Farming practice and land management at Knossos, Crete: New insights from $\delta^{13}C$ and $\delta^{15}N$ analysis of Neolithic and Bronze Age crop remains

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Introduction

Neolithic agriculture in the Aegean encompassed a diverse spectrum of cereals and pulses (Halstead 1994; Valamoti and Kotsakis 2007), and plausibly entailed intensive management (i.e. with careful tillage, weeding, manuring and watering, as needed) on a small scale in order to achieve marginal surpluses that buffered households and communities against poor harvests (Halstead 1981, 1987, 1989). This model is supported by isotopic evidence for the manuring of cereals and pulses, and for preferential watering of the latter, at Neolithic sites in Greece and Bulgaria (Bogaard *et al*. 2013; Vaiglova *et al*. 2014a). The availability of labour ultimately limits the size of the surplus that can be attained under such a system. Linear B texts indicate that Late Bronze Age palatial urban centres in the Aegean were at least partly sustained by surpluses gained from more extensive low-input cultivation sponsored by palatial elites (Halstead 1995a, 1995b, 1999a, 1999b, 2001; Killen 1993, 1998).

The 7th-2nd millennium BC sequence at Knossos, Crete, provides a key opportunity to examine local urbanisation and agricultural development. The sequence here offers unique evidence of *in situ* social change from the aceramic Neolithic to the rise and fall of the palatial centre during the Bronze Age (e.g., Cadogan *et al*. eds 2007; Isaakidou and Tomkins eds 2008; Whitelaw 2004). Textual information about the agricultural basis of the Knossian economy is available for the later Bronze Age, where texts detail the centralised production and mobilization of resources (Bendall 2007; Bennet 2008; Halstead 1995a, 1998, 1999a, 1999b, 2001; Killen 1993, 1998, 2004, 2008; Schoep 2001; Whitelaw 2001), arguably supplemented by exchange (Bennet and Halstead 2014; Halstead 1992, 2001; Nakassis *et al*. 2011; Parkinson *et al*. 2013). Strategic palatial intervention in farming is reflected in Linear B texts focused on the production of one type of cereal, most likely glume wheat, with less frequent mention of a second cereal, probably barley, in the context of religious offerings or provisions for religious personnel (Halstead 1995c). Palatial intervention in (glume) wheat production entailed loans of plough oxen owned by the palace, perhaps together with fodder disbursements to guarantee reasonable maintenance, likely based on share-cropping arrangements (Halstead 1995a, 1995b, 1999a, 1999b, 2001; Killen 1993, 1998, 2008). Such a system is reminiscent of extensive production arrangements on Ottoman *çiftlik* estates in 19th-early 20th century Greece (Halstead 1999a, 1999b, 2001). By contrast, available archaeobotanical evidence from Knossos, elsewhere in Crete and the southern Aegean, demonstrates that a range of cereals and pulses was grown that are *not* mentioned in Linear B texts (Jones 1987, 1988; Livarda and Kotzamani 2014; Sarpaki 1992, 2013). Thus, a significant portion of the agricultural economy must have fallen outside palatial monitoring, and the [comparative] nature and scale of this 'non-palatial' agriculture is unknown (Bennet and Halstead 2014; Halstead 1999a 1999b, 2001, 2014).

Recent advances in stable isotope analysis of charred crop remains, complemented by the functional ecological analysis of associated weed assemblages, permit direct inferences about the nature of crop growing conditions and land management practices (e.g. Bogaard *et al*. 2013, 2016a, b; Nitsch *et al*. 2015; Styring *et al*. in

press; Wallace *et al*. 2015). While expansion of existing archaeobotanical data for Bronze Age Knossos is a central aim of ongoing excavations at Knossos Gypsades, the hill south of the palace (Morgan 2015: 34-5), two key assemblages from earlier excavations offer potential to investigate crop growing conditions and land management at Knossos towards the beginning and end of the Neolithic-Bronze Age sequence: a small set of cereal and pulse samples from John Evans' 1968 excavations of Neolithic layers under the Central Court, studied by Hans Helbaek (Evans 1968: 269); and Late Bronze Age cereal and pulse storage deposits from the Late Minoan II burned destruction layer of Storeroom P in the Unexplored Mansion (Popham 1984), studied by Glynis Jones (1984, 1992; see also Sarpaki and Jones 1990). Crop storage deposits from the Unexplored Mansion include a range of pulses – that is, crops outside the strategic interest of palatial bureaucracy – as well as emmer (a glume wheat), hulled barley and free-threshing wheat. The Unexplored Mansion assemblage thus offers an opportunity to reconstruct the husbandry of pulses and cereals in the Final Palatial period, all representing crops destined for consumption in an elite context.

In this study we use stable isotope analysis of crop remains from these Knossian assemblages in order to infer growing conditions, specifically crop water status from carbon isotope ($\delta^{13}C$) values, and potential manuring from nitrogen isotope ($\delta^{15}N$) values. In particular, we wish to compare crop growing conditions in the Neolithic and Late Bronze Age, and to shed new light on the nature and diversity of LM II agricultural strategies for the production of crops stored in an elite building.

Stable isotope analysis

Stable carbon isotopes

Plant $\delta^{13}C$ values reflect the water status of the plant during its growth period (e.g. Farquhar and Richards 1984). In C_3 plants (trees, legumes and all cereals reported in this study), differences in $\delta^{13}C$ values relate to the rate of passage of carbon dioxide (CO_2) through stomata, which is regulated according to water availability (Ehleringer *et al*. eds 1993; Farquhar *et al*. 1989). As a result, C_3 plant $\delta^{13}C$ values are strongly correlated with environmental factors such as precipitation, plant water status and relative humidity (Aguilera *et al*. 2008; Araus *et al*. 1997, 1999; Ferrio *et al*. 2005; Fiorentino *et al*. 2012; Flohr *et al*. 2011; Fraser *et al*. 2013; Masi *et al*. 2014; Riehl *et al*. 2014; Wallace *et al*. 2013, 2015).

Since plant $\delta^{13}C$ values depend on atmospheric CO_2 $\delta^{13}C$ values, which have decreased over the last 10,000 years (Francey *et al*. 1999; Indermühle *et al*. 1999), plant $\delta^{13}C$ values are routinely converted to $\Delta^{13}C$ values to allow comparison with modern plant values (Farquhar *et al*. 1982):

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

Generally, plants experiencing water stress have lower $\Delta^{13}C$ values, but absolute values depend on species-specific characteristics. In present-day experiments, $\Delta^{13}C$ values for two-row barley (*Hordeum vulgare* var. *distichon*) are about 1‰ higher, and values for six-row barley (*Hordeum vulgare* var. *hexastichon*) about 2‰ higher, than those of wheat grown under the same conditions (Anyia *et al*. 2007; Flohr *et al*. 2011;

Wallace *et al*. 2013). Comparison of *prehistoric* six-row barley and free-threshing wheat from a single year's harvest, preserved in a village-wide destruction horizon at Late Neolithic Hornstaad-Hörnle 1A, south-west Germany, however, suggests that in ancient varieties the offset between *six-row* barley and wheat could be closer to *c.* 1‰ (Styring *et al*. 2016b). Lentils and wheats grown in similar conditions in experimental control plots have similar $\Delta^{13}C$ values, although lentil $\Delta^{13}C$ values may be more sensitive to late season drought (Wallace *et al*. 2013).

Stable nitrogen isotopes

Processes favouring nitrogen (N) loss from soils result in a net increase in soil and plant $\delta^{15}N$ values. In arid and semi-arid environments (<400 mm rainfall per year), plant $\delta^{15}N$ values are negatively correlated with rainfall, as N is lost from the soil as ammonia (Hartman and Danin 2010). The presence of excess amounts of organic N, especially in the form of deliberately applied animal manure, has been shown to greatly increase crop $\delta^{15}N$ values in both controlled experiments and traditional farming systems (Bogaard *et al*. 2007, 2016; Bol *et al*. 2005; Fraser *et al*. 2011; Kanstrup *et al*. 2011, 2012). For pulses, atmospheric N fixation by *Rhizobium* bacteria typically results in $\delta^{15}N$ values that are close to that of N_2 in air, 0‰ (Virginia and Delwiche 1982). However, when soil N concentration is sufficiently high, direct N_2 fixation is inhibited and assimilation of soil N can be favoured (Andrews *et al*. 2011; Ledgard *et al*. 1996; Peoples *et al*. 2009; Vinther 1998). While experimentally-grown cereals have demonstrated $\delta^{15}N$ values of >3‰ with moderate (15-20t/ha) application of farmyard manure, and $\delta^{15}N$ values of >6‰ with higher applications (30-35t/ha), pulses show much smaller increases in $\delta^{15}N$ values (~2‰), and only under high or extremely high manure applications (>70 t/ha) (Treasure *et al*. 2015), a pattern also noted in traditionally managed pulse plots in Evvia, Greece (Fraser *et al*. 2011).

There is a high degree of natural variability in plant isotopic ratios: grains from a single ear vary up to 2.0‰ in $\delta^{15}N$ (Bogaard *et al*. 2007) and up to 0.7‰ in $\delta^{13}C$ (Heaton *et al*. 2009), with smaller within-pod variability found for pulses (Fraser *et al*. 2013; Treasure *et al*. 2015). This variability is reduced when multiple seeds are homogenized. For $\delta^{15}N$ values, homogenizing multiple batches of 10-15 cereal grains from the same field produces standard deviations ranging from 0.12 to 0.91‰ (Kanstrup *et al*. 2012; Nitsch *et al*. 2015), with manured fields tending to have higher variability (Kanstrup *et al*. 2012). The variability in $\delta^{13}C$ values is typically half that of $\delta^{15}N$ (Nitsch *et al*. 2015).

Materials

We analysed remains of carbonized cereal grains and pulse seeds from Evans' 1968 excavations of Neolithic strata below the Central Court (Evans 1968: 269), and LM II storage deposits in the Unexplored Mansion (Jones 1984; Popham 1984). Both of these assemblages resemble stored product concentrations.

The Neolithic material consists of three samples of free-threshing wheat grain (*Triticum aestivum/durum*) from Stratum X, now dated securely (by AMS-dating of free-threshing wheat grains) to the early 7th millennium cal BC (Douka *et al*. in press), and one sample of lentil (*Lens culinaris*) from the same context, all originally studied by Hans Helbaek. The wheat grain was stored in two parts, one labelled I and the other II; we infer that this labelling relates to a first and second shipment of the

grain material to Helbaek, mentioned in an unpublished report held in the archive of the British School at Athens (Sarpaki 2013).

The Late Bronze Age crop remains analysed here derive from Storeroom P of the Unexplored Mansion, which was destroyed by fire in LM II (Popham 1984). Crop remains were found in concentrations associated with their original storage jars, and each concentration was dominated by a particular cereal or pulse taxon (Jones 1984, 1992). Cereal species predominating in distinct concentrations included emmer (*Triticum dicoccum*) and hulled barley (*Hordeum vulgare*). The barley included twisted grains indicative of the six-row variety (*H. vulgare* var. *hexastichon*), but the additional presence of two-rowed barley (*H. vulgare* var. *distichon*) among the non-twisted grains could not be ruled out. Pulse species predominating in distinct concentrations included winged vetchling (*Lathyrus ochrus*) and Celtic bean (*Vicia faba*).

Three hulled barley concentrations (sample numbers 4, 5 and 6) were found close together and may represent a single stored product associated with Pot 75 (Jones 1984). Similarly, two concentrations each of emmer (samples 1 and 2) and Celtic bean (samples 9 and 10) could represent products that were originally stored together but their association is uncertain due to a lack of spatial information for the individual samples. The near complete absence of weeds from the crop stores suggests that they were products cleaned for consumption, although emmer concentration 1 contained significant amounts of chaff fragments, which may reflect storage in spikelet form, with grains enclosed by glumes. The evidence suggests that Storeroom P served as a larder for crops awaiting the final stages of food preparation. Since its storage capacity was insufficient to supply the long-term needs of the inhabitants of the Unexplored Mansion, bulk storage of staple goods presumably occurred elsewhere (Jones 1984).

Analytical methods

Samples were pre-screened for contamination from the burial environment using fourier transform infrared spectroscopy (FTIR). Visual inspection under a microscope showed no signs of surface soil contamination, and lack of contamination was confirmed by FTIR, following reference contamination comparisons for humic acids, carbonates and nitrates (Vaiglova *et al*. 2014b). Since chemical and mechanical degradation can remove seed/grain material and alter $\delta^{15}N$ ratios (Vaiglova *et al*. 2014b) these samples were not pre-treated.

Samples of 5 or 10 seeds/grains were homogenized in an agate mortar and pestle. The homogenized powders 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 normalization to the VPDB scale was obtained using four replicates each of IAEA-C6 and IAEA-C7, while for $\delta^{15}N$ the standards were USGS40 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 0.07‰, and 0.35‰ for $\delta^{15}N$. Details of the analytical conditions are reported in Tables S1-2. These calculations were performed using the statistical programming language R. (3.0.2). In calculating $\Delta^{13}C$ values, the $\delta^{13}C$ value of atmospheric CO_2 was estimated using reference tables from the

AIRCO2_LOESS system (Ferrio *et al*. 2005). The plant isotope results reported are corrected for the minor effect of charring on $\delta^{13}C$ (by subtracting 0.11‰) and $\delta^{15}N$ (by subtracting 0.31‰) (Nitsch *et al*. 2015), except where otherwise indicated.

Results

Full results of the stable carbon and nitrogen isotope analysis of seed samples from Knossos are reported in supplementary Table S3.

1. Neolithic material

$\Delta^{13}C$ values of the three free-threshing wheat samples range from 16.7 to 17.6‰, while the single lentil sample has a value of 17.4‰ (Figure 1). These values are similar to modern plants grown in moderately well watered conditions (Wallace *et al*. 2013). $\delta^{15}N$ values for the three free-threshing wheat samples range from 5.1 to 5.7‰. The variability observed in $\Delta^{13}C$ and $\delta^{15}N$ values for free-threshing wheat is consistent with a single growing condition (Bogaard *et al*. 2016; Nitsch *et al*. 2015). The single lentil sample has a $\delta^{15}N$ value of 1.5‰ (Figure 2). The lower $\delta^{15}N$ value of the lentil sample is typical of nitrogen-fixers, deriving N from atmospheric N_2 with a value of 0‰, but elevation above this value suggests intensive manuring (Fraser *et al*. 2011; Treasure *et al*. 2015). The much higher $\delta^{15}N$ values of the three free-threshing wheat samples reflect the assimilation of nitrogen with a higher $\delta^{15}N$ value, possibly originating from manure. These values are not as high as the most intensively manured cereals in modern experiments (Fraser *et al*. 2011) but are comparable to those observed in traditional manuring regimes of high labour-intensity, as in Asturias, Spain (Bogaard *et al*. 2016; Fraser *et al*. 2011). Similar $\delta^{15}N$ as well as $\Delta^{13}C$ values for free-threshing wheat grain samples were observed at Middle-Late Neolithic Kouphovouno, near Sparta (Vaiglova *et al*. 2014a), where free-threshing wheat appears to have been grown under more intensively manured conditions than hulled (probably two-row) barley.

2. Bronze Age material

$\Delta^{13}C$ values of pulses at the Unexplored Mansion range from 15.7 to 18.8‰, while cereal $\Delta^{13}C$ values are generally higher, ranging from 18 to 19.4‰ (Figures 1 and 3). It is striking that the Knossian Bronze Age emmer appears very well watered, while the barley is moderately to well watered (Figure 1). For $\delta^{15}N$, barley values tend to be higher than those of other species, ranging from 3.6 to 5.5‰. The three emmer samples from sample 1 have much lower $\delta^{15}N$ values, between 2.0 and 3.1‰, while the single emmer sample from sample 2 is higher, with a $\delta^{15}N$ value of 4.8‰, similar to the barley samples (Figure 3b). For pulses, the $\delta^{15}N$ values of winged vetchling are relatively low (ranging from 0.6 to 1.3‰) compared to those of Celtic bean (1.8 to 2.0‰), but both are elevated above 0‰ and consistent with intensive manuring (Fraser *et al*. 2011; Treasure *et al*. 2015).

For each species, most of the measured values may be subsamples of material from the same deposit (Figure 3b). For barley, subsamples come from sample 4 (n=4), sample 5 (n=4), sample 6a (n=1) and sample 6b (n=1). There are no differences in $\delta^{15}N$ or $\Delta^{13}C$ values among barley samples, all of which may derive from pot 75 (Jones 1984). The average $\delta^{15}N$ value of all barley samples is 4.8 ± 0.6‰, and for $\Delta^{13}C$ is 18.7 ± 0.5. This variability is consistent with all samples being grown in similar conditions (Bogaard *et al*. 2016; Nitsch *et al*. 2015). For emmer, the variability among the three subsamples from sample 1 (average $\delta^{15}N$: 2.7 ± 0.6‰,

average $\Delta^{13}C$: 18.9 ± 0.2‰) is also consistent with a single set of growing conditions, while the much higher $\delta^{15}N$ value of the single subsample from sample 2 (4.8‰) suggests that this crop was grown in soil with a higher $\delta^{15}N$ value, potentially due to organic matter in the form of animal manure. This contrast between the emmer in samples 1 and 2 coincides with a possible spatial separation within Storeroom P, sample 1 deriving from pot 54 and sample 2 from anywhere in the southwest part of the room (Jones 1984).

Turning to the pulses (Figure 3b), isotopic analysis of subsamples from concentrations of winged vetchling (sample 7, 6 subsamples) and Celtic bean (sample 9, 3 subsamples; sample 10, 3 subsamples) are also largely consistent with the hypothesis that each concentration derived from the same growing conditions. Assessment of variation in pulse seed $\delta^{13}C$ and $\delta^{15}N$ values (data from Fraser *et al*. 2011; Wallace *et al*. 2013) shows that experimentally grown pulse seed samples from the same treatment have similarly low variability, with an average standard deviation of 0.25‰ for $\delta^{15}N$ and 0.5‰ for $\delta^{13}C$.

Finally, variability was also assessed between twisted and straight grains of hulled barley, assumed to derive from the same, six-row hulled barley crop, in which each rachis node produces both straight (central) and twisted (lateral) grains. In order to test this assumption two subsamples of twisted grains and two of straight grains were analysed from each of the barley samples, 4 and 5. Figure 4 shows that, for each set of twisted grain values, the straight grain $\delta^{13}C$ and $\delta^{15}N$ values from the same sample lie within the 95% range. If the twisted and straight grains derived from isotopically different growing conditions (e.g. if the straight grains derived from two-row barley, growing in different conditions to six-row barley), larger differences would have been expected. These results are therefore consistent with Jones' original inference that six-row barley is represented (Jones 1984).

Discussion

Isotopic evidence for cereal cultivation practices

Estimates of modern annual precipitation around Knossos vary from 483mm (Hellenic National Meteorological Service, average for AD 1955-1996, http://www.hnms.gr/hnms/greek/climatology/climatology_region_diagrams_html?dr_city=Heraklion) to 589mm (Hijmans *et al*. 2005). Recent palaeoclimatic reconstruction of past annual precipitation across Europe suggests that Bronze Age rainfall in Crete did not differ greatly from recent conditions and was if anything higher (Mauri *et al*. 2015: Figure S3). Under these environmental conditions unmanured cereals would be expected to have values similar to those in temperate Europe (Bogaard et al. 2013; cf. Hartman and Danin 2010; Styring et al. 2016a). Aridity is therefore unlikely to be the primary driver of elevated soil $\delta^{15}N$ at Knossos; lower $\delta^{15}N$ ratios, closer to zero, have been observed for archaeological cereals in other parts of the Aegean with similar rainfall levels (Kouphovouno: Vaiglova *et al*. 2014a; Archontiko: Nitsch *et al*. 2017; see Figure 2).

Elevated $\delta^{15}N$ values of Neolithic cereals and pulses are consistent with intensive levels of manuring, and suggest manuring/middening as a component of high-labour

investment in arable land at Aceramic Neolithic Knossos. Comparably high $\delta^{15}N$ values in Neolithic free-threshing wheat have been noted at Middle-Late Neolithic Kouphovouno near Sparta (Vaiglova *et al*. 2014a) as well as for cereals elsewhere in Neolithic Europe (Bogaard *et al*. 2013; Styring *et al*. 2016b), consistent with an intensive cultivation strategy. At 6th millennium BC Kouphovouno and at late fourth-third millennium BC Sipplingen, on Lake Constance, free-threshing wheat grew in significantly more ^{15}N-enriched conditions than barley (Styring et al. 2016b; Vaiglova et al. 2014a). Further work on the Neolithic crop assemblage from Knossos is needed to explore inter- as well as intra-crop variation in growing conditions. It is clear, however, that factors such as cultural preference and crop variety or landrace could influence strategic manuring of particular crops; in the northern Aegean during the Bronze Age, hulled barley rather than free-threshing wheat was manured preferentially (Figure 2; Nitsch *et al*. 2017).

Intensive 'horticultural' production of cereals and pulses featuring manual tillage would tend to yield only marginal surpluses, with labour as the key limiting factor (Halstead 2014: 47, 53, 248). The desire for more surplus may have driven political expansion (Whitelaw this volume), and ultimately established the system of extensive production under palatial control that is reflected in Linear B texts (Halstead 1992b, 1999a, 1999b; Killen 1993). The cost of maintaining specialized draught animals suggests that extensive cultivation was likely limited to areas under palatial control managed for the production of relatively stress-tolerant cereals, and used to support a system of elites and craft specialists (Halstead 1999a, 1999b, 2014; Killen 1993, 1998).

The $\delta^{15}N$ values of Late Bronze Age cereals from the Unexplored Mansion are mostly lower than those of Neolithic free-threshing wheat at Knossos (and Kouphovouno); the $\delta^{15}N$ values of the Bronze Age emmer wheat are significantly lower than those of Knossian Neolithic free-threshing wheat, while $\Delta^{13}C$ values are significantly higher (Pillai's Trace = 0.88, F = 14.5, df = (4,5), p = 0.015). Of all the cereals recovered from Storeroom P at the Unexplored Mansion, emmer is most likely to correspond to the cereal type in whose production palatial elites at Knossos intervened according to the Linear B evidence (Halstead 1995c). Other LBA cereal $\delta^{15}N$ values, especially of barley, are consistent with moderate manuring. The (six-row) hulled barley $\delta^{15}N$ values from Knossos are notably higher than those for (two-row) hulled barley at Neolithic Kouphovouno; on the other hand, the Knossos barley $\delta^{15}N$ values are moderate to low compared with (mixed two- and six-row) hulled barley values from Bronze Age sites in the northern Aegean (Figure 2; Nitsch *et al*. 2017). Moderate manuring of the Knossos barley is inconsistent with radically extensive, low-labour input cultivation, but this is in agreement with the Linear B evidence, which lacks indications of elite involvement in production of the cereal most plausibly identified as barley (Halstead 1995c).

The stable carbon isotope data for the Knossos cereals add a further dimension to the discussion of crop growing conditions and land management. The area of Knossos could have sustained rainfed cultivation, although local variation in topography and soil type would have meant some areas would be more prone to drought than others (Halstead 2008). As in modern Crete, completing tillage and sowing as early as possible would allow crops to ripen before the summer drought (Halstead 2014: 25; Isaakidou 2008).

$\Delta^{13}C$ values of the Neolithic wheat samples are consistent with moderately to well watered conditions, similar to results from elsewhere in the Aegean (Figure 1; Nitsch *et al*. 2017; Vaiglova *et al*. 2014a; Wallace *et al*. 2015). The relatively high $\Delta^{13}C$ values of barley and especially emmer from the Unexplored Mansion are striking, given that rainfall around Knossos, though variable, would not necessarily be higher than in the northern Aegean. The implication is that these cereals had *privileged* access to very well watered conditions. The $\Delta^{13}C$ values could in theory reflect irrigation (cf. Müller Celka *et al*. 2014); the fact that Late Bronze Age emmer appears better watered than earlier ripening, more drought-tolerant barley (Figure 1) is at least consistent with a deliberate water management strategy. Comparably high $\Delta^{13}C$ values were determined in wheat and barley samples from Bronze Age Abu Salabikh in southern Iraq, where artificial watering is obligatory (Wallace *et al*. 2015; Figure 2).

In combination, the nitrogen and carbon isotope data for cereals from Knossos suggest that the Neolithic wheat was more intensively manured than the Bronze Age cereals, which instead had a particularly favourable water status. As emmer is considered the most likely candidate for direct palatial production in the Linear B texts (Halstead 1995c), it is notable that its growing conditions reflect mostly low to no manure inputs but very high water status relative to that inferred from isotopic results from all Bronze Age wheat analysed from the northern Aegean (Nitsch *et al*. 2017). Strategic sowing of wheat in well watered soils is a relatively low-input way of ensuring adequate yields in a potentially extensive system (cf. Wallace *et al*. 2015).

Isotopic evidence for pulse cultivation practices

Intensive manuring of pulses has been observed in traditional agricultural regimes in Evvia, Greece (Jones *et al*. 1999) and Asturias, Spain (Charles *et al*. 2002). Manuring rates in Evvia were particularly intensive, resulting in the formation of 'dung-soil' (*koprokhoma*) (Jones *et al*. 1999). It has been shown experimentally that extremely high rates of manuring (>70t/ha) can increase broad bean $\delta^{15}N$ values by up to 2‰ (Treasure *et al*. 2015), while values in modern Evvia gardens were up to 4‰ or higher (Figure 3c). $\delta^{15}N$ values of the very heavily manured pulses are significantly higher (+1.9‰) than those of unmanured pulses in the Evvia study ($t(13)4.476$, $p = 0.001$; Figure 3c).

Late Bronze Age pulses from the Unexplored Mansion have higher $\delta^{15}N$ values than unmanured pulses, as does the single lentil sample from Neolithic Knossos, and are comparable to heavily manured examples (Fraser *et al*. 2011; Treasure *et al*. 2015). In pre-mechanised Greek farming, pulses required a large amount of labour to harvest (by uprooting rather than cutting), and were most often grown for household consumption, in part also due to the difficulty of transporting them without losing seeds from drying pods (Halstead 2014: 70, 78-9, 103; Jones *et al*. 1999). Pulses are not referenced in Linear B texts (Halstead 1992), but their abundance at southern Aegean sites (Halstead 1994: 204-5, table 1; Livarda and Kotzamani 2014; Sarpaki 1992), including the elite Unexplored Mansion and the palace itself (Evans 1928: 54, 1935: 595, 621), suggests that they were an important component of human diet across the social spectrum. They may also have served an important agricultural role in maintaining soil fertility in rotation with other crops (Sarpaki 1992), though in the

Unexplored Mansion assemblage it is clear that the heavily manured pulses could not have been grown together, or in rotation with, the moderately to unmanured cereals (Figure 2). It is also apparent that winged vetchling was less intensively manured than Celtic bean, perhaps reflecting differential status and/or response to manuring.

$\Delta^{13}C$ values of the Knossian pulse samples are consistent with moderately to well watered conditions, similar to results from elsewhere in the Aegean (Figure 1; Nitsch *et al*. in press; Vaiglova *et al*. 2014a; Wallace *et al*. 2015). In comparison with modern irrigated pulses in Evvia, the $\Delta^{13}C$ values of the Unexplored Mansion pulse crops suggest that any artificial watering was variable, which would be consistent with hand-watering of pulses (cf. Wallace *et al*. 2013). Pulse crops in the Bronze Age northern Aegean were similarly variable in their water status but often better watered than the pulses at the Unexplored Mansion, in contrast to the cereals (Figure 1). Modern experiments have shown that well watered pulses tend to have higher $\Delta^{13}C$ values than wheat grown under the same conditions (Wallace *et al*. 2013). The fact that the Unexplored Mansion pulses tend to have *lower* $\Delta^{13}C$ values than the emmer wheat, and also appear to be more intensively manured, therefore suggests that these crops were grown under *different* regimes. While the Neolithic cereals and lentil sample from Knossos, like the northern Aegean pulses and cereals, were grown in *comparable* conditions in terms of both carbon and nitrogen isotope values, and so were potentially grown together or in rotation, the Unexplored Mansion pulses were likely grown *separately* to the wheat, and perhaps also the barley.

Variability in crop growing conditions

Models of agricultural catchment area and settlement size suggest that by the Late Minoan I period at most 60% of Knossos' population could have been sustained on food grown within a two-hour walk of the settlement (Whitelaw this volume). The implication is that a significant amount of food would have been brought into the city from further away. The storage vessels of the Unexplored Mansion are characterized by low storage capacity but were highly transportable (Christakis 2008: 76). Characterisations of possible supply systems range from palatially controlled redistribution, to market supply or provisioning by individual family rural estates (Bennet and Halstead 2014; Whitelaw this volume).

Large-scale redistribution would be expected to mix harvests from different fields, different growing conditions, and possibly different isotope ratios. The natural variability in $\delta^{15}N$ values for individual cereal grains grown together under the same conditions (Bogaard *et al*. 2007) is low compared to the potential variation due to differences in manuring: measurements of 10 homogenized grains from the same field vary by ± 0.12 to 0.91‰ (1 standard deviation, Kanstrup *et al*. 2012; Nitsch *et al*. 2015). Halving the batch size (Nseeds = 5) increases the expected variability by a factor of $\sqrt{2}$ (Nitsch *et al*. 2015). The measured standard deviations in $\delta^{15}N$ values for three to four different batches of five barley grains from samples 4 and 5 and ten grains from sample 1 (ranging from 0.41 to 0.63‰) from the Unexplored Mansion are consistent with random variability under the same or similar growing conditions. This supports the hypothesis that the grains in these samples were grown, processed, transported and stored as a single unit. On the other hand, a simulation of two equal mixtures of cereal grains with different $\delta^{15}N$ values illustrates that, with the amount of material available for measurement here, it would be difficult to detect *slightly* greater

variation due to a combination of growing conditions (Figure 5). Nevertheless, for mixtures where the difference in isotope ratios is 5‰ or greater, the range of simulated standard deviations (for four measurements of either five- or ten- grain homogenized aliquots) is generally larger than the standard deviations actually measured. Applying a similar simulation to the pulse samples (Figure 6) suggests that concentrations derive from relatively homogenous growing conditions, a possible exception being sample 10 (Celtic bean), which has more highly variable $\delta^{13}C$ values, suggesting a mixture of growing conditions with less similar $\delta^{13}C$ values. The same simulation approach to the Neolithic free-threshing wheat $\delta^{15}N$ values suggests that these also derived from relatively homogenous growing conditions (Figure 7).

In sum, while the relative homogeneity of the isotope results within individual concentrations is consistent with the hypothesis that each of the crops subsampled from the Unexplored Mansion was grown under the same set of conditions and potentially derive from the same field, the possibility remains that that the grains measured represent mixtures of crops grown under similar conditions. Nevertheless, our results suggest that it is *unlikely* that the Unexplored Mansion cereal and pulse stores derive from large-scale redistribution involving considerable variation in growing conditions and land use history.

Conclusions

Agriculture was the economic basis of Aegean Bronze Age urbanism, featuring 'agro-towns' with a majority of the population directly engaged in crop production (e.g. Whitelaw this volume). Isotopic measurements of Bronze Age crops from the Unexplored Mansion at Knossos suggest distinctive agricultural strategies for the cereals and pulses. The emmer wheat and hulled six-row barley were grown under conditions of low to moderate manuring and good water supply. The pulses were intensively manured and variably watered. Pulse cultivation strategies at Knossos resemble those of recent small-scale cultivators in Evvia (Figure 3c-d), and are comparable to those of the Bronze Age northern Aegean (Figures 1-2; Nitsch *et al*. 2017). These intensive strategies for pulses provide a clear contrast with extensive cereal cultivation recorded in Linear B texts. Whether or not the Unexplored Mansion cereals represent extensive, palace-mediated production is ambiguous: while they appear less intensively manured than the few Neolithic cereal samples from Knossos analysed here, or indeed some north Aegean Bronze Age cereal assemblages (Nitsch *et al*. in press), their high water status could reflect privileged access to well watered land in the Knossos valley (cf. Whitelaw 2011) or elsewhere. In any case, it is very *unlikely* that the cereals and pulses in the storeroom of the Unexplored Mansion derived from an *integrated* system of cereal-pulse rotation. Perhaps this elite household was supported by intensively cultivated pulses grown on 'allotment' plots within or on the margins of the urban sprawl of Late Bronze Age Knossos, while the cereals were grown in the valley or other well watered areas. Moreover, the relative homogeneity of the isotope ratios *within* individual storage deposits of the Unexplored Mansion suggests that crops from specific land holdings could well be represented, and excludes mixtures of crops from wide-ranging growing conditions and land use histories, as might be expected if they derived from large-scale palatial redistribution.

A model of extensification based on Linear B texts would suggest a fundamental shift in agricultural practices underlying the urban expansion of Knossos in the Bronze Age. Yet isotopic comparison of Neolithic and Bronze Age crops from Knossos, and comparisons with emerging Neolithic-Bronze Age production elsewhere in Greece, suggests a more complex scenario in which an elite Late Bronze Age household was provisioned at least in part through *intensive* management of pulse crops that are unaccounted for in Linear B texts. Nevertheless, ecological contrasts between cereal and pulse growing regimes in this elite Late Bronze Age household suggest an 'unravelling' of the intensive subsistence-oriented farming that had emerged in the Neolithic (Halstead 1981, 2000), as reflected in emerging crop isotope results from Kouphovouno (Vaiglova *et al.* 2014a) and now Knossos, and persisted in diversified form in Bronze Age northern Greece (Nitsch *et al.* 2017). A disconnect between Late Bronze Age cereal and pulse growing strategies at Knossos would also be consistent with a special status of cereal growing, and perhaps even restricted rights to grow cereals and/or have access to well watered land in the Final Palatial period (Eleni Hatzaki pers. comm.). It is worth noting in this connection that the far more modest Late Bronze Age household recently excavated on the Lower Gypsades hill (Morgan 2015: 34-5; http://www.bsa.ac.uk/index.php/research/projects-cat/261-knossos-gypsades-excavations), south of the palace at Knossos, has yielded exclusive evidence for *pulse* crop storage, perhaps reflecting the importance of intensive pulse cultivation across the social spectrum of the urban landscape.

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Figure captions

Figure 1. $\Delta^{13}C$ values of wheats, barley and cereals at Neolithic and Bronze Age Aegean sites. Data from Kouphovouno reported by Vaiglova *et al*. (2014). Data from Archontiko and Thessaloniki Toumba are from Nitsch *et al*. (2017). Dashed horizontal lines represent "well watered" (upper) and "moderately watered" (lower) thresholds based on studies of modern crops in different agronomic conditions (Wallace *et al*. 2013). The reference lines for barley assume a mixture of barleys comparable to modern two- and six-row varieties.

Figure 2. $\delta^{15}N$ values of wheats, barley and cereals at Neolithic and Bronze Age Aegean sites. Data from Kouphovouno reported by Vaiglova *et al*. (2014). Data from Archontiko and Thessaloniki Toumba are from Nitsch *et al*. (2017).

Figure 3. A) $\Delta^{13}C$ and $\delta^{15}N$ values from crops from the Bronze Age (Late Minoan II) destruction of storeroom P of the Unexplored Mansion at Knossos, showing (B) subsamples grouped by associated pot (as described by Jones 1984). C) $\Delta^{13}C$ and $\delta^{15}N$ values from modern pulses grown under a variety of manuring and irrigation regimes in Evvia, Greece ($\Delta^{13}C$ originally reported by Wallace *et al*. 2013; $\delta^{15}N$ originally reported in Fraser *et al*. 2011). D) $\Delta^{13}C$ and $\delta^{15}N$ values of pulses from storeroom P at Knossos compared with the 50% confidence interval ellipse of modern pulse values from Evvia.

Figure 4. Comparison of twisted and straight barley grains from the same deposit. For each pair of twisted grain samples, the lines show the estimated 67% (solid) and 95% (dashed) range of expected $\Delta^{13}C$ and $\delta^{15}N$ values for the population of seeds grown under similar growing conditions, based on a 1sigma range of ± 0.5‰ for $\Delta^{13}C$ and ± 1.0 for $\delta^{15}N$. For each pair of twisted grains, the values of the two straight grain samples from the same deposit lie within the 95% range. If the twisted and straight grains derived from isotopically different growing conditions, larger differences would have been detected.

Figure 5. Probability density distribution of simulated standard deviations in $\delta^{15}N$ values of four measurements of homogenized aliquots of 5 grains (A) or 10 grains (B) based on 1000 simulated 50/50 mixture of two different isotope ratios (differences ranging from 0 to 6‰). Also shown are the actual measured $\delta^{15}N$ standard deviation of three to four measurements of grains from samples 4, 5 and 1.

Figure 6. Probability density distribution of simulated standard deviations of four $\delta^{15}N$ measurements (A) and four $\delta^{13}C$ measurements (B) of homogenized aliquots of 5 pulse seeds based on 1000 simulated 50/50 mixture of two different isotope ratios (differences ranging from 0 to 6‰). Also shown are the actual measured standard deviations of three to seven measurements of pulse seeds from samples 7, 9 and 10

Figure 7. Probability density distribution of simulated standard deviations in $\delta^{15}N$ values of three measurements of homogenized aliquots of 10 grains based on 1000 simulated 50/50 mixture of two different isotope ratios (differences ranging from 0 to 6‰). Also shown is the actual measured $\delta^{15}N$ standard deviation of three measurements of Neolithic free-threshing wheat grains.