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From Traditional Farming in Morocco to Early Urban Agroecology in Northern Mesopotamia: Combining Present-day Arable Weed Surveys and Crop Isotope Analysis to Reconstruct Past Agrosystems in (Semi-)arid Regions

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ABSTRACT
We integrate functional weed ecology with crop stable carbon and nitrogen isotope analysis to assess their combined potential for inferring arable land management practices in (semi-)arid regions from archaeobotanical assemblages. Weed and GIS survey of 60 cereal and pulse fields in Morocco are combined with crop sampling for stable isotope analysis to frame assessment of agricultural labour intensity in terms of manuring, irrigation, tillage and hand-weeding. Under low management intensity weed variation primarily reflects geographical differences, whereas under high management intensity fields in disparate regions have similar weed flora. Manured and irrigated oasis barley fields are clearly discriminated from less intensively manured rain-fed barley terraces in southern Morocco; when fields in northern and southern Morocco are considered together, climatic differences are superimposed on the agronomic intensity gradient. Barley $\delta^{13}C$ and $\delta^{15}N$ values clearly distinguish among the Moroccan regimes. An integrated approach combines crop isotope values with weed ecological discrimination of low- and high-intensity regimes across multiple studies (in southern Morocco and southern Europe). Analysis of archaeobotanical samples from EBA Tell Brak, Syria suggests that this early city was sustained through extensive (low-intensity, large-scale) cereal farming.

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Archaeobotany; stable isotopes; functional plant ecology; agricultural intensity; Bronze Age; Northern Mesopotamia

Introduction

In arable habitats, variation in stable carbon and nitrogen isotope values in cereals and pulses has been shown to reflect water status and soil nitrogen composition, respectively, with implications for water management and manuring (e.g. Araus et al. 1997; Bogaard et al. 2007; Fraser et al. 2011; Wallace et al. 2013; Fiorentino et al. 2015). Thus variation in crop stable isotope values offers a useful way to investigate the ecology of present and past farming systems. Interpretation of crop stable isotope values is usefully constrained through integration with functional ecological analysis of associated weed flora, which provides complementary insights into soil productivity and disturbance levels. A model for identifying cultivation intensity (i.e. labour and resource inputs per unit area) that integrates crop stable isotopes with functional weed attributes or traits has successfully been developed for temperate Europe (Bogaard et al. 2016). The aim of this paper is to develop a similar model for application to (semi-)arid regions.

A recent pilot study of stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope values in cereals grown under a range of intensity levels in Morocco was conducted in order to assess their potential for investigating past farming practice in (semi-)arid regions (Styring et al. 2016). This study integrated the results of isotopic survey of traditionally managed barley fields, extending from the Mediterranean north to the arid south of Morocco, with those of a previous study of plant isotopic variation with rainfall in the eastern Mediterranean (Hartman and Danin 2010). A working model was developed for disentangling the effects of aridity and manuring on cereal $\delta^{15}N$ values (Styring et al. 2016, figure 4). This study opens the way for using cereal $\delta^{15}N$ alongside $\delta^{13}C$ values as evidence of arable growing conditions in (semi-)arid areas such as northern Mesopotamia, where early processes of urbanisation have variously been related to agricultural intensification (increasing inputs of, for example, manure or midden material per unit area – Wilkinson 1982, 1993; Wilkinson et al. 1994), extensification (expansion of arable with decreasing inputs per unit area – Halstead in Wilkinson et al. 1994; Halstead 1995) or a combination of the two (Ur 2015; cf. Wilkinson 2003, 118, figure 6.16).

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A set of functional plant traits has been shown globally to occur in a limited set of combinations repeatedly acquired as vascular plants have evolved (Díaz et al. 2004, 2015). Functional trait variation in weed flora fits within these more general patterns of convergence around stress-tolerant, ruderal and competitor strategies (Grime 2001). Here we use a set of functional plant traits or attributes that, consistent with the predictions of ecological theory, have been shown previously to discriminate between the weed flora of relatively high- and low-intensity cultivation regimes (i.e. high and low soil productivity and [mechanical] soil disturbance) in southern Europe (Jones et al. 2000; Bogaard et al. 2016). We assess weed flora along gradients of intensity in Morocco, where climatic conditions range from sub-humid/semi-arid in the north to semi-arid/arid in the south. We also consider the usefulness of other functional traits relating to drought tolerance and avoidance.

The study regions in Morocco

The present-day farming sites belong to two separate geographical zones, in the north and south of the country (Table 1). The northern zone is situated in the central-western Rif and forms part of the Mediterranean eco-region; the southern zone is situated on the southern slope of the Anti-Atlas mountains and forms part of the Saharan eco-region (Figure 1) (Benabid 2000; Rankou et al. 2013).

The northern zone is located in a 'hot spot' of Mediterranean biodiversity (Médail et Quezel 1997; Moore et al. 1998). The northern farming study sites occur within the thermo-mediterranean vegetation zone in and around the Rif mountain chain. The study sites of Aarkub, Chmaala and Essafouren are situated on the Mediterranean slope of the chain in a semi-arid climate with woodland vegetation characterised by *Tetraclinis articulata* (Vahl) Masters (Benabid 1982). The study sites of Bellota and Agda are located on the continental slope of the periphery of the Rif chain, in pre-Rif folds with a sub-humid climate and characterised by *Quercus suber* L. woodland (Benabid 1982). Subsistence farming of a traditional mountain type is practised across the sites of the northern zone (Hmimsa and Ater 2008). Tillage was generally by donkey-, mule- or cattle-drawn plough (wooden or metal *charrue*) (Table 2). Management intensity ranged from relatively low (little to no manuring or hand-weeding and no irrigation) to high (hand-dug; intensive manuring, weeding and some irrigation) (Table 2). Arable fields tended to be small but varied in size, from *c.* 141 m^2 on average at Bellota to *c.* 1727 m^2 at nearby Agda, depending primarily on local topography rather than husbandry: management intensity was relatively low at both of these sites. Most of the fields surveyed had been established decades ago or longer, but two

Table 1. Summary of climatic and vegetation zones of the farming study sites in Morocco; bioclimate classifications follow Emberger (1955), revised by Sauvage (1963) and Achhal et al. (1980), vegetation stages according to Benabid (1982, 2000) and eco-regions and climax vegetation formations according to Benabid (2000) and Rankou et al. (2013).

Eco-region	Province	Commune	Site	Bioclimate	Rainfall (mm)[a]	Vegetation zone	Climax vegetation	Agrosystem
North Mediterranean	Chefchaouen	Steihat	Aarkub	Semi-arid	597	Thermo-mediterranean	Sclerophyllous forest with *Tetraclinis articulata*	Traditional mountain system (alluvial plains; Mediterranean slope of central Rif)
		Bni Bouzra	Chmaala		665			
			Essafouren		665			
	Ouezzane	Bellota	Agda	Sub-humid	703		Sclerophyllous forest with *Quercus suber*	Traditional mountain system (pre-Rif folds, continental slope of central Rif)
			Bellota					
South Saharan	Sidi Ifni	Tighirt	Agni Ouram	Semi-arid to arid	272	Infra-mediterranean	Macaronesian woodland formations with Argan (*Argania spinosa*)	Traditional mountain system (SW slopes of Anti-Atlas)
			Issili Zemmouren					
			Id Lahso Omar					
	Guelmim	Amtoudi	Id Aïssa	Arid	194			Oasis system
			Aguelouy					
	Tata	Tagmoute	Tougrare		222	Saharan	Steppe to woodland formations with *Acacia* sp.	

[a]Data from Aquastat (http://www.fao.org/nr/water/aquastat/climateinfotool/index.stm).

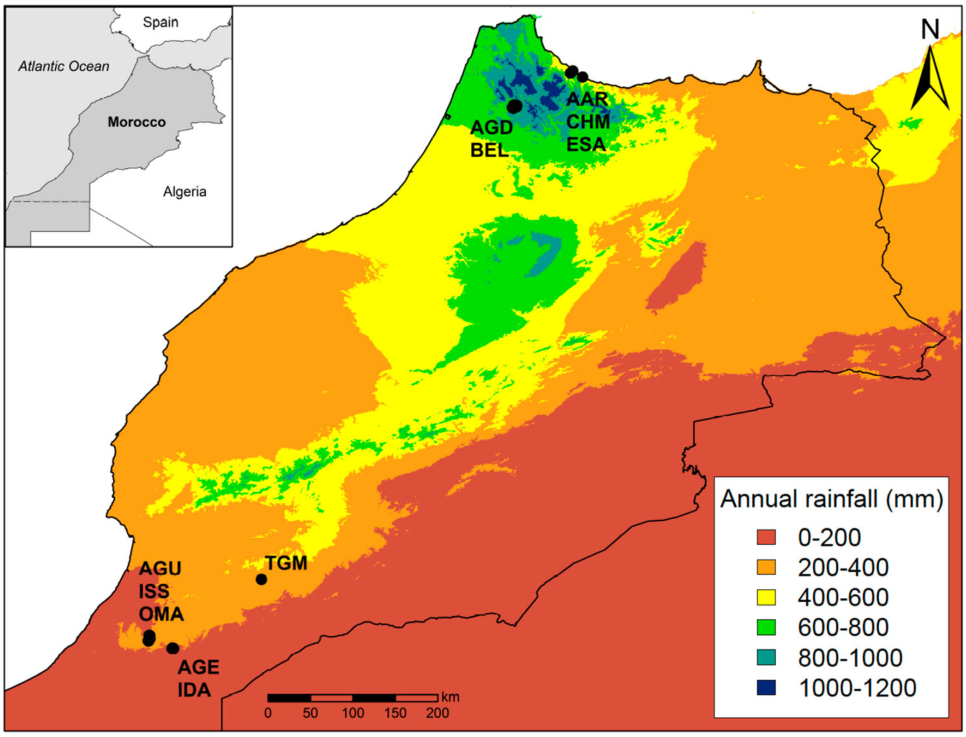

Figure 1. Map showing the present-day farming study sites in Morocco.

of the fields at Agda had just been cleared (by burning) of mature woodland that had grown for 30+ years; both were being initially cultivated with pulses at the time of the survey.

The southern zone is situated at the limit of the Mediterranean eco-region under strong Saharan influence, and can be considered part of the Saharan eco-region (Benabid 2000; Rankou et al. 2013). This eco-region is characterised by climatic aridity and low precipitation. Aside from Tougrare (Tata), which occurs within a Saharan vegetation zone (steppic, with arboreal vegetation typically of *Acacia* species), the other southern study sites belong to the infra-mediterranean vegetation zone. Among the latter, the Tighirt study sites (Table 1) experience oceanic influences, and climax vegetation is characterised by Macaronesian elements and trees such as *Argania spinosa* (L.) Skeels (Benabid 2000). The agrosystems encountered in the southern zone are of two types: mountain agrosystems (Tighirt sites) on the south-west slopes of the Anti-Atlas, and oasis systems (Amtoudi sites). The rainfed terraced fields of the mountain system were managed with relatively low intensity (tractor-ploughed, biennial manuring, variable weeding) whereas the oasis fields were very intensively tilled (by animal-drawn plough plus hand-digging), irrigated, manured and weeded (Table 2). Oasis fields were frequently shaded to varying degrees by date palm and other trees.

A total of 60 crop fields was included in this study, with one additional field sampled for stable isotope analysis only (Table 2). The most frequent crop among these fields, encountered in all zones, was hulled 6-row barley; in the south this was a local landrace, rather than a commercial variety, used to make couscous. Other cereals included bread wheat (*Triticum aestivum* L.), durum wheat (*Triticum durum* Desf.) and einkorn wheat (*Triticum monococcum* L.), while pulse crops were broad bean (*Vicia faba* L.), chickpea (*Cicer arietinum* L.), bitter vetch (*Vicia ervilia* (L.) Willd.) and lentil (*Lens culinaris* Medikus). All of the cereals were autumn(-winter) sown, while the pulses varied from winter- to spring-sown. Harvest times ranged from late April (southern oasis fields) to June (northern mountain system).

Materials and methods

Field methods

In March–May, 2014, floristic surveys were carried out of the weeds in 60 cereal and pulse fields, using methods comparable to those employed in similar surveys of the weeds associated with different husbandry regimes in France (Bogaard et al. 2016), Spain (Jones et al. 1995; Charles et al. 2002), Jordan (Palmer 1998; Charles and Hoppé 2003) and Greece (Jones et al. 1999). The weed species present in five 1m^2 quadrats were recorded along a linear transect from one end of each field to the other.

GPS data locating the boundary of every field surveyed and the specific location of every quadrat within each field were recorded using a handheld GPS unit. The data were analysed using ArcGIS 10.3.1 in order to detect any associations between topographical

Table 2. Summary of agricultural practices at the farming study sites.

Zone	North					South					
Province	Chefchaouen			Ouezzane		Sidi Ifni			Guelmim		Tata
Commune	Steihat	Bni Bouzra		Bellota		Tighirt			Amtoudi		Tagmoute
Site	Aarkub (AAR)	Chmaala (CHM)	Essafouren (ESA)	Agda (AGD)	Bellota (BEL)	Agni Ouram (AGU)	Issili Zemmouren (ISS)	Id Lahso Omar (OMA)	Id Aïssa (IDA)	Aguelouy (AGE)	Tougrare (TGM)
Field type	Terraced fields	Alluvial plain fields		Terraced fields		Terraced fields			Oasis plots		
Number of fields	3	1	1	13	10	5	5	5	11[a]	5	1
Surveyed hectares	0.38	0.02	0.27	2.24	0.14	0.25	0.13	1.05	0.13	0.03	0.09
Average field hectares	0.13	–	–	0.17	0.01	0.05	0.03	0.21	0.01	0.01	–
Soils	Dark brown dung-enriched on serpentine	Dark brown dung-enriched alluvial soils		Deep coarse brown soils on schist		Shallow, stony and rich in calcium carbonate (lithosols)			Dark brown dung-enriched alluvial soils		
Rotation regime	Cereal-pulse/summer vegetables			Cereal-pulse(-fallow)		Continuous cereal			Winter cereal-summer maize/vegetables		
Crops surveyed	Bread wheat; pea	Barley; oat	Bread wheat	Hulled 6-row barley; durum wheat; chickpea, lentil, bitter vetch, broad bean	Hulled 6-row barley, einkorn; chickpea, broad bean	Hulled 6-row barley			Hulled 6-row barley		
Sowing time	Oct			Cereals Oct–Dec; pulses Nov-May		Oct			Oct		
Tillage	Donkey-drawn plough or hand-dug only	Donkey-drawn plough (*charrue*)		Cattle- or mule-drawn plough (*charrue*)		Tractor or animal-drawn plough (*charrue*)			Donkey-drawn plough (*charrue*) plus hoe		
Manuring (ruminant dung)	Annual spreading of manuring from stables/pens			No manure spread; summer stubble grazing		Biennially or less frequent, depending on availability			Spread at rate of c. 100 t/ha, larger pieces broken up by hoe		
Irrigation	n/a	Every two weeks as needed, to point of saturation	Occasional, to point of saturation	n/a		n/a			Every 15 days to point of saturation, 28 × per year (for winter plus summer crops)		
Weeding	Frequent, for animal fodder etc.			Frequent to none	None	Frequency variable			Frequent, for animal fodder etc.		
Harvest time	May			June		May			Late April–May		

[a]1 of these fields was sampled for crop isotope analysis only (weed flora not surveyed).

variables and weed floristic composition or crop isotope values.

Ecological attributes of the most commonly occurring weed species identified in this survey were measured during the same study season. Species were selected for the measurement of functional attributes if they occurred in seven or more of the 60 fields (12% of fields), a threshold providing a reasonable balance of species' richness and field numbers suitable for the exploratory multivariate statistical technique used (see below). These species are listed in Supplementary Table 1. The attributes measured are summarised in Table 3 (see Charles, Jones, and Hodgson 1997; Bogaard et al. 1999; Jones et al. 2000; Bogaard et al. 2001; Charles et al. 2003 for fuller explanations).

Well-grown, fully established specimens were selected for measurement of functional attributes so that *species* potential was assessed rather than individual plant performance under variable conditions. Detailed protocols for the measurement of each of these attributes are given in Jones et al. (2000) and Bogaard et al. (2001). Canopy height and diameter were converted to a log scale. Data on flowering duration were extracted from Maire (1952–1987), supplemented by other Floras where necessary.

Laboratory analysis

Pairs of isotopic measurements ($\delta^{13}C$ and $\delta^{15}N$) were obtained from 47 of the fields, 33 cereal (including one Amtoudi oasis barley field that was not surveyed for weeds) and 14 pulse. Ten ripe ears or pods were randomly selected from each field, or were selected from the five weed quadrat locations per field. Half of the collected ears/pods were then threshed, and a random subset of 50 grains/seeds was homogenised using a Spex 2760 FreezerMill to give an average isotope value representative of the growing conditions at each location (cf. Bogaard et al. 2016).

Pairs of isotopic measurements ($\delta^{13}C$ and $\delta^{15}N$) were also obtained from 28 charred cereal grain and 5 charred pulse seed samples (comprising 4–10 individual grains/seeds) from the archaeological site of Tell Brak. Cereal grains and pulse seeds were examined at ×7–45 magnification for visible surface contaminants, such as adhering sediment or plant roots; these were removed by gentle scraping. Around 10% of the total number of samples from the site were scraped clean, crushed and analysed using Fourier transform infrared spectroscopy with attenuated total reflectance (FTIR-ATR): Agilent Technologies Cary 640 FTIR instrument with a GladiATR™ accessory from PIKE Technologies. Each sample was measured once, the background was subtracted and a baseline correction was carried out using Agilent Resolution Pro to look for the presence of carbonate, nitrate and/or humic contamination (cf. Vaiglova et al. 2014). Peaks characteristic of carbonate contamination (870 and 720 cm^{-1}) were observed in three of the FTIR spectra. It was therefore decided to acid pre-treat all of the cereal grain samples to dissolve any carbonate (cf. Bronk Ramsey 2008). This procedure consists of treatment

Table 3. The functional attributes measured and their possible ecological significance within an arable context.

Functional attribute measured	Ecological attribute for which measurement is a surrogate	Relationship to habitat conditions	References
Attributes relating to the duration and quality of the growth period			
Maximum canopy height and diameter	Maximum plant size, the product of growth rate and period of growth	Positively correlated with potential productivity and negatively with disturbance of habitat	Grime (2001)
Leaf area per node/leaf thickness	Plant growth rate	Positively correlated with potential productivity of habitat	Jackson (1967); Dale (1982); Givnish (1987); Jones et al. (2000)
Mean specific leaf area (SLA: leaf area/dry leaf weight)	Plant growth rate	Positively correlated with potential productivity of habitat	Reich, Walters, and Ellsworth (1992); Reich (1993); Wright et al. (2004)
Attribute relating to the capacity to regenerate under conditions of high disturbance			
Length of flowering period	Duration of life cycle and potential to regenerate from seed	Positively associated with disturbance	Grime, Hodgson, and Hunt (1988); Sans and Masalles (1995); Bogaard et al. (2001)
Vegetative spread	Ability of perennials to regenerate vegetatively from root fragments	Positively associated with disturbance	
Attribute relating to drought avoidance			
Timing of flowering	Ability to complete life cycle before dry season	Late completion of flowering associated with moist conditions	Parker (1968)
Attribute relating to drought tolerance			
Mean stomatal size	Capacity to restrict transpirational water loss	Positively correlated with moist, productive conditions and negatively with droughted conditions	Salisbury (1928); Carpenter and Smith (1975); Donselman and Flint (1982); Raven (2014)
Mean stomatal density	Capacity to restrict transpirational water loss	Negatively correlated with moist, productive conditions (given the negative relationship between size and density) and positively with droughted conditions	(as above)
Epidermal cell size	Capacity to minimise loss of turgor	Negatively correlated with droughted conditions	Cutler, Rains, and Loomis (1977)
Epidermal cell wall undulation	Provides structural support in conditions of high turgor	Positively correlated with moist conditions	Linsbauer (1930); Watson (1942)

with 10 ml of 0.5 M hydrochloric acid at 70°C for 30–60 minutes, then rinsing in distilled water three times before freeze drying. The samples were then crushed using an agate mortar and pestle.

The homogenised powders of each plant sample were weighed into tin capsules for IRMS analysis on a SerCon EA-GSL mass spectrometer, with $\delta^{13}C$ and $\delta^{15}N$ measured separately. An internal alanine standard was used to calculate raw isotopic ratios. For $\delta^{13}C$ two-point normalisation to the VPDB scale was obtained using four replicates each of IAEA-C6 and IAEA-C7, while for $\delta^{15}N$ the standards were caffeine and IAEA-N2. Reported measurement uncertainties are the calculated combined uncertainty of the raw measurement and reference standards, after Kragten (1994). The average measurement uncertainty for $\delta^{13}C$ was ±0.09‰, and ±0.23‰ for $\delta^{15}N$. These calculations were performed using the statistical programming language R. (3.0.2). The $\delta^{13}C$ and $\delta^{15}N$ values of carbonised crop remains were corrected for the effect of charring by subtracting 0.11‰ and 0.31‰, respectively, from their determined $\delta^{13}C$ and $\delta^{15}N$ values (Nitsch, Charles, and Bogaard 2015).

The $\Delta^{13}C$ values of modern cereal grains and pulse seeds were calculated from the determined $\delta^{13}C$ values ($\delta^{13}C_{plant}$) and an average $\delta^{13}C$ value of atmospheric CO_2 ($\delta^{13}C_{air}$) determined from air sampled at weekly intervals during the months that the crops were growing (White et al. 2015), using the equation below. We have therefore used more up to date measurements of the $\delta^{13}C$ value of atmospheric CO_2 than in Styring et al. (2016), with the result that the modern Moroccan cereal $\Delta^{13}C$ values are slightly lower than those reported in Styring et al. (2016). The $\Delta^{13}C$ values of archaeological cereal grains/pulse seeds were calculated from the determined $\delta^{13}C$ values ($\delta^{13}C_{plant}$) and a $\delta^{13}C_{air}$ value approximated by the AIRCO2_LOESS system (http://web.udl.es/usuaris/x3845331/AIRCO2_LOESS.xls; Ferrio et al. 2005) to enable comparison with the modern values. The equation was defined by Farquhar, Ehleringer, and Hubick (1989):

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

Data analysis

In the modern weed studies discussed here, the number of quadrats out of five in which each taxon occurred was recorded. By contrast, archaeobotanical data, to which the weed ecological model developed here is ultimately applied, were quantified on the basis of numbers of seeds per sample. The relationship between number of seeds produced and number of plants reaching maturity is complex. For a given allocation of resources a species may produce either many small seeds or fewer larger ones (Shipley and Dion 1992; Henery and Westoby 2001) and the optimal strategy, few large seeds with potentially higher seedling survivorship, or many small widely dispersed seeds, depends upon ecological circumstance (Grime 2001). The quantitative data from the modern weed survey studies are thus not directly comparable with archaeobotanical data. Analysis was therefore conducted in two ways: quantitatively (using the number of quadrats in which each taxon was found); and semi-quantitatively (using presence/absence of species in each cultivated field). The latter is more directly comparable between modern and archaeobotanical datasets but involves some loss of information (Charles et al. 2002).

Discriminant analysis was used to distinguish crop fields cultivated under relatively high- and low-intensity regimes in southern Morocco, and in southern and northern Morocco combined. For this purpose, an average score for each attribute was determined for each cultivated field as follows:

$$\frac{\sum_i^n a_i k_i}{\sum_i^n k_i}$$

For the quantitative measure: k_i = number of quadrats in which the ith species was recorded, a_i = value of attribute for the ith species, and n = number of species recorded in each field. For the semi-quantitative measure, k is always equal to 1 and so the numerator is simply the sum of the attribute values for the species in the cultivated field and the denominator is the number of species in each field. The success of the discriminations was measured in terms of the percentage of fields correctly reclassified as 'low intensity' or 'high intensity', using the discriminant function extracted in each analysis.

Semi-quantitative data from southern Morocco were combined with those from previous studies in southern Europe (Jones et al. 1999, 2000; Bogaard et al. 2016) in order to discriminate between relatively high- and low-intensity regimes across different climate zones. Archaeobotanical samples from mid-late third-millennium Tell Brak, Syria (Charles and Bogaard 2001) were entered into the classification phase of this analysis as cases of 'unknown' cultivation regime. SPSS version 20.0 was used to perform discriminant analyses, using the 'leave-one-out' option. The identification of probable arable weed taxa associated with crops, and of crop processing stages, is dealt with in Charles and Bogaard (2001). Since crop processing does not appear to bias functional weed ecological inferences of management intensity (Bogaard, Jones, and Charles 2005), samples representing various processing (by-)products are considered here.

Canoco for Windows 4.5 and CanoDraw for Windows (ter Braak and Smilauer 2002) were used to carry out correspondence analyses of the weed survey data from Morocco in order to explore variation in floristic composition among fields. The weed data were used in the form of number of quadrats out of five per field in which each taxon occurred. In the figures, axis 1 is plotted horizontally and axis 2 vertically. Statistical calculations related to the isotopic data were performed using the statistical programming language R. (3.0.2).

For the Morocco study, topographic analysis was based on the SRTM 1 Arc-Second Global digital elevation model (URL: https://lta.cr.usgs.gov/SRTMVF). A wide range of topographic variables was analysed, using the Hydrology, Solar Radiation and Surface toolsets in ArcGIS 10.3.1.

Results

Causes of floristic variation in the weed flora

Correspondence analysis of all 60 quadrat-surveyed crop fields in Morocco (Figure 2(a)) on the basis of 72 weed species occurring in at least seven of the fields presents a clear contrast on axis 1 (horizontal) between fields in the northern Rif region (right) and other regions (left). In Figure 2(b), with fields coded by husbandry, axis 2 (vertical) distinguishes high-intensity systems in *both* northern and southern Morocco, concentrated near the positive (top) end of the axis, from relatively low-intensity management especially in southern Moroccan rain-fed terraces towards the negative (bottom) end (Figure 2(b)). Crop taxonomy (Figure 2(c)) clearly does not drive this patterning: crop variation along axis 1 merely reflects geography (Figure 2(a)), and hulled 6-row barley – the dominant crop in this study – occurs under all of these regimes (Figure 2(c)). In sum, Figures 2(a–b) show that geographical differences between northern and southern Morocco dominate where management intensity is low, but are minimised or eliminated under high-intensity management featuring intensive manuring, weeding and, especially in the south, irrigation (Table 2).

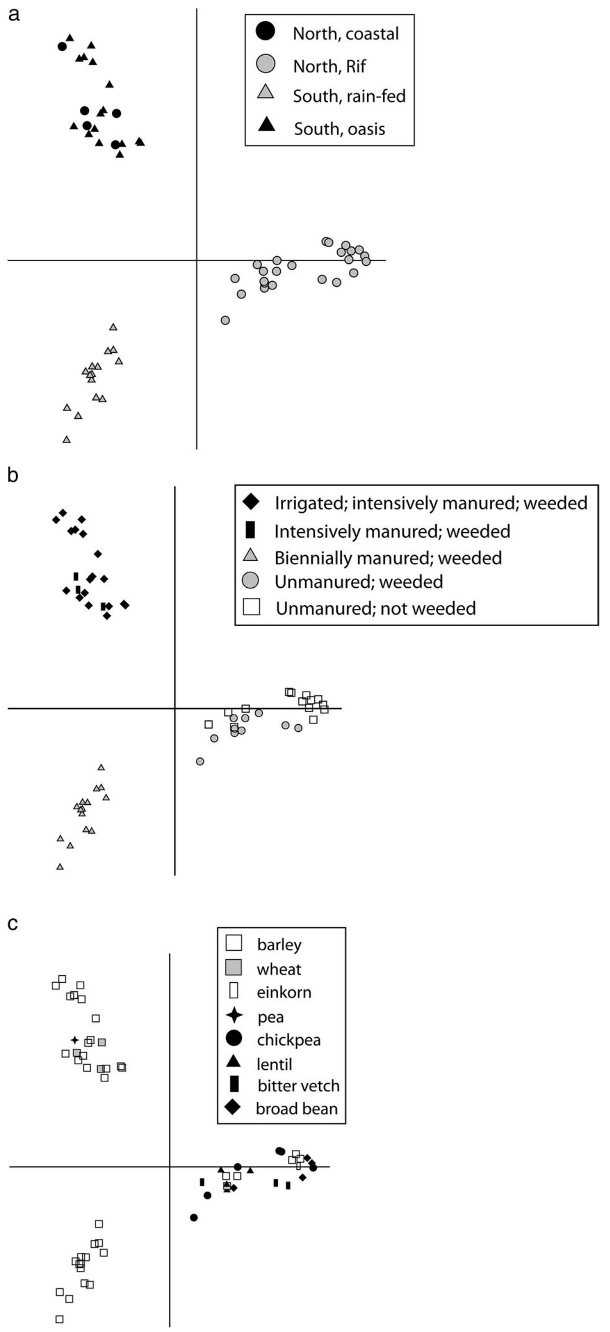

Figure 2. Correspondence analysis of Moroccan fields showing (a) geographical zones; (b) farming regimes; (c) crop.

In Figure 3 weed taxa are classified to show the extent of patterning in selected functional attributes that relate to soil productivity. Specific leaf area or SLA (Figure 3(a)), which is positively correlated with productivity (Table 3), shows some patterning in relation to management intensity on axis 2 (Figure 2(b)), with a few taxa having the highest values associated with high intensity, and others having the lowest values with low intensity. Taxa with intermediate values are generally distributed. Similarly, Figure 3(b), coded by values for leaf area per node: thickness, shows an association of low values with low-intensity management.

In terms of species' ability to recover from mechanical soil disturbance, duration of flowering (Figure 3(c)), which reflects the length of the germination period (Table 3), shows some weak patterning: species with long-flowering periods are generally distributed, perhaps reflecting the practice of hand-weeding in most regimes and all regions (Table 2), but those which flower for <3 months are mostly concentrated in fields with relatively low-intensity management. Figure 3(d), in which fields are represented as pie-charts showing the number of species per flowering duration category, shows that long-flowering species are especially concentrated in the high-intensity regimes, whereas short-flowering species tend to be best represented in low-intensity systems. Figure 3(e) shows the classification of perennial species (only) with and without vegetative spread (the ability to regenerate from root fragments under high disturbance – Table 3). Though the pattern is based on a small group of species, perennials that do not regenerate from fragments are associated with lower intensity management. The association of the high-intensity regimes with long-flowering annuals and perennials that can spread vegetatively by rhizomes, bulbils or stolons reflects the fact that these plots were weeded very frequently (e.g. every

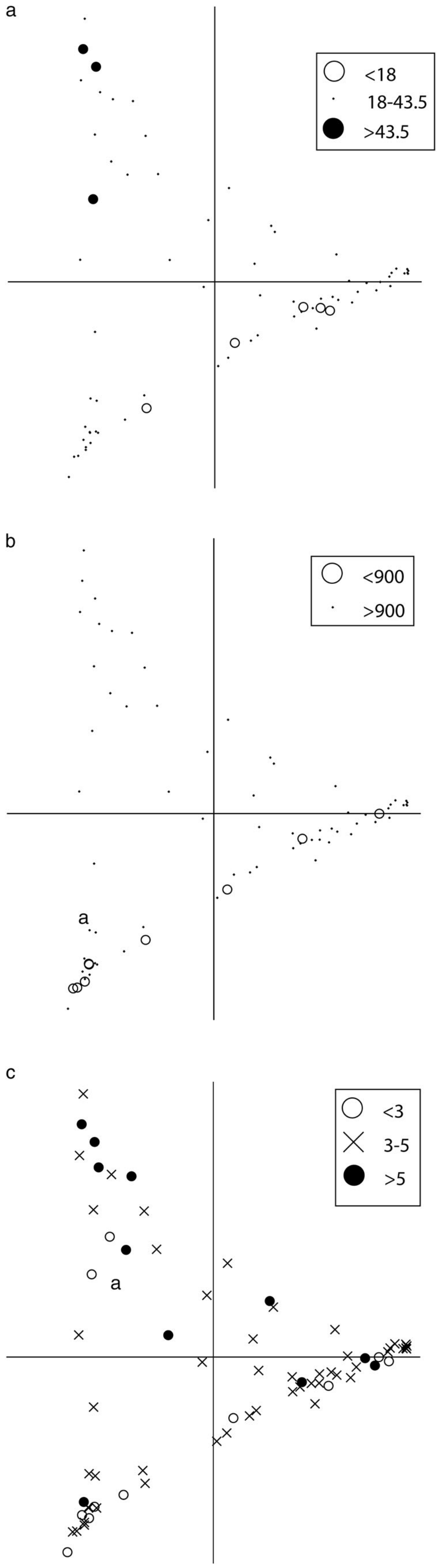

Figure 3. Correspondence analysis of Moroccan weed taxa showing (a) SLA; (b) leaf area per node:thickness; (c) flowering period; (d) fields as pie-charts showing number of weed taxa present per flowering duration category; (e) vegetative spread.

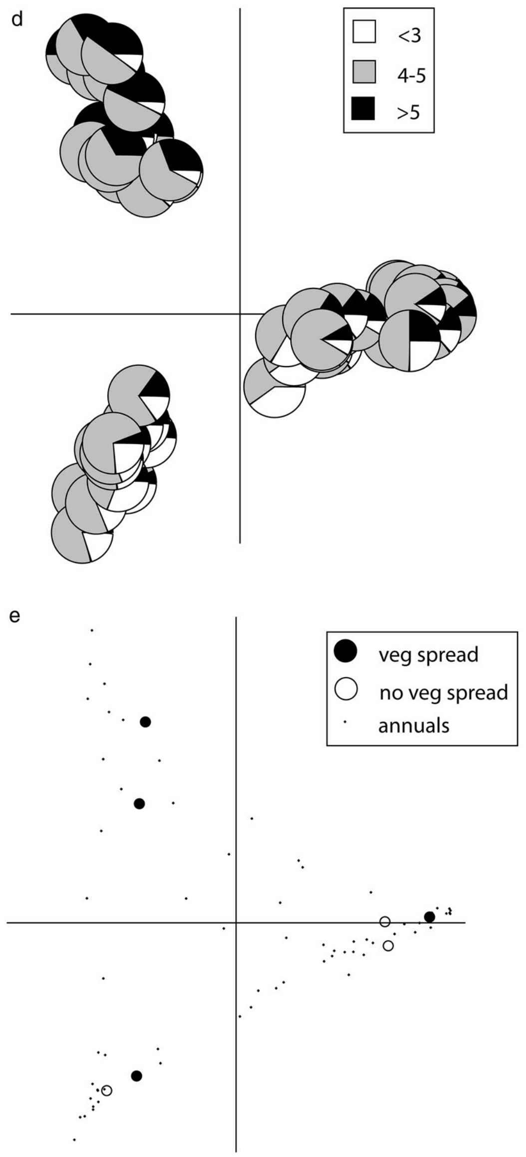

Figure 3. Continued

morning by women in the oasis). The weeds removed were generally viewed by farmers as a resource rather than simply as plants lowering crop yield, and were often used, for example, as salad greens or as fodder for penned goats. The kinds of palatable plants with fast-growing leaves (e.g. high SLA – see Wright et al. 2004) valued for these uses are indeed those expected to grow under highly productive conditions.

None of the drought-related attributes showed the predicted patterning in the correspondence analysis, perhaps in part because each of the regimes studied was located in a different rainfall zone, complicating further potential relationships among species' drought tolerance, drought avoidance and seasonality (cf. Charles et al. 2003). Thus, late-flowering species, previously shown in a single study region in Jordan to distinguish artificially watered fields (Charles et al. 2003), were ubiquitous across the Moroccan regimes (plot not shown).

Overall, the weed flora of the Moroccan fields vary primarily by geography (north versus south), but these differences are overwritten where management intensity is high. Contrasts between high- and low-intensity management show patterning in relation to functional traits reflecting species' potential growth rate, and hence their ability to respond to high soil productivity, as well as functional attributes reflecting species' response to disturbance: the length of the flowering period and (for perennials) vegetative spread.

Ecological comparison of Moroccan regimes on the basis of weed functional attribute values

Discriminant analysis was used to distinguish between the weed flora of low- and high-intensity agrosystems in Morocco, using five functional attributes previously shown to distinguish between high- and low-intensity cultivation regimes in southern Europe (Jones et al. 2000; Bogaard et al. 2016) as discriminating variables. Additional drought tolerance/avoidance attributes (Table 3) were also included as discriminating variables but contributed little to the regime comparisons considered below, likely due to the conflation of agronomic with climatic differences in water availability among the study regions. Analyses including drought tolerance/avoidance attributes are therefore not shown.

Discriminant analysis was carried out initially on the southern Moroccan fields only, to distinguish high-intensity management of oasis fields from lower intensity management of rain-fed terraced fields. A 100% correct reclassification of both southern oasis and rain-fed fields was achieved on the basis of fully quantitative (Figure 4) and semi-quantitative data (Figure 5). In both of these analyses, functional attributes discriminate between high-intensity oasis and low-intensity rain-fed fields as predicted. Species that grow rapidly (high SLA, leaf area per node: thickness) and have tall, broad canopies are associated with intensively maintained oasis conditions; a long-flowering period is also associated with greater disturbance (more thorough tillage and weeding) in oasis fields compared to rain-fed terraced fields. Thus, a restricted set of functional attributes relating to soil productivity and disturbance has been shown to distinguish contrasting intensity levels, whether based on fully quantitative or semi-quantitative data, as in previous studies in southern Europe (Jones et al. 2000; Charles et al. 2002; Bogaard et al. 2016).

Further discriminant analyses performed on the basis of semi-quantitative data – i.e. the form that is applicable archaeologically – showed that the southern Moroccan regimes can be separated (with a 100% correct reclassification) on the basis of a single functional attribute, SLA (plot not shown). This result reflects the extremity of the productivity contrast between oasis and rain-fed terraced fields (Table 2). Previous discriminant analyses of relatively high- and low-intensity fields in Evvia, Greece (Jones et al. 2000) and Asturias versus Haute Provence (Bogaard et al. 2016) involved more subtle ecological contrasts requiring a broader suite of functional attributes (reflecting soil fertility and disturbance) to be distinguished successfully. It is also worth noting that a relatively high degree of

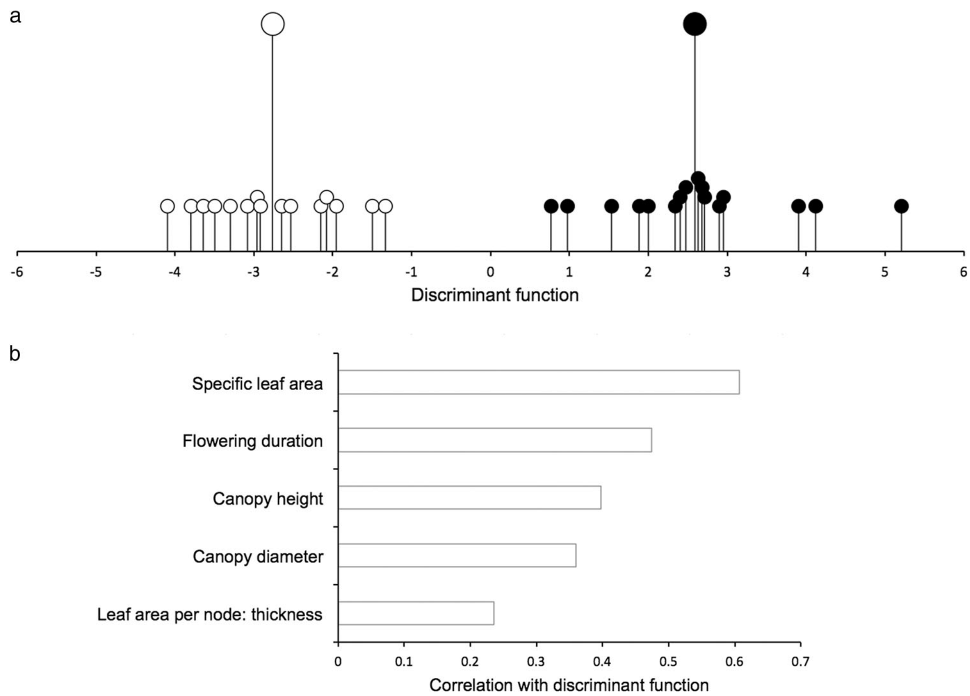

Figure 4. (a) The relationship of southern rain-fed terraced fields (open circles, $n = 15$) and oasis fields (filled circles, $n = 16$) to the discriminant function extracted to distinguish these two groups on the basis of fully quantitative data (larger symbols indicate group centroids); (b) correlations between the discriminating variables and the discriminant function.

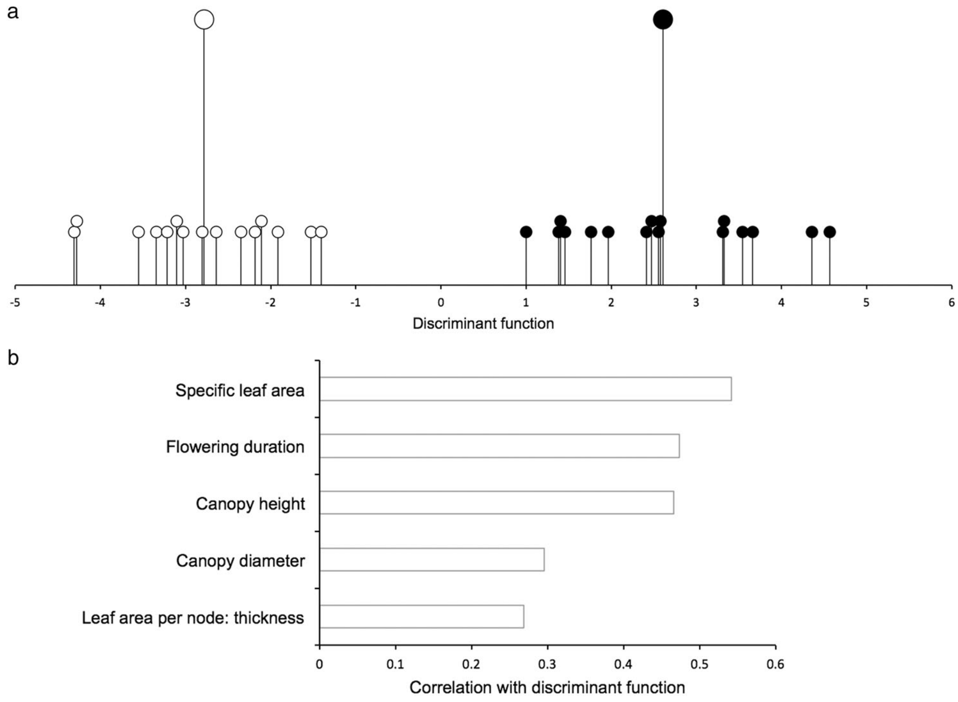

Figure 5. (a) The relationship of southern rain-fed terraced fields (open circles, $n = 15$) and oasis fields (filled circles, $n = 16$) to the discriminant function extracted to distinguish these two groups on the basis of semi-quantitative data; (b) correlations between the discriminating variables and the discriminant function.

shade coincides with high fertility in the Moroccan oases, as in a previous study of pulse gardens and fields in Evvia, Greece (Jones et al. 2000). The dominance of SLA as a functional trait relating to fertility in both studies likely reflects the fact that species with a high SLA are both fast-growing and relatively shade-tolerant (Hodgson et al. 2011).

Discriminant analyses were also conducted to distinguish relatively low cultivation intensity in both southern *and* northern Morocco, on the one hand, from high-intensity regimes in both regions, on the other. On the basis of fully quantitative data, a 90% correct reclassification (54 out of 60 fields) was achieved, while a 95% correct reclassification (57 out of 60 fields) was achieved on the basis of semi-quantitative data (Figures 6–7). In both analyses, comparison of the distribution of northern and southern fields along the discriminant function reveals a climatic bias, superimposed on the cultivation intensity gradient: northern fields (both low- and high-intensity) tend to be shifted towards the positive ('high-intensity') end of the axis relative to the southern fields (Figures 6–7).

Comparison of Moroccan regimes on the basis of crop stable isotope values

Table 4 and Figure 8 (Supplementary Table 2) show that barley grain samples from oasis and rain-fed systems in southern Morocco are clearly distinguished: the carbon discrimination ($\Delta^{13}C$) values of oasis barley are higher than those from rain-fed fields (a difference of 2.97‰, 95%CI[2.10, 3.83‰], $p = 0.000$), as are the $\delta^{15}N$ values of oasis barley (a difference of 6.50‰, 95%CI[4.90, 8.09‰], $p = 0.000$). These contrasts plausibly reflect differences in irrigation and manuring, respectively, between oasis and rain-fed terrace fields (Table 2). Barley samples from rain-fed fields in northern Morocco, where precipitation is much higher (Table 1), have $\Delta^{13}C$ values as high as or higher than those of barley in oasis fields (a difference of 1.29‰, 95%CI[0.12, 2.46‰], $p = 0.027$), but are much lower in their nitrogen isotope values (a difference of 13.36‰, 95%CI[11.19, 15.53‰], $p = 0.000$), likely due to a combination of the lack of manuring and lower aridity. Ripe crop samples from the intensively managed northern fields were not available for analysis. The $\Delta^{13}C$ values of one durum wheat and 14 pulse samples from northern Morocco are offset from those of barley (a difference of 0.86‰, 95%CI[−0.06, 1.78‰], $p = 0.066$), likely due to differences in physiology (Araus et al. 1997; Wallace et al. 2013), but their low $\delta^{15}N$ values likewise reflect low manuring (Table 4).

Styring et al. (2016) have developed a model incorporating eastern Mediterranean plant isotope surveys by Hartman and Danin (2010) to assess the $\delta^{15}N$ values of grain from cereals growing under varying rainfall conditions and manuring regimes. The model (Figure 9) correctly identifies that the oasis barley $\delta^{15}N$ values reflect very intensive manuring, and that northern Moroccan fields received little to no manure, while the rain-fed terraces in southern Morocco mostly correspond with intermediate manuring rates. It thus appears possible to disentangle elevation in $\delta^{15}N$ due

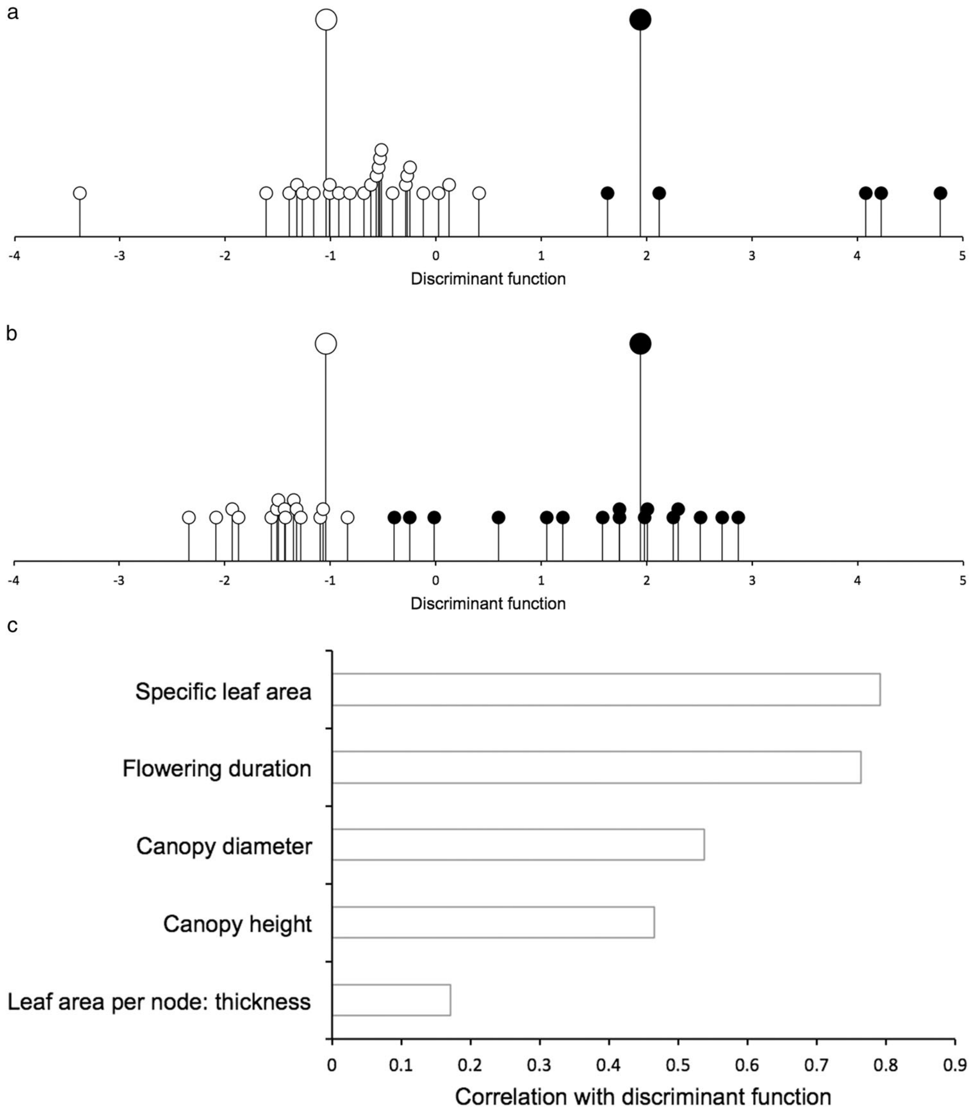

Figure 6. (a) The relationship of northern rain-fed terraced fields (open circles, $n = 24$) and intensively managed fields (filled circles, $n = 5$) and (b) of southern rain-fed terraced fields (open circles, $n = 15$) and oasis fields (filled circles, $n = 16$) to the discriminant function extracted to distinguish these two groups on the basis of fully quantitative data; (c) correlations between the discriminating variables and the discriminant function.

to aridity *per se* from additional enrichment due to manuring, though more work is needed to ground-truth aridity effects in cereals.

The effect of topography on crop isotope values was assessed using variables extracted from the GPS survey of each field. Multiple linear regressions of the stable carbon and nitrogen isotope values of barley from the southern rain-fed barley fields showed no significant effect of slope, aspect, solar radiation or distance to water. The variation in isotope values amongst these fields, therefore, is governed by other factors, including subtle differences in crop husbandry.

The relationship between weed ecology and cereal isotope values across Moroccan regimes

Figure 10(a–b) plot mean SLA value per field against barley $\Delta^{13}C$ and $\delta^{15}N$ values for the southern Moroccan systems (oasis and rain-fed terrace fields); SLA was used here since it was the key discriminating variable for successfully distinguishing these regimes on the basis of presence/absence data (above). Multiple linear regression models with coefficients for SLA, $\Delta^{13}C$ value, $\delta^{15}N$ value and agricultural regime show a significant effect of regime (i.e. irrigation and manuring) on SLA ($\beta = 3.262‰$, standard error (SE) = 1.332‰, $t = 2.450$, $p = 0.0232$), $\delta^{15}N$ value ($\beta = 5.170‰$, SE = 1.928‰, $t = 2.681$, $p = 0.014$) and $\Delta^{13}C$ value ($\beta = 3.255‰$, SE = 0.946‰, $t = 3.441$, $p = 0.00245$). As is apparent in Figure 10, clear relationships between SLA and crop stable isotope values occur *between* regimes, not among the fields *within* each regime; a similar result was observed in a previous study (Bogaard et al. 2016, Figure 11). The implication is that a close correlation between weed ecological traits and crop stable isotope values should only be expected *across* contrasting regimes, not within a single, relatively homogenous agrosystem.

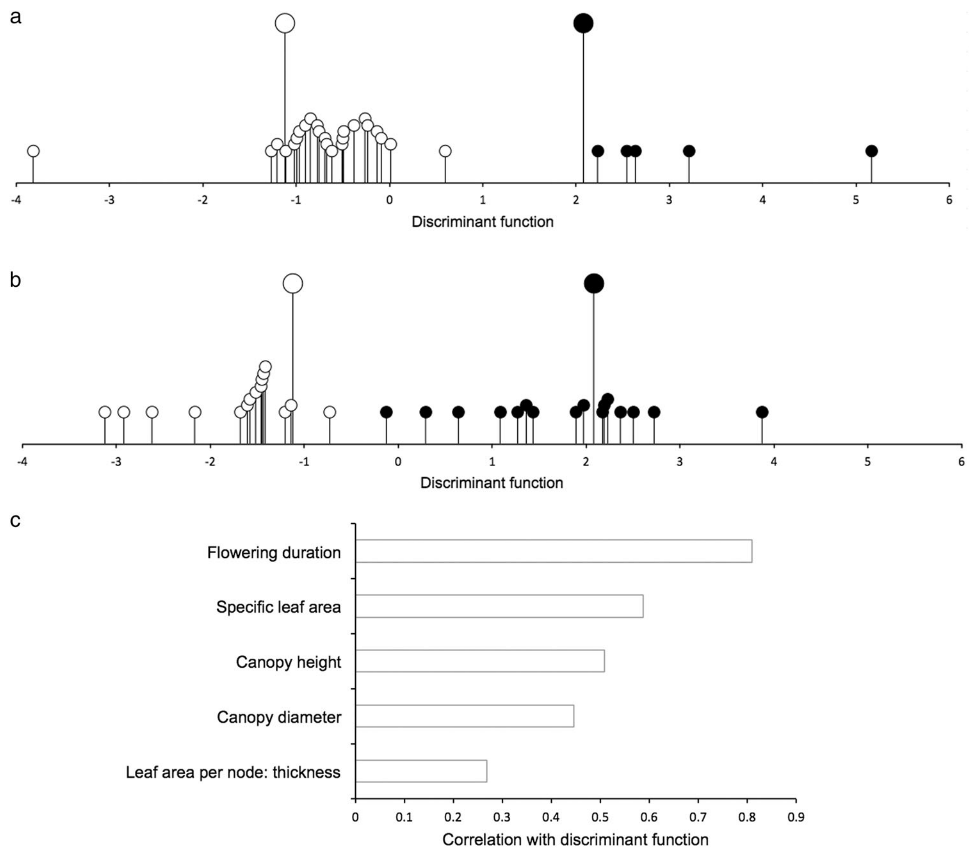

Figure 7. (a) The relationship of northern rain-fed terraced fields (open circles, $n = 24$) and intensively managed fields (filled circles, $n = 5$) and (b) of southern rain-fed terraced fields (open circles, $n = 15$) and oasis fields (filled circles, $n = 16$) to the discriminant function extracted to distinguish these two groups on the basis of semi-quantitative data; (c) correlations between the discriminating variables and the discriminant function.

Table 4. Mean $\delta^{13}C$, $\Delta^{13}C$ and $\delta^{15}N$ values of crops in each Moroccan agrosystem.

			$\delta^{13}C$			$\Delta^{13}C$			$\delta^{15}N$		
Region	*Agrosystem*	*Crop*	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*n*
Rif region	Rain-fed terraced fields	Hulled 6-row barley	−27.6	0.6	5	19.4	0.6	5	0.8	0.7	5
Rif region	Rain-fed terraced fields	Durum wheat	−26.6		1	18.3		1	0.1		1
Rif region	Rain-fed terraced fields	Pulses	−26.8	1.3	14	18.5	1.4	14	0.0	0.8	14
South	Oasis	Hulled 6-row barley	−26.3	0.7	11	18.1	0.7	11	14.1	0.9	11
South	Rain-fed terraced fields	Hulled 6-row barley	−23.5	0.9	15	15.1	0.9	15	7.6	1.9	15

Figure 10(c–d) consider the same relationships for the northern Moroccan pulse fields (cereal fields with isotope measurements in this region are too few to be considered). Two mixed-effects models, with fixed effects of $\delta^{15}N$ value or $\Delta^{13}C$ value and SLA and a random effect of farm, showed a significant relationship between pulse $\delta^{15}N$ values and SLA ($\beta = 0.306$, SE = 0.0606, $t = 5.043$, $p = 0.0010$) but no significant relationship between pulse $\Delta^{13}C$ values and SLA ($\beta = 0.276$, SE = 0.210, $t = 1.313$, $p = 0.226$). This is consistent with the expectation that organic matter makes the major contribution to soil productivity (as gauged by SLA) rather than water status in this sub-humid zone (cf. Tables 1, 2). The pulses with the highest $\delta^{15}N$ values (>0‰) are all from chickpea and broad bean fields at the Bellota farming study site, where residual manuring from previous land use likely explains variation at this recently established organic farm; no manuring is currently practised (Table 2). It is worth noting that two pulse fields at Agda in northern Morocco that had recently been cleared of mature (≥30-year-old) woodland by burning had low $\delta^{15}N$ values (<0‰), indicating that clearance and/or burning did not significantly raise $\delta^{15}N$ values (cf. Styring et al., in press). Again, clear relationships between SLA and crop stable isotope values were apparent *between* regimes, but not *within* each regime.

Comparison of Moroccan regimes with previous studies of cultivation intensity

Discrimination of the Moroccan weed ecological data (above) has revealed two potential problems with these agrosystems for classifying archaeobotanical samples from (semi-)arid regions. First, the southern regimes are 100% successfully discriminated using a

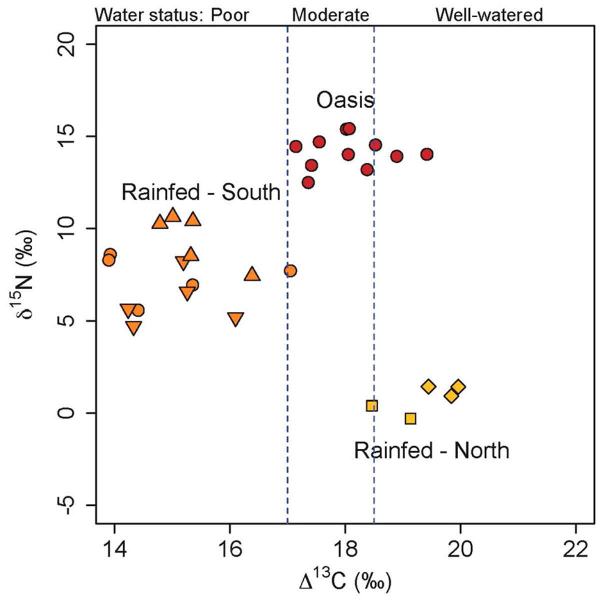

Figure 8. Plot of modern barley grain $\delta^{15}N$ against $\Delta^{13}C$ values, with watering bands (cf. Styring et al. 2016: Figure 2; for watering bands, see Wallace et al. 2013); see Figure 9 for legend.

single functional trait, SLA, based on semi-quantitative data (i.e. the form that would be used to classify archaeobotanical samples). As a model, this discriminant function would tend to conflate subtle differences in cultivation intensity intermediate between these low- and high-intensity extremes.

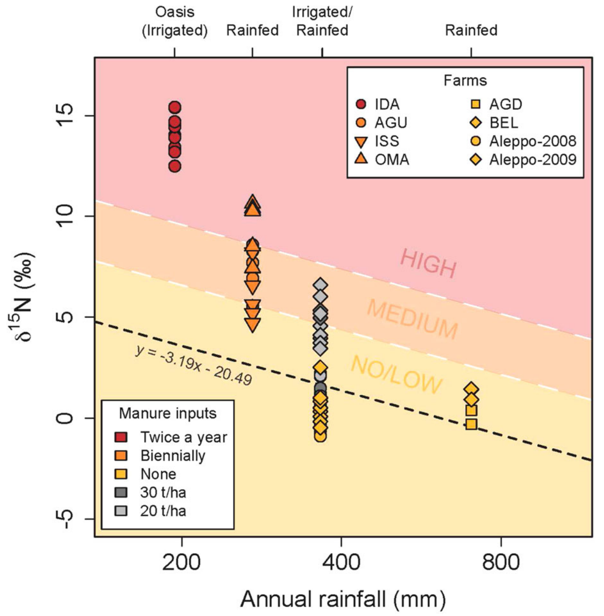

Figure 9. Plot of modern Moroccan barley and Syrian bread wheat $\delta^{15}N$ values against a natural log scale of rainfall, showing manuring bands adjusted for the regression between unmanaged plant $\delta^{15}N$ values and rainfall (after Styring et al. 2016: Figure 4); AGD and BEL are in northern Morocco, IDA, AGU, ISS and OMA in southern Morocco (see Figure 1).

Secondly, the discriminant function extracted (on the basis of semi-quantitative data) to distinguish intensity levels in both northern and southern Morocco incorporates a clear climatic bias.

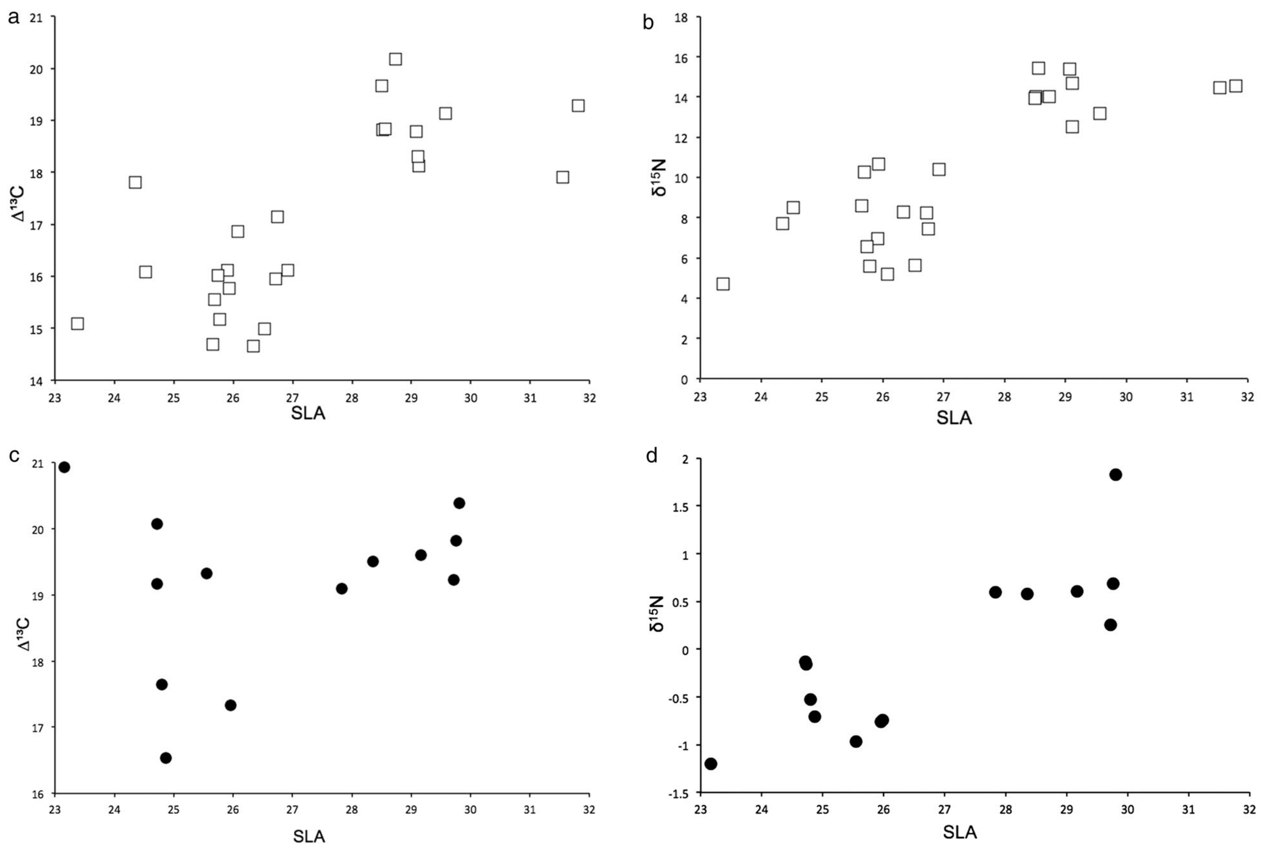

Figure 10. Plots of mean SLA value per field against (a) barley $\Delta^{13}C$ and (b) $\delta^{15}N$ values in southern Moroccan rain-fed terraces and oasis fields; and (c) pulse $\Delta^{13}C$ and (d) $\delta^{15}N$ values in northern Morocco.

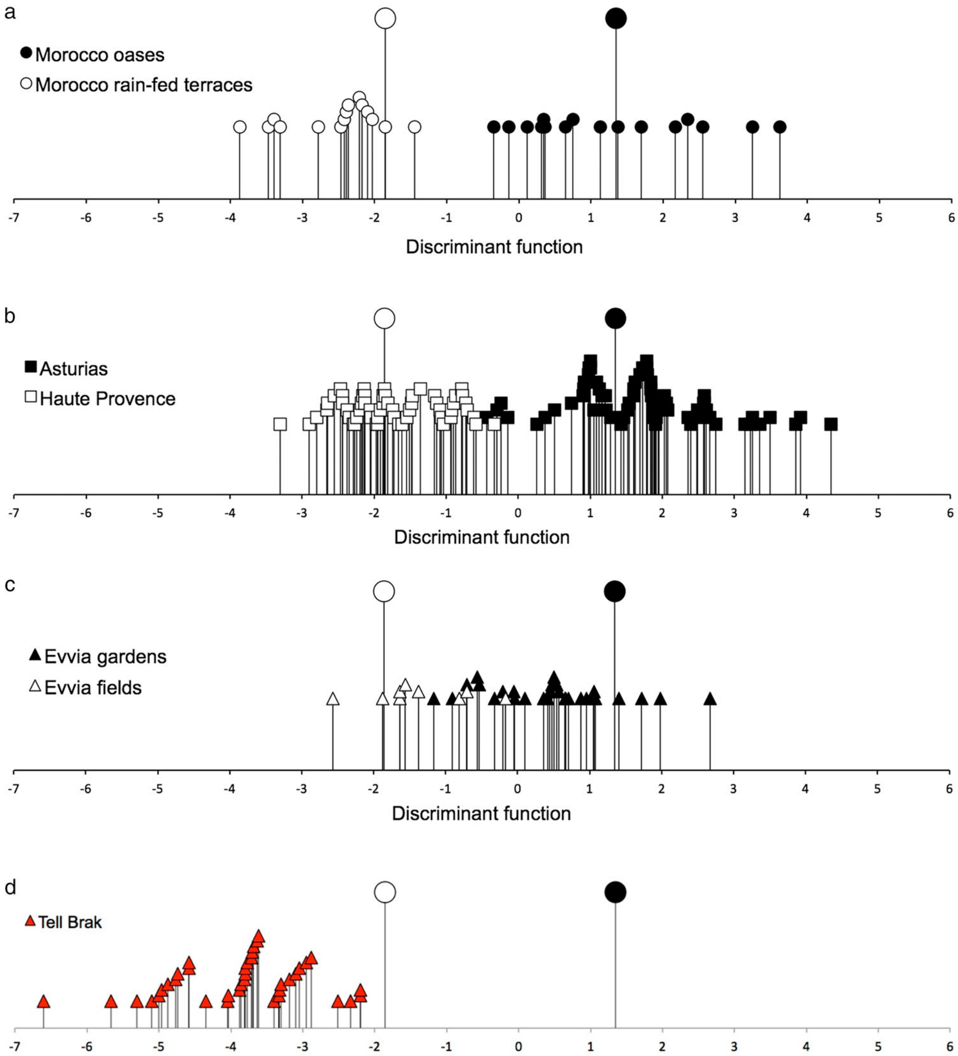

Figure 11. (a) The relationship of southern rain-fed terraced fields ($n = 15$) and oasis fields ($n = 16$), (b) Haute Provence fields ($n = 56$) and Asturian fields ($n = 65$) and (c) Evvian pulse fields ($n = 9$) and gardens ($n = 29$) to the discriminant function extracted to distinguish low- (open circles) and high-intensity (filled circles) regimes on the basis of semi-quantitative data (larger symbols indicate group centroids); (d) the relationship of archaeobotanical samples from Tell Brak to the discriminant function.

In order to derive a more nuanced model for classification of archaeobotanical samples from (semi-)arid regions, we combined the dramatic contrast between oases and rain-fed fields in southern Morocco with other, previously published studies of contrasting intensity in southern Europe: Evvia, Greece (Jones et al. 2000), Asturias and Haute Provence (Bogaard et al. 2016). In this combined analysis, three forms of high-intensity cultivation (Moroccan oases, Evvian gardens, Asturian plots) were discriminated from three low-intensity regimes (Moroccan rain-fed terraces, Evvian fields, Haute Provence fields). The discriminant function extracted to distinguish these various high- and low-intensity regimes on the basis of semi-quantitative data correctly reclassified 94% of fields (179 out of 190 fields) using four of the functional attributes (SLA, canopy diameter, leaf area per node: thickness and canopy height) (Figures 11(a–c), Figure 12). The inconsistent quality of flowering data available for these regions may explain the lack of contribution of flowering duration to this combined analysis (cf. Jones et al. 2010). The weed flora of the high-intensity regimes are distinguished above all by being fast-growing species with large canopies (Figure 12). This combination of attributes places emphasis on fertility rather than soil disturbance *per se*, but the greater importance of growth rate (as measured by SLA) over canopy size

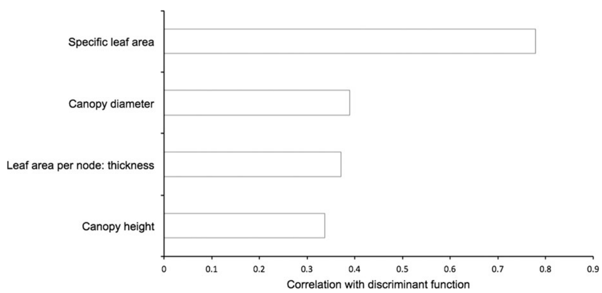

Figure 12. Correlations between the discriminating variables and the discriminant function for the analysis shown in Figure 11.

reflects the key role of adaptations that enable weeds under high-intensity management to respond to high fertility under potentially high disturbance conditions (Table 3).

The relative position of the various regimes along the same discriminant function (Figure 11(a–c)) indicates differences that primarily reflect crop husbandry rather than climate. Thus, the Evvian 'fields' tend to have higher discriminant function scores than the Haute Provence fields, despite a climatic bias in the opposite direction (i.e. higher rainfall in Haute Provence), because the Evvian 'fields' were more intensively managed (cf. Jones et al. 1999; Bogaard et al. 2016). The Asturias and Haute Provence continuum along the discriminant function is broader than that in Evvia, in agreement with expectations based on farming practices rather than climate, and aligns closely with the Moroccan range, albeit with a slight positive offset of Haute Provence fields relative to Moroccan rain-fed terraces that may reflect climatic differences.

The discriminant analysis of combined studies illustrates how the various intensity contrasts compare ecologically to one another – from the 'extremity' of the contrast in Morocco to the subtlety of that in Evvia – while also balancing climatic differences more successfully than the analysis combining northern and southern Morocco. The resulting weed ecological model, together with the stable isotope data from Morocco, offer an integrated approach for distinguishing different cultivation intensity levels in (semi-)arid regions archaeologically.

Application of the model to archaeobotanical data from Bronze Age Tell Brak, northern Mesopotamia

We applied this 'weed plus isotope' approach to archaeobotanical material from Early Bronze Age (mid-late third-millennium cal BC) Tell Brak, an early urban centre of *c.* 70 ha in northern Mesopotamia (Charles et al. 2001; Oates, Oates, and McDonald 2001; Ur, Karsgaard, and Oates 2011). This material derives from primary and secondary contexts, ranging from crops stored in pots in small storage rooms of high-status late Early Jazira (EJ) III (c. 2400 cal BC) households destroyed by fire in areas CH and ER, to an Akkadian public building ('Southern Building') (c. 2300–2200 cal BC) in area FS and post-Akkadian (c. 2200–1950 cal BC) domestic contexts (Oates, Oates, and McDonald 2001, 15–98). As in other semi-arid regions (mean annual rainfall 300–600 mm; FAO 1987; Noy-Meir 1973; Webb et al. 1978), rain-fed farming is possible in northern Mesopotamia, but water is the major limitation to growth. We have estimated Brak's EBA rainfall as *c.* 310–450 mm pa, using δ^{18}O variation in the Soreq cave sequence (Bar-Matthews and Ayalon 2004, 2011; Lawrence et al. 2016) to estimate deviation from present-day rainfall (363 mm pa), where a decrease in δ^{18}O value of 1‰ = *c.* 200 mm more rainfall (Bar-Matthews and Ayalon 2004). The landscape around the site does not lend itself to large-scale irrigation but would encompass variable soil moisture, with better watered soils along wadis a few km to the south and east (Wilkinson et al. 2001). Aside from irrigation, labour-intensive inputs of relevance to this region are manuring, which can also improve the water use efficiency of some crop species (Hati et al. 2006), and soil working (disturbance through tillage and/or hand-weeding). If crops represented in the assemblage considered here were produced locally, it is expected that they would reflect rain-fed conditions, whereas well-watered crops would suggest mobilisation from irrigated and/or higher rainfall conditions elsewhere.

The discriminant function extracted above to distinguish high- and low-intensity regimes across multiple modern studies (Figures 11–12) was used to classify 38 archaeobotanical samples (Supplementary Table 3), each of which contained a minimum of ten potential weed seeds identified more or less to species (Charles and Bogaard 2001, Table 33). Figure 11(d) shows that all of the Brak samples are located along the negative end of the discriminant function; all were classified as 'low-intensity' (with high probability >0.90). This result cannot be due to climatic differences between Tell Brak and the modern study areas since many of the samples have more negative discriminant scores than the southern Moroccan rain-fed fields, despite the fact that rainfall at Tell Brak throughout this period tended to be higher. The classification of the Tell Brak samples indicates that conditions in the fields from which these weed flora derive were often less productive than the modern fields cultivated at low intensity.

Stable carbon and nitrogen isotope values were determined for 33 crop subsamples from 27 contexts, 26 of which were included in the weed analysis (Supplementary Table 4). Some contexts contained a mixture of crops and so provided multiple subsamples for isotopic analysis. Barley Δ^{13}C values suggest poorly to moderately well-watered conditions (Figure 13) in comparison with thresholds established for modern barley (Wallace et al. 2013).

Cereal δ^{15}N values from Brak most closely resemble those of the rain-fed terraced fields in southern Morocco (Figures 13–14), which received manure every two years or more, the rate depending on availability (Table 2). Taking into account the annual rainfall levels inferred for this period at Brak (*c.* 310–450 mm pa, see above), the cereal δ^{15}N values encompass variable conditions, from a small minority of samples suggesting intensive manuring through to the bulk of samples in the medium to no/low manuring bands (Figure 14). The accuracy of manuring intensity estimated using this method can be tested by inputting estimated

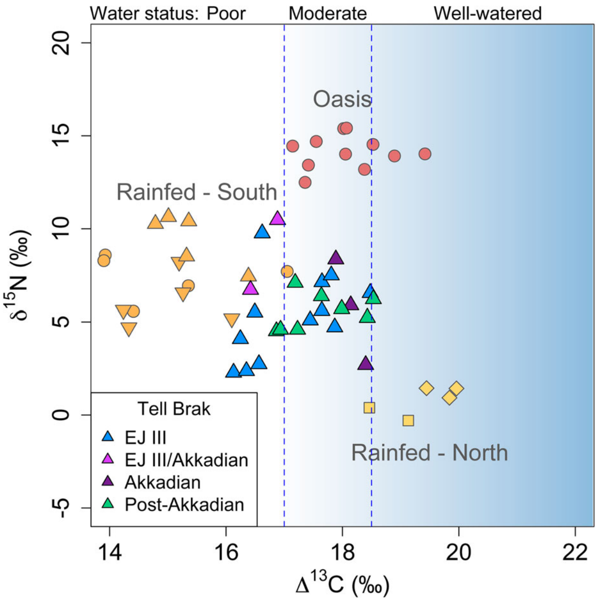

Figure 13. Plot of Tell Brak (two-row) barley $\delta^{15}N$ against $\Delta^{13}C$ values, coded by chronological period, with modern Moroccan (six-row) barley plotted for reference (see Figure 8). Watering bands approximating a mixture of 2- and 6-row barley (Wallace et al. 2013) are shown.

$\delta^{15}N$ values of herbivore forage into the model. These would be expected to have received no manure and therefore to fall into the no/low manuring band. The $\delta^{15}N$ values of herbivore forage are estimated from bone collagen $\delta^{15}N$ values of wild herbivores, by subtracting the mean offset between herbivore bone collagen and diet (c. 4‰; e.g. Steele and Daniel 1978) from the $\delta^{15}N$ values of preserved herbivore bone collagen. All seven plant $\delta^{15}N$ values estimated from gazelle bones from Tell Brak (dating to the 4th and 2nd millennium cal BC – Styring et al., submitted) fall into the no/low manuring band when calibrated against present-day annual rainfall (363 mm) and six out of seven fall into the no/low manuring band when calibrated against the highest inferred rainfall (450 mm) (the wild plant $\delta^{15}N$ value that fell into the medium manuring band was estimated from a gazelle who had consumed significant quantities of C_4 plants (indicated by a $\delta^{13}C$ value of −18.0‰) and these have been found to have significantly higher $\delta^{15}N$ values than C_3 plants (cf. cereals) from the same sites (Hartman and Danin 2010)). The $\delta^{15}N$ values inferred for wild herbivore forage at Tell Brak, therefore, agree with those expected for unmanaged vegetation (Figure 14).

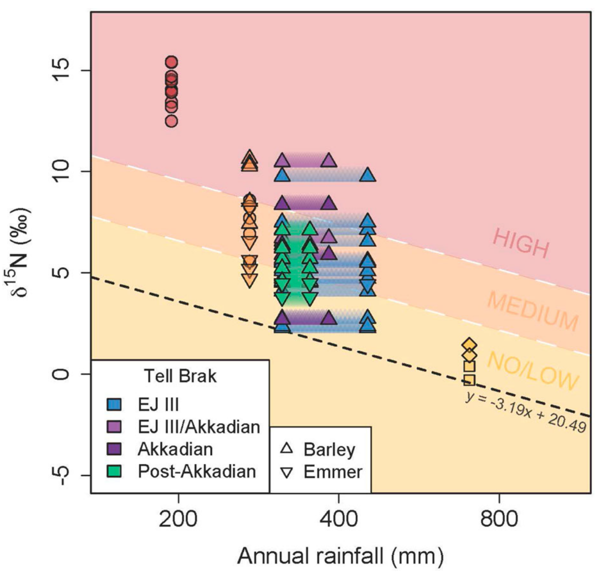

Figure 14. Plot of Tell Brak cereal $\delta^{15}N$ values against a natural log scale of rainfall, with manuring bands adjusted for the regression between unmanaged plant $\delta^{15}N$ values and rainfall. The $\delta^{15}N$ values of modern Moroccan barley and Syrian bread wheat grains are plotted for reference (see Figure 9).

Bringing together the results of the weed ecological analysis and crop isotope analysis, the Brak samples reflect growing conditions maintained through low-intensity management relative to the modern high-intensity regimes. These conditions resemble rain-fed fields in a semi-arid setting and likely encompassed variable levels of manuring, mostly medium to low. As expected *within* a single agrosystem (above, Figure 10), there is no significant correlation between crop stable isotope values and weed ecological discriminant scores on a sample-by-sample basis.

Discussion and conclusions

Our aim was to develop an integrated approach combining weed functional ecology and crop stable isotope ratios to investigate agricultural intensity (labour inputs per unit area of arable land) in (semi-)arid regions. This was achieved by conducting combined weed ecology and crop isotope survey of fields under contrasting agrosystems in Morocco, and by integrating these results with previous work to develop a weed ecological model (Figures 11–12), complementing a recently developed cereal $\delta^{15}N$ model (Figure 9) (Styring et al. 2016) and the established potential of crop $\Delta^{13}C$ values for inferring water status (Figure 8) (Wallace et al. 2013). Application of this 'weed plus isotope' approach to an EBA archaeobotanical assemblage from early urban Tell Brak, Syria identifies low-intensity management of rain-fed fields as the prevailing agrosystem. Area yields under such a management regime would be low, implying that the arable catchment was extensive enough to feed the city. This result is consistent with local production in Brak's hinterland and excludes mobilisation of crops from irrigated and/or higher rainfall conditions elsewhere.

Landscape survey around Tell Brak and other third-millennium cal BC cities has identified 'hollow ways' radiating out from urban cores and plausibly tracing the extent of their arable catchments (Wilkinson et al. 1994; Wilkinson 2003, 111–20; Ur, Karsgaard, and Oates 2011; Ur 2015). The evidence reported here is consistent with this picture, but clarifies that cereal production was predominantly under extensive, low-intensity management. If infield 'sherd scatters' are rightly interpreted as deliberate spreading of settlement waste to raise yields, the practice seems to have had limited impact, at least on *cereal* productivity; it may primarily have benefited garden crops (cf. Wilkinson et al. 1994, 495, n. 2). As Halstead (in Wilkinson et al. 1994, 507) anticipated, 'the extensification model raises the possibility that the key to maintenance of Upper Mesopotamian centres lies not only in the intensive middening scatters which surround them but also in the areas of sparse scatters and, presumably, more extensive cultivation'.

In chronological terms, Brak's barley $\Delta^{13}C$ values increase if anything through time (Figure 14) alongside climatic aridification in the late 3rd millennium cal BC (Bar-Matthews and Ayalon 2004). Similarly, Riehl et al. (2014) observed drier barley values during aridification episodes *only* in the most marginal settings, also noting that water management could mask its effects. At Brak it is possible that cultivators facing drier conditions shifted focus towards better watered soils, e.g. along the Jaghjagh stream that flows *c.* 3 km from the site. Thus, both the Brak results and those reported by Riehl et al. (2014) reflect the difficulty of using crop carbon values as evidence of climate change *per se*, highlighting instead their potential to measure agronomic adaptation to (independently verified) climate change.

In a recent stable carbon isotope study of crops from late 5th to later third-millennium cal BC levels at Tell Brak, Wallace et al. (2015) found that barley tended to be grown under drier conditions than wheat, suggesting strategic planting of wheat in wetter soils (e.g. along the Jaghjagh stream). Comparison of barley and wheat samples from late third-millennium samples reported here (Supplementary Table 4) suggests that this contrast persisted, though wheat samples are few in number. Pulse samples are also few but suggest a range of conditions from poorly to well watered (cf. Wallace et al. 2013) (Supplementary Table 4).

Variability in barley $\delta^{15}N$ values, best represented in material from the EJ III burned buildings dating to *c.* 2400 cal BC (Figures 13–14), plausibly reflects a spectrum of intensity evidenced spatially through landscape survey: from intensively managed 'infield' areas, corresponding to sherd scatters dating to the mid-late third-millennium cal BC immediately surrounding the settlement, to more extensively managed fields further away from the urban core, the extent of which are arguably indicated by 'hollow ways' resulting from human and animal traffic in and out of the site past arable fields (Ur, Karsgaard, and Oates 2011). It is possible that the dramatic increase in 'manure scatter' during this particular period represented a concerted effort to raise soil productivity levels, which were often lower than those documented in the low-intensity modern fields discussed here (Figure 11).

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