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A House on the Hill: Late Bronze Age Pulses and Isotope Agroecology at Knossos Gypsades, Crete

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ABSTRACT

New archaeobotanical and isotopic analyses from the lower Gypsades hill, Knossos provide a detailed snapshot of agricultural practices associated with a modest household during the Late Bronze Age, a few hundred metres to the south of the palace. The discovery of *in situ* charred concentrations of five pulse crops in a storage room enabled archaeobotanical and stable carbon and nitrogen isotopic investigations of the household's agricultural practices at the time of the fire that destroyed the building. This event took place around the time of or soon after the destruction(s) of the palace. In conjunction with previous archaeobotanical and isotopic investigations at Knossos, particularly those of the Final Palatial Minoan Unexplored Mansion, the archaeobotany and isotope ecology of the Gypsades household illustrate its strategies of resilience under shifting political circumstances and climatic conditions.

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Introduction

The archaeology of prehistoric Knossos provides a unique opportunity to trace *in situ* change and continuity in agriculture as the settlement developed from a Neolithic village to a Bronze Age city (e.g. Cadogan et al. 2007; Styring et al. 2022; Whitelaw, Bredaki, and Vasilakis 2019). The agroecology of Knossos thus offers rare insights into land-use practices that enabled its long-term sustainability (e.g. Bogaard 2025). The activities of individual households at Knossos are an ideal frame of reference in this context (Hatzaki 2011, 2020), but detailed archaeobotanical investigations are needed to assess agricultural practices at this social scale. Here we present new archaeobotanical results from recent excavations on the lower Gypsades hill, a few hundred metres to the south of the Bronze Age palace at Knossos (Figure 1a). The new data from Knossos Gypsades provide a 'snapshot' of agricultural practice relating to a modest household of the Late Bronze Age (Figure 1b), during its occupation in LM IIIB Early, at the time of the palace's destruction(s) or soon after (Hatzaki et al. In press; Driessen and Mouthuy 2022; Hatzaki and Kotsonas 2020; Whitelaw 2022). Here we combine the results of primary archaeobotanical analysis with stable carbon and nitrogen isotope determinations of charred crop seeds to reconstruct the storage and cultivation practices of this household at the time of the house's final destruction. Through comparison with previous archaeobotanical investigations at Bronze Age Knossos (e.g. Jones 1984, 1992), including stable isotope analysis of preserved crops (Nitsch et al. 2019), our results provide new insights into the productive and social landscape of the city through a tumultuous period.

Site Background

Excavations at Knossos on the lower Gypsades hill in 2014–2015 uncovered most of a Late Bronze Age house (Building 1), a two-storey structure with a ground floor measuring *c.* 160 m^2 (Figure 1b) (see Hatzaki et al. In press, for the excavation results summarised here). In its size, layout and internal features, the building fits within the range of Late Bronze Age houses at Knossos, albeit at the modest end of the scale (Hatzaki et al. In press). Within Building 1, a large ground floor room (Space 106, *c.* 6 × 4 m, Figure 1b) was destroyed by fire in Late Minoan III, most likely during the ceramic phase LM IIIB Early, ending the use-life of the house in the early Post-Palatial period. Visible concentrations of seeds charred *in situ* by this burning event across the western end of Space 106 have lent the building its name, 'House of the Charred Seeds' (HoCS) (Figure 1b). The seeds in question, detailed further below, all belong to the botanical legume family and specifically to seed crops

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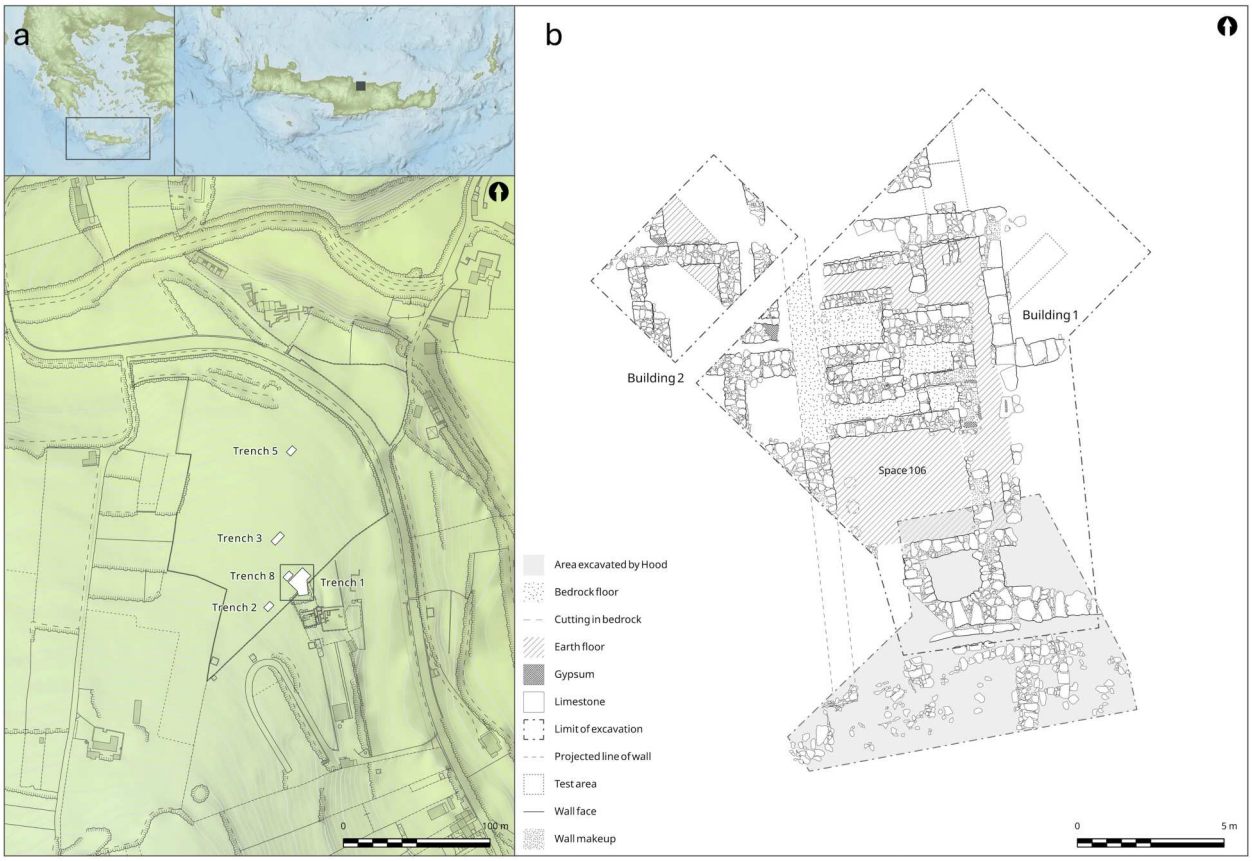

Figure 1. Maps of Knossos Gypsades: a. location of Knossos Gypsades excavations, showing trenches; b. plan of the Trench 1 area at Knossos Gypsades, including Building 1 ('The House of the Charred Seeds', HoCS) (after Hatzaki et al. In press).

collectively known as 'pulses' when stored in dried form, as here. Radiocarbon dates on two individual pulse seeds from one of the concentrations align with expectations; Bayesian modelling of the LM IIIB Early ceramic phase using these two dates, alongside dates for other ceramic phases in the excavated Gypsades sequence, indicates a *Boundary* Start date between 1456 and 1261 cal BC (95.4% confidence interval), and a *Boundary* End date between 1382 and 1177 cal BC (95.4% confidence interval) (Hatzaki et al. In press).

Previous archaeobotanical work in Bronze Age Crete including Knossos has been summarised elsewhere (Henkel and Margaritis 2024; Livarda and Kotzamani 2013). Given the pulse concentrations from the Gypsades HoCS presented in this paper, and the timeframe, the most relevant previous work at Knossos is that by Glynis Jones on the Minoan Unexplored Mansion (MUM) archaeobotanical assemblage (Jones 1984). In storeroom P of the elite MUM, which burned during the LM II ceramic phase of the Final Palatial period (Popham 1984), concentrations of multiple cereal and pulse crops reflect pantry-scale storage of cleaned crops processed for consumption (Jones 1984).

The aim of our study is to present evidence for crop storage in the HoCS on the lower Gypsades hill, together with stable carbon and nitrogen isotope measurements of its pulse seed concentrations. Previous stable carbon and nitrogen isotope analysis of the MUM stored crops (Nitsch et al. 2019) provides a key comparison with isotopic results presented here. This comparison enables us to consider pulse production at Knossos in the Final Palatial (MUM) and subsequently in the early Post-Palatial period (HoCS) at the site, as well as under elite (MUM) versus non-elite (HoCS) circumstances. Continuity of farming practice through time and between these social settings would offer evidence of strategies that proved resilient to changing circumstances, including aridification (Finné et al. 2017; 2019; Kaniewski et al. 2013; Manning et al. 2023) and palatial destruction(s) (Hatzaki et al. In press; Driessen and Mouthuy 2022; Hatzaki and Kotsonas 2020; Whitelaw 2022).

Stable Isotope Analysis

The ratio of the stable isotopes of carbon (^{12}C and ^{13}C) in plant tissues reflects the water status of the plant during growth (Ehleringer, Hall, and Farquhar 1993; Farquhar, Ehleringer, and Hubick 1989). Differences in the $\delta^{13}C$ values of C_3 plants (including all of the plant taxa reported in this study) are related to the movement of carbon dioxide through stomata. This

movement is regulated depending on the plant's water availability, with water-deficient plants closing stomata to prevent water loss. Environmental factors such as plant water status, precipitation and relative humidity all impact $\delta^{13}C$ values.

To allow comparison with modern data, archaeological plant $\delta^{13}C$ values are routinely converted to carbon discrimination ($\Delta^{13}C$) values. This accounts for change in the atmospheric $\delta^{13}C$ value over time (Farquhar, O'Leary, and Berry 1982, 1989; Ferrio et al. 2005). Plants with low $\Delta^{13}C$ values tend to indicate water stress, while higher values reflect optimal water status (Wallace et al. 2013).

Modern studies have provided guidelines as to the $\Delta^{13}C$ values of crops grown under different water availability regimes (Wallace et al. 2013). Experiments have shown that there are species-specific differences in $\Delta^{13}C$ values among cereals, barley tending to be 1–2 ‰ higher than wheat grown under the same conditions (Anyia et al. 2007; Flohr, Müldner, and Jenkins 2011; Wallace et al. 2013). Experiments on pulse species have focused on lentil and broad bean. Such studies have shown that lentil, when grown under well-watered conditions, tends to have $\Delta^{13}C$ values similar or higher than wheat grown under the same conditions, while in water-stressed conditions lentil's $\Delta^{13}C$ values tend to be lower than those of wheat (Wallace et al. 2013). Experiments with broad beans have indicated that there is large variation between individual seed values when cultivated under the same conditions (>3 ‰) (Treasure, Gröcke, and Lester 2024).

Stable nitrogen isotope ($\delta^{15}N$) values are influenced by a range of environmental conditions, including aridity, salinity and seasonal wetting and drying, as well as anthropogenic manuring of crops. $\delta^{15}N$ values can be used to investigate the anthropogenic addition of manure to fields; modern studies show that the addition of animal manure increases cereal crop $\delta^{15}N$ values (>3 ‰) (Bogaard et al. 2013; Fraser et al. 2011). Pulse crops can fix atmospheric N via *Rhizobium* bacteria, resulting in lower $\delta^{15}N$ values (close to 0 ‰) than non-nitrogen fixing plants such as cereals. $\delta^{15}N$ values of pulses can be elevated via the addition of manure to the soil, but these increases are relatively modest (>1.5 −2 ‰) compared with those in cereals and are observed only under very intensive manuring levels (Fraser et al. 2011; Treasure, Church, and Gröcke 2015, 2024).

The isotopic ratios of plants also vary naturally. The inherent variability of cereals and pulse seed $\delta^{13}C$ (or $\Delta^{13}C$) and $\delta^{15}N$ values has motivated researchers to homogenise multiple seeds to measure an average of those seeds. Modern research provides an understanding of the natural variability within single fields, homogenised batches of cereal grain from the same field having standard deviations for $\delta^{15}N$ values from ±0.12 to ±0.91 ‰, with $\delta^{13}C$ typically half that (Kanstrup et al. 2012; Nitsch, Charles, and Bogaard 2015). The variability of $\delta^{15}N$ values tends to increase with intensity of manuring (Treasure, Church, and Gröcke 2015, 2024). For pulse species, research has indicated that the natural variability of bulk isotope samples of pulses (e.g. broad bean) from a single field is reflected in a $\delta^{15}N$ standard deviation of ±0.3 to ±1.6 ‰, depending on the intensity of manuring (Fraser et al. 2011). The standard deviation of $\delta^{13}C$ values of bulk isotope samples of pulses (e.g. lentil) from a single field range from ±0.75 to ±1.5 ‰ (Wallace et al. 2013). The variability in $\delta^{15}N$ values of single pulse seeds grown in the same field also reflects manuring level, with research showing that unmanured broad beans have a standard deviation of ±0.4 ‰ compared to ±1.45 ‰ in intensively manured beans (Treasure, Gröcke, and Lester 2024). Single-seed analysis of broad beans shows variability in $\delta^{13}C$ values within single fields ranging from ±0.1 to ±1.48 ‰, while intensively manured fields tend to exhibit higher variability (Treasure, Gröcke, and Lester 2024).

Methods

Sampling

During the 2014–2015 excavation seasons at Knossos Gypsades, a bulk sediment sample was taken for flotation from every excavation unit. Where available, at least 30 litres of sediment were processed from each unit, while smaller units were processed in their entirety. The flotation machine was based on the Siraf design (French 1971; Williams 1973). The light fraction was retained in a chiffon with a mesh aperture of <0.2 microns and the heavy residue in a scientific mesh with an aperture of 1 mm. During excavation of Space 106 in the 'House of the Charred Seeds' (HoCS), visible concentrations of different pulse species were observed in the field. The densest concentrations consisted of pure charred seeds with no sediment matrix and were 100% sampled on-site, without flotation. This dual recovery procedure (routine bulk sampling and flotation of excavation units, plus direct sampling of visible seed concentrations) was implemented for two reasons. Firstly, direct sampling of visible concentrations allowed the excavation team to monitor variation in the composition of seed deposits as an aid to the designation of these units as distinct stratigraphic deposits, particularly in cases where the properties of surrounding sediment were otherwise very similar. Multiple samples were sometimes taken within the same excavation unit in Space 106, to maximise the likelihood of capturing subtle spatial variation in botanical composition. Secondly, it was

observed that during the flotation process some pulse species (e.g. Celtic bean) were very fragile and prone to fragmentation; direct sampling of pure pulse seed concentrations, without flotation, maximised the total amount of intact seeds recovered. Where both hand-collection and flotation were used to recover seeds from the same excavation unit, hand-picked seeds were later re-amalgamated with their 'parent' sample.

Processing and Further Sample Selection

Of the 162 samples taken from Space 106 of the HoCS during excavation in 2014-2015, 88 samples were selected for full analysis based on archaeological prioritisation during excavation (that is, contextual integrity as gauged, for example, through on-site ceramic processing, signs of *in situ* burning etc.) and/or archaeobotanical richness criteria. Samples were initially sub-sampled down to *c.* 30 ml of material using a riffle box (cf. Van der Veen and Fieller 1982). This subsample was then split further into 4, 2, 1, and 0.3 mm fractions using stacked geological sieves before scanning and identification. Full analysis entailed sorting of sufficient additional subsamples of the coarse (>1 mm) flot to achieve *c.* 400–500 identified items (where possible), and thus to enhance the accuracy and precision with which the sample could be taken to represent the deposit sampled (Van der Veen and Fieller 1982). In addition, at least 1/8 of the fine flot (<1 mm, >0.3 mm) was sorted for each of the selected samples; very little material was present in the fine flots.

Botanical identifications were made using a Kyowa low-power (x7-x45) incident light microscope. The quantification of plant items was achieved using the minimum number of individuals (MNI) principle, enabling a standardised count of fragmented plant parts. The MNI is calculated by counting identifiable diagnostic and non-repeating plant parts (i.e. cereal grain apical and embryo ends, glume bases and rachis internodes from cereal chaff, pulse seed radicles) to ensure that fragmented plant parts are not counted more than once (Jones 1991). This approach was applied to the quantification of pulse seeds, such that two separated cotyledons were counted as one whole seed. Where pulses were more fragmented, the minimum number of seeds was calculated by visually estimating the number of pulse fragments required to make up one whole seed.

The 88 samples selected contained 10 or more pulse remains identified to the species level (see Supp. data 1 for a list of samples included in this study). For the purposes of exploratory analysis, all samples are shown separately rather than amalgamated into concentrations, since part of our aim here is precisely to delineate separate concentrations of pulse crops as 'behavioural events' (Jones 1991).

Stable Carbon and Nitrogen Isotope Analysis

A combination of bulk and single-seed samples from the HoCS was selected for isotopic analysis, since these provide complementary information on variability in isotope values. At least two bulk samples consisting of 10 seeds each were taken from concentrations of each of five pulse species identified in the HoCS assemblage: Celtic bean, grass pea, bitter vetch, winged vetchling and lentil. Additionally, 10 single seeds were analysed isotopically from at least one excavation unit of each species concentration. In the case of grass pea, multiple spatially distinct concentrations were encountered in the HoCS. To assess whether such concentrations derived from the same growing conditions, additional grass pea samples were selected to represent the two spatially separate concentrations, one around feature F.1027 and the other to the southeast (Figure 1b). In total, 12 bulk samples and 62 single-seed samples were analysed isotopically (see Supp. data 2). For the single-seed samples, all species except lentil are represented by ten individual seeds from a single excavation unit. For lentil, due to limited availability of seeds in selected units, seeds were subsequently chosen from supplementary units to reach the target minimum 10 single seed samples per species.

Pulse seeds were selected for isotopic analysis based on preservation, the selected items falling within the optimal charring window defined by Nitsch, Charles, and Bogaard (2015) based on experimentally charred modern seeds heated to temperatures from 215 to 260 °C. Within this range of conditions, minor and predictable changes in $\delta^{13}C$ and $\delta^{15}N$ values due to the process of charring can be accounted for with an offset ($\delta^{13}C$: –0.11 ‰, $\delta^{15}N$: –0.31 ‰). The archaeobotanical items selected represent a small proportion of the total pulse items retrieved during excavation (~1% of identified pulse seeds) and were all photographed prior to analysis. Photographs of the items were taken on a Nikon SMZ25 microscope with Pixelink camera with NIS-Elements software and are available online (see Stroud 2026).

A percentage of the samples was pre-screened for contamination using Fourier transform-infrared spectroscopy (FT-IR) with ATIR attachment at the Research Laboratory of Archaeology and the History of Art, University of Oxford. Comparison with reference contamination spectra from Vaiglova et al. (2014) showed the presence of carbonate contamination (see Supp. data 3). The samples were pre-treated using an acid pre-treatment (0.5 M HCL for 30 mins at 80 °C). Samples were rinsed three times or until a neutral pH was reached. The samples were then freeze-dried. The samples were homogenised into powder and weighed into capsules for analysis on a SerCon EA-GSL mass spectrometer. $\delta^{13}C$ and

δ^{15}N values were obtained simultaneously and an internal alanine standard was used to calculate raw isotopic values and to correct for drift. To normalise the δ^{13}C and δ^{15}N values to the international VPDB and AIR scales, respectively, samples of an internal standard of alanine (which had not been used to drift correct) and SEAL collagen were used. Details of the expected and obtained values of the standards can be found in Table 1. A check standard of PEA protein and repeated duplicates of COW collagen were used to calculate accuracy, precision and overall uncertainty, as per Szpak, Metcalfe, and Macdonald (2017). These results can be found in Table 2. The overall uncertainty was also calculated as per Kragten (1994) to allow comparison with the uncertainty of the stable isotope measurements on pulse seed samples from MUM (Nitsch et al. 2019), which is similar (Table 2).

To allow comparison of δ^{13}C values from different time periods and with modern experiments, the δ^{13}C values were converted into Δ^{13}C values as follows:

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

The $\delta^{13}C_{air}$ value (the δ^{13}C value of atmospheric CO_2) was calculated from the reference tables in the AIR-CO2_LOESS system (Ferrio et al. 2005, 2024; Francey et al. 1999; Indermühle et al. 1999; Leuenberger, Siegenthaler, and Langway 1992; NOAA ESRL Carbon Cycle Cooperative Global Air Sampling Network 2015). The date used for the HoCS samples was 1456–1177 BC (–6.48), while for the Minoan Unexplored Mansion the date was 1470–1410 BC (–6.46 value). The isotopic values were also corrected for the effect of charring by subtracting 0.11 ‰ from the δ^{13}C values and 0.31 ‰ the δ^{15}N values as per Nitsch, Charles, and Bogaard (2015). All statistical analysis and graphs were conducted in R (version 4.4.1) using R Studio version 2024.04.2 + 764.

Results

Archaeobotanical Results

The 88 samples (see supp. data 1 for raw data) selected for full archaeobotanical analysis from Space 106 of the HoCS were found to contain abundant well-preserved pulse seeds exclusively, as summarised in Figure 2 and Table 3 (see Figure 3 for photographed examples). Overall, grass pea (*Lathyrus sativus* L./*cicera* L.) is the dominant component of the assemblage, occurring in 84% of samples (74 of 88) and totalling 8378 seeds. There were 10 samples that contained 100% grass pea seeds; their spatial distribution will be discussed further below. Bitter vetch (*Vicia ervilia* L. Willd.) and Celtic bean (*Vicia faba* L.) were recovered from 60% and 59% of samples, respectively (53/88 and 52/88 samples), totalling 4671 bitter vetch and 1623 Celtic bean seeds. The final two pulse species recovered from the HoCS were lentil (*Lens culinaris* Medik.) and winged vetchling (*Lathyrus ochrus* L. DC.). These taxa were identified at lower frequencies in comparison to the other pulse species, with ubiquities of 42% and 39%, respectively (37/88 and 34/88 of samples), and totalling 720 lentil and 1073 winged vetchling seeds.

Spatial Distribution

The archaeobotanical results were mapped by plotting the samples in Space 106 as graduated pie charts. The pie charts include all pulse seeds identified to species; indeterminate pulse seeds were excluded for the purposes of assessing spatial distribution. Figure 4 shows significant clustering of samples by predominant pulse species across the western end of Space 106, where the seed concentrations occurred. Samples dominated entirely by grass pea are located in the southern/south-western part of the room, including some recovered within a broken LM IIIA pithos base, set within a circular depression in the earthen floor (F.1027, Figure 4). During excavation it was observed that the pithos was likely already broken at the time of the fire; additional body sherds were not found (Eleni Hatzaki, personal observations). Moreover, grass pea seeds in the pithos base likely fell in from above during the destruction of the room, since a substantial lower fill of the pithos base consisted of seed-free sediment (Hatzaki et al. In press). Samples containing primarily lentil were located in the north-western corner of the room. Samples dominated by Celtic bean occurred between the grass pea and lentil areas in the central-western end of the room. Samples situated in the middle of the western part of the room contained relatively high concentrations of bitter vetch, including some clearly dominated by this taxon. To the north-east of this bitter vetch concentration, increasing proportions of Celtic bean and winged vetchling were observed, including a couple of small samples dominated by winged vetchling. The north-west corner and especially the middle part of the western end of Space 106 contained concentrations of burned building material overlying the seed concentrations, likely protecting the seed-rich deposits from high temperatures that would otherwise have reduced them to ash.

Seed densities per litre of sediment were also examined. Figure 5a shows that there are two especially seed-rich areas: in the south-western part of the room, where samples composed entirely of grass pea are located (Figure 5d), and in the middle of the western part of the room, where samples are of more mixed overall composition but with a predominance of bitter vetch (Figure 5b). Grass pea concentrations

Table 1. The real values of the calibration and check standards used in the analysis along with their measured mean value per run.

ID	Measured values		No. per run	Runfile	Real value	
	δ^{15}N (‰)	δ^{13}C (‰)			δ^{15}N (‰)	δ^{13}C (‰)
PEA	1.75 ± 0.24	−26.65 ± 0.19	5	240102	1.97 ± 0.1	−26.47 ± 0.08
ALANINE	−1.50 ± 0.11	−27.18 ± 0.07	8	240102	−1.5 ± 0.07	−27.18 ± 0.16
SEAL	16.14 ± 0.07	−12.54 ± 0.2	4	240102	16.14 ± 0.09	−12.54 ± 0.13
PEA	1.97 ± 0.15	−26.63 ± 0.06	5	240103	1.97 ± 0.1	−26.47 ± 0.08
ALANINE	−1.50 ± 0.1	−27.18 ± 0.1	9	240103	−1.5 ± 0.07	−27.18 ± 0.16
SEAL	16.14 ± 0.1	−12.54 ± 0.1	5	240103	16.14 ± 0.09	−12.54 ± 0.13

are notably highest in samples outside and to the south of the pithos base (F1027) (Figure 5d). By contrast, samples containing relatively high proportions of lentil, Celtic bean and winged vetchling had much lower overall densities. In particular, lentil was sparsely distributed across the far western end of Space 106, with a low-level concentration in the north-west corner of the room. This distribution suggests that lentil was stored separately to the other pulse species and perhaps in a different kind of container that did not provide optimal preservation conditions. There may also have been salvage operations after the fire to remove fallen timbers and containers (Hatzaki et al. In press).

Overall, spatial analysis of the archaeobotanical results demonstrates that different pulse species were stored separately in distinct areas of the western part of Space 106, becoming partly mixed during the destruction and collapse of the building and/or possible salvage operations. Distinct spatial concentrations are especially clear for grass pea, bitter vetch, lentil and Celtic bean, and possible also for winged vetchling, though this taxon mostly occurs in mixed samples in the north-east part of the area. Spatial distribution is explored further below in conjunction with the results of stable isotope analysis.

Stable Carbon Isotope Values

The δ^{13}C values of the pulse samples ranged from –20.8 to –26.4 ‰. The mean δ^{13}C values varied among the species, lentil having the lowest mean value at –24.6 ± 0.9 ‰, similar to bitter vetch at –24.4 ± 0.6 ‰. Winged vetchling and Celtic bean had similar means, –23.7 ± 1.3 ‰ and –23.5 ± 1.3 ‰, respectively, while grass pea had the highest mean value, –22.8 ± 0.8 ‰. These means and standard deviations include both bulk and single seed samples, which will alter the variability given single seeds are more variable compared to bulk. To explore variability, Table 4 shows the means, standard deviations and confidence intervals of the bulk samples, single-seed samples, all samples combined and a converted bulk mean. The converted bulk value is a mean taken from both the bulk samples values and the mean value of the single seeds (converting the ten single seed values to one 'bulk' value). Note that the converted bulk value for lentil is the mean of five values: the two bulk samples values and the means of the three units from which single seeds were drawn (see Supp. data 2).

Table 2. The accuracy, precision and standard uncertainty of the isotopic samples as per Szpak, Metcalfe, and Macdonald (2017) method as well as the mean standard deviation of samples as per Kragten (1994).

	Szpak et al. (2017) method			Kragten (1994) spreadsheet method	
	Accuracy	Precision	Standard uncertainty	HoCS	MUM
Carbon	0.19‰	0.13‰	0.23‰	0.18‰	0.07‰
Nitrogen	0.19‰	0.15‰	0.24‰	0.18‰	0.35‰

Differences among the converted bulk means of the five species suggest that at least some were cultivated under distinct conditions of water availability. Comparison of the converted bulk mean Δ^{13}C values to the watering bands from Wallace et al. (2013) provides an indication of water status (Figure 6). Wallace et al. (2013) produced a set of bands informed by experimental cultivation and watering of barley, wheat and lentil, offering an interpretative framework against which archaeological samples can be compared. Comparison with these bands shows that grass pea, with the lowest Δ^{13}C value (16.6 ± 0.5 ‰), falls within the moderately watered band, while the other species fall in the well-watered band. Statistically, there is a difference among the species (ANOVA, p-value < 0.001), with grass pea significantly different from bitter vetch, lentil and winged vetchling at the <0.05 level. The difference between grass pea and Celtic bean is not significant (Tukey Honest Significant Differences post hoc test, p-value = 0.09, Table 5). There is more than a 1 ‰ difference between the means of grass pea and those of bitter vetch, winged vetchling and lentil, while the difference between grass pea and Celtic bean is less than 1 ‰. Bitter vetch and lentil also differ statistically from Celtic bean (Table 5), with a greater than 1 ‰ difference. Examination of the confidence intervals around the differences between means shows that the true difference between the two species could be greater than 1 ‰ for grass pea vs lentil, while grass pea vs bitter vetch is borderline (confidence endpoint at –0.97 ‰).

Comparison of the means of the five species, based only on the single-seed values, also indicates that some

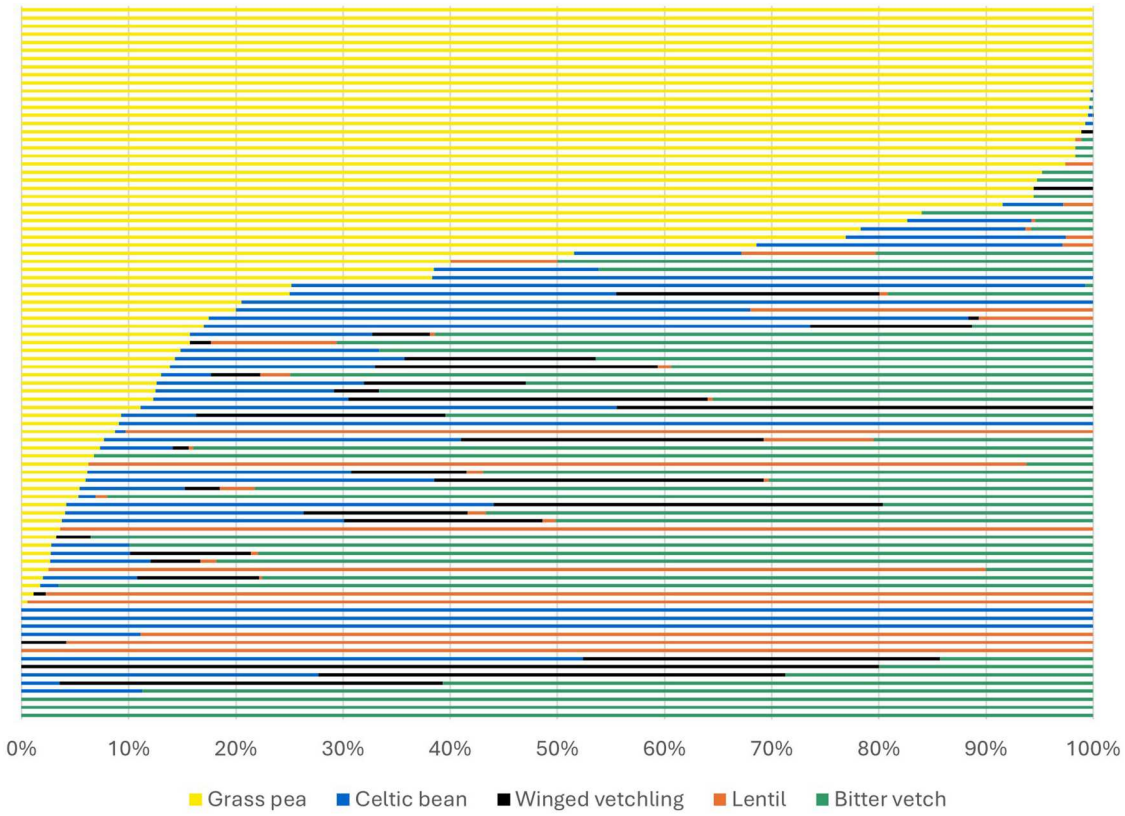

Figure 2. Overview of sample composition from the HoCS in terms of five major pulse species.

species benefited from higher water availability during growth than others, similar to the results found when comparing converted bulk values. Comparison of the single-seed $\Delta^{13}C$ values to the Wallace et al. (2013) watering bands shows that grass pea falls below the well-watered band, with a mean of 16.7 ± 0.9 ‰, while bitter vetch (18.4 ± 0.7 ‰) and lentil (18.6 ± 1 ‰) are consistently within the well-watered band. The single-seed data also exhibit high variability in the winged vetchling and Celtic bean samples, with $\Delta^{13}C$ values ranging from the poorly watered band to the well-watering band. Statistically there is a difference among the species (ANOVA p-value < 0.001) with grass pea significantly different from bitter vetch and lentil at the <0.05 level (Tukey HSD post hoc test, Table 6). This differs from the converted bulk data, where there was also a significant difference between winged vetchling and grass pea and lentil, as well as Celtic bean and lentil (see Table 5).

Comparing the means of the species, there is a greater than 1 ‰ difference between grass pea and both bitter vetch and lentil, while lentil differs from Celtic bean by 1.1 ‰. Winged vetchling differs from lentil and grass pea by 0.97 ‰ and −0.93 ‰, respectively, and Celtic bean differs from bitter vetch by −0.9 ‰. The confidence intervals can be used as a gauge on the reliability of the difference between the sampled populations. Examining the confidence intervals around the difference between means indicates a low probability that these differences represent a true population difference of greater than 1 ‰, with all pairs potentially having a difference between means of less than 1 ‰ (grass pea vs. bitter vetch: 0.43 ‰, lentil vs. grass pea: 0.72 ‰) (Table 6).

Table 3. Summary of archaeobotanical samples analysed from the HoCS.

Pulse Species	Presence	Ubiquity (%)	Total Sum	Max/ Sample
Lentil	37	42	720	182
Celtic bean	52	59	1623	183
Grass pea	74	84	8378	2051
Bitter vetch	53	60	4671	706
Winged Vetchling	34	39	1073	252

Stable Nitrogen Isotope Values

The $\delta^{15}N$ values of the pulse samples ranged from −0.7 to 2 ‰. Mean $\delta^{15}N$ values differ among species: grass pea has the lowest mean at 0.3 ± 0.6 ‰, while lentil (0.5 ± 0.4 ‰), bitter vetch (0.5 ± 0.5 ‰.) and winged vetchling (0.6 ± 0.4 ‰) are slightly higher. Celtic bean has the highest mean at 1.4 ± 0.4 ‰. These means include both bulk samples and single-seed samples. To explore variability, Table 4 shows the means, standard deviations and confidence intervals of all bulk samples, all single-seed samples, all samples together and converted bulk means. Here again, the converted bulk value is calculated by averaging the bulk samples values along with the mean value of the single seeds (converting the ten single seed values to one 'bulk' value). Note that the converted bulk value

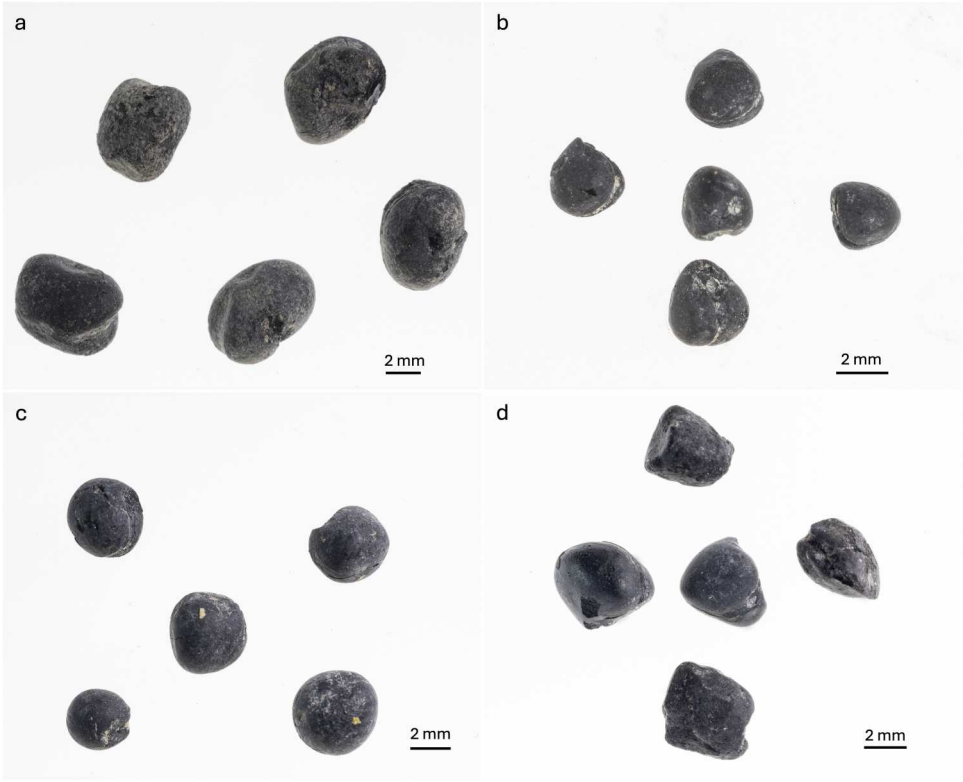

Figure 3. Example photographs of the five pulse species recovered from the HoCS. a. Celtic bean, b. bitter vetch, c. winged vetchling, d. grass pea (Photographs by I. Cartwright).

for lentil is the mean of five values as explained in the carbon results (see Supp. data 2).

Statistically, there is a difference among the species when using the converted bulk values (ANOVA, p-value = 0.05 see Table 4), with Celtic bean significantly different from lentil at the <0.05 level. The comparison between lentil and Celtic bean is moderately significant at $p = 0.09$ (Tukey HSD post hoc test). Comparing the means of these species, there is a greater than 0.67‰ difference between the Celtic bean and grass pea, while the difference between Celtic bean and winged vetchling, and Celtic bean and lentil, is >0.6 ‰ (Table 6). None of the pairs of species exhibit a greater than 1 ‰ difference.

Examining only the single-seed data shows that there is a statistically significant difference among the species (ANOVA, p-value < 0.001), with Celtic bean significantly different from all other species at the $p < 0.05$ level (Table 6). This differs from the converted bulk data due to the enrichment of the individually measured Celtic beans from unit #10346 located in the centre of the western end of Space 106, compared to the two bulk Celtic bean samples from units #10340 and #10344 located to the north-east. Looking at the differences between the means of these species, there is a greater than 1 ‰ difference between Celtic bean and all species except winged vetchling (Table 6), the difference between Celtic bean and winged vetchling being −0.92 ‰ (CI −0.3, −1.54). The confidence intervals can be used as a gauge on the reliability of the difference between the sampled populations. All confidence intervals indicate that the differences could be less than 1 ‰ (~0.4 ‰) (Table 6), which is smaller than what would be expected of differing growing conditions (Treasure, Gröcke, and Lester 2024).

Spatial Differences

Plotting the $\delta^{13}C$ and $\delta^{15}N$ values of the samples shows spatial variation in isotopic values, including *within* species (Figure 7). Mapping highlights differences in $\delta^{13}C$ values among the grass pea-rich samples, lentil samples and the mixture of species in the centre to north-east of the storage area (Figure 7a). Notably, high $\delta^{13}C$ values of grass pea from units #10301, #10381 and #10297 (Area 1 around F.1027) contrast with lower values including grass pea samples to the southeast (Area 2, units #10312, #10319, #10315). Comparison of the converted $\Delta^{13}C$ values of the grass pea bulk and the single-seed samples from the two areas shows isotopic differences. Figure 8a shows the single-seed samples from unit #10301 and unit #10312 while Figure 8c shows bulk sample and mean single entity sample $\Delta^{13}C$ values from six units within the two grass pea concentrations.

Statistically, there is a significant difference between the single-seed $\Delta^{13}C$ means of unit 10301s1 (16.14 ± 0.71 ‰) and unit 10312s1 (17.25 ± 0.82 ‰) (Welch Two Sample t-test, $p = 0.005$, difference in means 1.11 ‰, CI: 0.4, 1.83 ‰). Although the difference

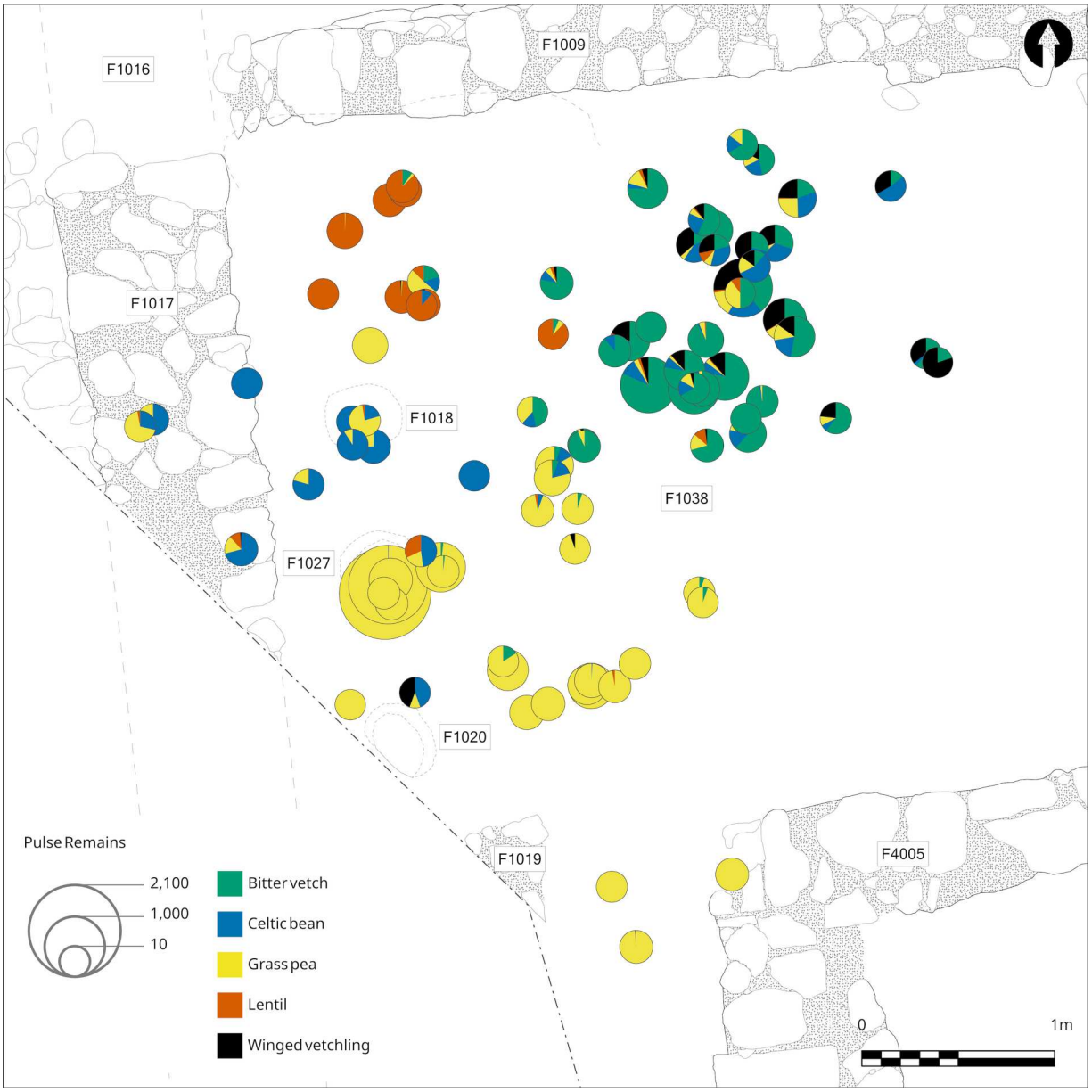

Figure 4. Plan of the western end of Space 106 with graduated pie charts showing archaeobotanical sample distribution, composition and total seed counts.

between the two units is greater than 1 ‰, the confidence intervals indicate that this difference could be a little as 0.4 ‰. The difference between the bulk seed $\Delta^{13}C$ means for Area 1 (16.29 ± 0.13 ‰) and Area 2 (17 ± 0.36 ‰) is limited and not significant (Welch Two sample t-test, $p = 0.063$); however, the limited sample size reduces statistical robustness. Interpolating all of the data spatially highlights the difference in $\delta^{13}C$ values (Figure 7a).

Examination of grass pea's $\delta^{15}N$ values shows that the difference between means is only 0.1 ‰ among the single-seed samples (unit #10301 vs #10312s1), resulting in an insignificant p-value of 0.8 (Welch Two sample t-test). For the bulk samples, the difference is only 0.15 ‰, with an insignificant p-value of 0.4 (Welch two sample t-test) (Figure 8d).

Spatial plotting of the $\delta^{15}N$ values of all isotopically measured samples shows that most locations have $\delta^{15}N$ values below 1%, which is expected of pulses without recent intensive manuring (Figure 7b). The higher $\delta^{15}N$ value of the Celtic bean sample from unit #10346, located centrally in the storage area, stands out. Comparison with Figure 5c, showing the densities of Celtic bean samples, indicates a spatial separation of this sample from the samples to the east. Isotopically, this separation is also evident, as indicated above, such that the Celtic bean sample is statistically significantly different from grass pea, lentil and winged vetchling (Table 7).

Discussion

Use of the HoCS

Meticulous excavation and detailed sampling of archaeobotanical remains in Space 106 of the HoCS shows that the western part of this room was used

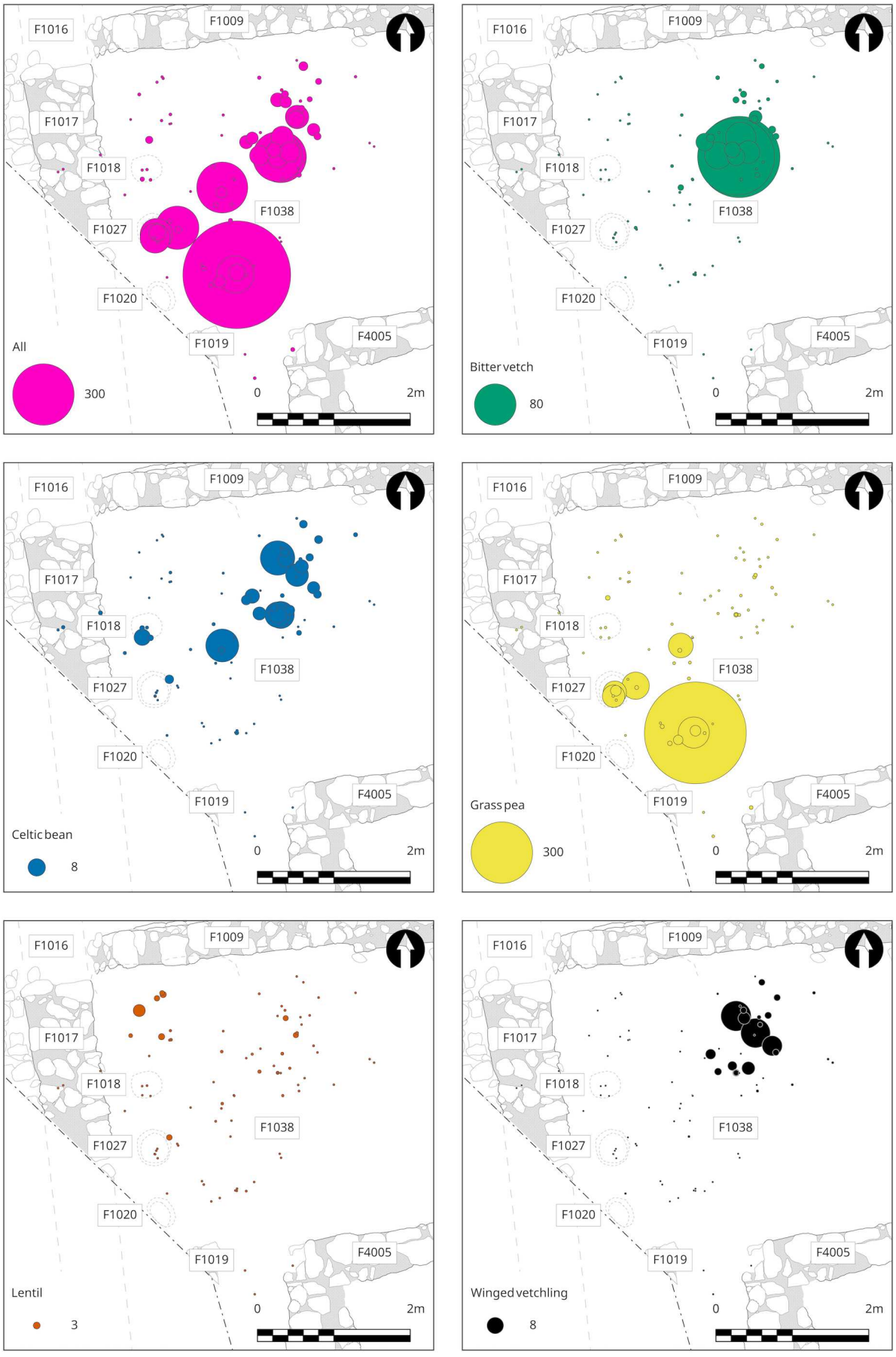

Figure 5. Plan of the western end of Space 106 with graduated symbols (by size) showing the density (items per litre of sediment) and distribution of each individual pulse species: a. all species; b. bitter vetch; c. Celtic bean; d. grass pea; e. lentil; f. winged vetchling.

Table 4. Means of species δ^{15}N, δ^{13}C and Δ^{13}C values and their standard deviations (sd) and 95% confidence intervals (CI), as well as number of items and the type of sample (single, bulk, all, converted bulk (CB)).

English	δ^{15}N (‰)	Sd (‰)	CI	δ^{13}C (‰)	sd	CI	Δ^{13}C (‰)	sd	CI	No.	Type
Bitter vetch	0.50	0.56	0.16, 0.82	−24.4	0.70	−24.9, −24.0	18.36	0.74	18.0, 18.8	10	single
Celtic bean	1.59	0.2	1.48,1.71	−23.54	1.46	−24.4, −22.7	17.46	1.52	16.6, 18.4	10	single
Winged vetchling	0.67	0.36	0.45,0.88	−23.72	1.46	−24.6, −22.9	17.65	1.52	16.8, 18.6	10	single
Grass pea	0.35	0.64	0.08,0.62	−22.79	0.90	−23.2, −22.4	16.69	0.94	16.3, 17.1	20	single
Lentil	0.54	0.40	0.33,0.77	−24.61	0.96	−25.1, −24.1	18.58	1.01	18.0, 19.1	12	single
Bitter vetch	0.65	0.06	0.61,0.69	−24.58	0.17	−24.7, −24.5	18.55	0.18	18.4, 18.7	2	bulk
Celtic bean	0.70	0.29	0.5, 0.91	−23.48	0.29	−23.7, −23.3	17.4	0.30	17.2, 17.6	2	bulk
Winged vetchling	0.25	0.11	0.17, 0.33	−23.78	0.61	−24.2, −23.3	17.71	0.63	17.3, 18.2	2	bulk
Grass pea	0.25	0.23	0.09, 0.45	−22.72	0.36	−23.0, 22.5	16.61	0.37	16.4, 16.9	4	bulk
Lentil	0.15	0.59	−0.26, 0.57	−24.29	0.46	−24.6, −24	18.25	0.48	17.9, 18.6	2	bulk
Bitter vetch	0.52	0.51	0.24, 0.79	−24.43	0.64	−24.8, −24.1	18.39	0.67	18.1, 18.8	12	all
Celtic bean	1.44	0.4	1.21, 1.64	−23.53	1.32	−24.2, −22.8	17.45	1.38	16.7, 18.2	12	all
Winged vetchling	0.60	0.37	0.40, 0.8	−23.73	1.33	−24.4, −23.0	17.66	1.39	16.9, 18.4	12	all
Grass pea	0.33	0.59	0.10, 0.56	−22.78	0.83	−23.1, −22.5	16.67	0.86	16.3, 17	24	all
Lentil	0.48	0.43	0.27, 0.70	−24.57	0.90	−25.0, - 24.1	18.53	0.94	18.1, 19.0	14	all
Bitter vetch	0.6	0.1	0.5, 0.69	−24.52	0.16	−24.7, −24.4	18.48	0.17	18.4, 18.7	3	CB
Celtic bean	1.0	0.55	0.50, 1.59	−23.5	0.21	−23.7, −23.3	17.42	0.22	17.2, 17.6	3	CB
Winged vetchling	0.39	0.26	0.17, 0.67	−23.76	0.43	−24.2, −23.3	17.69	0.45	17.3, 18.2	3	CB
Grass pea	0.28	0.18	0.16, 0.42	−22.74	0.44	−23.1, −22.4	16.63	0.46	16.3, 17.0	6	CB
Lentil	0.38	0.37	0.03, 0.60	−24.56	0.45	−24.9, −24.2	18.51	0.47	18.2, 18.9	5	CB

for pulse storage at the time of the fire. Prior use of this area for storage is indicated by circular depressions cut into the floor to receive storage containers at the western (back) end of Space 106, including one (F.1027) that contained a broken pithos base at the time of the fire (Figure 1b). When the fire occurred, cleaned pulse seeds may have been stored in perishable containers such as baskets or sacks, possibly hanging from the ceiling. During the destruction and collapse of the building such containers fell to the floor and were destroyed, but the pulse seeds themselves were protected from high temperature burning by the collapse of overlying building material. Our sampling of discrete concentrations of grass pea in the south-western part of the room, lentil in the north-west, Celtic bean in the central-western end of the room, bitter vetch in the middle of the western area of the room and Celtic bean and winged vetchling (mostly mixed with other species) to the north-east (Figure 4) suggests that most or all species were stored separately. This spatial patterning is reinforced, and further dimensions added, by the stable carbon and nitrogen isotope measurements.

Isotopic Inferences on Pulse Growing Conditions

The pulses stored in the western part of Space 106 were cultivated under a certain range of conditions, as seen when compared to data from modern pulse 'gardens' in central Evvia (Figure 9). Comparison with the Evvia data shows that the Celtic bean samples from unit #10346 occur within the 'manure + irrigation' ellipse. The other Celtic bean samples as well as the grass pea and winged vetchling fall within the 'no manure + no irrigation' ellipse (that is, no *recent* very intensive manuring – see Fraser et al. 2011), while the bitter vetch and lentil samples fall outside and to the right of the 'no manure + no irrigation' ellipse due to higher Δ^{13}C values. In sum, from Figure 9 we infer that Celtic bean was grown partly in more intensively manured conditions than the other species, while lentils and bitter vetch were grown in wetter conditions.

Intra-species variation in cultivation conditions is also apparent (Figures 7 and 9). The higher δ^{15}N values of Celtic bean samples from unit #10346, towards the central-western end of the room, were enriched above the values of Celtic bean samples from units #10340 and #10344 to the north-east. Research on the impact of manuring on the δ^{15}N values of pulses has been conducted on Celtic bean and suggests that very intensive manuring can increase δ^{15}N values by up to 1.5 ‰ (Treasure, Church, and Gröcke 2015, 2024). The single-seed Celtic bean sample mean of 1.59 ± 0.2 ‰ from unit #10346 falls within the range for heavily manured beans identified by Treasure, Church, and Gröcke (2015), and within the 50% confidence interval ellipses constructed from the modern Evvia data, where even higher values were observed (Figure 9). In contrast, the mean value of bulk samples of Celtic bean to the north-east in the storage area is lower, at 0.7 ± 0.3 ‰, suggesting that Celtic beans stored in the HoCS were cultivated under multiple conditions. It is apparent that the cultivation plot from which the seeds in unit #10346 were harvested was more heavily manured than the plot(s) associated with units #10340 and #10344. This isotopic contrast among Celtic bean samples reinforces the spatial patterning seen in their distribution, with a concentration in the central-western end of the room, distinct from a concentration of Celtic bean and other species including winged vetchling in the north-east part of the storage area (Figures 4–5).

Ethnographic research has documented preferential manuring of broad beans in infield plots (*sókhora*) in Evvia, as this practice was found to produce beans

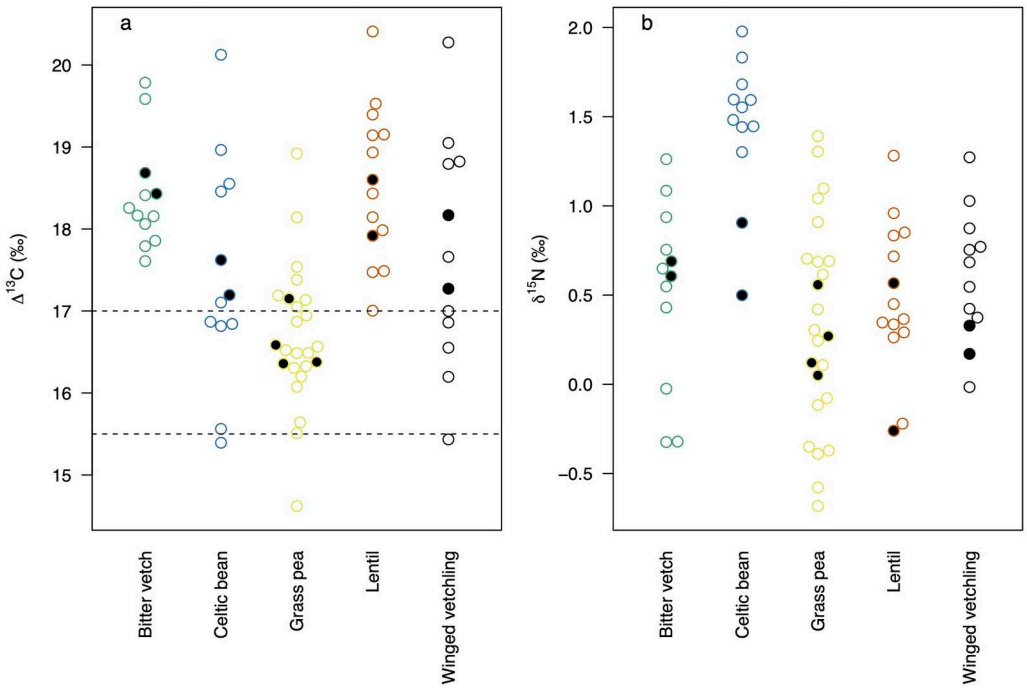

Figure 6. The Δ^{13}C and δ^{15}N values of the HoCS samples: a. Δ^{13}C values plotted with watering bands from Wallace et al. (2013), b. δ^{15}N values. Open symbols indicate single seed values, while black filled symbols indicate the values of bulk samples.

that 'cooked better' (Halstead 2014, 208). Further north, cultivation of pulses on light *defekiá* patches also resulted in easily cooked seeds (Halstead 2014, 207). This attention to soil type for broad bean cultivation reflects the influence of manuring on cooking qualities, likely due to the production of seeds with thinner testas (seed coats). These observations may help to explain the ^{15}N-enrichment observed in the Celtic beans from the HoCS. Moreover, this phenomenon of relatively ^{15}N-enriched Celtic bean has also been detected in the Final Palatial MUM pulse assemblage (Nitsch et al. 2019), as discussed below, and is consistent with an intention to grow Celtic bean for human consumption. It is possible that the HoCS contained harvests from infield garden plots with varying levels of manure, reflecting specific crops and their intended uses.

Δ^{13}C values show variability among and within pulse species as well. Among species, lentil and bitter vetch values reflect higher water availability, whereas grass pea's Δ^{13}C values indicate relatively dry conditions. These species-specific differences hint at variations in cultivation conditions, though further modern research is needed to determine whether

Table 5. The results of a Tukey multiple comparison of means post hoc test on the samples (converted bulk) of the five pulse species Δ^{13}C values.

Species	Δ^{13}C Mean (‰)	Confidence Interval (CI)	Difference between means	Lower Confidence endpoint	Upper Confidence endpoint	*p*-value (adj)
Celtic bean -bitter vetch	17.4 18.5	17.2, 17.6 18.4, 18.7	−1.066	−2.09	−0.05	**0.039***
Grass pea – bitter vetch	16.6 18.5	16.3, 17.0 18.4, 18.7	−1.850[§]	−2.73	−0.97	**>0.001***
Lentil – bitter vetch	18.5 18.5	18.2, 18.9 18.4, 18.7	0.029	−0.88	0.94	1.000
Winged vetchling – bitter vetch	17.7 18.5	17.3, 18.2 18.4, 18.7	−0.793	−1.81	0.228	0.169
Grass pea –Celtic bean	16.6 17.4	16.3, 17.0 17.2, 17.6	−0.784	−1.67	0.1	0.094**.**
Lentil – Celtic bean	18.5 17.4	18.2, 18.9 17.2, 17.6	1.095[§]	0.18	2.01	**0.015***
Winged vetchling – Celtic bean	17.7 17.4	17.3, 18.2 17.2, 17.6	0.273	−0.75	1.29	0.918
Lentil – grass pea	18.5 16.6	18.2, 18.9 16.3, 17.0	1.880	1.12	2.64	**>0.001***
Winged vetchling – grass pea	17.7 16.6	17.3, 18.2 16.3, 17.0	1.058	0.17	1.94	**0.016***
Winged vetchling – lentil	17.7 18.5	17.3, 18.2 18.2, 18.9	−0.822	−1.74	0.09	0.088**.**

The table shows the means and CIs, the differences between means, the lower and upper endpoints of 95% family-wise confidence intervals of that difference and the adjusted *P* values. '*' significant at <0.05 level '.' significant at <0.1 level.

Table 6. The difference between the HoCS pulse species means using only single seed data, their lower and upper confidence intervals as well as the adjusted *p*-values showing significant (*) differences between means based on a Tukey Honest Significant Differences test

	$\Delta^{13}C$ (‰)				$\delta^{15}N$ (‰)			
	Difference between means	Lower Confidence endpoint	Upper Confidence endpoint	*p*- value (adj)	Difference between means	Lower Confidence endpoint	Upper Confidence endpoint	*p*- value (adj)
Celtic bean -bitter vetch	−0.90	−2.34	0.54	0.41	1.09	0.47	1.71	**0.00***
Grass pea-bitter vetch	−1.67	−2.92	−0.43	**0.00***	−0.15	−0.69	0.39	0.93
Lentil-bitter vetch	0.22	−1.15	1.60	0.99	0.04	−0.56	0.64	1.00
Winged vetchling-bitter vetch	−0.70	−2.14	0.73	0.64	0.17	−0.45	0.79	0.94
Grass pea-Celtic bean	−0.77	−2.02	0.47	0.41	−1.24	−1.78	−0.70	**0.00***
Lentil-Celtic bean	1.12	−0.25	2.50	0.16	−1.05	−1.65	−0.46	**0.00***
Winged vetchling-Celtic bean	0.20	−1.24	1.63	1.00	−0.92	−1.54	−0.30	**0.00***
Lentil-grass pea	1.90	0.72	3.07	**0.00***	0.19	−0.32	0.70	0.82
Winged vetchling-grass pea	0.97	−0.28	2.21	0.20	0.32	−0.21	0.86	0.45
Winged vetchling-lentil	−0.93	−2.30	0.45	0.33	0.13	−0.46	0.73	0.97

$\delta^{13}C$ values align across species grown under the same water availability. Within species, differences in $\Delta^{13}C$ values between grass pea concentrations in the HoCS storage space suggest that they were cultivated under different conditions, the $\Delta^{13}C$ values of grass pea located around F1027 reflecting drier conditions for example, while the lentils in the north-western corner reflect wetter conditions (Figure 7a). This kind of variability in watering conditions could reflect soils with different moisture levels and/or differences due to variable hand-watering (Wallace et al. 2013). In any case, the contrast in stable carbon isotope values *among* grass pea samples in the south-western part of Space 106 again reinforces spatial patterning (Figures 4–5), indicating that there were multiple concentrations harvested from distinct growing areas.

In sum, the isotopic values of stored pulses in the western part of Space 106 in the HoCS, combined with the spatial patterning of seeds and species, suggest that crops were stored according to their location of cultivation, rather than as pooled harvests of each species from various growing conditions. The implication is that multiple plots and techniques were employed for pulse production by cultivators storing their harvests within the HoCS at the time of its destruction by fire. This variability echoes the wider range of isotope values observed across the pulse plots of entire modern villages in central Evvia (Figure 9) (Jones et al. 1999) and plausibly reflects the strategies of one household across several cultivation plots.

Comparison with Other Isotopic Data

Comparison of the isotopic data from the LM IIIB Early HoCS with previously published crop isotopic values from the elite LM II MUM at Knossos (Nitsch et al. 2019) reveals continuity in the cultivation and management of particular pulse species from Final Palatial to Post-Palatial periods (Figure 10). At MUM, a difference in $\delta^{15}N$ values between Celtic bean and winged vetchling was observed, comparable to that seen in the HoCS data (Figure 10c and 10d). Nitsch et al. (2019) postulated that the MUM Celtic bean was more intensively manured than winged vetchling, possibly reflecting differential status (intended as food versus fodder) and/or the species' response to manuring. The new data from HoCS reinforce this contrast, indicating that Celtic bean was the only pulse species that received recent very intensive manuring comparable to the Treasure, Gröcke, and Lester (2024) experimental data and intensively manured pulses sampled in central Evvia (Fraser et al. 2011). In contrast, lentil, bitter vetch, winged vetchling and grass pea all exhibited lower $\delta^{15}N$ values consistent with the winged vetchling values observed at MUM (Figure 10d). In the recent past, winged vetchling in the Greek islands has been grown as a flexible 'food-or-fodder' crop (Jones 1992) and other pulses have also played this dual role (Halstead 2014, 291–292). The fact that all pulses were stored together, irrespective of their growing conditions, is consistent with a flexible definition of food versus fodder depending on need, as documented

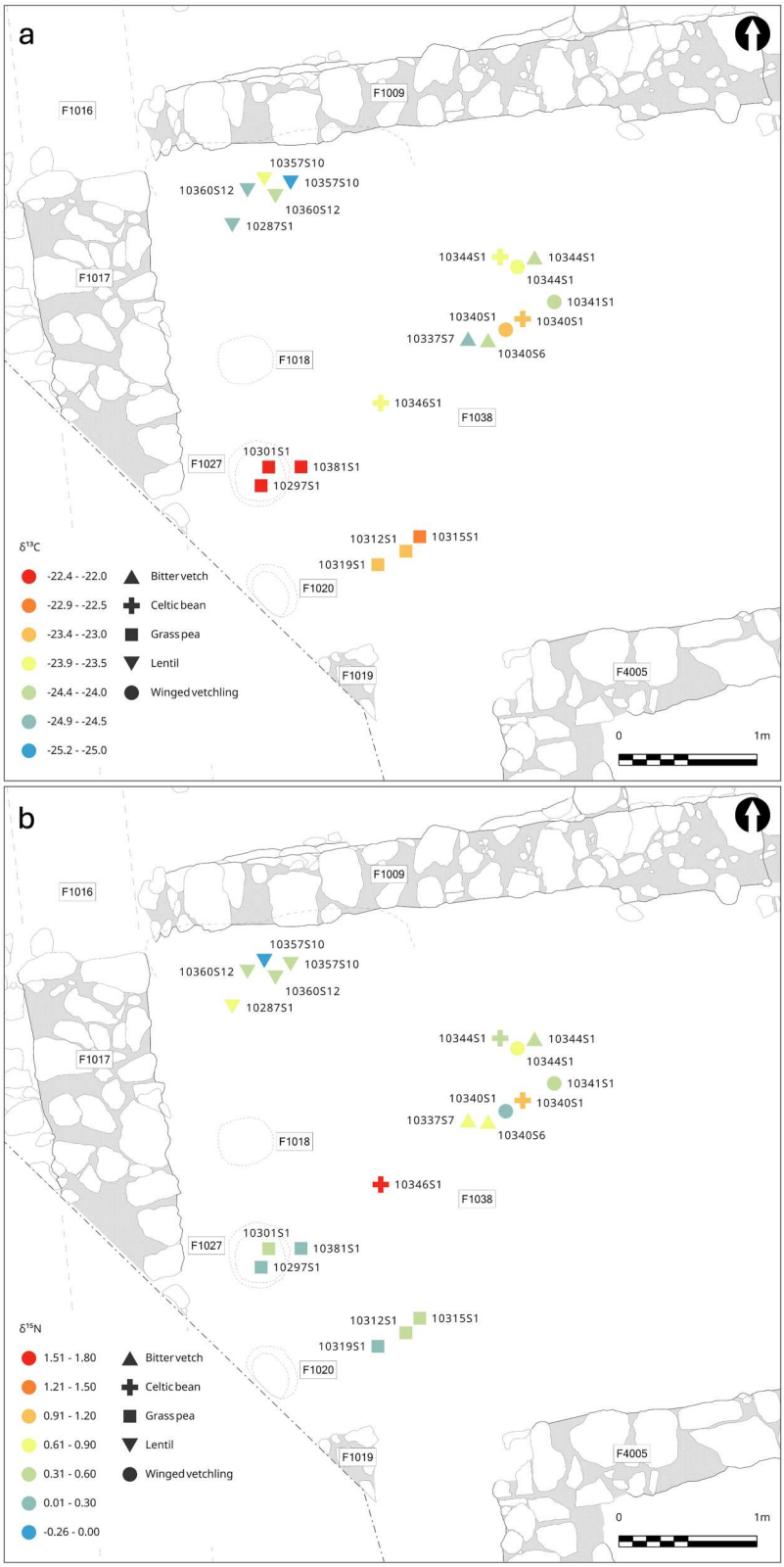

Figure 7. Plan of the western end of Space 106 mapping a. the $\delta^{13}C$ values of archaeobotanical pulse samples; b. the $\delta^{15}N$ values of archaeobotanical samples.

ethnographically in the Aegean (Halstead and Jones 1989).

The $\Delta^{13}C$ values of the samples from the LM II and LM IIIB Early are similar, with Celtic bean and winged vetchling – the two species present in both MUM and the HoCS – showing less than a 1 ‰ difference in their means between the two periods (Figure 10b). The Late Bronze Age was characterised by aridification in the Aegean and Anatolia, culminating in multi-year droughts that have been linked with political collapse (Finné et al. 2017; 2019; Kaniewski et al. 2013; Manning et al. 2023). The $\Delta^{13}C$ values from MUM and

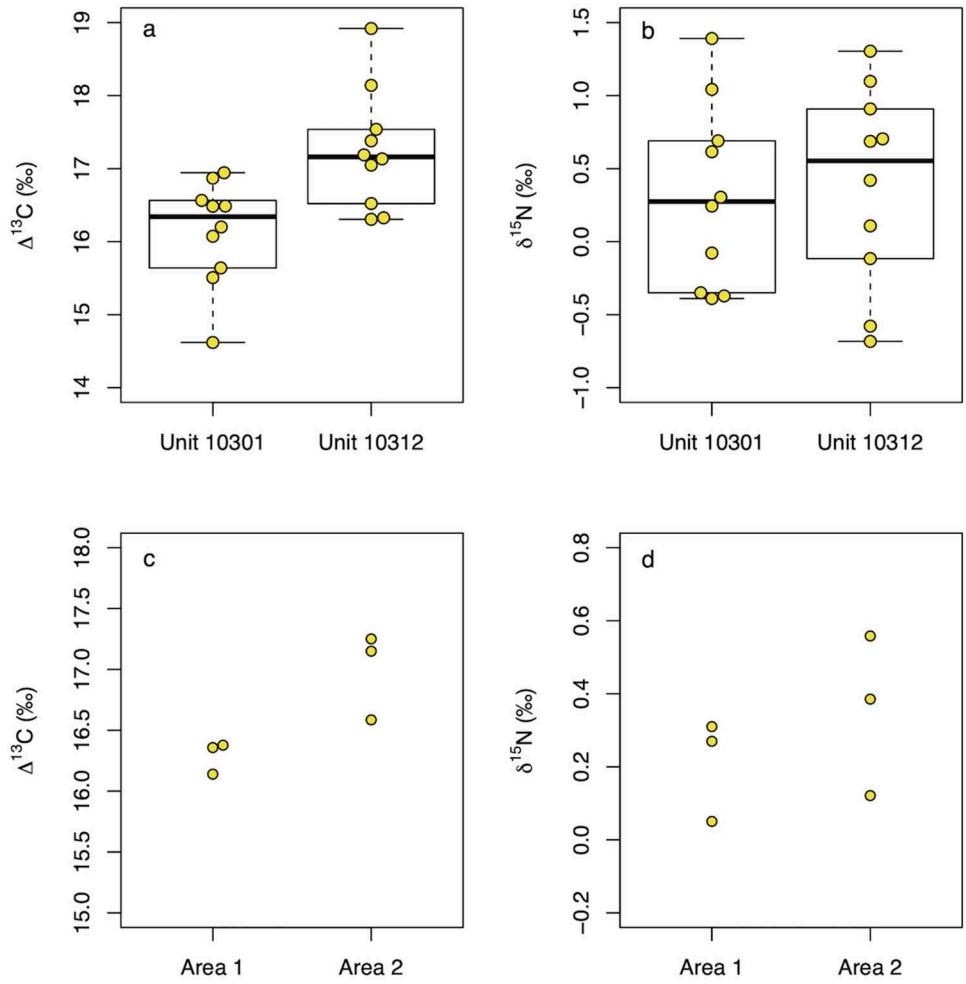

Figure 8. Comparison of grass pea isotope values from units 10301 and 10312: a. single-seed $\Delta^{13}C$ values; b. single-seed $\delta^{15}N$ values; c. bulk sample and mean single-seed sample $\Delta^{13}C$ values; d. bulk sample and mean single-seed sample $\delta^{15}N$ values.

Table 7. The results of a Tukey multiple comparison of means post hoc test on the samples (converted bulk) of the five pulse species $\delta^{15}N$ values.

	Mean (‰)	Confidence Interval (CI)	Difference between means (‰)	Lower conference endpoint (‰)	Upper conference endpoint (‰)	*P*-value (adj)
Celtic bean – bitter vetch	1.0 0.6	0.81, 1.5 0.5, 1	0.400	−0.391	1.191	0.54
Grass pea – bitter vetch	0.28 0.6	0.36, 0.65 0.5, 1	−0.316	−1.001	0.369	0.62
Lentil – bitter vetch	0.38 0.6	0.26, 0.73 0.5, 1	−0.221	−0.928	0.486	0.867
Winged vetchling – bitter vetch	0.39 0.6	0.48, 0.67 0.5, 1	−0.208	−0.999	0.582	0.922
Grass pea – Celtic bean	0.28 1.0	0.36, 0.65 0.81, 1.59	−0.716	−1.401	−0.031	**0.038***
Lentil – Celtic bean	0.38 1.0	0.26, 0.73 0.81, 1.59	−0.621	−1.328	0.087	0.099
Winged vetchling – Celtic bean	0.39 1.0	0.48, 0.67 0.81, 1.59	−0.608	−1.399	0.182	0.176
Lentil – grass pea	0.38 0.28	0.26, 0.73 0.36, 0.65	0.095	−0.491	0.682	0.986
Winged vetchling – grass pea	0.39 0.28	0.48, 0.67 0.36, 0.65	0.108	−0.577	0.792	0.988
Winged vetchling – lentil	0.39 0.38	0.48, 0.67 0.26, 0.73	0.012	−0.695	0.720	1.00

The table shows the differences between means, the lower and upper endpoints of a 95% family-wise confidence intervals of the difference between means and the adjusted *p*-values.
'*' significant at <0.05 level.
'.' significant at <0.1 level.

HoCS provide two points in time, separated by a *c.* 200-year span, to examine crop water status (Figure 10a and 10b). In the HoCS, lentil and bitter vetch, the two pulses with the 'wettest' water signatures, exhibit $\Delta^{13}C$ values similar to the cereals from MUM, which were grown in wetter conditions than the

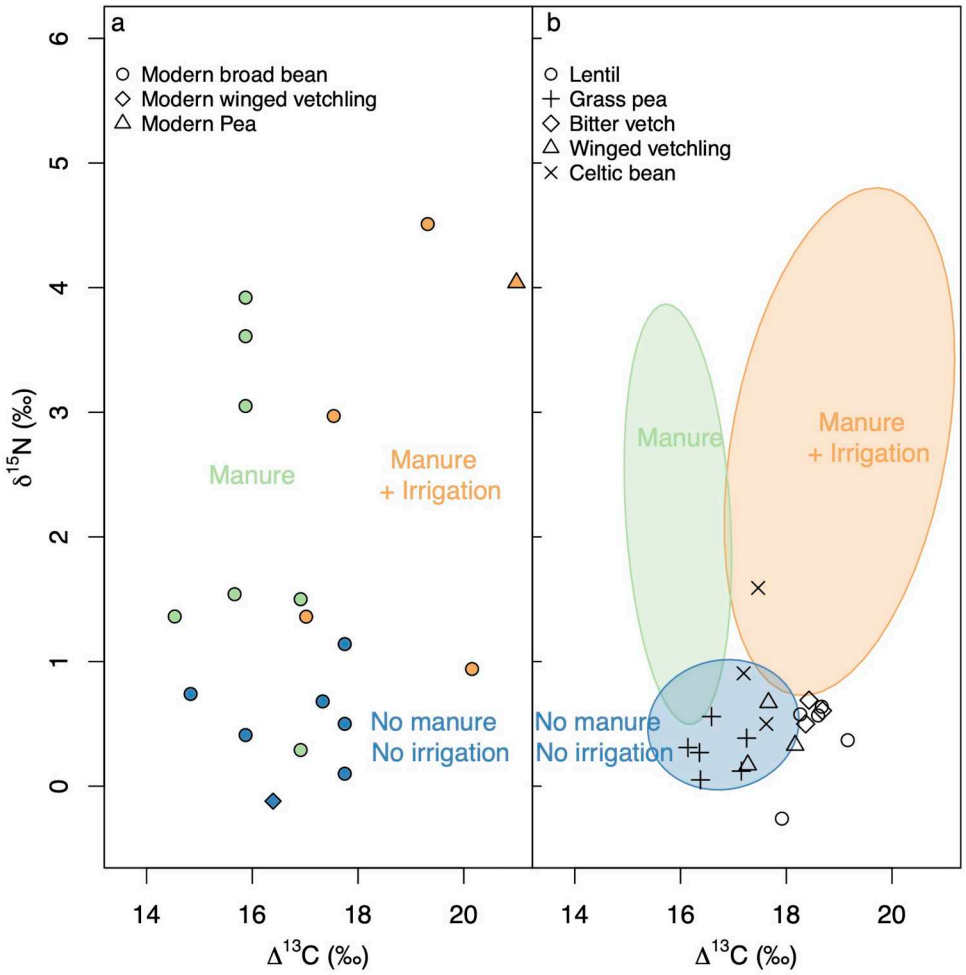

Figure 9. Comparison of $\Delta^{13}C$ and $\delta^{15}N$ values from modern and HoCS pulses: a. scatter plot of 'garden' pulses grown under a range irrigation and manure conditions in Evvia, Greece (data from Wallace et al. 2013 and Fraser et al. 2011; after Nitsch et al. 2019: Figure 3); b. scatter plot of HoCS pulse $\delta^{15}N$ and $\Delta^{13}C$ values alongside 50% confidence interval ellipses from the modern Evvia data.

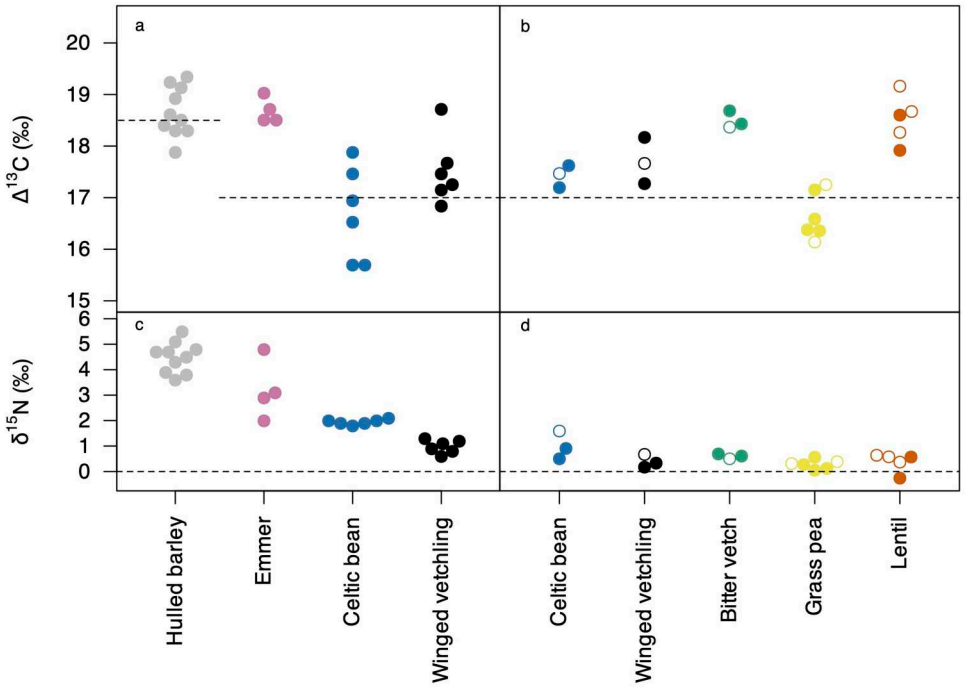

Figure 10. Comparison of the $\Delta^{13}C$ values from a. the Minoan Unexplored Mansion (Final Palatial) and b. HoCS (Post-Palatial). The open circles represent mean single-seed samples, the closed circles represent bulk samples. The dashed line represents the water threshold between well-watered and moderately watered as described by Wallace et al. (2013). 10c. and d. show the $\delta^{15}N$ values from the Minoan Unexplored Mansion (Nitsch et al. 2019), and HoCS respectively. The open circles represent mean single-seed samples, the closed circles represent bulk samples. The dashed line highlights the $\delta^{15}N$ value of 0 for ease of comparison.

MUM pulses (Nitsch et al. 2019). Grass pea in the HoCS is the only pulse species showing evidence of growth under predominantly suboptimal water conditions. The shift to (partly) better watered pulses in the HoCS compared to MUM is likely to reflect variation between years, plots of land and/or household strategies more directly than climate change *per se*. Overall, the isotopic data from MUM and the HoCS suggest that, *despite* climatic variability, Knossian cultivators were able to cultivate certain crops under optimal conditions of water availability.

Moreover, continuity of pulse cultivation practices between the LM II and LM IIIB Early suggests that these strategies were resilient to both climate change and political upheaval. There are several dimensions to this resilience. First, there is continuity in the cultivation of a similar, diverse range of pulse species. Secondly, there is continuity in strategic manuring of Celtic bean, echoing ethnographic evidence that manuring enhances its cooking properties. Thirdly, pulse diversity and variability in growing conditions between and within pulse crops are plausibly linked with a flexible definition of 'food-or-fodder' in both two contexts.

Conclusions

The archaeobotany and isotope ecology of stored pulse crops in the HoCS provide rare insight into the agroecological strategies of a household at Late Bronze Age Knossos. The focus on pulses, diversity of stored species *and* isotopic variability among and within pulse species all point to risk-averse and resilient cultivation practices by this modest household at Knossos Gypsades. While the immediate context of cultivation practices evidenced in the House of the Charred Seeds at Knossos Gypsades was around the time of the destruction(s) of the palace at Knossos or soon thereafter, overlapping pulse cultivation practices are apparent during the early Final Palatial period (LM II), from the archaeobotany and isotope ecology of stored crops preserved in the elite Minoan Unexplored Mansion (Jones 1984, 1992; Nitsch et al. 2019). Our results thus contribute to understanding of what made households resilient over the long term and under shifting political and climatic circumstances.

Most remarkable of all, similar pulse cultivation practices, including endemic species such as winged vetchling, have persisted in the Greek islands and eastern Aegean from at least the later fourth millennium BC (Diffey et al. 2025; Livarda et al. 2025; Maltas et al. 2021, 2022) until recently (Ertuğ 2004; Halstead and Jones 1989; Jones 1992; Thanopoulos et al. 2021; Thomas et al. 2012, 2013). This combined insight from archaeology and ethnography offers lessons on food security and sustainability, in the Aegean and beyond.

Disclosure Statement

The authors report there are no competing interests to declare.

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