Changing Land Use and Political Economy at Neolithic and Bronze Age Knossos, Crete: Stable Carbon ($\delta^{13}C$) and Nitrogen ($\delta^{15}N$) Isotope Analysis of Charred Crop Grains and Faunal Bone Collagen

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S1. INTERPRETATION OF $\delta^{13}C$ AND $\delta^{15}N$ VALUES OF C_3 GRAIN CROPS IN RELATION TO CHANGING LAND USE

Plant $\delta^{13}C$ values reflect photosynthetic pathway, being higher in C_4 than C_3 plants (O'Leary 1981). Among C_3 plants (including the sampled cereal and pulse crops from Knossos and most plants available to the sampled fauna), they also reflect growing-season water availability, being higher in arid conditions (Farquhar *et al.* 1989). Water availability to crops reflects climate and local topography/geology, but also husbandry practices including irrigation. For example, in Mediterranean experiments, $\delta^{13}C$ values are higher for unirrigated than fully irrigated free-threshing wheat (*Triticum aestivum* and *T. durum*) and broad bean (*Vicia faba*) by roughly 1‰ and 2‰, respectively (Wallace *et al.* 2013, 11 fig. 3). Absolute $\delta^{13}C$ values differ between species, however, being 1‰ lower for two-row (*Hordeum vulgare* var. *distichon*) and perhaps 2‰ lower for six-row hulled barley (*Hordeum vulgare* var. *hexastichon*) than for free-threshing wheat with similar water availability (Anyia *et al.* 2007; Flohr *et al.* 2011; Wallace *et al.* 2013; cf. Styring *et al.* 2016a). Moreover, while broadly similar for lentil and wheat grown under similar conditions, $\delta^{13}C$ values may be more sensitive to late-season drought in lentil (Wallace *et al.* 2013).

Plant $\delta^{13}C$ values depend on that of atmospheric CO_2, which has decreased over the last 10,000 years (Francey *et al.* 1999; Indermühle *et al.* 1999), and so are routinely converted to $\Delta^{13}C$ when comparing ancient and modern plant values (Farquhar *et al.* 1982):

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

Grain $\Delta^{13}C$ values of ≥17‰ for free-threshing wheat and lentil and ≥18.5‰ for hulled barley (assuming an offset from wheat equivalent to a mixture of modern two- and six-row barley) may be regarded as well watered and of ≤16‰ for wheat, ≤15.5‰ for lentil and ≤17‰ for barley as poorly watered, while intermediate values suggest moderate water availability (Wallace *et al.* 2013, 17 fig. 5). $\delta^{15}N$ values are higher for C_4 than C_3 plants and, in both, increase with aridity (Hartman & Danin 2010). Addition of organic nitrogen, especially animal manure, increases $\delta^{15}N$ in *cereals* (Bol *et al.* 2005; Bogaard *et al.* 2007; 2013; 2016; Fraser *et al.* 2011; Kanstrup *et al.* 2011; 2012). *Pulses* typically exhibit $\delta^{15}N$ close to 0‰ (Virginia & Delwiche 1982), unless soil nitrogen concentration is high enough to inhibit fixation from air and favour assimilation from soil (Ledgard *et al.* 1996; Vinther 1998; Andrews *et al.* 2009; Peoples *et al.* 2009). Experimentally grown cereals in central north-western Europe have demonstrated $\delta^{15}N$ values of >3‰ and >6‰ with moderate (15–20 t/ha) and high (30–35 t/ha) farmyard manure applications, respectively, while pulses show much smaller increases (~2‰) and only under extremely high applications (>70 t/ha) (Fraser *et al.* 2011; Treasure *et al.* 2016); equivalent ranges for (un)manured cereals are expected at the rainfall levels (~500 mm/year) around Knossos (cf. Styring *et al.* 2016b; 2017). In Greece, some pulses are manured very heavily for ease of cooking rather than high yields (Halstead 2014, 208).

Isotopic ratios may differ between grains from a single cereal ear by ≤2.0‰ in δ^{15}N (Bogaard *et al*. 2007) and ≤0.7‰ in δ^{13}C (Heaton *et al*. 2009), although within-pod variability in pulses is lower (Fraser *et al*. 2013; Treasure *et al*. 2016). Homogenizing multiple grains from the same field reduces variability (Kanstrup *et al*. 2012), with standard deviations for batches of 10 cereal or pulse grains of ~0.5‰ in δ^{15}N and 0.25‰ in δ^{13}C (Nitsch *et al*. 2015).

S2. INTERPRETATION OF δ^{13}C AND δ^{15}N VALUES OF ANIMAL BONE COLLAGEN IN RELATION TO CHANGING LAND USE

Expectations regarding δ^{13}C and δ^{15}N values in animal bone collagen are complicated by trophic-level shifts between plant diet and animal tissue and by the diversity of plants potentially consumed. For ruminants of similar sizes to cattle, sheep, and goats (cf. Tieszen 1991, 240), diet-bone collagen offsets have been suggested of ~5‰ in δ^{13}C (Drucker *et al*. 2008, 72 table 2) and 3–5‰ in δ^{15}N (Bocherens & Mariotti 2002, 1328–9 and table 2; Bocherens & Drucker 2007; Kendall *et al*. 2018, 140 table 2). For pigs a δ^{13}C offset of 4‰ has been suggested (Froehle *et al*. 2010), while their omnivory may raise their δ^{15}N values relative to the ruminants. For heuristic purposes, offsets of 5‰ for δ^{13}C and an intermediate 4‰ for δ^{15}N are adopted here for the ruminants, pig and also horse. These trophic-shift estimates are subject to variation and uncertainty (eg, Howland *et al*. 2003; Sponheimer *et al*. 2003; Caut *et al*. 2009; Makarewicz & Sealy 2015; Codron *et al*. 2018; Kendall *et al*. 2018), however, so only approximate values for average diet can be inferred from bone collagen measurements. To explore the degree of carnivory in Knossian dogs, we heuristically apply prey-predator offsets of ~1‰ in δ^{13}C and ~4‰ in δ^{15}N, based on data for temperate wolf and lynx with well documented prey composition (Bocherens & Drucker 2003, 48 tables 2–3; Fox-Dobbs *et al*. 2007, 463 table 2).

To address Knossian land use, the expected isotopic signal of livestock diet must be modelled by different routes for C$_3$ forage (harvested fodder/grazed pasture) from cultivated land, for 'rough' C$_3$ pasture on uncultivated land, and for C$_4$ forage.

C$_3$ forage from cultivated land

First, for C$_3$ cereal and pulse *grain*, potentially subject to a great variety of husbandry regimes, measurements of specimens from Knossos itself (see below) provide locally relevant values and, although these are too sparse for phase-by-phase analysis, pooled Neolithic and pooled Bronze Age data offer some control over the effects of long-term changes in growing conditions on the δ^{13}C and δ^{15}N values of crops potentially used as fodder. Secondly, using these data, approximate values can be estimated for fodder from C$_3$ crop-cleaning by-products by subtracting from grain values 2.5‰ (chaff ~2‰: Wallace *et al*. 2013; straw/leaf ~3‰: Winkler *et al*. 1978, 259 table 2) for cereal δ^{13}C, 1.5‰ (pod/straw/leaf: Treasure *et al*. 2016, 558 table 3) for pulse δ^{13}C, 2.4‰ for cereal δ^{15}N (chaff: Fraser *et al*. 2011, 2799), and 0.5‰ for pulse δ^{15}N (pod/straw/leaf: Treasure *et al*. 2016, 558 table 3). Thirdly, livestock grazing harvested fields would have consumed a mix of fallen ears, crop stubble and weeds, with δ^{13}C and δ^{15}N thus intermediate between grain and straw/chaff, principally of cereals given that harvesting probably removed most of the pulse crop (Halstead 2014, 78–80). Animals grazing these fields during any ensuing fallow period (assuming dominance of non-leguminous weeds, especially after pulse crops and on manured land), or perhaps grazing early growth of cereals (potentially recovering to yield a grain crop) or poor crops not worth harvesting for grain (Halstead 2006, 50), should likewise have exhibited dietary values intermediate between ripe grain and straw/chaff of cereals in δ^{13}C (Winkler *et al*. 1978, 259 table 2) and δ^{15}N (eg, grain minus 1.4‰ (Styring *et al*. 2016b, 10)). δ^{13}C and δ^{15}N values for stubble/fallow(/young cereal) graze (henceforth 'stubble/fallow') are estimated, therefore, as measured C$_3$ cereal grain ranges minus 1.5‰ and 1.4‰, respectively. Figure S1a–b shows, for Neolithic and Bronze Age Knossos respectively, the modelled δ^{13}C and δ^{15}N values of C$_3$ grain fodder, C$_3$ chaff/straw fodder and cereal stubble/fallow pasture as confidence ellipses at one (68%) and two (95%) standard deviations. While livestock grazing across a range of stubble, fallow or crop fields

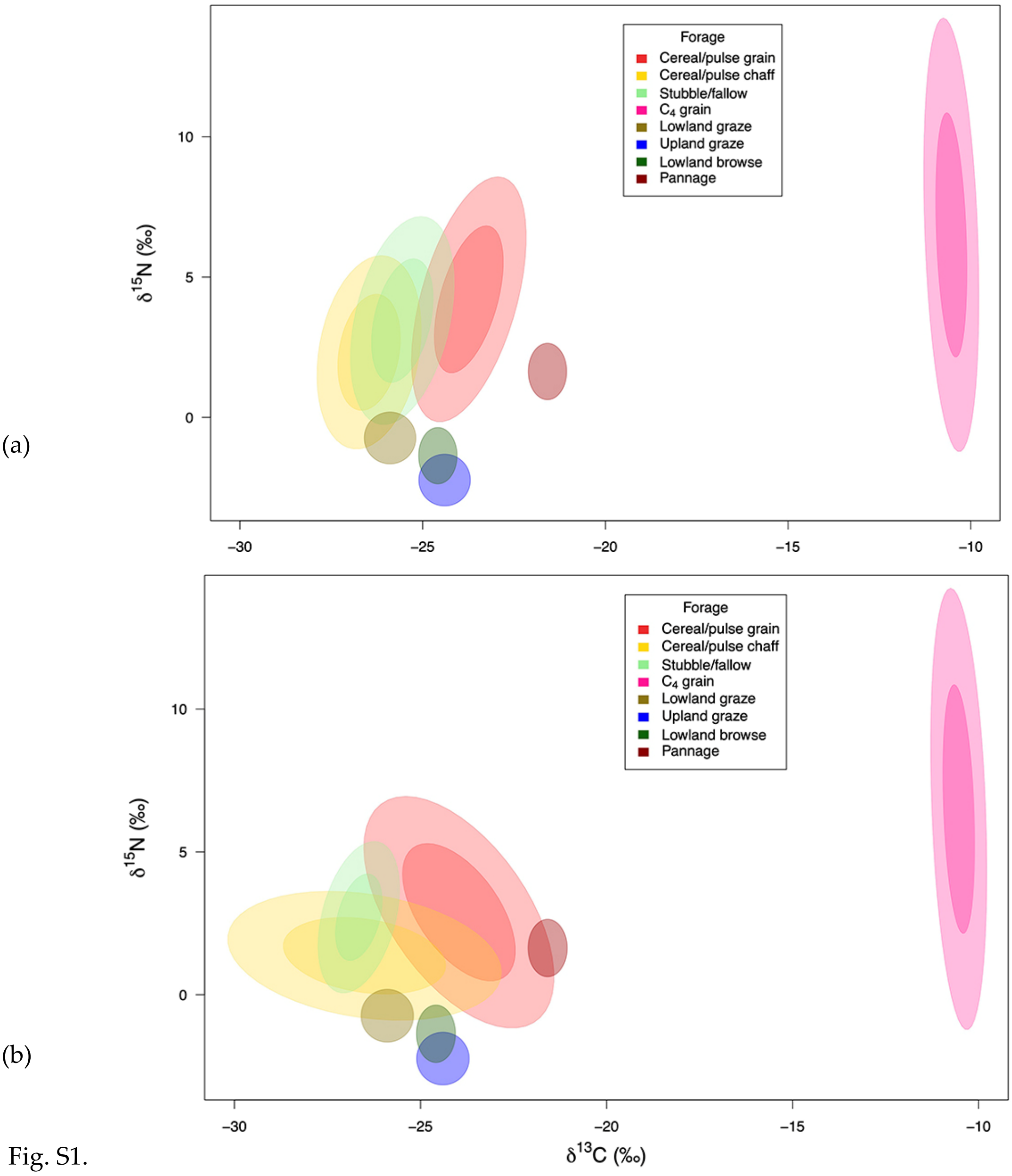

Fig. S1.

Modelled $\delta^{13}C$ and $\delta^{15}N$ ranges for forage categories available to animals consumed at (a) Neolithic and (b) Bronze Age Knossos: ellipses for cultivated forage at 68% and 95% confidence intervals based on values for ancient cereal and pulse grains from Knossos (Table 2); ellipses for uncultivated forage at a 95% confidence interval based on values for modern plants growing at 500 mm mean annual rainfall in the east Mediterranean (Table S7) with allowance of + 1.8‰ for changes in the $\delta^{13}C$ value of atmospheric CO_2 (after Ferrio *et al*. 2005)

are likely to exhibit 'averaged' $\delta^{13}C$ and $\delta^{15}N$ values within the 68% ellipses, any animals largely foddered from, or pastured on, a particular cultivated plot may exhibit more extreme values outside this range.

'Rough' C_3 pasture on uncultivated land

Hartman and Danin (2010) analysed leaves of various plant life forms from protected sites over a 75–1000 mm/year mean annual rainfall gradient in the eastern Mediterranean, showing that, as expected, both $\delta^{13}C$ and $\delta^{15}N$ values of C_3 plants decline with increasing rainfall (Hartman & Danin 2010, 845 fig. 4 and suppl. data). From these data (Hartman 2008, appx A), we constructed two regression models comparing the pooled wet- and dry-season $\delta^{13}C$ and $\delta^{15}N$ values for annuals/forbs and trees/shrubs (representing grazed and browsed rough pasture, respectively) against mean annual precipitation. From these models, we calculated $\delta^{15}N$ and $\delta^{13}C$ values expected for annuals/forbs and trees/shrubs growing under 500 mm mean annual rainfall (comparable with the Knossos region over the last century), together with their upper and lower confidence intervals (Table S7); we excluded data for geophytes, as relatively uncommon, and dwarf shrubs, as relatively unpalatable to herbivores (Zohary & Orshan 1966, 17–18), and consider below the implications of assuming 600 mm rather than 500 mm rainfall (cf. Mauri *et al*. 2015).

Hartman and Danin sampled plants in summer 2006 and spring 2007, thus with estimated atmospheric $\delta^{13}C$ values of -8.2‰, 1.8‰ lower than the 7th–2nd millennia BCE mean of -6.4‰ (range -6.7 to -6.3‰) (Indermühle *et al*. 1999; Ferrio *et al*. 2005; http://web.udl.es/usuaris/x3845331/AIRCO2_LOESS.xls/). Because we compare these modern plant values with ancient faunal samples dated with variable precision, we allow for changing atmospheric $\delta^{13}C$ values not by converting to $\Delta^{13}C$, but by adding 1.8‰ to 2006–7 values (Table S7). Figure S1 shows the modelled $\delta^{13}C$ and $\delta^{15}N$ values of grazed and browsed lowland rough pasture as ellipses only at a 95% confidence level, because the baseline stable isotope data are derived from single measurements per life form, season and highly localised (10 m radius: Hartman 2008, 23) sampling site and so inevitably understate the variability of each pasture type.

Based on the lowland rough graze and browse ellipses, we model two further types of uncultivated forage (Fig. S1), not represented in the Hartman and Danin study: summer grazing at high altitude, traditionally exploited on Crete by seasonally mobile herds of goats and especially sheep; and autumn-winter pannage (acorns, etc) in low-altitude woodland, widely exploited across the Mediterranean to fatten small livestock, especially pigs (Parsons 1962; Albarella *et al*. 2007, 303; Halstead & Isaakidou 2011, 166; Hadjikoumis 2012, 359).

Relative to lowland rough graze, $\delta^{13}C$ values of highland annuals and forbs should be depressed 1–2‰ by higher rainfall (eg, 1100 mm/yr for Anogia, at *c*. 740 m asl below Mt Psiloritis: Tsiros *et al*. 2020), raised 1–2‰ by growth during summer (Hartman & Danin 2010, 845 fig. 4), and raised ~1‰ per 1000 m altitude by falling atmospheric pressure (Körner *et al*. 1988, 628 fig. 2b; 1991). Rough graze at 1000–2000 m on the Psiloritis or Lasithi mountains should thus have $\delta^{13}C$ values ~1–2‰ higher than in the central lowlands, while east Mediterranean (Hartman & Danin 2010, 845 fig. 4a–b) and global (Handley *et al*. 1999, 192 fig. 1b) data suggest that higher precipitation should depress $\delta^{15}N$ values by 1–2‰.

We model pannage on lowland Crete, using local rough browse as a baseline and west Mediterranean data for the offset between oak leaves (browse) and acorns (pannage). Average $\delta^{13}C$ values of mature deciduous and evergreen oak leaves from open woodland in central Italy (Valentini *et al*. 1992) and southern France (Damesin *et al*. 1997), adjusted for sampling date (1990 & 1993) and higher mean annual rainfall (~900 mm), match the age-corrected dry-season mean for east Mediterranean shrubs/trees at 500 mm rainfall of ~-24‰ (Hartman 2008, appx A). $\delta^{13}C$ values of *shelled* acorns (as pigs consume them: Zeman *et al*. 2016, 581) of deciduous and evergreen oaks from southern Spain (González-Martin *et al*. 1999) and evergreen oaks from southern Portugal (Alegria *et al*. 2020), again adjusted for sampling date (?1997 and 2017, respectively) and mean annual rainfall (~500–550 mm: https://www.ipma.pt/pt/oclima/normais.clima/1971-2000/normalclimate7100.jsp), are ~-20 and -21‰, respectively. This implies a 3‰ offset in $\delta^{13}C$ values from browse to pannage for lowland central Crete, while a mean 2‰ offset in $\delta^{15}N$ values is suggested by Portuguese evergreen oak data (Alegria *et al*. 2020).

C_4 forage

Knossian livestock potentially consumed C_4 plants as cultivated fodder or rough pasture. Common millet and tiger nut were *possibly* cultivated, and used as fodder, on palatial-era Crete, but neither is represented in macroscopic archaeobotanical assemblages and thus available for analysis. Figure S1 therefore displays 68% and 95% confidence ellipses for δ^{13}C and δ^{15}N values of common millet of similar date to palatial Knossos from Archontiko and Toumba Thessalonikis (Nitsch *et al*. 2017, 116–17 figs 4–5), in an area of northern Greece with similar modern annual rainfall (~450 mm) to lowland central Crete (Tsiros *et al*. 2020). For tiger nut, δ^{13}C values of modern leaves from eastern North America (-12.7 and -11.1‰: Li *et al*. 1999, 211 table 1) would, if age-corrected (collection dates not reported), approximate to those plotted for millet. C$_4$-rich or saline coastal rough pasture should also exhibit δ^{13}C values comfortably higher than C$_3$ vegetation (Farquhar *et al*. 1989, 520). In the east Mediterranean study, C$_4$ plants were scarce above 350 mm annual rainfall, but available δ^{13}C values are unrelated to rainfall, suggesting an 'age-corrected' range of ~-13 to -10‰ (Hartman & Danin 2010, appx B) for Neolithic–Bronze Age lowland central Crete; a δ^{15}N value of ~1‰ might tentatively be extrapolated from lower-rainfall sites (Hartman & Danin 2010, appx C), but higher values would be anticipated for saline coastal rough pasture (Heaton 1987). The plotted ellipses for millet (Fig. S1) may thus serve as an approximate guide to δ^{13}C and δ^{15}N values of C$_4$ cultivated fodder or saline rough pasture on central Crete.

Overview of modelled forage values

As expected, the clearest distinction among forage categories is between C$_3$- and C$_4$-dominated fodder/pasture (Fig. S1) with low and high δ^{13}C values, respectively. Among C$_3$ forage, rough pasture is distinguished fairly clearly, by lower δ^{15}N values, from cultivated fodder or pasture on cultivated land; a similar distinction between C$_4$ rough pasture and C$_4$ forage from cultivated land is unlikely given expected raised δ^{15}N values for the former in saline coastal environments. Among C$_3$ forage on cultivated ground, cereal/pulse grain exhibits higher δ^{15}N and especially higher δ^{13}C values than chaff/straw, with stubble/fallow pasture intermediate. Among C$_3$ rough pasture, δ^{13}C distinguishes between lowland graze (low values), lowland browse/upland summer graze (intermediate), and lowland pannage (high), while δ^{15}N separates pannage (high) from lowland graze/browse (intermediate) and upland graze (low).

S3. LABORATORY ANALYTICAL METHODS AND QUALITY CRITERIA: PLANT REMAINS

Visual inspection under a microscope showed no signs of surface soil contamination, and lack of contamination was confirmed by Fourier transform infrared spectroscopy (FTIR), following reference contamination comparisons for humic acids, carbonates, and nitrates (Vaiglova *et al*. 2014). Accordingly, the samples were not pre-treated. Samples of *c.* 5–10 grains were homogenised in an agate mortar and pestle. The homogenised powders were weighed into tin capsules for IRMS analysis with δ^{13}C values and δ^{15}N values measured separately. An internal alanine standard was used to calculate raw isotopic ratios (Table S8). Raw δ^{13}C values were two-point normalised to the VPDB scale using IAEA-C6 and IAEA-C7, while δ^{15}N values were normalised to the AIR scale using Caffeine and IAEA-N2. Raw and normalised data are presented in Table S1.

Reported measurement uncertainties are the calculated combined uncertainty of the raw measurement and reference standards, after Kragten (1994). The average measurement uncertainty was ±0.07‰ for δ^{13}C values and ±0.35‰ for δ^{15}N values. Full details of the analytical conditions are reported in Table S8. Plant data reliability was assessed by comparing δ^{15}N values to C:N ratios as per Szpak and Chiou (2020). There is no significant relationship between the δ^{15}N values and C:N ratios (Fig. S2). The δ^{15}N and δ^{13}C values were also compared to reported values from other sites in the region and show similarities. Both results suggest that the samples' isotopic values are a representation of the original isotopic compositions of the plants.

For some analyses, plant δ^{13}C values were converted to carbon discrimination values (Δ^{13}C values) to allow for comparison with modern research, following Farquhar *et al*. (1982; 1989). The δ^{13}C

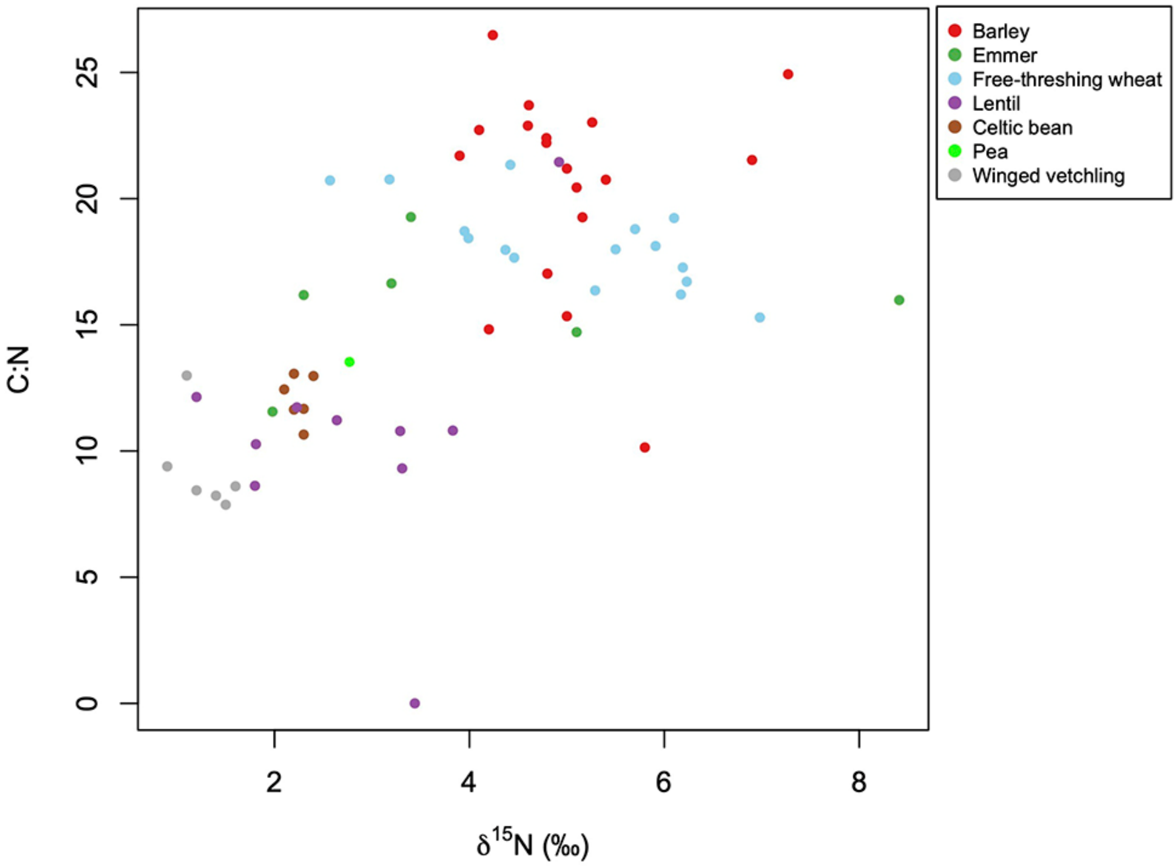

Fig. S2.
Scatterplot of Knossos plant $\delta^{15}N$ values and C:N ratio

value of atmospheric CO_2 was estimated using reference tables from Ferrio *et al*. (2005) based on the date range of the samples (Table S1). The plant isotope results cited in the text are also corrected for the minor effect of charring on $\delta^{13}C$ values (by subtracting 0.11‰) and $\delta^{15}N$ values (by subtracting 0.31‰) (Nitsch *et al*. 2015), except where otherwise indicated. Full results of the plant remains isotope analysis are reported in Table S1. All calculations were performed using the statistical programming language R (RStudio version 1.4.1717).

S4. SAMPLING PROTOCOL, LABORATORY ANALYTICAL METHODS AND QUALITY CRITERIA: FAUNAL REMAINS

Sampling protocol

In the context of the *AGRICURB* project, faunal isotopic analysis was undertaken not as a 'control' for human palaeodietary reconstruction, but to explore variability in the diets and hence management strategies of different animal species consumed at Knossos in successive phases of the Neolithic and Bronze Age. Key research questions of *AGRICURB* included the scale of animal husbandry and its degree of integration with agriculture, and hence the extent to which livestock were associated with the cultivated or 'natural' landscape. Ideally, therefore, analysis would have targeted both domestic and 'wild' species, but the latter were largely restricted at Knossos to Bronze Age fallow deer, for which, as human introductions to the island of Crete, a free-range life-style must be demonstrated rather than assumed. Analysis has thus focussed mainly on the four common domesticates: cattle, sheep, goats, and pigs.

Samples were selected for analysis on the following criteria:

1. presence of thick cortical bone, as this is less prone to diagenetic deterioration of collagen than more porous cancellous bone and is thus more likely to contain adequate amounts of well-preserved

collagen for isotopic analysis; cortical bone turns over more slowly than cancellous bone and so offers an isotopic record of the animal's diet in the long term (cf. Sealy *et al*. 1995); this criterion is met especially in the diaphysis of major weight-bearing limb elements and in the mandible;

2. presence also of a well-preserved epiphysis (in the case of limb bones) or teeth (in the case of a few mandibular specimens), as these are most securely identifiable to species and also provide information on age at death and thus enable exclusion of specimens from very young animals with δ^{15}N values elevated by suckling (eg, Balasse & Tresset 2002);
3. avoidance of specimens worked into artefacts and of parts of specimens bearing butchery marks, pathological traces and key morphological or biometrical information on species, age, or sex;
4. derivation, as far as possible, from a single anatomical element, given that bone collagen turnover rates vary between elements of different size and structure (Rodière *et al*. 1996, 181); and
5. derivation, as far as possible, from the same side of the body (and, if not possible, taking account of size, robusticity and morphological details), to avoid duplicate samples from the same individual.

Criteria 1 and 3 were met by all sampled specimens and criterion 2 by 97% of those that yielded usable results (99% if postcranial specimens of clearly adult robusticity are considered 'fused'; see below). As regards criterion 4, distal humerus was the most abundantly and well-preserved body part and also bears numerous characteristics enabling discrimination even between morphologically similar taxa, such as sheep and goat (Boessneck *et al*. 1964) or fallow and red deer (Lister 1996). Distal humerus accounts for 73% of samples with usable results, other postcranial body parts for 18% and mandibles (one Neolithic dog; otherwise Bronze Age sheep and goats, some included in a previous incremental multi-isotope analysis of their teeth: Isaakidou *et al*. 2019) for 9%. Other postcranial elements make up only 2% of samples with usable results for sheep and 5% for goat, but 28% for pig (less abundant), 60% for cattle (heavily fragmented) and 55% for dog, 75% for fallow deer and 100% for badger and horse (all scarce).

Distal humerus (and likewise proximal radius) fuses late in the first (sheep, goat, pig) or early in the second (cattle) year (Silver 1969), by which time the common domesticates in this study should have been weaned for at least a few months. The δ^{15}N values of fused specimens of distal humerus (and other limb elements that fuse at a similar or greater age) and likewise of sheep and goat mandibles with erupting or worn second molar (Deniz & Payne 1982; Jones 2006) should thus no longer reflect a suckling diet (Table S2: 'Weaning status'). Such specimens make up 83% of samples with usable results or, including indeterminate specimens for which size and/or robusticity indicates a subadult or adult, 89%. A further 8% of usable results, comprising specimens with fusing distal humerus (/proximal radius) or sheep/goat mandibles with first molar in wear but second molar unerupted, were probably also weaned well before death. Only 3% of usable results (comprising unfused distal humerus/proximal radius, sheep/goat mandibles with first molar unworn or just coming into wear, and specimens preserving no evidence of age) have been categorised as *potentially* still suckling at death and, in practice, age at death may have been underestimated for some or even all the ostensibly young postcranial specimens if castration (to encourage weight gain) had delayed fusion. Only the two youngest goat mandibles, with erupting 1st molar implying an age perhaps around 3–4 months, can be attributed to animals likely to have died before or soon after weaning and these two specimens indeed yielded δ^{15}N values apparently influenced by suckling (see main text).

Sample extraction

After photographing selected specimens from different views, sections of cortical bone were sawn from the thickest part of the shaft with a Dremel rotary tool for smaller bones or a hacksaw for the larger cattle bones. Samples were extracted at Oxford or at the Knossos Research Centre of the British School at Athens, where the Neolithic and Bronze Age assemblages, respectively are stored. We followed the standard practice of extracting pieces of 1–5 g. While a minimum of 1 g of dry bone is required to obtain an adequate quantity of collagen for isotopic analysis, 5 g was obtained where possible (ie depending on species and size of the original specimen), to allow for loss from surface cleaning, any laboratory errors, such as malfunction of measuring instruments, accidental loss, etc. The surfaces of the sawn samples were subsequently cleaned by abrasion prior to pounding in a mortar. All analytical stages from surface cleaning onwards were performed at the Research Laboratory for Archaeology and the History of Art (RLAHA) of the University of Oxford, following standard Laboratory protocols.

Collagen extraction

Collagen extraction followed the Longin (1971) method modified as described by Richards and Hedges (1999). All samples were run on a SerCon 20-22 EA-GSL isotope mass spectrometer. An internal alanine standard (δ^{13}C -26.91‰ and δ^{15}N -1.63‰) was used to calculate raw isotopic ratios and correct for drift. Raw δ^{13}C and δ^{15}N values were normalised to the VPDB and AIR scales using an internal standard of seal collagen (SEAL δ^{15}N 17.3±0.29‰, δ^{13}C -13.3±0.11‰) and Caffeine-2 (U. Indiana δ^{15}N 1±0.2‰, δ^{13}C -27.771±0.043‰). The reported measurement uncertainties are the calculated combined uncertainty of the raw measurement and reference standards (after Kragten 1994). Values of measured standards are reported in Table S8. The average measurement uncertainty for collagen δ^{13}C and δ^{15}N values was ±0.09‰ and ±0.2‰ respectively. All calculations were performed using RStudio (1.3.1073) and R (3.2.4). Full results of the stable carbon and nitrogen isotope analysis are reported in Table S2a (Neolithic) and S2b (Bronze Age).

Quality criteria

Apart from specimens with no or poor collagen preservation, a number of measurements were excluded from the analysis, when collagen exhibited: (a) a C:N ratio outside the range of 2.9–3.6 (following DeNiro 1985), and/or (b) low yields of nitrogen and/or carbon (see Table S2a–b). For the latter, assemblage-specific minima were set at 50 μg (Neolithic) and 60 μg (Bronze Age) for nitrogen and 150 μg (Neolithic) and 200 μg (Bronze Age) for carbon. Three further Neolithic samples were excluded from analysis due to poor analytical conditions. The breakdown of successful sample frequency by period and species is presented in Table S4 and discussed in the main text.

S5. ANIMAL BONE COLLAGEN RESULTS: PHASE-BY-PHASE OUTLIERS

Outliers, representing δ^{13}C or δ^{15}N values exceeding interquartile range × 1.5 for each chronological phase, were defined for sheep (Fig. 7a–b), goat (Fig. 7c–d) and cattle (Fig. 7e–f), but not pig (Fig. 7g–h) or the less common animal species. The quality control measures adopted provide grounds for optimism that outliers are not 'rogue' results of poor sample preservation or laboratory error, but rather represent animals of atypical dietary history. As the following discussion shows, a dietary explanation is not intrinsically implausible for any of the outliers. Scatterplots of the faunal bone collagen δ^{13}C and δ^{15}N values by phase are presented in Figure S3.

Sheep

For Neolithic sheep, phase-by-phase outliers (Fig. S4a) extend only modestly beyond the 95% confidence ellipse, especially towards lower $\delta^{13}C_{diet}$ or higher $\delta^{15}N_{diet}$ and may represent animals reared during an unusually wet period or tethered (in the case of an EN outlier) on a heavily manured garden, respectively. For the Bronze Age (Fig. S5a), conversely, outliers extend the sheep $\delta^{13}C_{diet}$ range mainly towards higher values, with the highest (-22.4‰) of FP date possibly reflecting some intake of C_4 grain fodder or C_4-rich/saline coastal rough pasture (the associated $\delta^{15}N_{diet}$ value of 2.5‰ is compatible with either). Interpreting individual cases is hazardous, however, because bone collagen data represent 'averages' of potentially considerable seasonal or lifetime variation. For example, two non-outlier FP mandibles (MUM75 and RR191: Fig. 7b, nos 1-2), slaughtered in their second or third year and previously identified by incremental δ^{13}C and δ^{18}O analysis of tooth enamel as vertically transhumant in their first or first and second summers (Isaakidou *et al*. 2019, 50), fall within the modelled range for cultivated land and well outside that for upland summer grazing. Conversely, for FP mandible MUM72 (Fig. 7b, no. 3), incremental dental data exhibit increased δ^{13}C values in *winter*, suggesting seasonal consumption of C_4-rich/saline coastal pasture or grain fodder, but the $\delta^{13}C_{diet}$ value of the mandibular bone collagen suggests long-term diet dominated by lightly manured cultivated land and perhaps C_3 rough pasture. The bone collagen and incremental dental enamel values for $\delta^{13}C$ are of course not directly comparable: in addition to contrasting temporal resolution, the former largely reflect protein intake and the latter whole diet or energy consumption (Lee-Thorp *et al*. 1989, 588). Nonetheless, the apparent divergences between the two datasets caution against overly detailed interpretation of bone collagen outliers.

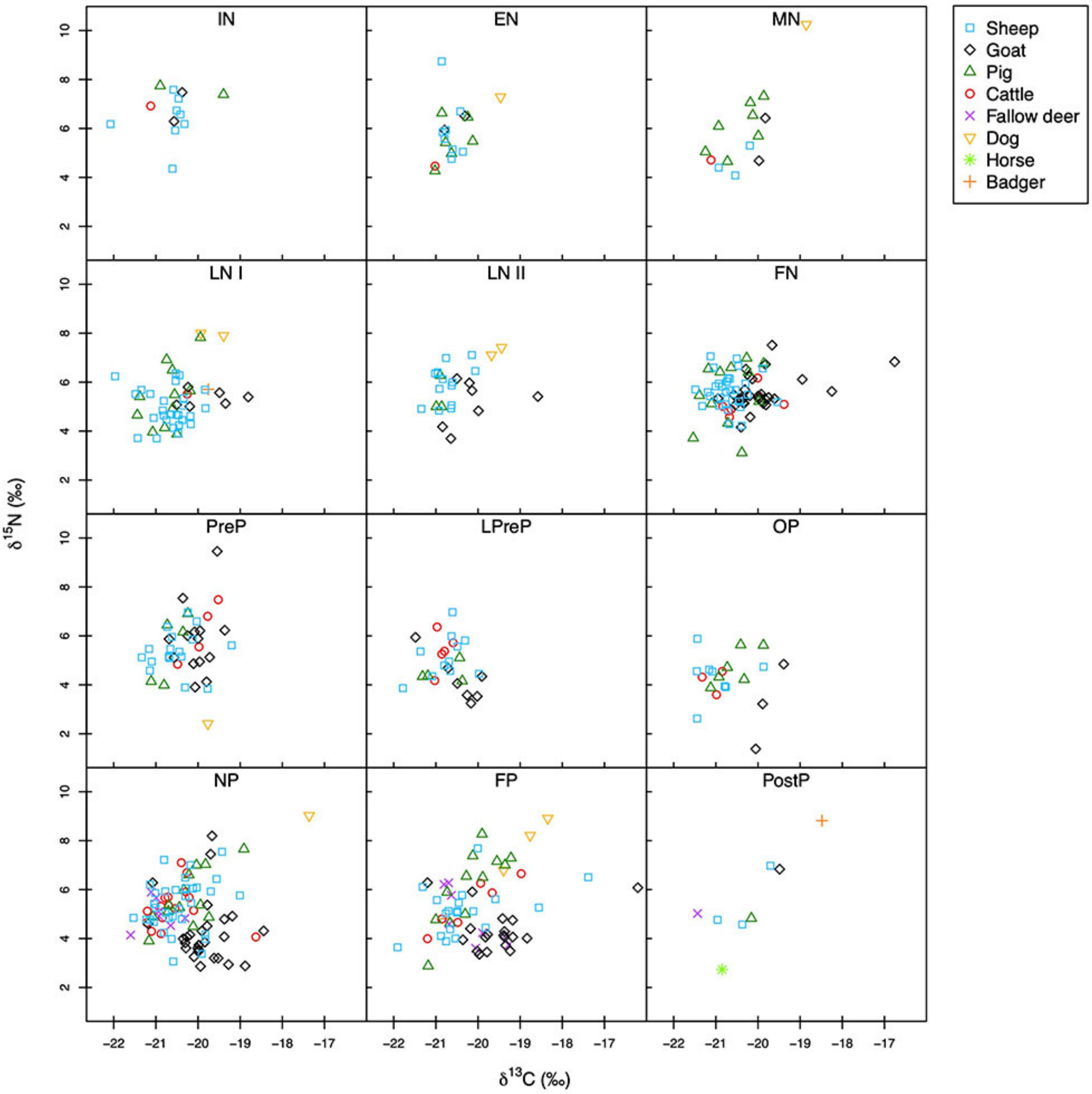

Fig. S3.
Scatterplots of Knossos faunal bone collagen $\delta^{13}C$ and $\delta^{15}N$ values by phase

Goat

Outliers (Figs S4-S5) extend positively the $\delta^{13}C$ range for Neolithic and Bronze Age and the $\delta^{15}N$ range especially for Bronze Age Knossos goats. Two (NP) high-$\delta^{15}N_{diet}$ cases (~4‰) are mandibles of three-month old kids (with erupting first molars), probably enriched by suckling (cf. Balasse & Tresset 2002), but the most salient (PreP) outlier ($\delta^{15}N_{diet}$ 5.5‰; $\delta^{13}C_{diet}$ -24.5‰) suggests generously manured forage, perhaps including substantial C_3 grain, and may represent a pampered 'house-goat'. Strikingly high $\delta^{13}C_{diet}$ outliers of FN (-21.8‰; $\delta^{15}N_{diet}$ 2.8‰) and FP (-21.2‰; $\delta^{15}N_{diet}$ 2.1‰) date may also represent animals reared intensively with (lightly manured) C_3 grain supplements or smaller C_4 grain rations (arguably implausible for FN) or grazing C_4-rich/saline coastal rough pasture. The difficulty of interpreting individual cases, however, is again highlighted by a non-outlier FP mandible (MUM73: Fig. 7b, no. 6). Slaughtered in its second or third year and identified by incremental dental $\delta^{13}C$ and $\delta^{18}O$ analysis as potentially foddered in at least its first year (Isaakidou *et al*. 2019, 50), bone collagen data place this animal among the goats consuming cultivated and/or rough lowland graze.

Cattle

The three $\delta^{15}N$ outliers (Fig. 6f) fall within the corresponding Neolithic or Bronze Age 95% ellipse, but the sole $\delta^{13}C$ outlier (Fig. 6e), of NP date, has a high $\delta^{13}C_{diet}$ associated with a fairly low $\delta^{15}N_{diet}$ value. This combination argues against C_4-rich/saline coastal pasture or C_4 grain fodder as the source of raised $\delta^{13}C_{diet}$ and, by elimination, perhaps favours C_3 grain fodder grown under extensive conditions (Fig. S5c), although a diet dominated by rough browse in an arid area or period cannot be excluded.

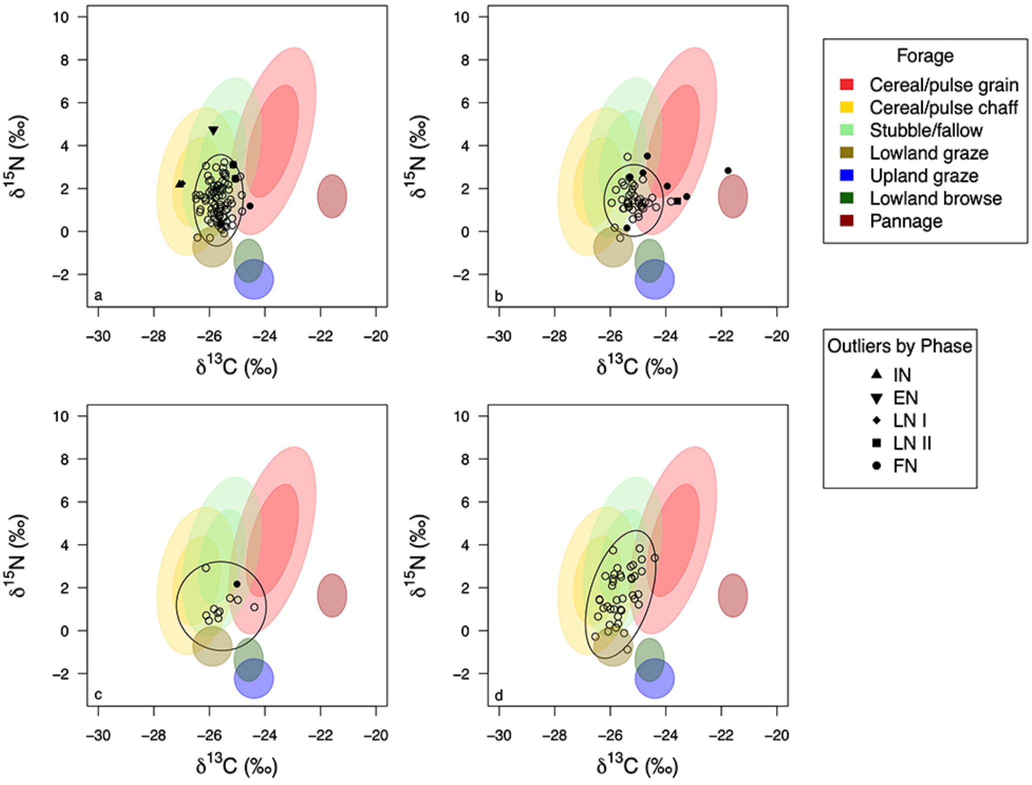

Fig. S4.

$\delta^{13}C$ and $\delta^{15}N$ values with 95% confidence ellipses, highlighting outliers (filled symbols) by phase, for a) sheep, b) goat, c) cattle and d) pig at Neolithic Knossos, compared with modelled forage categories (after Fig. S1a); bone collagen values adjusted for trophic level shifts of ~5‰ in $\delta^{13}C$ and ~4‰ in $\delta^{15}N$ values

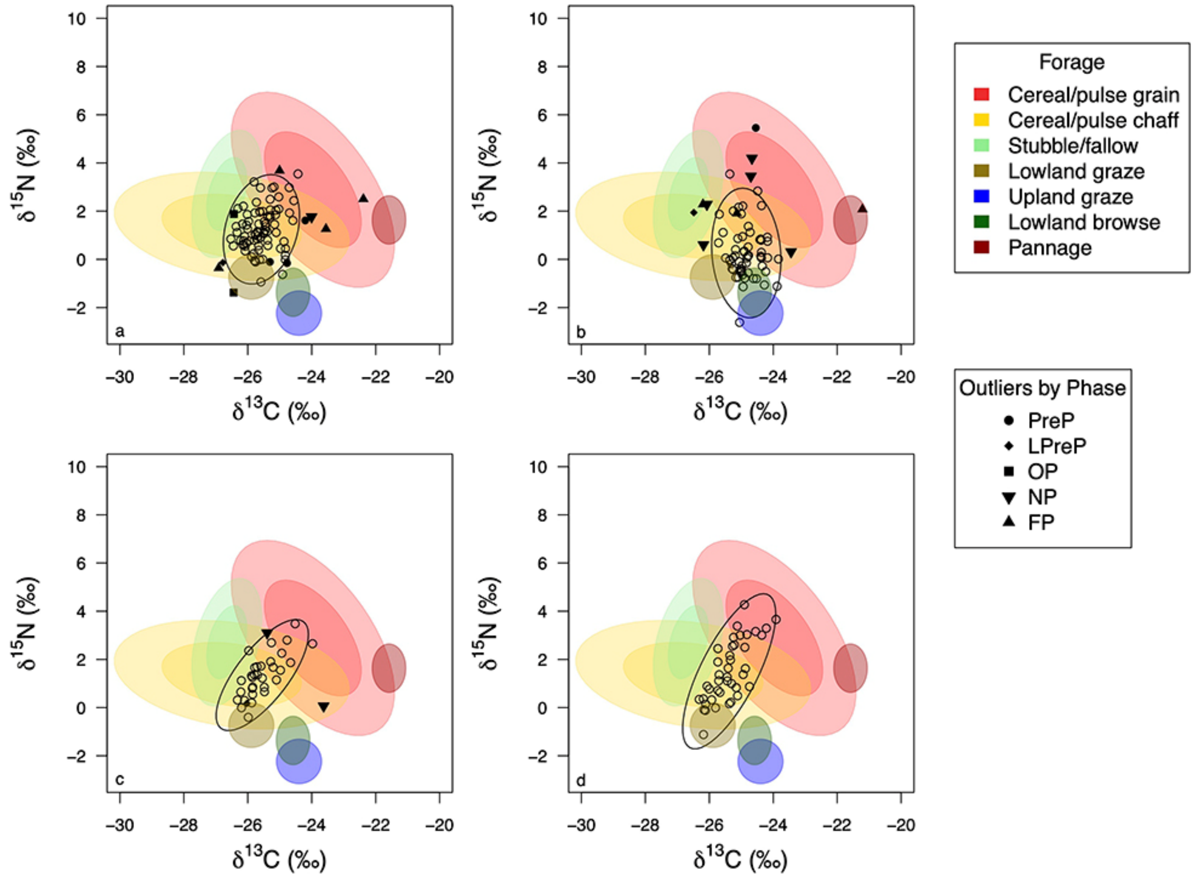

Fig. S5.
δ^{13}C and δ^{15}N values with 95% confidence ellipses, highlighting outliers (filled symbols) by phase, for a) sheep, b) goat, c) cattle and d) pig at Bronze Age Knossos, compared with modelled forage categories (after Fig. S1b); bone collagen values adjusted for trophic level shifts of ~5‰ in δ^{13}C and ~4‰ in δ^{15}N values

S6. EVALUATION OF ASSUMPTIONS UNDERPINNING MODELLING OF LIVESTOCK DIET

For clarity, δ^{13}C and δ^{15}N ranges for different forage types have been modelled assuming mean annual rainfall of ~500 mm and plant-bone collagen trophic-level shifts of 5‰ for δ^{13}C values and 4‰ for δ^{15}N values. The resulting dietary reconstructions are plausible in terms of livestock feeding preferences and Knossos' changing size and regional status. Here we consider whether alterations to these underpinning assumptions would yield contrasting, but equally plausible, reconstructions.

Pollen-based, continental-scale climatic models, as yet with scant *local* empirical support (Mauri *et al*. 2015), suggest mean rainfall generally closer to 600 mm for Neolithic–Bronze Age lowland central Crete. At 600 mm, δ^{13}C ranges should be lower for east Mediterranean annuals, forbs and shrubs/trees by ~0.4, 0.1–0.2 and 0.4–0.6‰, respectively, and δ^{15}N ranges by ~0.4, 0.4–0.5 and 1‰ (Hartman & Danin 2010, 845 fig. 4). These adjustments, especially to δ^{15}N values, would reinforce the association of Knossian livestock (as inferred for 500 mm rainfall) with stubble/fallow graze and, except for Bronze Age goats, their divorce from rough browse and graze.

For δ^{13}C values, a 6‰ trophic-level shift would lower estimated dietary ranges by 1‰. Excluding outliers, this would mostly confirm (sheep, cattle and pigs) or strengthen (Neolithic goats) reliance on stubble-fallow graze but would associate Bronze Age goats more with rough graze and less with browse, despite their preference for the latter and its probably greater local availability. Conversely, a 4‰ shift would raise $\delta^{13}C_{diet}$ values by 1‰, shifting Neolithic goats and Bronze Age sheep, cattle, and pigs from stubble/fallow pasture towards reliance on C_3 grain fodder. Routine foddering with grain does not match the generally gracile build especially of Knossos sheep (Isaakidou 2005), however, and would undermine interpretation of the highest $\delta^{13}C$ outlier as an intensively reared 'house-goat'.

For $\delta^{15}N$ values, a 3‰ shift would raise estimated dietary values by 1‰, enhancing the association of all livestock with forage (including C_3 grain) from well manured cultivated land, to a degree perhaps incompatible with FP archaeobotanical and textual indications of extensive cultivation, and largely divorcing all but some Bronze Age goats from rough browse. Conversely, a 5‰ shift would lower estimated dietary values by 1‰, increasing implied use of rough pasture without negating primary dependence on forage from cultivated land, perhaps especially stubble/fallow graze. In sum, adopting different values for mean rainfall or trophic-level shifts yields dietary reconstructions that either broadly mirror those outlined above or are less compatible with livestock feeding preferences and other known constraints.

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