Crop water availability in early agriculture: evidence from carbon isotope discrimination of seeds from a tenth millennium BP site on the Euphrates

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Abstract

The analysis of carbon isotope discrimination (Δ) in crop plant remains from archaeological sites may help to assess water availability for early agriculture. This study presents the analysis of Δ in seeds of naked wheat (Triticum aestivum/durum), lentil (Lens orientalis/culinaris), and flax (Linum sp.) found at the archaeological site of Tell Halula in the valley of the Middle Euphrates (Syria). This Neolithic site is the oldest in this region of the Fertile Crescent where the cultivation of domesticated plants has been reported, with seed remains ranging from 9550 to 8465 BP. Most of the seeds analysed showed Δ values greater than 16 ‰, reaching 20 ‰ for some samples of flax. For wheat, Δ values were much higher than those reported in present-day (1996) durum wheat crops cultivated under rainfed conditions in north-west Syria under environments with somewhat higher rainfall than Tell Halula. Similarly, grains of present-day (1997) barley cultivated in the archaeological site also showed lower values than those found in archaeological kernels. An empirical relationship between Δ of mature kernels and total precipitation (plus irrigation where applicable) from heading to maturity (r² = 0.82, n = 11) was established for durum wheat, currently cultivated in different environments of the Mediterranean basin. The resulting relationship was applied to the data on Δ of wheat fossil kernels from Tell Halula to estimate the accumulated water inputs during the time (about 6 weeks) the kernels were produced. Calculated water inputs for wheat during early agriculture were (over 110 mm) at least 5 times higher than current-day rainfall accumulated in Tell Halula during the same phenological period. These results strongly suggest that early agriculture wheat was cultivated at Tell Halula under much wetter conditions than are currently to be found in the area. The presence of flax and its very high Δ values also support this conclusion. Whether such humid conditions during cultivation were due to moister conditions prevailing at this time, by planting in alluvial areas or by irrigation works is discussed.

Keywords: early agriculture, flax, lentil, stable carbon isotope discrimination, water regime, wheat

Abbreviations: Δ, stable carbon isotope discrimination; δ¹³C, ratio of ¹³C/¹²C relative to PeeDee belemnite standard; pi/pa, ratio of intercellular to atmospheric partial pressure of CO₂; BP, before present; L-N, Late Neolithic; M- and L-PPNB, Middle and Late Pre-Pottery Neolithic B (PPNB).

Introduction

The environmental conditions prevailing when agriculture was first developed in the Old World, in the Fertile Crescent (Near East) during the early Holocene, are somewhat obscure. Although recent data on climatic conditions are more precise chronologically (Baruch & Bottema 1991; Moore & Hillman 1992) and can explain the environmental setting during the transition from hunter/gathering to farming communities, such data are indirect and not conclusive (Hillman 1996). Present palaeoclimatological and archaeological findings suggest
a more humid environment was to be found in the Near East at the birth of agriculture. However, much remains to be discovered about the precise nature of the environment and crop growing conditions (Zohary 1996; Hole 1998), not least the crop water status during these crucial millennia for which no reliable (direct) data are available (Rossignol-Strick 1993).

For C3 plants, such as those crops first cultivated in the Fertile Crescent, carbon isotope discrimination (Δ) in crop grains constitutes an integrated record of the ratio of intercellular to atmospheric partial pressure of CO₂ (p_i/p_a) and, thus, of the water status during the growth of these grains (Farquhar & Richards 1984). For example, in cereals the water regime during grain filling strongly affects the Δ values of mature kernels (Condon et al. 1987, 1992; Craufurd et al. 1991; Romagosa & Araus 1991; Araus et al. 1997a,b). Decreased water availability (and increased evapotranspiration) causes lower p_i/p_a and, thus, a decrease in Δ of grains because of the effects of these environmental factors on stomatal conductance or photosynthetic capacity (Farquhar & Richards 1984; Condon et al. 1992). Therefore, from the analysis of Δ of grains it should be possible, in principle, to infer water status during grain filling (Araus et al. 1997a). In this context, the measurement of Δ from seeds found in archaeological sites has been proposed as a method for evaluating the water status at the time these crops were grown (Araus & Buxó 1993; Araus et al. 1997a,b).

The beginnings of agriculture in the Old World seems to be associated with cereal domestication. Indeed, even in those cases where experimental studies provide a theoretical indication of a time-lapse between the first attempts of cultivation and morphological domestication (Hillman & Davies 1990; Willcox 1991, 1992), to date cultivation occurring prior to morphological domestication has not been identified from plant remains found in the Near East (Willcox 1996). In this context, the Pre-Pottery (aceramic) Neolithic B (PPNB) site of Tell Halula is the oldest archaeological site on the Euphrates at which domesticated crops have been reported (Molist et al. 1995; Willcox 1996; see also Hole 1998). Thus, levels from the tenth millennium before the present (BP) at Halula indicate the appearance of domesticated crops such as naked wheat (Triticum aestivum/durum), emmer (Triticum dicoccum) and barley (Hordeum vulgare) (Molist et al. 1995; Willcox & Català 1996; Willcox 1996). The domestication of these cereals went hand-in-hand with the introduction of several companion plants to the Fertile Crescent. Most common in the PPNB farming villages are the remains of two pulses: lentil (Lens culinaris) and pea (Pisum sativum); and of a single oil-and-fibre crop, flax (Linum usitatissimum) (Zohary 1996). These companion crops were very probably domesticated (and taken into cultivation) simultaneously with the wheats and barley, or just a short time later (Zohary 1996), although in the domestication of lentils this may have occurred before any other crop (Ladizinsky 1987, 1989). Whatever the case, as with cereals, domestication of grain legumes would have only been possible only under cultivation (Zohary 1989).

In the present study the Δ of fossil seeds is analysed to determine the water status of several crops (wheat, lentil and flax) of the Neolithic crop assemblage grown in Tell Halula. The period studied corresponds to the first millennium of cultivation of domesticated plants at this archaeological site.

Materials and methods

Archaeological site and plant material

Tell Halula is an archaeological site situated in the Middle Euphrates region, Syria (Fig. 1). This site comprises (to date) three periods: Middle and Late PPNB, and Late Neolithic (pre-Halaf) and is being excavated by the Universitat Autonoma de Barcelona. The present-day natural vegetation in the region is a degraded steppe, with a total annual rainfall of about 250 mm (see legend in Fig. 1). At present the land above the valley floor is extensively used for lamb and goat grazing and rainfed cultivation of barley, whereas durum wheat and horticultural crops are only cultivated where supplementary irrigation is available.

Samples of seeds of durum wheat [Triticum durum Desf., including T. aestivum/durum (after van Zeist & Bakker-Heeres 1982), lentil (Lens orientalis/culinaris), and flax (Linum sp.) were used for stable carbon isotope analysis (Fig. 2). They were found in a carbonized state and were gathered in disparate fashion from domestic fires, cooking ovens and room floors. Six stratigraphic levels from the archaeological site were studied. Soil samples were treated using a standard flotation tank in the field with 0.3 mm (flotation) and 2.5 mm (wet) sieves. Plant remains were then dried slowly before transport and sorting of seeds. Material was compared with modern reference material which had been gathered from various locations in the Near East. In order to characterize the weed plant assemblage associated with these early crops, determination of weed plants from carbonized material recovered in the same stratigraphic sequences was also performed. Palaeobotanical determinations were performed at the Institut de Prehistorie Orientale of the CNRS Jûles, France (Willcox 1996; Willcox & Català 1996). The three crop species considered in this study were present throughout the stratigraphic sequence studied. The chronology of archaeological samples, in years before the present (BP), was based on stratigraphic dating and
Fig. 1 Map of the location of the archaeological site studied. Tell Halula is situated in the Euphrates region (Syria) about 100 km east of Aleppo and 30 km south-east of Memjib (a). This site is on the west river bank, 4 km from the main Euphrates valley, on a side valley (b). The site is an artificial mound (i.e. Tell) 8 m in height, roughly circular (360 × 300 m) in shape, delimited to the south and east by two rivers (wadis) tributaries of the Euphrates (c). Latitude and longitude above sea level of the archaeological site are 35°55′N, 38°30′E, 300 m. Average (1978–94) annual precipitation of the closest meteorological stations around Halula are: Membij (36°01′N, 38°05′E) 282 mm, El Khafseh (36°12′N, 38°04′E) 211 mm and Mazra et Maskaneh (36°32′N, 37°57′E) 206 mm. Accumulated precipitation during April, the first half of May, corresponding, in the case of winter barley, with the period from heading-anthesis to maturity (Araus et al. 1997a), was 33, 28 and 27 mm, respectively. Precipitation during the second half of April plus May, corresponding, in the case of durum wheat, with the period between heading and maturity was 23, 18 and 18 mm, respectively.
radiocarbon ages. Radiocarbon determinations were performed at Beta Analytic Inc. (Miami, FL, USA). Dating ranged from c. 8700 ± 60 BP to 7690 ± 130 BP uncalibrated. Calibrated ages were determined according to Stuiver & Reimer (1986) by using the computer program CALIBTH3. After calibration the range of dates for the material studied was 9550–8465 BP. In addition samples from the present day (1997) were taken from hulled barley cultivated in the same Tell and its surroundings.

Fig. 2 Scanning electron micrographs of charred seeds of durum wheat (a), lentil (b) and flax (c) found in the site of Tell Halula and used for stable carbon isotope analysis.

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Carbon-isotope analysis

Prior to stable carbon isotope analysis, seed samples were cleaned as reported elsewhere (Araus & Buxó 1993). The isotopic $^{13}$C/$^{12}$C ratios were determined by mass spectrometric analysis at Isotope Services, Inc., Los Alamos, New Mexico, USA and the ‘Serveis Científics de l’Universitat de Barcelona’, Barcelona, Spain. Results are expressed as $\delta^{13}$C values, where:

$$\delta^{13}\text{C}(%) = [(R \text{ sample}/R \text{ standard}) - 1] \times 1000,$$

(1)

R being the $^{13}$C/$^{12}$C ratio. A secondary standard calibrated against Peedee belemnite (PDB) carbonate was used for comparison. Sample sizes of 5–10 mg were used. The precision of analysis was less than 0.10 ‰. The percentage of carbon in the set of samples was also determined using a C/N analyser with atropine as the standard. The potential effect of carbonization on $\delta^{13}$C of archaeological grains was ignored based on findings reported elsewhere (Marino & DeNiro 1987; Araus et al. 1997a,b). Moreover, the total carbon content of fossil seeds was closely similar to those of intact present-day seeds, which suggests a slight carbonization process (Table 1). The stable nitrogen composition ($\delta^{15}$N) of present-day barley seeds collected at the archaeological site was also analysed by mass spectrometric analysis. The ratio $^{15}$N/$^{14}$N in the samples was measured in relation to that of a standard of atmospheric $\text{N}_2$, according to the same expression than (1) (Amaro et al. 1995).

Discrimination against $^{13}$C relative to air ($\Delta$) was calculated from $\delta_{a}$ and $\delta_{p}$, where a and p refer to air and plant, respectively; as follows (Farquhar et al. 1989):

$$\Delta = \frac{\delta_{a} - \delta_{p}}{1 + \delta_{p}}.$$

(2)

On the PDB scale, $\delta_{a}$ currently has a value of approximately – 8.00 ‰. For calculation of $\Delta$ values of grain samples from the archaeological site, $\delta_{a}$ values were inferred from the work of Marino et al. (1992) as reported elsewhere (Araus & Buxó 1993). Thus the $\delta_{a}$ values used for the samples of the six different stratigraphic levels were as follows: first level (c. 8700 BP uncalibrated) – 6.609 ‰, second (c. 8350 BP) – 6.583 ‰, third (c. 8300 BP) – 6.580 ‰, fourth (c. 8100 BP) – 6.568 ‰, fifth (c. 7880 BP) – 6.552 ‰, and sixth (c. 7690 BP) – 6.539 ‰.

Water inputs during grain filling of archaeological kernels

Precipitation accumulated during grain filling for the archaeological kernels of durum wheat was estimated from comparisons with present-day data. First we established an empirical relationship, for the durum wheat currently cultivated in the Mediterranean area, between carbon discrimination of mature kernels on the one hand and total water inputs accumulated from heading to crop maturity on the other. The $\Delta$ of wheat kernels from Tell Halula was then used to calculate precipitation at the time when these kernels were produced using the relationship derived from contemporary data.

For a set of 11 environments (locations and/or years of culture), mostly in the Mediterranean areas of Spain and Syria, the correlation between $\Delta$ of mature kernels of durum wheat and the precipitation (plus irrigation where applied) from heading to maturity was studied. The timing of wheat heading and the further duration of grain filling under Mediterranean conditions was based on the records from these trials. Thus, total precipitation during grain filling was calculated as the total rainfall (plus irrigation) during April plus the first half of May (autumn sowing) or during the second half of April plus May (winter sowing). Current precipitation at Tell Halula was estimated from historical (means from 1978 to 1994) records of rainfall from the three meteorological stations closest to this site (see Table 1). Given that old wheat cultivars may have had a longer cycle and, thus, later flowering, total precipitation during grain filling was inferred as the overall rainfall during the second half of April plus May.

Results and discussion

$\Delta$ of fossil seeds vs. those of current-day seeds

The carbon isotope composition ($\delta^{13}$C) of the fossil seeds collected in the six stratigraphic levels studied at Tell Halula, along with their total carbon content values are detailed in Table 1. After calculation of carbon isotope discrimination ($\Delta$), and except for two samples (one of wheat and the other of lentil), all the seeds studied showed $\Delta$ values greater than 16 ‰, reaching 20 ‰ for some samples of flax (Fig. 3e). Mean $\Delta$ values of the seeds found in the different stratigraphic levels corresponding to either Middle Pre-Pottery Neolithic B (PPNB), Late PPNB and Late Neolithic were plotted for each plant species (Fig. 3b). Flax seeds showed higher values of $\Delta$ than wheat kernels and lentil seeds during the Middle and Late PPNB. Lentil seeds also tended to show higher $\Delta$ values than wheat during the Late Neolithic, although differences were not significant. This could reflect the growth habit (Araus et al. 1997c), lentils being less determinate plants than wheat.

Values of $\Delta$ of fossil seeds are very high for rainfed crops growing under Mediterranean conditions. Thus, for example, $\Delta$ of wheat kernels were much higher than those reported in present-day (1996) durum wheat crops cultivated under rainfed conditions in north-west Syria (Araus et al. 1997b) in environments with somewhat

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Table 1 Carbon isotope composition ($\delta^{13}$C, ‰) and carbon content (C, %) of fossil seeds of durum wheat, lentil and flax found in Middle Pre-Pottery Neolithic B (M-PPNB), Late Pre-Neolithic B (L-PPNB) and Late Neolithic (L-N) levels at Tell Halula. All the dates are in uncalibrated radiocarbon years BP. Means with different letters are significantly different ($P_{\leq}0.05$) by Duncan's comparison test.

<table>
<thead>
<tr>
<th>Archaeological levels</th>
<th>Radiocarbon ages</th>
<th>Durum wheat</th>
<th>Lentil</th>
<th>Flax</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$\delta^{13}$C</td>
<td>C</td>
<td>$\delta^{13}$C</td>
<td>C</td>
</tr>
<tr>
<td>M-PPNB 8800–8600</td>
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<td>41.48</td>
<td>–23.27</td>
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<td></td>
<td>–23.26</td>
<td>37.27</td>
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<td>–23.64</td>
<td>46.50</td>
<td>–25.34</td>
<td>51.99</td>
</tr>
<tr>
<td>Mean ± SE</td>
<td>–23.42 ± 0.24bcd</td>
<td>43.89 ± 0.88bc</td>
<td>–22.42 ± 0.33bcd</td>
<td>31.74 ± 4.35a</td>
</tr>
<tr>
<td>L-PPNB 8500–8200</td>
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<td>49.06</td>
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<td></td>
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<td>44.40</td>
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<td>47.08</td>
<td>–22.90</td>
<td>49.10</td>
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<tr>
<td>Mean ± SE</td>
<td>–23.50 ± 0.33bcd</td>
<td>46.23 ± 0.79bc</td>
<td>–23.40 ± 0.39bcd</td>
<td>41.38 ± 2.31bc</td>
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<tr>
<td>L-N (Pre-Halaf) 8200–7600</td>
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<td>45.17</td>
<td>–22.79</td>
<td>42.31</td>
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<tr>
<td></td>
<td>–23.30</td>
<td>46.44</td>
<td>–22.89</td>
<td>41.60</td>
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<td></td>
<td>–23.56</td>
<td>44.98</td>
<td>–24.39</td>
<td>37.38</td>
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<tr>
<td>Mean ± SE</td>
<td>–22.95 ± 0.39bcd</td>
<td>45.53 ± 0.37bc</td>
<td>–23.36 ± 0.42bcd</td>
<td>40.79 ± 0.97b</td>
</tr>
</tbody>
</table>

higher rainfall (Breda and Tel Hadya with about 340 and 390 mm per year, respectively) than Tell Halula (about 250 mm). Thus, $\Delta$ values (mean ± SD) for Breda and Tel Hadya were 14.0 ± 0.4 ‰ and 15.3 ± 0.4 ‰, respectively, which is clearly below those measured in the fossil kernels (around 17 ‰) during the three periods studied (Fig. 3a). Indeed fossil kernels showed $\Delta$ values even slightly higher than those (16.7 ± 0.5 ‰) of durum wheat cultivated with supplementary irrigation at Tel Hadya (Araus et al. 1997b) and not much different from those typical (over 17.5 ‰) of durum wheat grown in absence of water stress (e.g. full irrigation, Araus et al. 1997c).

Samples from present-day (1997) hulled barley kernels cultivated at seven points of the archaeological site were also analysed. These barley crops grow without significant (if any) amounts of chemical nitrogen fertilization, as inferred from the low total nitrogen content (mean ± SE = 1.52 ± 0.11%) and the high $^{15}$N isotopic composition ($^{15}$N = 6.63 ± 1.26 ‰) of kernels (Amaro et al. 1995), a situation resembling that expected in ancient agriculture. Mean ± SE of $\Delta$ was 16.02 ± 0.19 ‰. This value is again clearly below $\Delta$ values for all the archaeological seeds. Moreover, under present-day conditions, $\Delta$ of durum wheat would be even lower. Considering that barley attains maturity at least 2–3 weeks earlier than durum wheat, under Mediterranean conditions the grain filling period for barley usually takes place under wetter conditions than those expected for durum wheat. Indeed this difference in phenology between both crops is one of the main reasons why barley is the only cereal cultivated under rainfed conditions in areas with rainfall regimes comparable to that which currently predominates in Tel Halula.

**Water status during wheat cultivation**

The relationship between $\Delta$ of wheat kernels and water status from heading to maturity under Mediterranean...
conditions was studied in more detail. Carbon isotope discrimination of kernels from recent years was positively correlated with accumulated precipitation (plus irrigation where applied). Differences in water inputs (on a logarithmic scale) between environments explained 82% ($\Delta = 6.95 + 4.85 \log \text{water received from heading to maturity}$; $r^2 = 0.82$) of the variability observed in the $\Delta$ of mature kernels (Fig. 4). The fitting line showed the same slope ($P \leq 0.05$) as that previously reported for barley (see dotted line in Fig. 4) cultivated under mediterranean conditions (Araus et al. 1997a). However, fitting line for wheat was shifted somewhat to the right ($P = 0.077$), which would agree with a higher vapor pressure deficit during the latter part of wheat growth than that of barley and might be explained by the later occurrence of this period in the former crop. Thus, for barley cultivated under Mediterranean conditions differences between environments in terms of water status (also on a logarithmic scale) from heading to maturity explained 73% of the variability in $\Delta$ of mature kernels (Araus et al. 1997a). The results of Stewart et al. (1995) which show a strong (linear) correlation ($r^2 = 0.78$) between annual rainfall and $\delta^{13}$C across a set of 12 plant communities also support the usefulness of $\delta^{13}$C (or $\Delta$) as an indicator of moisture availability. In both cases, the further addition (by multiple regression) of the effect of evapotranspiration to that of water inputs did not explain a higher percentage of variability in $\Delta$ of kernels. $\Delta$ in photosynthate may also respond to mean relative humidity in the atmosphere by itself as derived from the model of Ball et al. (1987). Thus, for example, a shift in relative humidity in the canopy, ignoring offsets between leaf temperature and air temperature, from 50% to 60% would account for a 1.2% increase in $\Delta$. However, the variations in $\Delta$ in response to shifts in relative humidity seems to be substantially lower than those predicted by the model at low relative humidities. Actually whereas a relative humidity of 30% would lead to a $\Delta$ of about 15%, relative humidities of 20% and 10% would produce $\Delta$ values of 9% and −9%, respectively, which are far outside the range of experimental data.

From the equation fitted above (Fig. 4), and by using the corresponding $\Delta$ values of fossil kernels, the amount of water received (from heading to maturity) by the Neolithic wheat crops of Tel Halula could be calculated (Fig. 5). Thus, for the durum wheat kernels found in the Medium and Late PPNB sequences the total water received by the crop from heading to maturity surpassed...
Fig. 4 Relationship between total precipitation (plus irrigation if the case) from heading to maturity and carbon isotope discrimination of mature durum wheat kernels (continuous fitting line) for a set of 11 trials developed in Spain, Syria and Mexico. For each Spanish and Mexican trial, the $\Delta$ value used in the correlation was the mean of 6–10 varieties, whereas for Syrian trials $\Delta$ was the mean of 125 genotypes. Samples are drawn from breeding trials, including old and new varieties. Discrimination values from Syrian trials (Araus et al. 1997b) and from some of the Spanish trials (Araus et al. 1993) have been published previously. Broken line represents the relationship between water inputs and $\Delta$ for barley currently cultivated under mediterranean conditions as reported elsewhere (Araus et al. 1997a). Fitting equation for data of barley and wheat combined was $\Delta = 9.95 + 4.85 \log (\text{mm water})$, $r^2 = 0.72$, C.V. = 4.75.

Fig. 5 Comparison between present-day precipitation accumulated from heading to maturity of durum wheat and barley and water inputs calculated for durum wheat from the Neolithic at Tell Halula. Present-day data correspond to mean values (1978–94) of accumulated precipitation during April plus the first half of May (barley: open bars) and the second half of April plus May (durum wheat: filled bars) recorded in the three meteorological stations closest to Tell Halula (see legend of Fig. 1). Mean water inputs $\pm$ SE from heading to maturity of durum wheat (filled bars) during the three Neolithic periods were calculated using the $\Delta$ values of fossil kernels for each period and the equation in Fig. 4. In addition, precipitation from heading to maturity of barley (April and first half of May) cultivated at Tell Halula in 1996 was also estimated using the $\Delta$ values of kernels and the relationship between total water inputs during grain filling and $\Delta$ of mature barley reported elsewhere (Araus et al. 1997a).

With regard to the risk inherent in using present vegetation–climate relationships to reconstruct past water status from the archaeological record, the direct effect of changing atmospheric CO2 level on the relationship between water inputs and grain $\Delta$ should be considered. In long-term experiments, it has been reported that the $p_l/p_a$ ratio (calculated from leaf $\delta^{13}$C values) remained constant in a cereal plant such as oats grown at mean CO2 partial pressure from 160 to 330 $\mu$bar bar$^{-1}$, and for wheat it increased only slightly (about 4%) from 225 to 350 $\mu$bar bar$^{-1}$ (Masle et al. 1990; Polley et al. 1993). A recent study using $\delta^{13}$C of woody plant remains (Beerling 1996) reports that these plants probably maintained a nearly constant $p_l/p_a$ ratio in response to the increase in atmospheric CO2 concentrations over the Pleistocene. In fact, the coordination of stomatal and mesophyll functions minimizes variations in $p_l/p_a$ in C3 species (Wong et al. 1979) grown over a range of CO2 partial
pressures characteristic of the Last Glacial Maximum-to-present atmospheric concentrations (Polley et al. 1993). In fact Ehleringer (1995) postulates that $p_i$ can be considered as a ‘set point’ for photosynthetic activity, providing integrated information about photosynthetic metabolism. Thus $p_i$ as a ‘set point’ would be more stable than the absolute flux rates of $\text{CO}_2$ uptake. That is, whereas absolute flux rates will vary greatly in response to resource levels over the short-term or due to stress levels over the long-term, changes in the set point may be substantially less. Therefore, here we considered that changing $p_a$ values from about 270 µbar bar$^{-1}$, prior to industrialization, to a present-day value of 355 µbar bar$^{-1}$ would not affect the $p_i/p_a$ ratio and therefore based on the model of Farquhar et al. (1989), the $\Delta$ would not change. Furthermore, even if $p_i/p_a$ values from durum wheat plants of Neolithic were slightly lower than those of the present day, the inferred (i.e. calculated) precipitation from the archaeological sites may be slightly underestimated. On the other hand, the lower $p_a$ during Neolithic would lead to a higher stomatal conductance and therefore to higher transpiration rates. If it is accepted that $\Delta$ remains relatively steady within the range of changes in $p_a$ monitored during the Holocene, it can be concluded that a given $\Delta$ value could not have been attained in the past without greater amounts of water than those needed today. Therefore, in the worst case our approach would provide a conservative (low) estimate of the differences in water availability from past to present time.

Although other sources of uncertainty associated with carbonization of grains (Araus & Buxó 1993), differences in the rate of decline of soil water content, or changes in conditions of cultivation and in genotype are difficult to evaluate, the data available do not seem to invalidate this approach and it might even suggest (for some of these parameters) that a conservative estimate of water status in the past is obtained (see discussion in Araus et al. 1997a,b). There is for example the possibility of systematic differences between ancient (i.e. cultivated several millennia ago) and new wheats in $\Delta$. The available information suggests that modern varieties show consistently higher $\Delta$ values than the old (i.e. reported to be cultivated during the last century) varieties and landraces not only in wheat (see references in Blum 1996) but also in barley (Muñoz et al. 1998). A higher stomatal conductance and earlier flowering and maturation in new genotypes could be responsible (see Richards 1996). Whatever the cause a systematically lower $\Delta$ in older wheats would again lead to a conservative estimate of water status in the past.

Further insights into the palaeoenvironmental context of early agriculture

The above results clearly indicate that during the period studied wheat was cultivated at Tell Halula under a much better water status than could be expected from present-day (rainfed) conditions. Whereas the presence of flax also supports this conclusion, its very high $\Delta$ values should be interpreted with caution due to the fact that flax is a oil-rich seed and there is a discrimination against $^{13}\text{C}$ during the process of oil biosynthesis. Cultivation under moist conditions could have been possible as a result of more humid environmental conditions prevailing at this time or by planting in alluvial areas (Bar-Yosef & Kislev 1989). Another possibility lies in the existence of irrigation practices. Indeed one indirect method to assess the presence of ancient irrigation takes into consideration the development of weeds; for example, from the size of charred flax seeds which occurred in an archaeological assemblage of plant remains (Helbaek 1960). However, even when flax seeds were very abundant in all the stratigraphic levels studied at Tell Halula their length did not reach 3.0 mm, which has been proposed as the minimum size for domesticated plants. As yet, there is no archaeological evidence for irrigation in the early (i.e. Neolithic) agricultural sites of the Near East (Bar-Yosef & Kislev 1989; Hillman & Davies 1990), including Tell Halula (Molist et al. 1995). For durum wheat, although $\Delta$ of fossil kernels were higher than those of present-day kernels cultivated under rainfed conditions, due to the existence of a better water status in the past, they were still lower than the typical values of full irrigation crops under Mediterranean conditions (Araus et al. 1997c). Because $\Delta$ appears to show a logarithmic dependence on water accumulated from heading to maturity (Fig. 4), $\Delta$ values fall slightly below those reported for full irrigated wheat crops (over 17.5 ‰) and would seem to be associated with considerably lower amounts of water being available during grain filling. Thus, an $\Delta$ value 0.5 ‰ lower than 17.5 ‰ would correspond to the availability of an amount of water during grain filling which was about 30% lower than that for irrigated crops (Araus et al. 1997a). Of course, any condition in between rainfed and full irrigation (i.e. supplementary irrigation) would produce kernels with $\Delta$ values below those of full irrigation.

The existence of a wetter climate in the past is a more plausible possibility. Archaeobotanical evidence supports the possibility that environmental conditions during early agriculture were more favourable (i.e. cooler and moister) in this region than nowadays. The presence of charcoal from ash, vine, maple, plane, alder and elm from the gallery forest, and wild rye, wild einkorn, deciduous oak, wild almond, Pistacia, and Pyrus, from the hinterland, suggests moister and cooler conditions in the Middle Euphrates region during early agriculture (Harlan 1995; Wilcox 1996; see also Hillman et al. 1993). Particularly in Tell Halula, although no evidence of rye appears, the presence of Quercus, Amygdalus, Pistacia, Celtis and Olea
europaea during the PPNB suggests that climate was much more humid than during the present-day (Willcox & Catalá 1996; Willcox 1996). In addition, not only a higher overall precipitation (and perhaps a lower evapotranspiration), but also the seasonal distribution of precipitations, would be involved. Thus at the site of Mureybet (on the Middle Euphrates), it has been reported that about 8000 BP Poaceae pollen was, in relative terms, much more abundant than today (El-Moslimany 1994). This suggests that summer precipitation was much higher than today. A shift throughout the region to dominant winter rainfall (typical of Mediterranean climates) would have occurred after 6000 BP (El-Moslimany 1994). Because durum wheat and flax seed formation takes place in late spring (and also early summer for flax), any increase in precipitation during this period, even when total accumulated rainfall during cultivation does not vary, would eventually lead to higher Δ in seeds.

However, palaeoenvironmental reconstruction through the archaeobotanical study of past vegetation has serious limitations. Present-day natural vegetation corresponding to a degraded steppe could be the consequence of man’s effect on the landscape. Expansion of cultivation as well as the (early) great development of extensive goat and sheep pastoralism (Thirgood 1981), rather than climatic change, could be responsible (at least in part) for this increase in landscape degradation (Willcox 1996) and the contemporary steppe/weed vegetation. Thus, annual weed plants, usually associated with open landscape and the cultivation of cereals, among other crops, were already present in the early crop assemblage of Tell Halula. Among these annual plants it is worth mentioning the genera Agrostemma, Arnebia, Astragalus, Centaurea, Fumaria, Glaucium, Lithospermum, Rumex, Sherardia and Teucrium (Table 2). The weeds more specifically associated with legume cultivation are Astragalus, Atriplex, Chenopodium, Galium and Trifolium; whereas Lolium would more likely be associated with flax cultures.

Nevertheless the pattern of changes with time in Δ would agree with a gradual change in drier conditions. Thus, as a general trend mean Δ values tended to decrease throughout the millennium comprised between M-PPNB to Late Neolithic. This was particularly evident for flax (Fig. 3b), which is reported to be an indicator of high water availability (Hole 1998). Indeed the first evidence of domesticated plants (cereals) at Tell Halula appear a full thousand years after the Climatic Optimum was already established (Becker et al. 1991). Therefore, the progressive attenuation of the Climatic Optimum until around 6000 years ago, when climatic conditions were not very different from those prevailing at present were established throughout the Near East (Roberts & Wright 1993), would agree with this tendency to lower Δ values. However, the constancy in high Δ values for almost all the samples analysed in the three crops (Fig. 3) and the strong (more than five times) difference in water inputs estimated from past to present conditions at Tell Halula (Fig. 5) seems difficult to explain just by a wetter climate prevailing in the past. In this context a wetter climate combined with planting in naturally wet soils may have been typical. In fact one way of stabilizing yields that were fluctuating because of water stress is small-scale cultivation in areas fed by permanent springs and duly cleared of competing vegetation (Hillman 1996). The exploitation of naturally wet soils is widely found in early agricultural sites of the Near East (Bar-Yosef & Kislev 1989). It has been argued that cultivation, whenever possible, was based on the sowing of alluvial fans and terraces as well as the edges of freshwater swamps where the water table was always high and the soil was fertilized by silt deposited by periodic floods. As Hillman (1996) point out, once native vegetation was eliminated the moisture-enhanced soils on small terraces and other breaks of slope around the lower reaches of wadi systems which characterized most of the favoured (i.e. oasis) locations (see Fig. 1c for Tell Halula) would have made possible yields far greater than in the drier locations where the cereals grew naturally.

Table 2 Identified carbonized weed plant remains

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Middle PPNB</th>
<th>Late PPNB</th>
<th>Late Neolithic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agrostemma githago</td>
<td>—</td>
<td>P</td>
<td>—</td>
</tr>
<tr>
<td>Androsace</td>
<td>—</td>
<td>P</td>
<td>—</td>
</tr>
<tr>
<td>Arnebia</td>
<td>P</td>
<td>P</td>
<td>P</td>
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<tr>
<td>Astragalus</td>
<td>P</td>
<td>P</td>
<td>—</td>
</tr>
<tr>
<td>Atriplex</td>
<td>—</td>
<td>—</td>
<td>P</td>
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<tr>
<td>Avena</td>
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</tr>
<tr>
<td>Bromus</td>
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<td>P</td>
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<tr>
<td>Capparis</td>
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<td>P</td>
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<tr>
<td>Carex</td>
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<td>P</td>
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<tr>
<td>Centaurea</td>
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<td>Chenopodium</td>
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<tr>
<td>Fumaria</td>
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<tr>
<td>Galium</td>
<td>P</td>
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<td>P</td>
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<tr>
<td>Glaucium</td>
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<td>—</td>
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<tr>
<td>Heliotropium</td>
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<td>P</td>
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<tr>
<td>Iatis</td>
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<tr>
<td>Lithospermum</td>
<td>P</td>
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<td>P</td>
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<tr>
<td>Lolium temulentum</td>
<td>P</td>
<td>P</td>
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<tr>
<td>Malva</td>
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<td>P</td>
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<tr>
<td>Polygonum</td>
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<td>P</td>
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<tr>
<td>Reseda</td>
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<tr>
<td>Rumex</td>
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<tr>
<td>Setaria</td>
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<tr>
<td>Sherardia</td>
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<td>P</td>
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<tr>
<td>Teucrium</td>
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<td>—</td>
<td>P</td>
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<tr>
<td>Trifolium</td>
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</tbody>
</table>

P indicates a record

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Conclusions

To summarize, our results provide direct evidence that during early agriculture wheat crops were cultivated at Tell Halula under much wetter conditions than are suggested by present-day conditions. The presence of flux and its very high $\Delta$ values also support this conclusion. Higher water availability may have been attained exclusively from the moister (and cooler) conditions prevailing at this time. However, the large differences between present-day rainfall and the estimated water input in the past, also suggest the possibility that cultural practices such as planting in naturally wet soils were followed.

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