Collapse or Continuity?

Environment and Development of Bronze Age Human Landscapes

edited by

Jutta Kneisel, Wiebke Kirleis, Marta Dal Corso, Nicole Taylor and Verena Tiedtke

Offprint

Girolamo Fiorentino, Valentina Caracuta, Gianluca Quarta, Lucio Calcagnile and Daniele Morandi Bonacossi

Palaeoprecipitation Trends and Cultural Changes in Syrian Protohistoric Communities: the Contribution of $\delta^{13}C$ in Ancient and Modern Vegetation

KIEL archaeology

human development in landscapes
GRADUATE SCHOOL AT THE UNIVERSITY OF KIEL

Universitätsforschungen zur prähistorischen Archäologie

Band 205

Aus der Graduiertenschule
"Human Development in Landscapes"
der Universität Kiel

2012

Verlag Dr. Rudolf Habelt GmbH, Bonn

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Environment and Development of Bronze Age Human Landscapes

Proceedings of the International Workshop
"Socio-Environmental Dynamics over the Last 12,000 Years:
The Creation of Landscapes II (14th–18th March 2011)" in Kiel

Volume 1

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Gedruckt mit Unterstützung der Deutschen Forschungsgemeinschaft (DFG)

Redaktion: Joachim von Freeden, Frankfurt a. M.
Englisches Korrektorat: Giles Shephard, Berlin

ISBN 978-3-7749-3763-5

Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie.
Detaillierte bibliografische Daten sind im Internet über <http://dnb.d-nb.de> abrufbar.

Umschlagfoto: Jutta Kneisel, Bruszczewo
Umschlaggestaltung: Holger Dieterich, Kiel
Layout und Satz: www.wisa-print.de

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Introduction

Estimating the impact of climate changes on critical sectors, such as water resources, is a crucial task especially in semi-arid areas of the Near East, where the combined effect of human pressure and variation in terms of rainfall regime makes population and ecosystem more vulnerable.

The deficit in water availability, indeed, has long been a problem for simple as well as complex societies developed in "stressful" environments, since they have rarely been able to manage the risk of drought or to build resilience to climate changes (Lemos / Clausen 2009).

Within the Mediterranean basin, and well beyond it, there have been discovered several attestations of ancient well structured political estates trigged down by climate disease (Weiss et al. 1993; De Menocal et al. 2000; De Menocal 2001), nevertheless few studies have taken into account data from archaeological sites as a proxy record.

Often, biological archives, especially concerning plants recovered in archaeological layers, have been investigated for paleoclimatic information (McCorriston 1998; Miller 1998; Willcox 2002; Madella / Fuller 2006). Nevertheless, the resilience of vegetation to environmental stress (Holling 1973; Peterson et al. 1998) has limited the use of archaeobotanical remains in climate reconstruction to long-term changes.

Therefore, the aim of this study is to provide a qualitative estimation of the paleorainfall regime in Syria between the 3rd and the 2nd millennium BC, including both short- and medium-scale variations, using an *in-site* proxy and to compare the data so obtained to the historical upheavals occurred in the Near East.

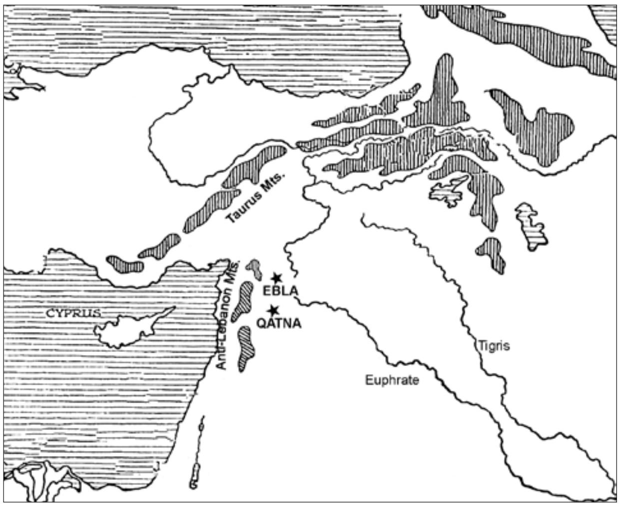

Fig. 1. Ebla and Qatna in the Near East context.

Carbon isotopes in plant remains recovered in archaeological layers were found to be the best tool for this goal, since the stable isotopes ^{12}C and ^{13}C provide valuable environmental information (Vernet et al. 1996; Araus et al. 1999; Ferrio et al. 2003; Ferrio et al. 2005a; Ferrio et al. 2006; Ferrio et al. 2007; Riehl et al. 2008; Voltas et al. 2008) as well as palaeoagricultural information (Heaton et al. 2009), while the unstable isotope ^{14}C indicates the absolute chronology of each climatic episode (Fiorentino / Caracuta 2007a; Fiorentino / Caracuta 2007b,

In: J. Kneisel / W. Kirleis / M. Dal Corso / N. Taylor / V. Tiedtke, Collapse or Continuity? Environment and Development of Bronze Age Human Landscapes [Proceedings of the International Workshop "Socio-Environmental Dynamics over the Last 12,000 Years: The Creation of Landscapes II (14th–18th March 2011)" in Kiel] (Bonn 2012) 17–34.

Fiorentino et al. 2008). However, since several factors may influence the plant carbon stable isotope ratios (Ehleringer et al. 1993; Heaton et al. 1999; Dawson et al. 2002; Ferrio et al. 2003), re-establishing climate signals from that parameter requires some knowledge of the local ecosystem's response behaviour (Schleser et al. 1999). For this reason, we tested the reliability of carbon isotope analysis in Syria by studying the response of modern plant communities to the local climate-forcing agents. The results of this analysis were used to interpret the climate signals inferred from the carbon isotope analysis of ancient charred plant remains collected at the archaeological sites of Ebla and Qatna (Fig. 1) in the area and dated by AMS (Accelerator Mass Spectrometry).

Theoretical framework

All paleoclimatic studies that use carbon isotopes are based on the principle that plants produce dry mass by photosynthesis and absorb carbon dioxide from the atmosphere (O'Leary 1981; O'Leary 1988; Stewart et al. 1995).

During this process both stable (^{13}C, ^{12}C) and unstable isotopes (^{14}C) are metabolised. Nevertheless, plants with a C_3 photosynthetic pathway contain proportionally less ^{13}C than the air since they discriminate against this heavier isotope with respect to the lighter ^{12}C (Farquhar et al. 1989; Farquhar / Lloyd 1993).

The discrimination *(isotope fractionation)* of this isotope occurs mainly, but not exclusively, during the passage of CO_2 through the stomata in the leaf. In principle, under conditions of water stress the stomata close up and the reservoir of CO_2 available for continued photosynthesis is reduced. In plants with a C_3 photosynthetic pathway, the carboxylating enzyme (RuBisCo) is then forced to fix a higher proportion of $^{13}CO_2$, and the $^{13}C \backslash ^{12}C$ ratio incorporated by the leaf increases. During moist conditions, the tendency is reversed (Leavitt et al. 2007; Ferrio et al. 2005b).

The model most widely used to describe isotopic discrimination in photosynthesis in leaves is that of Farquhar et al. (1989), who argues that variations in the leaf carbon isotope ratio ($\delta^{13}C_{plant}$)[1] of C_3 plants is dependent on intercellular CO_2 concentration *(ci)* as follows:

$$\delta^{13}C_{plant} = \delta^{13}C_{air} - a - (b-a)\ c\mathit{i} / c\mathit{a}$$

where $\delta^{13}C_{air}$ is the carbon isotope ratio of CO_2 in the air, a is the fractionation caused by the slower diffusion of $^{13}CO_2$ relative to $^{12}CO_2$, b is the fractionation caused by discrimination of RuBisCO against $^{13}CO_2$, and c*a* is the atmospheric carbon dioxide concentration (Farquhar et al. 1982).

$\delta^{13}C$ of atmospheric CO_2 is currently around -8‰, with latitudinal (Taylor / Orr 2000) and chronological variations in relation to complex cosmochemical phenomena (Bond et al. 2001; Mayewski et al. 2004), deforestation activities and the use of fossil fuels (McCarrol / Loader 2004). The $\delta^{13}C$ of CO_2 during the 3rd and the 2nd millennium has been found higher (-6.36‰) that those of modern times (-8.05‰) (http://web.udl.es/usuaris/x3845331/AIRCO2_LOESS.xls), thus resulting in changes in the $\delta^{13}C$ of ancient plant remains. However, since we do not intend to compare the data inferred from modern samples to those of the ancient plant remains in absolute terms, but just to point out which is the main factor in the carbon isotopes discrimination, variations due to the different $\delta^{13}C$ of CO_2 can be neglected.

The only parameter under the direct control of the plant is c*i*, which depends on stomatal conductance and the carboxylation rate. Thus, if environmental factors cause the plant to increase its stomatal conductance and / or decrease its carboxylation rate, then the resulting increase in c*i* will produce a lower $\delta^{13}C_{plant}$ (Heaton 1999). For this reason, the measurement of $\delta^{13}C$ in plants can provide an indication of environmental conditions during plant growth (Araus et al. 1997).

Variation in $\delta^{13}C$ has been ascribed to a range of biological and ecological factors relating to water use. The principal environmental parameters involved are those most commonly associated with photosynthesis: the organic carbon isotope composition of a plant has been discovered to be related to *light* (Vogel 1978; Francey et al. 1985; Jackson et al. 1993; Berry et al. 1997), *soil isotopic composition* (Raven / Farquar 1990; Condon et al.1992), *salinity* (Farquar et al. 1989), *temperature* (O'Leary 1995; Jedrysek et al. 2003) and *water availability* (O'Leary 1995; Stewart et al. 1995; Anderson et al. 1996; Araus et al. 1997; Wang / Han 2001; Guo / Xie 2006).

Several studies have focused on the correlation between $\delta^{13}C$ in plants and local climate-forcing agents, and it is commonly accepted that growth-limiting factors are also generally responsible for isotope discrimination (Schleser et al. 1999).

[1] The stable carbon isotope composition of a given sample is usually expressed as the difference between the $^{13}C / ^{12}C$ ratio measured for the sample (R_{sample}) and the PDB (Pee Dee Belemnite) standard ratio (RPDB): $\delta^{13}C(‰) = (R_{sample} / R_{standard} - 1) \times 1000$.

Numerous investigations have shown that the $\delta^{13}C$ values of plants are negatively correlated with water input. This negative correlation is more pronounced in arid environments than in humid areas (Stewart et al. 1995; Anderson et al. 1996; Austin / Vitousek 1998; Korol et al. 1999; Miller et al. 2001; Van de Water et al. 2002; Chen et al. 2005; Chen et al. 2007; Wang et al. 2005; Leavitt et al. 2007). A possible explanation lies in the assumption that water availability rather than other factors is the key climatic limiting factor in semi-arid areas (Nemani et al. 2003; De Menocal 2001).

As a result, variations in precipitation, atmospheric humidity and soil water availability are assumed to account for changes in the concentrations of $\delta^{13}C$ in plants in sub-arid areas. For instance, studies carried out in drought-affected regions in Asia have shown that a 100-mm increment in annual precipitation results in a decrease in leaf $\delta^{13}C$ of 0.49–1.5‰ (Wang / Han 2001; Chen et al. 2002; Weiguo et al. 2005; Guo / Xie 2006; Zeng / Shangguan 2007).

Although these studies consider various plant species, they analyse the $\delta^{13}C$ of one single anatomical component, that is, the leaves. In fact, the distinct physiological features of different plant tissues (leaf, stem, etc.) determine slight differences due to the additional fractionation of carbon isotopes *after* photosynthesis (Badeck et al. 2005; Nogués et al. 2005).

The question which arises now regards the possibility that the carbon stable isotope concentration in archaeological plant remains might be considered a reliable palaeoclimate tool and / or might record changes in the rainfall regime.

Dealing with ancient data, two aspects should be taken in consideration: the state of preservation and the unpredictability of archaeobotanical findings. Under Mediterranean conditions, plant remains are preserved in archaeological contexts as charred material, which does not seem to be a real problem since the original environmental signal of $\delta^{13}C$ is retained although charcoalification has occurred (Aguilera et al. 2008; Heaton et al. 2009)[2]. By contrast, the unpredictability of archaeological findings, which may entail all kinds of plant components and considerably vary in terms of type and species, is to be taken into account when trying to calibrate ancient palaeoclimate signals. Consequently, in order to interpret the climate signals found in ancient specimens, $\delta^{13}C$ analysis in paleoclimatic studies should be representative of the overall pattern of plants growing in a particular environment. This, of course, may generate additional noise, obscuring the climatic signal inferred from $\delta^{13}C$ in plants. Nevertheless, the general trend may be preserved, because $\delta^{13}C$ increases with decreasing rainfall along an aridity gradient both within single species and between species (Schulze et al. 2006). Based on this assumption, we tested the reliability of carbon isotope analysis in Syria by calibrating the response of modern vegetation to drought.

The context of study: regional climate and local environment

The Near East is characterised by a highly diversified environment, in which different climatic regimes (maritime, desert, steppe and mountainous) are found very close to each other. One of the most significant attempts to describe the climate system of the Levant region is based on the synoptic scale (Ziv / Yair 1994; Alpert et al. 2004a; Alpert et al. 2004b; Baruch et al. 2004) including four major components: the *Persian troughs*, low-pressure airstreams which lead to persistent summer weather conditions in the Near East countries (Alpert et al. 1990; Alpert et al. 2004b), the *Cyprus lows*, which contribute winter rainfall of short duration and high intensity (Shay-El / Alpert 1991; Alpert et al. 2004b), the RST or "*Sudan trough*", usually situated over the Red Sea throughout the year and deepening to the north, reaching the Near East during autumn (e. g. Dayan et al. 2001; Alpert et al. 2004b) and the *Sharav lows*, or North African depression, with hot and dusty winds affecting mostly the Near East steppe areas (Alpert et al. 2004b).

The combination of the subtropical high of the *Azores* and the *Persian trough* leads to northwesterly (Etesian) winds, which are connected with continual cool advection from eastern Europe and the Mediterranean towards the Levant (Saaroni et al. 2003; Ziv et al. 2004). In western Syria, the Anti-Lebanon mountain range acts as a barrier to the advection of humid western air, so that the whole country has a longitude-dependent pattern of precipitation (Perrin de Brichambaut / Wallén 1963). The E–W decrease in rainfall is gradual in the north, while in the south it is disturbed by longitudinal mountain ridges peaking over 3,000 m. A strong correlation between

[2] The effect of charring has been tested by the authors on modern Syrian land races of barley. The results of this analysis revealed that no changes occurred in the $\delta^{13}C$ ratio after the carbonisation, the correlation between fresh and charred value had, indeed, an $r^2 = 0.9$ (data presented to the XVI International Work Group of Palaeoethnobotany 2010).

altitude and precipitation exists everywhere in the country, not only in the western mountain ranges, but also in the Syrian desert where some ridges are dotted with arboreal components (Zohary 1973).

Throughout the country, rainfall accounts for most of the variability in modern vegetation, and plant community composition varies according to environmental gradients from the arid eastern steppe to the Oro-Mediterranean western woodlands. The arid and sub-arid ecosystems are characterised by the prevalence of perennial and annual grasses and forbs such as *Artemisia herba-alba, Poa siniaca, Noaea mucronata* and *Salvia spinosa*, having both the C3 and C4 photosynthetic pathways (Shomer-Ilan et al. 1981; Vogel et al. 1986), while in temperate ecosystems shrubs and trees predominate (Pabot 1957).

Materials and methods

The investigation of the relationship between carbon stable isotope plant values and rainfall took into account the modern ecological and vegetational pattern of Syria (Fiorentino / Caracuta 2007b). However, the effects of altitude on the latitude-dependent precipitation were ignored because they were embodied in the original dataset of the meteorological stations considered.

In total, 191 plant specimens (all from C_3 pathway species) were collected from 12 sites distributed along a rainfall gradient in Syria at longitudes between 34° and 42° E, latitudes between 37° and 34° N (Fig. 2) and altitudes between 0 and 2,000 m above sea level.

The selection of sites intended to cover a wide range of plant communities and ecosystems (the locations and dominant ecological patterns are shown in Fig. 2 and Table 1), while irrigated fields and cultivated plants were avoided.

Twenty-two species were sampled during spring and summer 2005, the number of samples varying from site to site according to their availability.

The aim was to determine the average plant responses of the complete range of life-form groupings at each point along the ecological gradient of reference. To this end, trees and shrubs as well as long- and short-lived plants were sampled. Small pieces of different tissues were taken from each plant with the aim of obtaining a satisfactory representation of the overall plant status. The plant samples were dried in the laboratory and ground to fine powder. The carbon isotope ratio relative to the PDB standard was determined using a Delta Plus Finnigan mass spectrometer and a Carlo Erba EA1110 ^{15}N / ^{13}C analyser-mass spectrometer (CHN) with an accuracy level of ± 0.2‰.

The rainfall data for the sampled sites were provided by ICARDA (International Center for Agricultural Research in the Dry Areas). They represent the 10-year mean annual precipitation values at the nearest meteorological station. Averages were calculated for the 10-year period prior to collection of plant material. These data were preferred to the 2005 precipitation data because Syria is affected by strong inter-annual variability (Perrin de Brichambaut / Wallén 1963) which may have influenced the carbon stable isotope concentration in long-lived plants.

The distance from the weather stations varied according to the site, the nearest being approximately 100 m (site 5), and the furthest approximately 15 km (site 3).

Concerning the archaeological samples, thirty-eight charred plant macroremains were collected at the Ebla and Qatna sites during the 2003–2006 campaigns. They were identified before being submitted to AMS radiocarbon dating and stable isotope measurements in order to eliminate C4 plants and long-lived plants which could have amplified the range of uncertainty of the ^{14}C dating.

In total, thirty-one annual fruits (caryopses, olive stones, legumes) and seven branches of perennial trees with no more than five growth rings were selected.

All the samples were mechanically cleaned under an optical microscope before being submitted to a chemical cleaning procedure consisting of alternate Acid (HCl, 10 ml, 1 M for 10h at room temperature) / Alkali (NaOH, 10 ml, 1 M at 60 °C) / Acid (10 ml, 1 M for 10h at room temperature) (D'Elia et al. 2004; Quarta et al. 2005).

The purified sample material was then oven-dried and combusted to CO2 at 900 °C in sealed quartz tubes together with copper oxide and silver wool. The sample of carbon dioxide was then cryogenically purified and finally converted to graphite by using hydrogen as a reducing medium and iron powder as a catalyst (D'Elia et al. 2004). The graphite was pressed into the sample holders of the accelerator mass spectrometer for the measurement of its isotopic composition (for further details see Calcagnile et al. 2005).

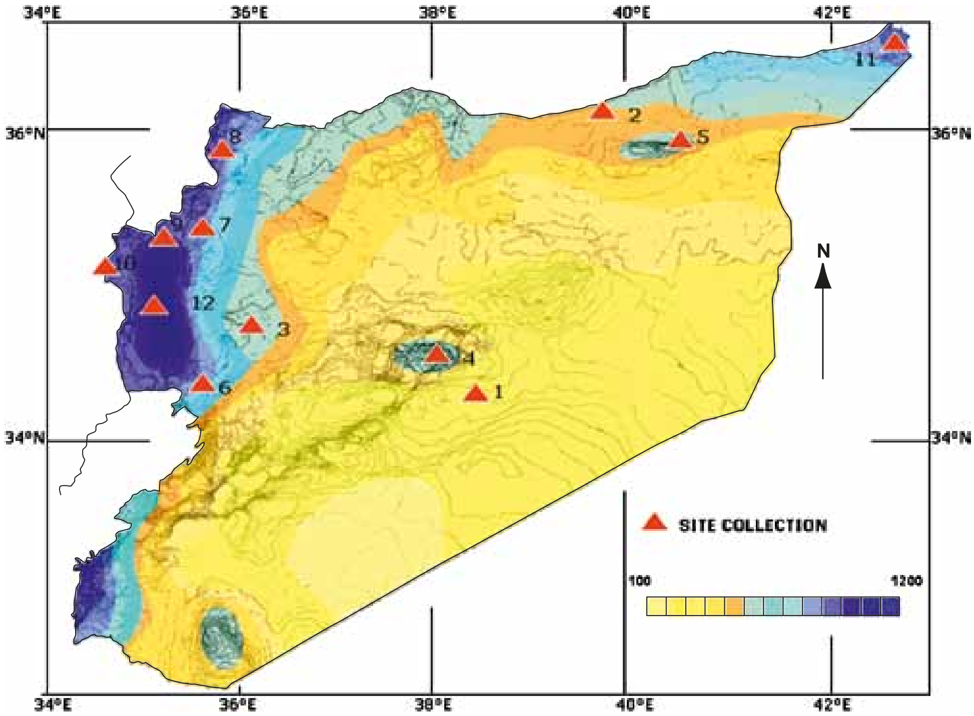

Fig. 2. Syria. Rainfall map and location of the sites where modern plants were collected (red triangles) (modified from the map drawn by U.S.S.R. geologists).

Site number	Location	Vegetation type*	Species (n)	Samples (n)	Mean δ13C (‰) (± SD)	δ13C range (‰)
1	E 38 17′ 00′′ N 34 33′ 00′′	Desert steppe	4	17	-25.5 (1.9)	-20.9/-28.1
2	E 40 22′ 17′′ N 36 39′ 31′′	Steppe	3	18	-25.7 (2.2)	-21.8/-29.1
3	E 36 45′ 00′′ N 35 08′ 00′′	Cultivated steppe	4	20	-26.5 (1.2)	-24.1/-28.5
4	E 38 21′ 00′′ N 34 55′ 00′′	Steppe forest	3	20	-26.4 (0.9)	-25.2/-27.9
5	E 40 11′ 00′′ N 36 25′00′′	Steppe forest	4	16	-26.7 (2.5)	-21.9/-28.6
6	E 34 44′ 21′′ N 36 43′ 59′′	Cultivated steppe	4	15	-26.9 (1.2)	-24.9/-29
7	E 36 35′ 00′′ N 35 43′ 00′′	Lower mediterranean	2	12	-26.6 (1.5)	-24.3/-28.4
8	E 36 40′ 00′′ N 36 40′ 00′′	Upper mediterranean	4	22	-27.5 (1.8)	-24.6/-30.5
9	E 36 18′ 03′′ N 35 54′ 14′′	Upper mediterranean	4	12	-27.4 (1.3)	-25.3/-29.1
10	E 35 47′ 58′′ N 35 30′ 45′′	Mediterranean maquis	4	12	-27.5 (1.5)	-25.2/-29.7
11	E 42 04′ 00′′ N 37 03 ′00′′	Upper mediterranean	4	18	-28.1 (0.9)	-26.8/-29.6
12	E 36 06′ 00′′ N 35 18′ 00′′	Oro mediterranean	4	8	-27.1 (1.7)	-27.4/-30.1

Table 1. Syria. δ13C analysis of modern plants.
* From Bottema / Berkuda 1979; FAO http://www.fao.org/countryprofiles/maps.asp?iso3=SYR&lang=en.

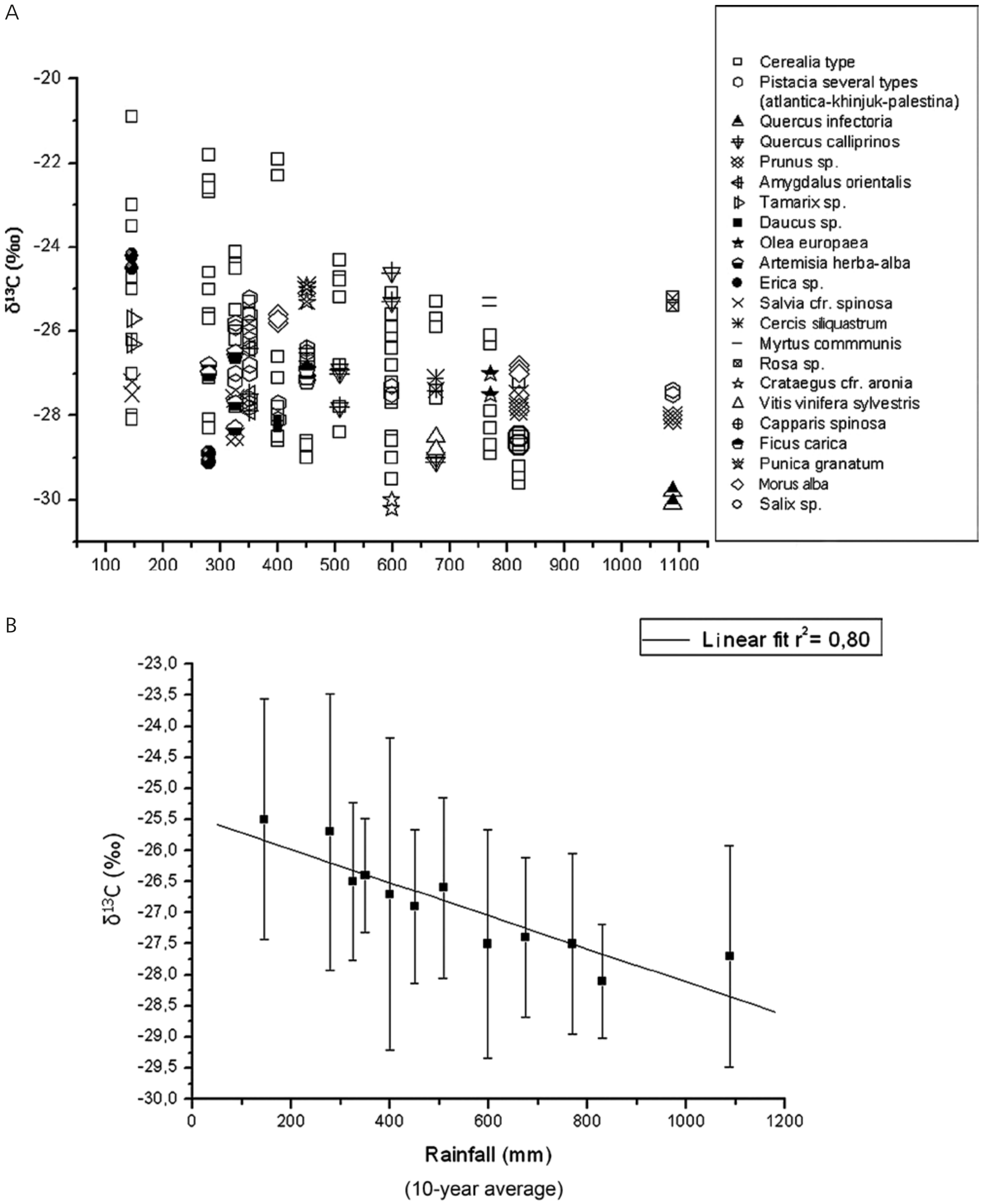

Fig. 3. Syria, modern plant remains. A–B) $\delta^{13}C$ values of modern plants *vs.* 10-year mean annual rainfall gradient.

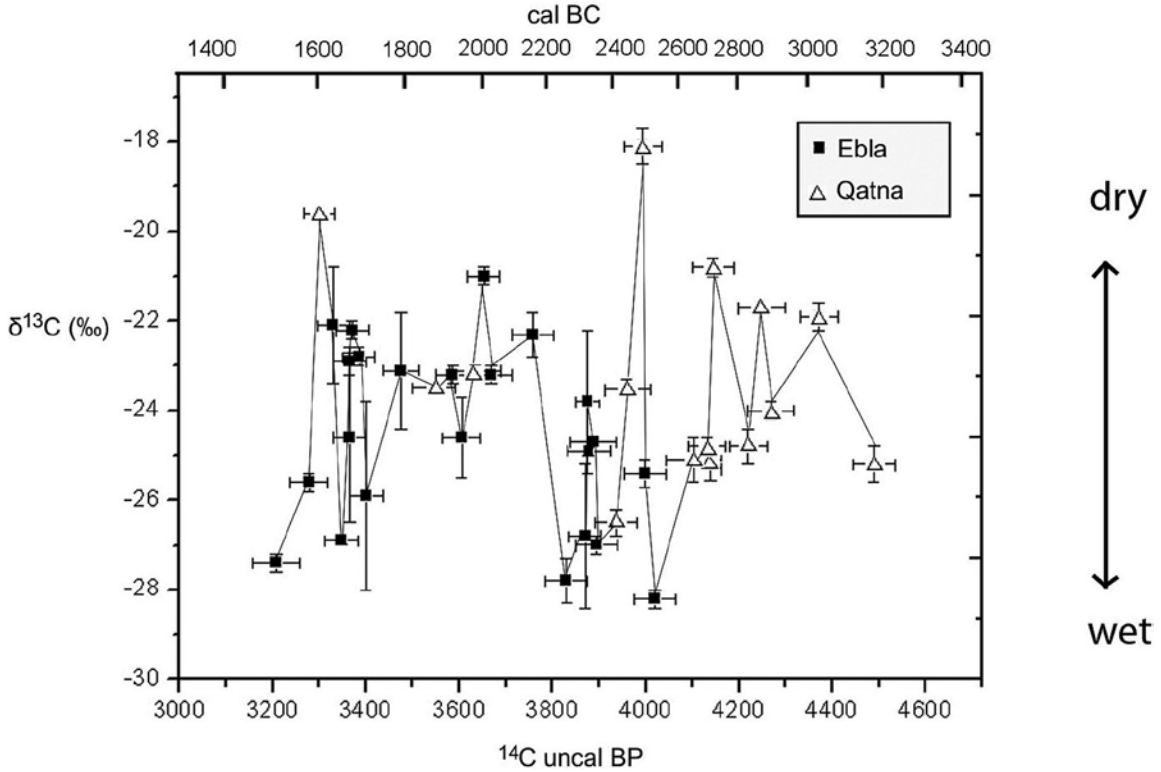

Fig. 4. Ebla and Qatna, archaeological plant remains. $\delta^{13}C$ as a function of measured radiocarbon age.

Results

$\delta^{13}C$ analysis of modern Syrian plants by IRMS

Several analyses have been focused on Syrian modern vegetation, but all of them were carried out on edible fruits (especially cereals) and were mostly intended to point out the response of wheat and barley to water stress during the grain filling (Araus et al. 1997; Araus et al. 2006; Riehl et al. 2008). The novelty of the present analysis consists in seeking to define the response of all the plant communities living in Syria to meteoric water input.

Following a rainfall gradient of approximately 1,000 mm, the mean $\delta^{13}C$ of 191 plants at 12 locations significantly decreases, from -25.5 ‰ (± 1.9 SD) at 145 mm to -28.1 ‰ (± 1.9 SD) at 820 mm. A relatively high $\delta^{13}C$ value at site 12 (1,088 mm) is probably due to the altitude, which affects plant growth in conditions of air pressure deficit. According to Körner et al. (1988), at high altitudes, plants experience differences between internal and external leaf CO_2, which can account for increases in $\delta^{13}C$ in the order of 2.6‰. Inter-community differences may be explained by water availability, while the intra-community differences shown in figure 3A can be attributed to the indirect influence of environmental variables, e. g. light, temperature, isotopic soil composition, salinity (Heaton 1999) and physiological features (Farquhar / Richards 1984; Francey et al. 1985; Jackson et al. 1993), such as different root systems (Jackson et al. 1996; Schenk / Jackson 2002; Chen et al. 2005; Sala et al. 1997).

Variability in $\delta^{13}C$ between sites was greater than variability within sites, with significant differences along the rainfall gradient.

Both individual and community-averaged $\delta^{13}C$ values were plotted against the 10-year average rainfall. The community-averaged $\delta^{13}C$ values were found to be closely related to rainfall, with a coefficient of correlation ($r^2 = 0.80$) (Fig. 3B).

The significant correlation between plant community $\delta^{13}C$ values and the rainfall gradient reflects the direct dependence of carbon fixation processes in plants on natural moisture. Of course, it is not possible to disentangle the effect of evapotranspiration or soil capillarity from that of rainfall, and this represents a limit when trying to quantify the variation of $\delta^{13}C$ in terms of rainfall changes. Nevertheless, we can assert that among all the environmental factors that can influence the $\delta^{13}C$ of Syrian plants water availability (rainfall) is the most important one.

Id Laboratory	Sample type	Taxa	Uncal BP	Year BC	δ¹³C (‰)
(E) LTL-319A	Legume	*Vicia* sp.	3208 ± 50	1610–1390	-27,4 ± 0,2
(E) LTL-389A	Cereal	*Hordeum* sp.	3278 ± 40	1690–1440	-25,6 ± 0,2
(Q) POZ-8348	Wood Charcoal		3330 ± 32	1690–1520	-19,6 ± 0,1
(E) VERA-3552	Cereal	*Triticum aestivum / compactum*	3330 ± 35	1690–1510	-22,1 ± 1,3
(E) LTL-390A	Cereal	*Triticum / Hordeum*	3347 ± 35	1700–1520	-26,9 ± 0,1
(E) VERA-3555	Cereal	*Hordeum* sp.	3365 ± 35	1750–1600	-24,6 ± 1,9
(E) VERA 3560	Wood Charcoal	Coniferae	3365 ± 35	1750–1600	-22,9 ± 0,3
(E) VERA 3557	Legume	Leguminosae	3370 ± 35	1750–1600	-22,2 ± 0,2
(E) VERA 3559	Legume	Leguminosae	3385 ± 35	1770–1600	-22,8 ± 0,2
(E) VERA 3554	Cereal	*Hordeum* sp.	3400 ± 35	1780–1610	-25,9 ± 2,1
(E) VERA 3558	Wood Charcoal	Pomoidaea	3475 ± 40	1890–1680	-23,1 ± 1,3
(E) LTL-395A	Stone	*Olea europaea*	3545 ± 45	1980–1740	-23,5 ± 0,1
(Q) POZ-8349	Wood Charcoal		3586 ± 36	2040–1870	-23,2 ± 0,2
(E) VERA 3556	Stone	*Olea europaea*	3605 ± 40	2040–1870	-24,6 ± 0,9
(E) LTL-387A	Stone	*Olea europaea*	3634 ± 55	2150–1870	-23,5 ± 0,1
(E) LTL-386A	Cereal	*Hordeum* sp.	3652 ± 35	2140–1910	-21,0 ± 0,2
(Q) LTL-2033A	Cereal	*Hordeum vulgare*	3669 ± 45	2150–1920	-23,2 ± 0,2
(E) LTL-791A	Wood Charcoal	*Quercus ilex* type	3757 ± 45	2300–2020	-22,3 ± 0,5
(E) LTL-393A	Cereal	*Triticum* sp.	3830 ± 45	2460–1910	-27,8 ± 0,5
(E) VERA 3550	Cereal	*Hordeum* sp.	3870 ± 35	2470–2270	-26,8 ± 1,6
(E) VERA 3551	Cereal	*Triticum* sp.	3875 ± 25	2470–2280	-23,8 ± 1,6
(E) LTL-394A	Wood Charcoal	Oleae europaea	3878 ± 45	2470–2280	-24,9 ± 0,1
(E) LTL-392 A	Cereal	*Triticum aestivum / compactum*	3887 ± 50	2490–2200	-24,7 ± 0,1
(E) LTL-847 A	Wood Charcoal	Pomoidaea	3895 ± 45	2480–2270	-27,0 ± 0,2
(Q) LTL-2040A	Cereal	*Hordeum vulgare*	3937 ± 45	2500–2290	-26,5 ± 0,3
(Q) LTL-2460A	Cereal	*Hordeum vulgare*	3985 ± 45	2630–2340	-23,5 ± 0,1
(Q) LTL2034A	Wood Charcoal	*Olea europaea*	3993 ± 40	2630–2450	-18,1 ± 0,4
(E) LTL-846 A	Wood Charcoal	Pomoidaea	3998 ± 45	2640–2430	-25,4 ± 0,3
(E) LTL-388 A	Cereal	*Gramineae*	4020 ± 45	2670–2450	-28,2 ± 0,2
(Q) LTL-2044A	Cereal	*Triticum dicoccum*	4102 ± 60	2880–2560	-25,1 ± 0,5
(Q) LTL-2459A	Cereal	*Hordeum vulgare*	4123 ± 45	2880–2570	-25,1 ± 0,2
(Q) LTL-2038A	Cereal	*Hordeum vulgare*	4132 ± 40	2880–2580	-24,8 ± 0,2
(Q) LTL-2036A	Cereal	*Hordeum vulgare*	4144 ± 45	2880–2580	-20,8 ± 0,2
(Q) LTL-2039A	Cereal	*Hordeum vulgare*	4219 ± 40	2820–2670	-24,8 ± 0,4
(Q) LTL-2042A	Cereal	*Hordeum vulgare*	4248 ± 50	2940–2830	-21,7 ± 0,1
(Q) LTL-2037A	Cereal	*Hordeum vulgare*	4268 ± 50	3030–2840	-24,0 ± 0,2
(Q) LTL-2043A	Cereal	*Hordeum vulgare*	4371 ± 40	3100–2900	-21,9 ± 0,3
(Q) LTL-2045A	Cereal	*Triticum dicoccum*	4489 ± 45	3360–3080	-25,2 ± 0,4

Table 2. Syria. δ¹³C analysis of archaeological plant remains. The thirty-eight AMS dates.

On this basis it is possible to evaluate changes in rainfall patterns over time in Syria by plotting the $\delta^{13}C$ of archaeological samples from two archaeological sites, Ebla and Qatna, against the ^{14}C-absolute chronology.

The $\delta^{13}C$ of ^{14}C-AMS-dated archaeological plant remains

Thirty-eight samples from the two archaeological sites of Ebla and Qatna were subjected to AMS analysis in order to obtain information about the stable carbon isotope composition and to establish the absolute chronology of the studied samples by ^{14}C dating. The average accuracy of AMS $\delta^{13}C$ measurements was ± 0.5‰, making it a reliable parameter, while ^{14}C measurements were accurate to ± 45 years (Fig. 4).

The ^{14}C of archaeobotanical samples indicates a time period of fifteen hundred years, from the 3rd millennium to the end of the 2nd millennium BC, while the $\delta^{13}C$ values resulting from this technique range from -28.2 ± 0.2 ‰ to -18.1 ± 0.4 ‰, with an average value of -24.0 ‰ (Table 2).

In particular, three phases of high $\delta^{13}C$ values were recognised (3000–2750 BC, 2300–2050 BC and 1800–1600 BC) separated by two periods of low $\delta^{13}C$ values (2650–2350 BC and 1600–1500 BC). Besides, an isolated $\delta^{13}C$ negative peak occurred in 2550 BC. Between 2050 and 1850 BC there was a moderate decrease of carbon stable isotope ratio compared to the centuries which preceded and followed that period (Fiorentino et al. 2008; Fiorentino / Caracuta 2007a; Fiorentino / Caracuta 2007b; Roberts et al. 2011) (Figs. 4–5).

Discussion

As shown by the calibration of modern plant response to climate conditions, changes in $\delta^{13}C$ of plants grown in Syria mainly depend on water availability that can result from natural as well as anthropic factors.

Previous studies, carried out in northern Mesopotamia, have revealed that irrigation can provide additional water to increase the productivity of grain fields and that carbon isotope analysis can be used to disentangle irrigation inputs from the moisture ones (Araus et al. 1997; Araus et al. 1999). Nonetheless, we can exclude the possibility that in northwestern Syria this kind of technology was adopted. In fact no big rivers, such as the Euphrates, flow in the area, so it would have been unworthy to dig channels to bring water to fields. Moreover, no mention of irrigational practices can be found in two towns' archives, which are otherwise full of information about all the other administrative matters (Archi 1991; Archi 1999; Milano 1987; Milano 1990). Considering the good amounts of documents dealing with water management in other Mesopotamian city-states, the absence of any references in the Qatna and Ebla's archives can be seen as proof of the fact that irrigation was not practised in the area. This is not surprising since the rainfall rate of northwestern Syria is higher than that of the northeast and can provide enough water to sustain a good rain-fed agriculture.

Therefore the $\delta^{13}C$ inferred from the Ebla-Qatna archaeological remains is entirely dependent on the water input during the plant growing, and thus provides information about climate fluctuations that occurred in Syria during this time period (Fig. 4): the increases in $\delta^{13}C$ values indicate water-starvation periods, while decreases reveal the establishment of more humid conditions.

The pattern of multi-centennial rainfall oscillations recorded by the Ebla-Qatna plant remains shows similarities with that identified in the Dead Sea levels and Soreq Cave speleothem records which indicated a long-term process of aridification that started around the 3rd millennium BC (see Fig. 5).

At the beginning of that millennium (~3000 / ~2800), the increase of $\delta^{18}O$ values of Soreq Cave corresponds to a decrease of the Dead Sea level likely due to a reduction in the rainfall rate. After a period of moister conditions (~2800 / ~2350), a new drop in the rainfall regime is recorded: the Ebla-Qatna curve marks an increase in $\delta^{13}C$ values *c.* 2600 which find correspondences with the decrease of the Dead Sea level and isotopic values of the Soreq Cave sequence. A long drought period struck the Near East for almost seven hundred years (~2400 / ~1700) with a interval of moister conditions in around ~2000 (for further details on the 3rd millennium "drought crises" see Anderson et al. 2007; Cremaschi 2007; Kuzucuoglu / Marro 2007; Wilkinson 2004; Issar 2003; De Menocal et al. 2000; Cullen et al. 2000; Frumkin et al. 1999; Bar Matthews et al. 1997; Weiss et al. 1993).

Moreover, the use of the AMS technique allowed us to synchronise climate variations with cultural changes, thanks to the simultaneous measurement of ^{14}C and $\delta^{13}C$ within the same archaeological plant remains. Thus it can be used as tool to define the impact of changes in water availability on human com-

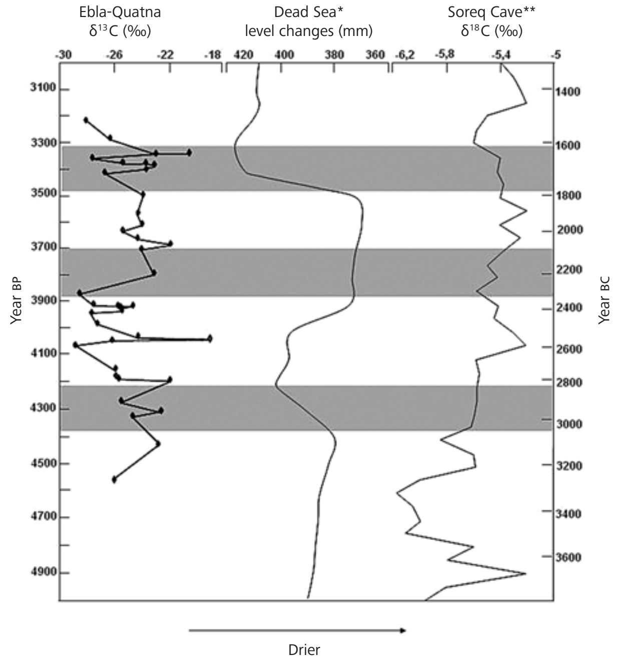

Fig. 5. The Ebla-Qatna $\delta^{13}C$ curve compared to the Dead Sea level oscillations* (after Migowski et al. 2006) and the Soreq Cave speleothem $\delta^{18}O$ curve** (after Bar-Matthews et al. 2000).

munities developing in the sub-arid region of the Near East (De Menocal 2001; Roberts et al. 2011).

It is not really coincidental that between the 3rd and the 2nd millennium BC Near Eastern history is punctuated by century-scale political "crises", some of them clearly linked to climate fluctuations pointed out by natural and anthropogenic records. The drought peak at 3000–2800 BC, which occurred concurrently with the end of the Jemde Nasr phase, seems to have trimmed down the growth rate reached in the preceding centuries with consequences on the city-size and the downward trend in long-distance trade exchanges (Schwartz 1993; Pinnock 2004). The coming of more humid conditions around 2400 BC led by contrast to the multiplication of city-states in the south and in the northern part of the Fertile Crescent (Nissen 1990) and the establishment of the first state in Egypt (Trigger et al. 1983). The same period coincides with the first systematic occupation of the Ebla site (Matthiae 1989; Klengel 1992) and the general flourishing of Syrian city-states. The complex system of gathering and redistribution which was developed by those communities and was the base of their power enabled them to get over the short, abrupt climate fluctuations, such as the one occurring in 2600 BC and lasting a few decades. However, between 2300 and 2100 BC, Bronze Age cultures experienced a series of crises culminating in a period of contraction or collapse of previous political structures which was more or less synchronous with a strong climatic signal. The environmental consequences of this climatic drying had greater impact in semi-arid and continental regions of the Near East and therefore varied from region to region, according to the degree of sensitivity of the impacted areas to precipitation decrease (Roberts et al. 2011).

The cultural renaissance which follows this phase is characterised by a huge cultural transformation which marked the transition from the culture of the Early Bronze Age IVB to that of the Middle Bronze Age I. The positive effect of the climate shift towards more humid conditions is visible also in Egypt, where the state power was re-established (Middle Kingdom) (Trigger et al. 1983).

Shortly before 1800 BC the political situation was still fragmented with several centres struggling for the power. The environmental data point to a general drought trend, where episodes of decrease in rainfall were followed by periods of increased moisture availability. The most relevant drought peak occurred around 1600 BC correlating to the repeated military expeditions and invasions by the Hittites from Anatolia (Matthiae 2006).

Conclusion

The qualitative reconstruction of paleoprecipitation trends from carbon isotope analysis in archaeological plant remains demonstrates that $\delta^{13}C$ analysis of ^{14}C-AMS-dated plants can be used to infer paleoclimatic change, although the modern calibration of plant response to drought revealed certain differences among life-group communities.

The use of radiocarbon dating adds a special value to carbon isotope analysis, since it allows paleoclimatic data to be compared to an absolute chronology with a time resolution of about fifty years. The value of this data lies in the opportunity – not found in any other archaeological indicator – to identify small- and medium-scale climate oscillations. As a result, short periods of water starvation can be identified and used to assess how climate influenced the growth rate, development and mutual relations of ancient societies in the sub-arid regions of the Near East (Millen Rosen 2007) and to evaluate the human perception of climate change (Ingold 2000).

ACKNOWLEDGEMENTS The authors are grateful to Donatella Magri, Department of Biology at the University of Rome "La Sapienza", for her insightful comments, Ian Walkoun of ICARDA for providing the rainfall data, and Jordi Voltas, Department of Forestry Science at the University of Lleida, for general discussion on the subject. Special thanks to Paolo Matthiae for allowing the study on Ebla material. The analyses carried out on the modern vegetation were partially funded by the IAM-CIHEAM international cooperation project called "Rationalization of irrigation systems in Ras al Ain – Syria". The AMS measurements were done at the CEDAD Laboratory of the University of Salento, at VERA-Laboratorium Institut für Isotopenforschung und Kernphysik – Universität Wien, and at Poznan Radiocarbon Laboratory Foundation of the Adam Mickiewicz University.

Summaries

SUMMARY Agricultural potential is commonly regarded as a key factor for the development of premodern complex societies in sub-arid regions. For this reason, the assessment of paleorainfall is considered fundamental to understand the influence of short-term climate fluctuations on ancient human communities, especially in those areas characterised by critical environmental conditions such as the steppes of the Near East. The relationship between natural resources and human adaptation has long been investigated by studying plant remains from archaeological deposits. Climate change has been found to be the main driving force for the modifications in plant cover. The present work aims to extend the archaeobotanical approach by using carbon isotope analysis of ancient plant remains to infer paleorainfall trends. Given that $\delta^{13}C_{plant}$ has been found to be influenced by local environmental parameters, we tested the isotopic response of modern plants to the main regional climate-forcing agents by sampling plant communities along a rainfall gradient in Syria and measuring the $\delta^{13}C$ values by IRMS techniques. In addition, we analysed the carbon isotope composition of 38 samples collected at Ebla and Qatna, two protohistoric sites in northwestern Syria, by means of AMS techniques to determine their $\delta^{13}C$ and ^{14}C values. The qualitative reconstruction derived from the carbon isotope data thus obtained enabled us to identify changes in paleorainfall trends over a period of fifteen hundred years, from the 3rd millennium to the 2nd millennium BC, and to test the response of local human communities to short-term climate changes.

RIASSUNTO Il potenziale agricolo di un'area è da molti considerato come il fattore determinante per lo sviluppo e la crescita delle società complesse di epoca pre-industriale. Per tale ragione, risulta fondamentale identificare l'andamento delle paleoprecipitazioni per comprendere l'influenza che le oscillazioni climatiche di breve corso hanno avuto sull'organizzazione delle comunità umane che si sono sviluppate in aree con condizioni ambientali critiche, come le steppe del Vicino Oriente.

La relazione tra risorse naturali e strategie di adattamento messe a punto dell'uomo è stata ripetutamente studiata mediante l'indagine dei resti vegetali recuperati in contesti archeologici; allo stesso tempo è stata messa in evidenza l'importanza del clima come variabile determinante nella distribuzione e nella composizione della copertura vegetale.

Con il presente lavoro, si intende estendere il tradizionale approccio archeobotanico attraverso l'impiego di una nuova metodologia di indagine, basata sull'analisi degli isotopi del carbonio (^{12}C, ^{13}C, ^{14}C) nei resti vegetali antichi, finalizzata all'identificazione degli andamenti della paleo-precipitazione.

Stabilito che $\delta^{13}C_{plant}$ dipende dalle condizioni ambientali locali, si è provveduto a testare la risposta della flora siriana alle variabili climatiche mediante il campionamento, lungo un gradiente pluviometrico, di 191 campioni e l'analisi del $\delta^{13}C$ tramite spettrometria di massa convenzionale (IRMS).

Contemporaneamente, 38 campioni di resti vegetali, recuperati dai siti siriani di Ebla e Qatna, sono stati datati al radiocarbonio tramite AMS, al fine di risalire, simultaneamente ai valori di ^{14}C e $\delta^{13}C$.

I dati ottenuti sul campione antico hanno permesso di datare le oscillazioni climatiche conseguenti alle variazioni del regime pluviometrico e di stabilire una correlazione tra queste e le vicende storiche che hanno interessato la regione tra il III e il II millennio a. C.

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