barley and wheat grains collected in northeast Spain with $\Delta^{13}C$ values in wood charcoals from southeast France, calculated from δ_a (see Fig. 2a) and wood $\delta^{13}C$ data reported by Vernet et al. (1996) for *Quercus humilis* (deciduous oak) and *Juniperus sp.* (juniper). As these two areas are close to each other and have similar climates, we would expect to find common trends in both studies, if climate were the main factor determining crop water status. As with cereals from northeast Spain, Vernet et al. (1996) found evidence of higher water availability in the past than at present. Moreover, both studies displayed relatively dry episodes (around 7000 B.P., 5000 B.P., 3000 B.P. and 1000 B.P.), alternating with wetter periods (around 6000 B.P. and 4000 B.P.), and concluding with a new decrease in water availability during the last millennium. The relatively good agreement between the results obtained for cereals and for trees suggests that most of the observed changes in crops may be explained by climatic conditions. In order to further check the climatic effect on crops, we are currently determining the carbon isotope signature of charcoals from the same sites where cereal grains were collected (Ferrio, Alonso, López, Araus and Voltas, submitted manuscript). By comparing the results of trees and cultivated plants co-occurring in the same sites, it may be possible to estimate more accurately the relative influence of human activities on the water status of crops.

An alternative approach for detecting selective water management strategies is based on the comparison of crop water status among different crops grown in the same area. This is shown in Fig. 4, putting together all the data in Table 1. Hence, we compared the relationship across sites between $\Delta^{13}C$ of barley and wheat grains (Fig. 4a) and that between $\Delta^{13}C$ of cereals (barley and wheat combined) and either *Vicia faba minor* (faba bean) or *Lens culinaris* (lentil) (Fig. 4b). We found that $\Delta^{13}C$ values in barley and wheat grains were well correlated, showing similar trends across the sites. This suggests that both cereals were grown under similar conditions, and that observed fluctuations were mostly due to common factors affecting their water status, such as climate. In

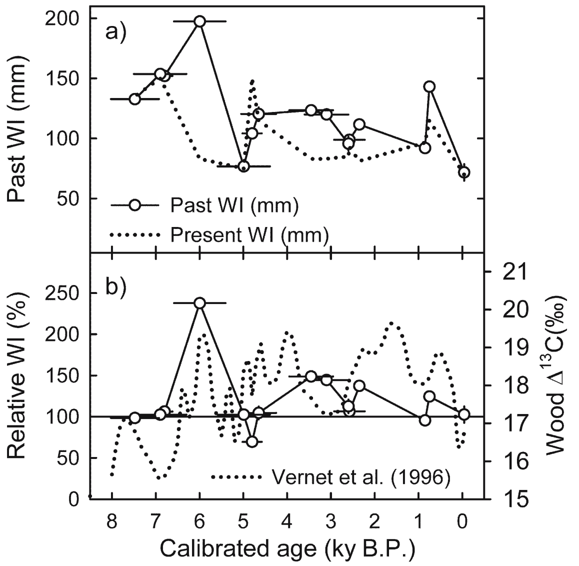

Fig. 3 **a** Evolution of estimated water inputs (WI) in archaeological cereal grains (*Hordeum vulgare* and *Triticum aestivum/durum* combined) collected in archaeological sites from northeast Spain, compared with average present values in the sites (as described in Table 1). **b** Evolution of WI, as a percentage respect current values. For reference, a horizontal line is plotted at WI = 100% of present values. The dotted curve indicates the evolution of $\Delta^{13}C$ in wood charcoals of deciduous oak (*Quercus humilis*) and juniper (*Juniperus* sp.), collected at several archaeological sites from southeast France. Charcoal $\Delta^{13}C$ values were calculated from wood $\delta^{13}C$ (Vernet et al. 1996) and air $\delta^{13}C$, as described in Eq. (1)

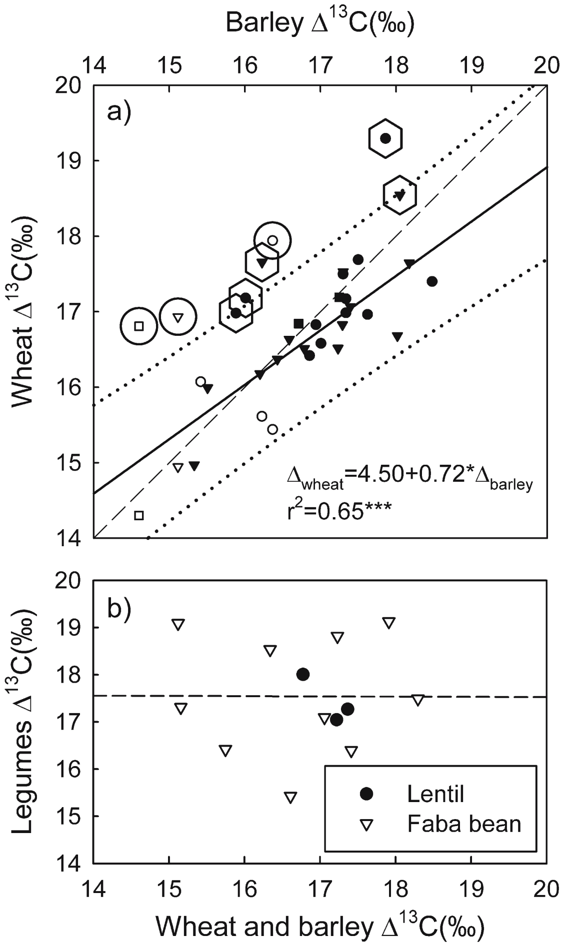

Fig. 4 Relationship between $\Delta^{13}C$ values of *Hordeum vulgare* (*hulled barley*) and either *Triticum aestivum/durum* (naked wheat) or *Vicia faba minor* (faba bean), across all the archaeological results from Table 1. **a** Detection of potential outliers for the relationship between wheat and barley, taking present data for comparison. Empty symbols—present-day samples, used for reference (see Table 2); filled symbols—archaeological samples; dotted lines - 95% confidence intervals for the regression line; dashed line - 1:1 reference line. Origin of the samples: circles - northeast Spain; triangles - southeast Spain; squares– northwest Syria. The encircled points correspond to present-day values for irrigated wheat, against rainfed barley; the points surrounded by hexagons are "outlier" archaeological sites where wheat displayed higher $\Delta^{13}C$ values, probably indicating differential agronomic practices for wheat and barley. **b** Relationship between $\Delta^{13}C$ of legumes (faba bean and lentil) and cereals (wheat and barley combined), indicating the flat (r^2 = 0.00) regression line obtained (no relationship)

contrast, values of $\Delta^{13}C$ for faba beans and lentils were unrelated to those of cereal grains, being also significantly higher (about 1% on average). Differences in $\Delta^{13}C$ between cereals and grain legumes could be explained (at least in part) in terms of differences in growth pattern. Whereas cereals are determinate plants, producing all ears at one time, and grain growth coincides with the onset of drought in the Mediterranean region, legumes are indeterminate plants, producing successive pods throughout the crop cycle (generally from March to June). Therefore, for faba beans and lentils, most seeds may develop under a higher water status. On the other hand, the possibility that legumes were irrigated, even when cereals were cultivated under rainfed conditions, cannot be discarded. Indeed, we found that $\Delta^{13}C$ values of archaeological faba beans were closer to those measured in present-day irrigated crops near the sites, than to those of rainfed crops (see Table 2). On the other hand, the frequency of legume seeds found in the archaeological contexts studied was considerably lower than that of cereal grains. In spite of the uncertainties associated to the uneven preservation of different types of plant remains (Wilson 1984; Wright 2003), the relative frequencies of cereals and legumes might indicate that the area of cultivation under grain legumes would be very small compared with that of cereals. If this were the case, such small cultivated areas would be probably devoted to labour-intensive garden crops with supplementary irrigation, thus explaining the high $\Delta^{13}C$ values observed. Intensive irrigated cultivation of faba bean could ensure a basic protein source in the human diet (Heiser 1990). The combination of extensive cereal crops expanding around human settlements with smaller plots of vegetables and legumes close to the living area has been reported to be the most common pattern in subsistence and pre-industrial agriculture (Hillman 1973). The above data suggest that this kind of management of water and soil resources could have begun during the early phases of agriculture.

Further analysis of the relationship between barley and wheat $\Delta^{13}C$ across the sites (Fig. 4a) can provide additional information on agronomic practices related to water management. Although both crops followed the same relationship between water inputs and $\Delta^{13}C$ (see Fig. 1), $\Delta^{13}C$ values of wheat in archaeological sites were generally lower than those of barley (most points fell below the 1:1 reference line plotted in Fig. 4a). This suggests that barley grains were grown with greater water availability than wheat. Would this mean that barley was selectively grown under better conditions than wheat? Apparently not: if we consider the current growth cycles of the two species, we will find that barley grows up faster than wheat, reaching maturity about two weeks earlier. Thus, even growing at the same site, barley grains in Mediterranean climates are generally formed under moister conditions than wheat grains, as drought increases greatly during the last weeks of the crop cycle (May-June). Consequently, it is expected that barley grains generally show higher $\Delta^{13}C$ values than the co-occurring wheat grains. However, in Fig. 4a there are some points where wheat has a considerably greater $\Delta^{13}C$ than barley, falling far away from the fitted regression line (St. Vicenç Enclar, Sitges UAB and Montou, in northeast Spain; Puente Tablas and Peñalosa, in southeast Spain, see also Table 1). It is likely that these potential outliers indicate some selective treatments to enhance the performance of wheat crops, but not applied in barley, including irrigation or sowing in naturally wet alluvial soils (Araus et al. 1997b; Bar-Yosef et al. 1989). When we plotted in Fig. 4a present-day values of rainfed barley, compared with either rainfed or irrigated wheat, we found that the plots for rainfed wheat fitted well within the regression line for the archaeological sites. In contrast, the plots of rainfed barley related to irrigated wheat fell out of the 95% confidence intervals of prediction for the regression line, and showed values for wheat $\Delta^{13}C$ similar to those of the presumed "archaeological" outliers. This further supports the idea that sites showing greater wheat $\Delta^{13}C$ involved a different water management for wheat and barley. As barley is less drought-sensitive than wheat, it is a common practice in dry areas to keep barley as a rainfed crop, reserving any additional water supply, or the moister soils, for example closer to a water course, for wheat. This practice is also followed now because most barley is used for animal feed, whereas wheat is preferred for human consumption. Again, we can find evidence of water and soil management practices during the period of early agriculture that resemble those currently found in some areas. This could be of interest not only to reconstruct ancient agronomic techniques, but also to evaluate the potential long-term impact of current practices, looking at their consequences in the past.

Conclusions

Despite the drawbacks of inferring past conditions based on present relationships, this novel approach can help to identify events in which early farmers started to develop a conscious water management strategy to improve their crops' performance. It also seems possible to relate these events to the climatic conditions in which they were developed, or to look for possible changes in response to climate and/or landscape modifications. In particular, our results suggest that, in general, ancient cereals (both wheat and barley) were grown under better water status than modern crops. The more favourable water conditions were probably due to climatic variations, as suggested by the relatively good agreement between crop and tree remains. Nevertheless, we found evidence that, in some cases, wheat was probably favoured by ancient farmers, who sowed it in better soils than barley, or under supplementary irrigation. Our results also indicate that legumes were usually grown under wetter conditions than cereals, most likely in small irrigated plots.

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References

Araus, J.L., Buxó, R. (1993). Changes in carbon isotope discrimination in grain cereals from the north-western Mediterranean basin during the past seven millenia. Australian Journal of Plant Physiology, 20, 117–128

Araus, J.L., Febrero, A., Buxó, R., Camalich, M.D., Martin, D., Molina, F., Rodriguez-Ariza, M.O., Romagosa, I. (1997a). Changes in carbon isotope discrimination in grain cereals from different regions of the western Mediterranean basin during the past seven millennia. Palaeoenvironmental evidence of a differential change in aridity during the late Holocene. Global Change Biology, 3, 107–118

Araus, J.L., Febrero, A., Buxó, R., Rodriguez-Ariza, M.O., Molina, F., Camalich, M.D., Martin, D., Voltas, J. (1997b). Identification of ancient irrigation practices based on the carbon isotope discrimination of plant seeds: a case study from the south-east Iberian Peninsula. Journal of Archaeological Science, 24, 729–740

Araus, J.L., Febrero, A., Catala, M., Molist, M., Voltas, J., Romagosa, I. (1999a). Crop water availability in early agriculture: evidence from carbon isotope discrimination of seeds from a tenth millennium BP site on the Euphrates. Global Change Biology, 5, 201–212

Araus, J.L., Slafer, G.A., Romagosa, I. (1999b). Durum wheat and barley yields in antiquity estimated from 13C discrimination of archaeological grains: a case study from the Western Mediterranean Basin. Australian Journal of Plant Physiology, 26, 345–352

Araus, J.L., Slafer, G.A., Buxó, R., Romagosa, I. (2003a). Productivity in prehistoric agriculture: physiological models for the quantification of cereal yields as an alternative to traditional approaches. Journal of Archaeological Science, 30, 681–693

Araus, J.L., Villegas, D., Aparicio, N., García-del-Moral, L.F., Elhani, S., Rharrabti, Y., Ferrio, J.P., Royo, C. (2003b). Environmental factors determining carbon isotope discrimination and yield in durum wheat under Mediterranean conditions. Crop Science, 43, 170–180

Bar-Yosef, O., Kislev, M.E., Harris, D.R., Hillman, G.C. (1989). Early farming communities in the Jordan Valley. In: Harris, D.R., Hillman, G.C. (eds) Foraging and farming: the evolution of plant exploitation, vol. 13. Unwin Hyman, London, pp 632–642

Barriendos, M., Martín-Vide, J. (1998). Secular climatic oscillations as indicated by catastrophic floods in the Spanish Mediterranean coastal area (14th–19th centuries). Climatic Change, 38, 473–491

Cleveland, W.S. (1979). Robust locally weighted regression and smoothing scatterplots. Journal of the American Statistical Association, 74, 829–836

Creus, J., Fernández-Cancio, A., Manrique-Menéndez, E. (1996). Evolución de la temperatura y precipitación anuales desde el año 1400 en el sector central de la Depresión del Ebro [Evolution of annual temperature and precipitation since 1400 A.D. in the central Ebro Depression]. Lucas Mallada, 8, 9–27

Eyer, M., Leuenberger, M., Nyfeler, P., Stocker, T.F. (2004). Comparison of two $\delta^{13}CO_2$ records measured on air from the EPICA Dome C and Kohnen Station ice cores. Geophysical Research Abstracts, 6, 1990

Farquhar, G.D., Ehleringer, J.R., Hubick, K.T. (1989). Carbon isotope discrimination and photosynthesis. Annual Review of Plant Physiology and Plant Molecular Biology, 40, 503–537

Farquhar, G.D., O'Leary, M.H., Berry, J.A. (1982). On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. Australian Journal of Plant Physiology, 9, 121–137

February, E.C. (2000). Archaeological charcoal and dendrochronology to reconstruct past environments of southern Africa. South African Journal of Science, 96, 111–116

Ferrio, J.P., Alonso, N., Voltas, J., Araus, J.L. (2004). Estimating grain weight in archaeological cereal crops: a quantitative approach for comparison with current conditions. Journal of Archaeological Science, 31, 1635–1642

Ferrio, J.P., Bertran, E., Nachit, M.M., Royo, C., Araus, J.L. (2001). Near infrared reflectance spectroscopy as a potential surrogate method for the analysis of $\Delta^{13}C$ in mature kernels of durum wheat. Australian Journal of Agricultural Research, 52, 809–816

Ferrio, J.P., Florit, A., Vega, A., Serrano, L., Voltas, J. (2003a). $\Delta^{13}C$ and tree-ring width reflect different drought responses in *Quercus ilex* and *Pinus halepensis*. Oecologia, 137, 512–518

Ferrio, J.P., Voltas, J. (2005). Carbon and oxygen isotope ratios in wood constituents of *Pinus halepensis* as indicators of precipitation, temperature and vapour pressure deficit. Tellus Series B-Chemical and Physical Meteorology, in press

Ferrio, J.P., Voltas, J., Araus, J.L. (2003b). Use of carbon isotope composition in monitoring environmental changes. Management of Environmental Quality, 14, 82–98

Folland, C.K., Karl, T.R., Christy, J.R., Clarke, R.A., Gruza, G.V., Jouzel, J., Mann, M.E., Oerlemans, J., Salinger, M.J., Wang, S.W. (2001). Observed climate variability and change. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (eds) Climate Change 2001: the scientific basis. Contributions of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. (http://www.grida.no/climate/ipcc_tar/wg1/index.htm), pp 101–181

Francey, R.J., Allison, C.E., Etheridge, D.M., Trudinger, C.M., Enting, I.G., Leuenberger, M., Langenfelds, R.L., Michel, E., Steele, L.P. (1999). A 1000-year high precision record of delta C-13 in atmospheric CO_2. Tellus Series B-Chemical and Physical Meteorology, 51, 170–193

Harlan, J.R. (1998). The living fields: our agricultural heritage. Cambridge University Press, Cambridge

Heaton, T.H.E. (1999). Spatial, species, and temporal variations in the $^{13}C/^{12}C$ ratios of C_3 plants: implications for palaeodiet studies. Journal of Archaeological Science, 26, 637–649

Heiser, C.B. Jr. (1990). Seed to civilization: the story of food, 3rd edn. Harvard University Press, Cambridge

Helbæk, H. (1960). Cereals and weed grasses in Phase A. In: Braidwood, R.J., Braidwood, L.S. (eds) Excavations in the plain of Antioch I. University of Chicago Press, Chicago, pp 540–543

Hillman, G.C. (1973). Agricultural productivity and past population potential at Asvan. Anatolian Studies, 23, 225–240

Hillman, G.C. (1996). Late Pleistocene changes in wild plant-foods available to hunter-gatherers of the northern Fertile Crescent: possible preludes to cereal cultivation. In: Harris, D.R. (ed) The origins and spread of pastoralism in Eurasia. University College London Press, London, pp 159–203

Hubick, K.T., Gibson, A., Ehleringer, J.R., Hall, A.E., Farquhar, G.D. (1993). Diversity in the relationship between carbon isotope discrimination and transpiration efficiency when water is limited. In: Ehleringer, J.R., Hall, A.E., Farquhar, G.D. (eds) Stable isotopes and plant carbon-water relations. Academic Press, San Diego, pp 311–325

Indermühle, A., Stocker, T.F., Joos, F., Fischer, H., Smith, H.J., 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, Antarctica. Nature, 398, 121–126

Jones, G., Charles, M., Colledge, S.M., 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—9th symposium IWGP, Kiel, pp 49–68

Korol, R.L., Kirschbaum, M.U.F., Farquhar, G.D., Jeffreys, M. (1999). Effects of water status and soil fertility on the C-isotope signature in *Pinus radiata*. Tree Physiology, 19, 551–562

Lambers, H., Chapin, F.S. III, Pons, T.L. (1998). Plant physiological ecology. Springer, Berlin Heildelberg New York

Leuenberger, M., Siegenthaler, U., Langway, C.C. (1992). Carbon isotope composition of atmospheric CO_2 during the last ice age from an Antartic ice core. Nature, 357, 488–490

Marino, B.D., DeNiro, M.J. (1987). Isotope analysis of archaeobotanicals to reconstruct past climates: effects of activities associated with food preparation on carbon, hydrogen and oxygen isotope ratios of plant cellulose. Journal of Archaeological Science, 14, 537–548

Riera, S., Wansard, G., Julià, R. (2004). 2000-year environmental history of a karstic lake in the Mediterranean pre-Pyrenees: the Estanya lakes (Spain). Catena, 55, 293–324

Rosen, A., Weiner, S. (1994). Identifying ancient irrigation: a new method using opaline phytoliths from emmer wheat. Journal of Archaeological Science, 21, 125–132

Saurer, M., Siegenthaler, U. (1989). 13C/12C isotope ratios in trees are sensitive to relative humidity. Dendrochronologia, 7, 9–13

Stuiver, M., Braziunas, T.F. (1987). Tree cellulose $^{13}C/^{12}C$ isotope ratios and climate change. Nature, 328, 58–60

Van-Klinken, G.J., van der Plicht, H., Hedges, R.E.M. (1994). Bone 13C/12C ratios reflect (palaeo-) climatic variation. Geophysical Research Letters, 21, 445–448

Vernet, J.L. (1990). The bearing of phyto-archaeological evidence on discussions of climatic change over recent millennia. Philosophical Transactions of the Royal Society of London, A330, 671–677

Vernet, J.L., Pachiaudi, C., Bazile, F., Durand, A., Fabre, L., Heinz, C., Solari, M.E., Thiebault, S. (1996). Le $\delta^{13}C$ de charbons de bois préhistoriques et historiques méditerranéens, de 35000 BP a l'àctuel. Premiers resultats. Comptes Rendus de l'Academie des Sciences, série II a, 323, 319–324

Voltas, J., Romagosa, I., Lafarga, A., Armesto, A.P., Sombrero, A., Araus, J.L. (1999). Genotype by environment interaction for grain yield and carbon isotope discrimination of barley in Mediterranean Spain. Australian Journal of Agricultural Research, 50, 1263–1271

Warren, C.R., McGrath, J.F., Adams, M.A. (2001). Water availability and carbon isotope discrimination in conifers. Oecologia, 127, 476–486

Willcox, G. (1996). Evidence for plant exploitation and vegetation history from three Early Neolithic pre-pottery sites on the Euphrates (Syria). Vegetation History and Archaeobotany, 5, 143–152

Wilson, D.G. (1984). The carbonisation of weed seeds and their representation in macrofossil assemblages. In: van Zeist, W., Casparie, W.A. (eds) Balkema, Rotterdam, pp 201–206

Wright, P. (2003). Preservation or destruction of plant remains by carbonization? Journal of Archaeological Science, 30, 577–583