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Late Bronze – Early Iron Age Agro-systems in Northern Greece: New Insights Through Stable Isotope Analysis from Methone, Pieria

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ABSTRACT

Throughout the Aegean, the Late Bronze Age (LBA) to the Early Iron Age (EIA) has been characterised as a period of societal change. After the collapse of palatial economies in the south (c.1200 BC), Greece entered a phase referred to in the past as the ‘Dark Ages’. Research into the nature of EIA agriculture has been relatively limited and although this situation has improved within the last decade there are still significant knowledge gaps. This paper will shed new light on LBA-EIA arable agriculture by presenting crop stable isotope analysis from the site of Methone in northern Greece. These data are used to examine site-specific agricultural strategies as well as allowing for an evidence-based understanding of economic variability in this region. The results reported show that at Methone and likely throughout Greece in the Early Iron Age, inhabitants continued to pursue relatively ‘low-input’ agricultural systems that were adapted to specific local settings and environmental conditions, even in the face of a period of potential aridity. Ultimately, this research provides a fresh approach to Iron Age (IA) Aegean agriculture whilst also highlighting the need to proceed with further research from other IA Aegean sites.

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Introduction

The period spanning the end of the Late Bronze Age and the beginning of the Early Iron Age saw significant change throughout the Aegean. In the south, large palatial economies prevailed during the Late Bronze Age (e.g. Halstead 1981; Renfrew 1982; White-law 2012). These societies had long established and maintained levels of social inequality, previously not seen in the Aegean through the exploitation of material and social networks, as well as by creating monopolies on prestige goods and having full or partial control of agricultural production (e.g. Knodell 2021, 64). Mycenaean and Minoan palaces acted as centralised places where resources, including staple and subsistence products, were both administered and accumulated (e.g. Halstead 1992; Killen 2008; Livarda and Kotzamani 2013; Renfrew 1972). By contrast, different social and economic forms predominated in the north during this period. Beyond the palatial heartland, from Thessaly and farther north in Greece, there is very little evidence of centralised organisation, and settlement patterns differ considerably by region (Knodell 2021, 72). Research into the

agricultural economy of northern sites, such as Arch-ontiko and Toumba Thessalonikis, has indicated that arable land management practices varied due to local micro-environmental factors and the intensity of crop and livestock husbandry integration (e.g. Nitsch et al. 2017; Valamoti 2023; Valamoti and Petridou 2022). In Pieria, the study area of this paper, since the late Neolithic period, but mainly in the Bronze Age, a movement of the population towards coastal areas is observed, which has been linked with an increase in trade in the Aegean, creating a series of settlements, amongst them Methone (Bessios 2010; and *pers. comm.*). Around these settlements many smaller sites, often temporarily occupied, also were established in this period while in the interior new small settlements appeared mostly on hilltops (Bessios 2010).

After the collapse of palatial societies in the south (c. 1200 BC), often linked potentially to a period of aridity known as the ‘3.2ka climate event’ (e.g. Drake 2012; Kaniewski et al. 2013; Manning et al. 2023), the area of modern Greece entered a period previously referred to as the ‘Dark Age’. This was initially seen as a time

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with significant transformations to settlement patterns, with populations abandoning towns and returning to rural areas, the diminishing of agricultural activities in favour of pastoralism (e.g. Desborough 1972; Snodgrass 1971), as well as widespread changes to social structure and administration. More recent examinations of this period, however, have suggested that the theory of Early Iron Age (EIA) depopulation is largely a relic of archaeological research (Morgan 2009; Papadopoulos 1996) and that many major settlements, such as Tiryns and Mycenae in the south, saw a continuity of occupation after the collapse of palace administrative structures (Thomas 2009). Moreover, this period saw the establishment or growth of other urban settlements as well as the proliferation of new art styles and burial practices associated with these communities (Lemos 2002; 2010). By the Early Iron Age in the northern Aegean, some settlements were abandoned but other new communities were established particularly on (semi-)mountainous areas or defensive hills. Other previously existing settlements expanded, and some larger population aggregations started being formed (Andreou 2019, 916–917, 922–927; Andreou and Kotsakis 2000; Krahtopoulou 2010, 56; Koukouli-Chrysanthaki 2014, 162–164). Within the Thermaikos Gulf, the EIA settlement pattern followed the LBA trend with coastal sites, such as Torone, Anchialos/Sindos and Toumba Thessalonikis still dominant and becoming denser with evidence for aggregation and population increase (Veropoulidou and Krahtopoulou *Forthcoming*; Krahtopoulou 2010, 56; Koukouli-Chrysanthaki 2014, 162; Andreou 2019, 916–917, 922–927). Intensive anthropogenic landscape management and

woodland destruction was also observed in Pieria during the EIA (Veropoulidou and Krahtopoulou *Forthcoming*; Krahtopoulou 2010, 239–252).

In terms of the agricultural economy of this period, significant gaps in our knowledge exist due to the relatively few primary bioarchaeological assemblages recovered from this period from across the Aegean. Although this situation has improved in the last decade (e.g. Alagich et al. 2021; Dibble and Finné 2021; Livarda 2008, 2012, 2014; Livarda et al. 2023; Livarda and Bouchard-Perron 2020; Margaritis 2017; Valamoti et al. 2018), research into the nature of EIA agriculture has still been fairly limited. It is the aim of this paper to shed new light on the nature of agro-systems in the north Aegean and contribute to a more in-depth understanding of the socio-economic organisation of the area through the application of new crop stable isotopic data from the site of Methone.

Site Background – Methone

The site of Methone is located in Pieria, northern Greece, on the west coast of the Thermaikos Gulf (Figure 1). Topographically, southern Pieria is fairly mountainous, whereas the northern and central regions are flat, including the plain of Katerini, one of the largest and most fertile areas in modern Greece (Godefroy, Salavert, and Margaritis 2023). The region is bounded geographically by the Haliakmon River to the north and the Peneios River delta in the south with many streams and passes connecting the lowland and mountainous areas (Poulaki-Pantermali 2013). The archaeological site itself is located c. 36 km from the

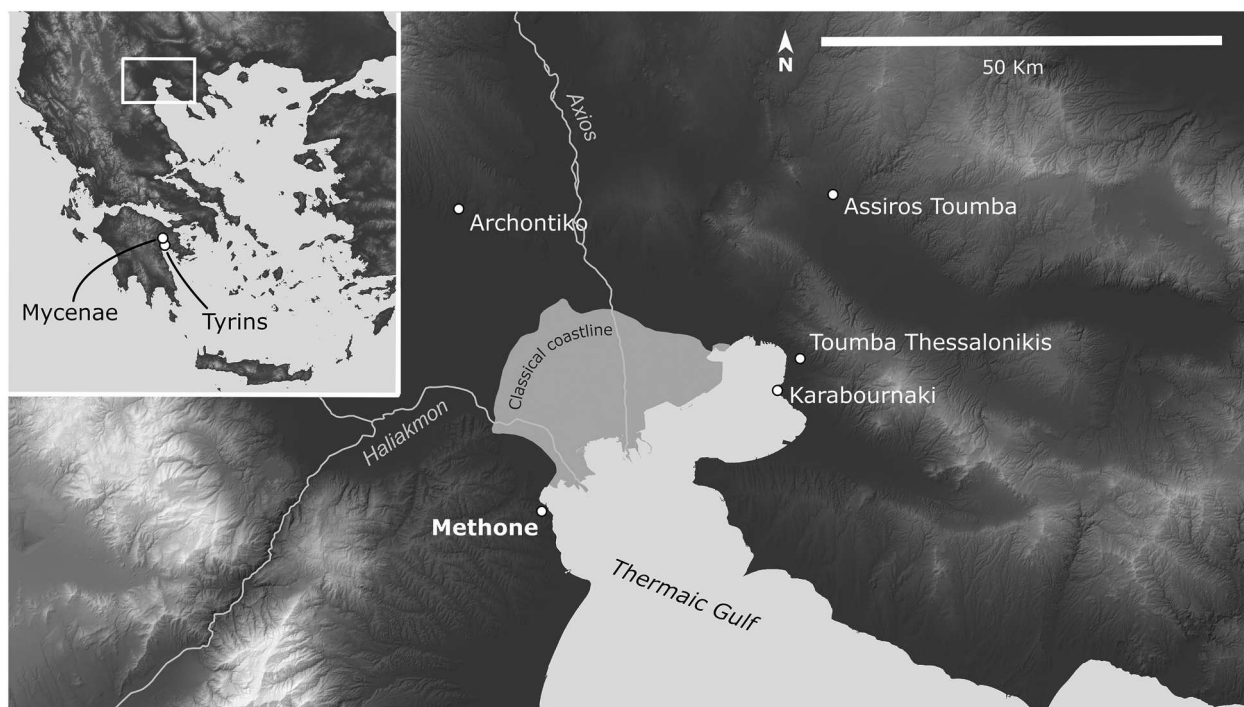


Figure 1. Map showing the location of Methone, and other sites mentioned in this paper in the northern Aegean.

modern city of Thessaloniki at an altitude of 15 m asl. The ancient settlement was situated on two adjacent hills and extended onto a flatter area to the north, reaching the sea. The site was also one of the safest harbours in the region due to the fact that it was not affected by the prevailing winds (Bessios, Athanassiadou, and Noulas 2023). Holocene coastal infilling and marine regression, however, have buried parts of the site and today the settlement is located some 500 m from the sea (Morris et al. 2020). The current climate of this area is characterised by mild wet winters and hot dry summers (Cfa humid subtropical, Koppen-Geiger classification), but average annual temperatures are generally lower than the typical Mediterranean climate (8–30°C¹). Mean annual rainfall is around 500–750 mm (cf. Polunin et al. 1987).

The ancient city of Methone was established in 733 B.C. by Eretrians as a Greek colony on the site of an indigenous settlement, and developed into a major port due to its location as an entry-point for upland products, such as timber, its access to the productive arable lands on the plain of Katerini and its strategic location linking the south to the north of the Aegean and beyond (Bessios, Athanassiadou, and Noulas 2023; Morris et al. 2020). Recent excavations by the Greek Archaeological Service (led by Athena Athanassiadou, Matthaios Bessios and Konstantinos Noulas) and an international research team² led by Sarah Morris and John Papadopoulos have shown that the site was continuously inhabited since the Late Neolithic (c. 5000 B.C.). The Late Bronze Age period is primarily represented by a series of rectangular rock-cut tombs on the West Hill. These contained burial goods including local Mycenaean-style vessels and other objects, such as beads and bronze pins (Morris et al. 2023). These burials were succeeded by the emergence of an Early Iron Age settlement. This involved the construction of apsidal structures, storage facilities, such as pits and pithoi set into the bedrock, and areas thought to be connected to craft production, such as bone-working and metallurgy (Papadopoulos 2023). The most interesting and spectacular Iron Age feature, however, was the discovery of a rectangular subterranean structure at least 11.8 m deep on the top of the East Hill at the site (Figure 2). Named by the excavators the ‘Hypogeion’, the construction of this feature was never completed and was filled, soon after it was opened, with a variety of materials over a short period of time c. 720–690 B.C. (Bessios 2023). Upon excavation, this very substantial pit contained one of the largest sets of Early Iron Age bioarchaeological finds recovered from the Aegean to date. These included well-preserved charred plant remains, charcoal, animal bones, seashells as well as a large quantity of pottery and some metal objects (Bessios 2023; Livarda et al. 2023).

Extensive environmental sampling has been carried out as part of the most recent excavations. This

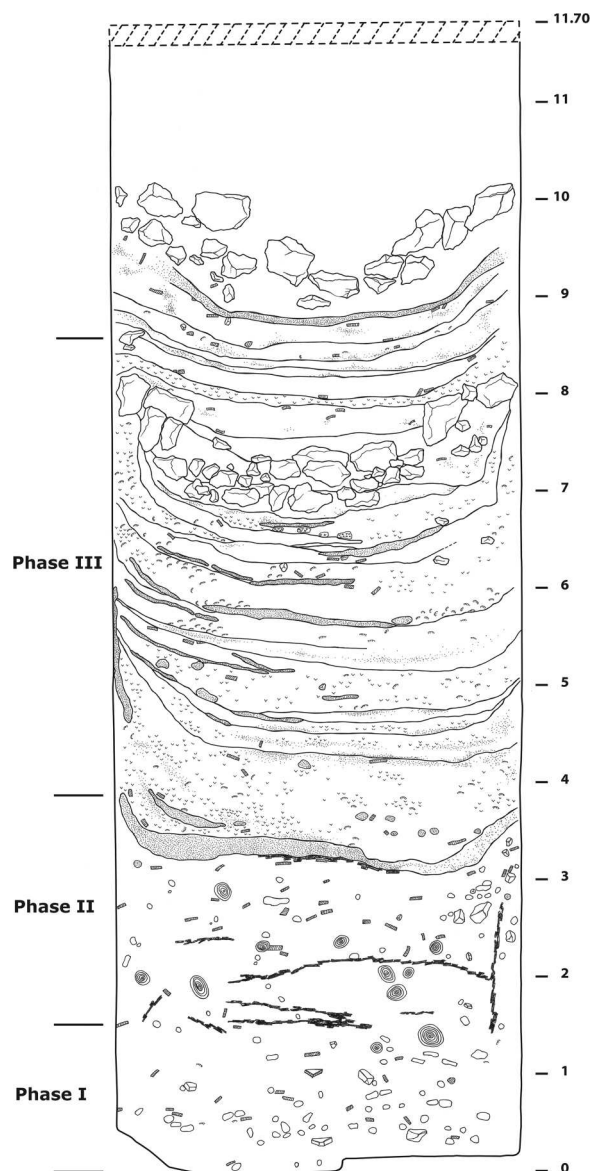


Figure 2. Plan of the ‘Hypogeion’ (cred. Ioannis Moshos).

involved the recovery of 423 soil samples, including 92 samples from the ‘Hypogeion’. Analysis of these samples has identified a number of crop taxa, such as hulled barley (*Hordeum vulgare* L.), the glume wheats emmer (*Triticum dicoccum* Schübl.) and einkorn (*Triticum monococcum* L.), and millet (*Panicum miliaceum* L.), as well as a number of pulses, such as lentil (*Lens culinaris* Medik.) and bitter vetch (*Vicia ervilia* L.). Fruit remains, such as olive (*Olea europea* L.), fig (*Ficus carica* L.) and grape (*Vitis vinifera* L.), as well as several wild species have also been recovered (Livarda et al. 2023; Livarda and Bouchard-Perron 2020). Generally, the density of plant remains across the settlement is fairly low and preservation was variable, particularly in samples from the tombs. By contrast, material from the ‘Hypogeion’ was much better preserved and included a wider range of weed/wild taxa. Overall, the results of archaeobotanical analysis (Livarda et al. 2023) are consistent with the systematic exploitation of the landscape around Methone and the

presence of a mixed agropastoral subsistence economy. The mixture of crop species suggests that they were cultivated throughout the agricultural year and that the site was permanently settled. Finally, the range of crops seems to remain consistent during the Late Bronze Age and Early Iron Age periods, suggesting that there was some continuity in terms of farming practices throughout the period when Methone was occupied (Livarda et al. 2023; Livarda and Bouchard-Perron 2020).

Methods

The analysis of stable isotope ratios in charred plant remains has become a valuable means of inferring both anthropogenic and environmental influences on plant growing conditions (e.g. Fiorentino et al. 2015). In particular, the measurement of carbon and nitrogen stable isotope values from archaeobotanical remains has been used to investigate crop husbandry conditions, including water availability and artificial soil enrichment levels (e.g. Bogaard et al. 2007; Ferrio et al. 2005; Fraser et al. 2011). A full explanation of carbon and nitrogen plant stable isotope ratios, which form the basis of this research, is provided in Supplementary Material 1.

Sample Selection

Charred plant remains included in this study represent the four most common crop species identified at Methone; *Triticum monococcum* (einkorn), *Triticum dicoccum* (emmer), *Hordeum vulgare* (barley) and *Lens culinaris* (lentil). Plant samples selected for single-grain stable isotope analysis were chosen based on a series of criteria. Firstly, seeds were only taken from samples that contained at least two of the species under study, and that contained at least three grains of each species. Selected seeds also corresponded with the criteria determined for the ‘optimal charring window’ of around 230–260°C (Charles et al. 2015; Nitsch, Charles, and Bogaard 2015; Stroud et al. 2023). Seeds selected had a completely matte blackened grain matrix with little external morphological distortion (Stroud et al. 2023). All seeds were weighed, and a number were also cross-sectioned to assess for large internal voids. In total, 85 grains from nine contexts were selected for stable isotope analysis (see Table 1 for list of all samples), to assess variation both within crop species and also across different chronological periods at Methone. Seeds were selected from three broad categories of archaeological contexts: Late Bronze Age tombs, Early Iron Age settlement, and the Early Iron Age Hypogeion. All four crop species were chosen from each context category with the exception of lentil from the Hypogeion. This is because there were very few lentils recovered from

Table 1. The number of samples selected for crop stable isotope analysis, by context and crop species.

Date	Context category	Species	No. of seeds
LBA	Tombs	Hulled Barley	9
		Emmer	9
		Einkorn	10
		Lentil	15
EIA	Settlement	Hulled Barley	3
		Emmer	3
		Einkorn	4
		Lentil	2
EIA	Hypogeion	Hulled Barley	15
		Emmer	9
		Einkorn	6
Total			85

within the Hypogeion, and no excavated contexts met the criteria set for stable isotope analysis.

Pre-Treatment

The nature of charred archaeobotanical material is such that plant remains are susceptible to a variety of different kinds of contamination during deposition and subsequent long-term burial (Vaiglova et al. 2014). The most commonly identified source of contamination are carbonates present naturally in the soil that can potentially distort the results of stable isotope analysis. To detect possible contamination, Fourier Transform Infrared Spectroscopy (FTIR) was used to screen three charred seeds taken from different samples from the Methone assemblage. The results showed peaks characteristic of carbonate contamination (870 and 720 cm⁻¹) present in each of the spectra (see Supplementary Information Figure 1), so all samples were pre-treated with 10 ml of 0.5 M HCL acid at 80°C for 30 min to remove this (following Vaiglova et al. 2014). Samples were then rinsed multiple times with distilled water to a neutral pH and dried in a drying oven for 24 h, before being crushed and (re-)weighed for analysis.

Stable Carbon and Nitrogen Isotope Measurements

Stable carbon and nitrogen isotope values were measured using an isoprime precisiON stable isotope ratio mass spectrometer coupled to a vario PYRO cube CNSOH elemental analyser at the Research Laboratory for Archaeology and the History of Art (RLAHA), University of Oxford, UK. Plant δ¹³C and δ¹⁵N values were measured separately, but as part of the same stable isotopic run, using a carbon dilution of 2%. Resultant carbon and nitrogen values were then calibrated relative to the Vienna Peedee Belemnite scale (VPDB) and AIR respectively. Accuracy or systematic error (*u(bias)*), following the protocol established by Szpak, Metcalfe, and Macdonald (2017) was calculated using variability in sample

replicates, calibration standards and check standards (see Supplementary Information Table 1 for analytical conditions). Overall, accuracy was determined to be 0.11 for $\delta^{13}\text{C}$ and 0.24 $\delta^{15}\text{N}$, and total analytical uncertainty (u_c) was estimated to be 0.14 for $\delta^{13}\text{C}$ and 0.28 $\delta^{15}\text{N}$. All stable isotope values ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) were corrected for the effect of charring by subtracting 0.11‰ and 0.31‰ from the normalised data, respectively (Nitsch, Charles, and Bogaard 2015). Finally, all $\delta^{13}\text{C}$ values were converted to $\Delta^{13}\text{C}$ so that comparisons could be made between the Methone samples and modern stable isotope studies. These calculations were made from the determined $\delta^{13}\text{C}$ ($\delta^{13}\text{C}_{\text{plant}}$) and a $\delta^{13}\text{C}_{\text{air}}$ value using the AIRCO2_LOESS system (Cleveland 1979; Ferrio et al. 2005; Francey et al. 1999; Indermühle et al. 1999; Leuenberger, Siegenthaler, and Langway 1992) and the equation determined by Farquhar, Ehleringer, and Hubick (1989).

Testing Data Reliability

A number of measured $\delta^{13}\text{C}$ values from both laboratory reference materials and archaeological samples were observed to register *c.* 1‰ higher than was expected. This was due to a machine error after the replacement of the carbon dioxide (CO_2) reference gas source. These $\delta^{13}\text{C}$ values (samples numbers 33, 34b, 54, 72 and 75) were removed from the rest of the analysis. The corresponding $\delta^{15}\text{N}$ values, however, were judged not to have been affected and were accepted after comparisons with values from other samples earlier in the machine run. The reliability of charred plant isotopic composition was assessed by plotting the $\delta^{15}\text{N}$ values against the C:N atomic ratio, following Szpak and Chiou (2020). Figure 3 shows no clear correlation between the two, suggesting that the isotopic composition was not subject to diagenetic alteration. Additionally, Figure 4

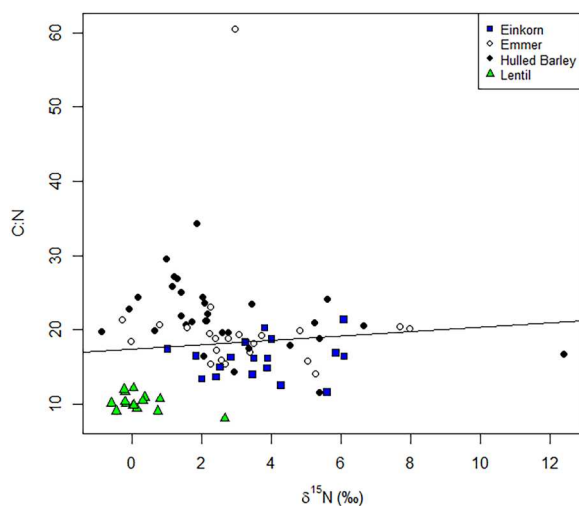


Figure 3. Scatterplot showing the $\delta^{15}\text{N}$ values against the C:N ratio of all species.

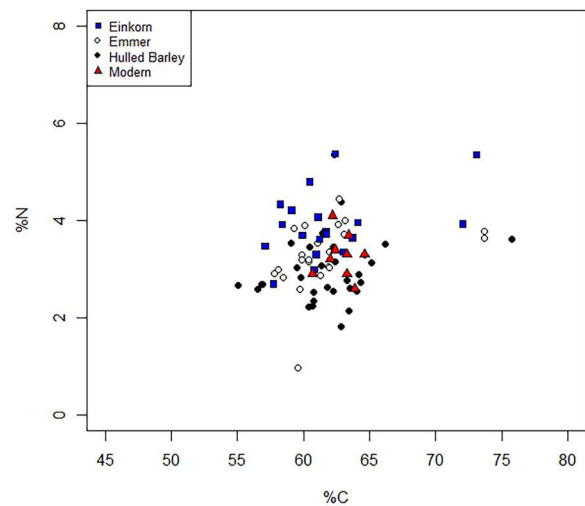


Figure 4. Scatterplot showing the %C and %N values of the cereal species from Methone and modern samples (from Fraser et al. 2013).

shows the percent carbon (%C) and the percent nitrogen (%N) of the cereal species (hulled barley, emmer wheat, einkorn wheat) from the Methone samples, plotted against modern charred cereal examples (Fraser et al. 2013). Although the archaeological samples appear more variable, the results of a Kruskal–Wallis test and post-hoc analysis (see Table 2) show that there is no significant difference between the modern and archaeological values. These results indicate then that the stable isotope values measured from grains from Methone can be accepted as reliable representations of the isotopic ratios of charred plant material from the site.

Results

Stable Carbon and Nitrogen Isotope Values of Charred Crop Remains

Figure 5 shows a scatterplot of all crop stable carbon and nitrogen isotope values, coded by crop taxa. Generally, there appears to be some slight clustering of

Table 2. The results of a Kruskal–Wallis test and post-hoc analysis on the %C and %N values of stable isotope values from Methone and modern charred material.

Statistical test	%C–%N	Species/source of material	Results
Kruskal–Wallis	%C	All	$H(4) = 5.79, p = 0.12$
Post-hoc Dunn	%C	Einkorn–Emmer	$p = 0.77$
Post-hoc Dunn	%C	Einkorn–Hulled Barley	$p = 0.81$
Post-hoc Dunn	%C	Emmer–Hulled Barley	$p = 0.68$
Post-hoc Dunn	%C	Einkorn–Modern	$p = 0.24$
Post-hoc Dunn	%C	Emmer–Modern	$p = 0.14$
Post-hoc Dunn	%C	Hulled Barley–Modern	$p = 0.57$
Kruskal–Wallis	%N	All	$H(3) = 23.28, p < 0.001$
Post-hoc Dunn	%N	Einkorn–Emmer	$p = 0.06$
Post-hoc Dunn	%N	Einkorn–Hulled Barley	$p < 0.001$
Post-hoc Dunn	%N	Emmer–Hulled Barley	$p = 0.09$
Post-hoc Dunn	%N	Einkorn–Modern	$p = 0.12$
Post-hoc Dunn	%N	Emmer–Modern	$p = 0.88$
Post-hoc Dunn	%N	Hulled Barley–Modern	$p = 0.28$

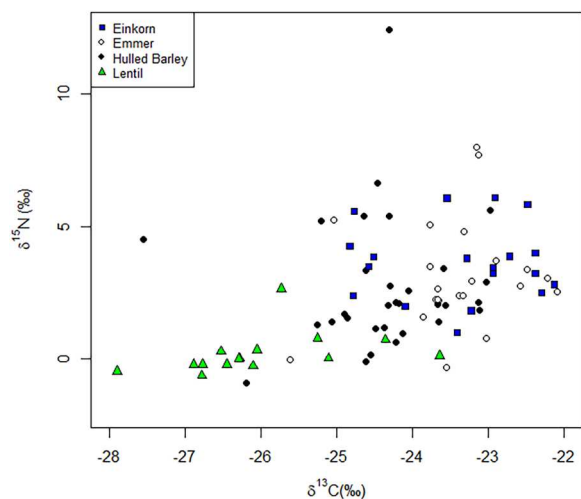


Figure 5. Scatterplot of all crop stable isotope carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) values, coded by crop taxa.

samples by taxa. This is most obvious with regards to values from lentil which are clustered together with relatively low $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, although this is in part due to their ‘nitrogen-fixing’ ability. By contrast, the einkorn wheat, emmer wheat and hulled barley have similarly variable and broadly comparable carbon and nitrogen isotope values. Supplementary Information Table 2 provides all stable carbon and nitrogen isotope measurements of the Methone samples. Figure 6 shows the $\Delta^{13}\text{C}$ values for each taxon. Overall, there appears to be some variability within each taxon, as indicated by the means and standard deviations (einkorn wheat $-17.4 \pm 0.98\text{‰}$, emmer wheat $-17.43 \pm 0.84\text{‰}$, hulled barley $-18.43 \pm 0.96\text{‰}$, lentil $-20.14 \pm 1.12\text{‰}$). All standard deviations are above the values reported for experimentally grown, averaged single-grain measurements reported for expected cereal inter-ear and intra-field variability (Styring et al. 2024). Due to the

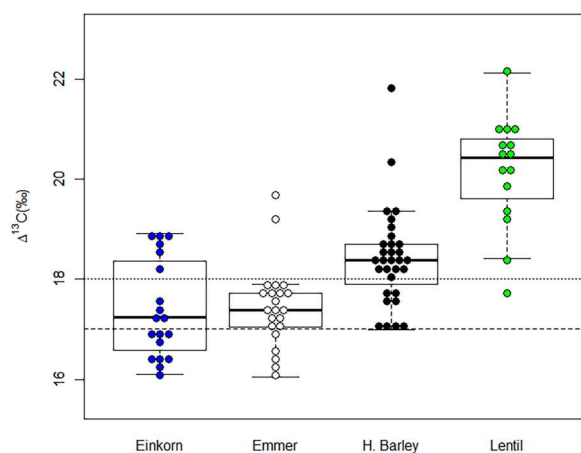


Figure 6. $\Delta^{13}\text{C}$ values of the four crop species. The lower dashed line indicates the lower limit of the ‘adequate water provision’ zone for wheat. The upper dotted line indicates the lower limit of the ‘adequate water provision’ zone for hulled barley.

physiological differences between barley and wheat, specifically the earlier completion of photosynthesis and grain ripening in the former (Araus et al. 1997; Wallace et al. 2013), an offset of -1.0‰ was applied to the values of the barley grains. A Kruskal–Wallis test was used to compare differences in $\Delta^{13}\text{C}$ values between the crop species (a Shapiro–Wilk test showed that the data are not normally distributed, $W = 0.948$, $p = 0.001$). The results showed that there is a statistically significant difference between the four crops ($H(3) = 30.94$, $p < 0.001$). An additional post-hoc Dunn test indicated that the $\Delta^{13}\text{C}$ values of lentil, in particular, are significantly different from all other taxa (see Table 3 for the results of statistical tests).

Stable nitrogen isotope ($\delta^{15}\text{N}$) values were also measured on grains/seeds of all four taxa (Figure 7). Einkorn wheat, emmer wheat and hulled barley again show a wide range of $\delta^{15}\text{N}$ values (means and standard deviations: einkorn wheat $-3.58 \pm 1.45\text{‰}$, emmer wheat $-3.07 \pm 2.02\text{‰}$, hulled barley $-2.74 \pm 2.54\text{‰}$) that were more variable than the average 1.64‰ standard deviation recorded from experimentally manured hulled barley from the same plot (Larsson, Bergman, and Lagerås 2019). By contrast, lentil exhibited less variability with a mean and standard deviation of $0.22 \pm 0.73\text{‰}$, indicating the use of a more uniform management system. A Kruskal–Wallis test was performed on all results (Shapiro–Wilk test: $W = 0.924$, $p < 0.001$) and indicated that there was again a significant difference between the four crop taxa ($H(3) = 34.784$, $p < 0.001$). The results of the post-hoc analyses indicated that these differences are specifically between lentil and all other crops (see Table 4 for the results of statistical tests). Certainly, the $\delta^{15}\text{N}$ values for lentil are visibly lower than those of the cereals (Figure 7), however, this is due to the ability of pulse plants to ‘nitrogen-fix’ and as a result pulse $\delta^{15}\text{N}$ values are generally around 0‰ (Raven, Andrews, and Quigg 2005; Treasure, Church, and Gröcke 2016).

Chronological and Contextual Variation

Figure 8(a,b) show crop $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values coded by chronological period (Late Bronze Age – Early Iron Age). Overall, there does not appear to be any clear patterning in either the carbon or nitrogen

Table 3. Results of an Kruskal–Wallis test and post-hoc analysis conducted on the $\Delta^{13}\text{C}$ values from all species with a 1‰ offset applied to the hulled barley

Statistical Test	Species	Results
Kruskal–Wallis	All	$H(3) = 30.94$, $p < 0.001$
Post-hoc Dunn	Einkorn–Emmer	$p = 1$
Post-hoc Dunn	Einkorn–H. Barley	$p = 1$
Post-hoc Dunn	Emmer–H. Barley	$p = 0.93$
Post-hoc Dunn	Einkorn–Lentil	$p < 0.001$
Post-hoc Dunn	Emmer–Lentil	$p < 0.001$
Post-hoc Dunn	H. Barley–Lentil	$p < 0.001$

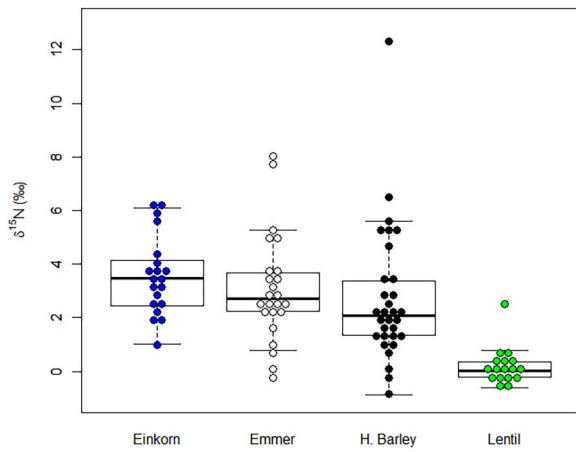


Figure 7. $\delta^{15}\text{N}$ values of all four crop species.

Table 4. Results of a Kruskal–Wallis test and post-hoc analysis conducted on the $\delta^{15}\text{N}$ values from all species

Statistical Test	Species	Results
Kruskal–Wallis	All	$H(3) = 34.78, p = <0.001$
Post-hoc Dunn	Einkorn–Emmer	$p = 0.51$
Post-hoc Dunn	Einkorn–H. Barley	$p = 0.08$
Post-hoc Dunn	Emmer–H. Barley	$p = 0.28$
Post-hoc Dunn	Einkorn–Lentil	$p = <0.001$
Post-hoc Dunn	Emmer–Lentil	$p = <0.001$
Post-hoc Dunn	H. Barley–Lentil	$p = <0.001$

isotope values by date. Furthermore, Wilcoxon rank sum tests were carried out on the $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of all crops by chronological period and indicated that there is no statistical difference between isotopic values from the Late Bronze Age or the Early Iron Age (see Table 5 for all statistical results). Instead, these values show a remarkable homogeneity, with the cereal³ samples from each period having very similar mean values (LBA – $\Delta^{13}\text{C}$: $17.7 \pm 1.0\text{‰}$, $\delta^{15}\text{N}$: $3.0 \pm 2.2\text{‰}$, EIA – $\Delta^{13}\text{C}$: $18.0 \pm 1.0\text{‰}$, $\delta^{15}\text{N}$: $3.1 \pm 2.1\text{‰}$).

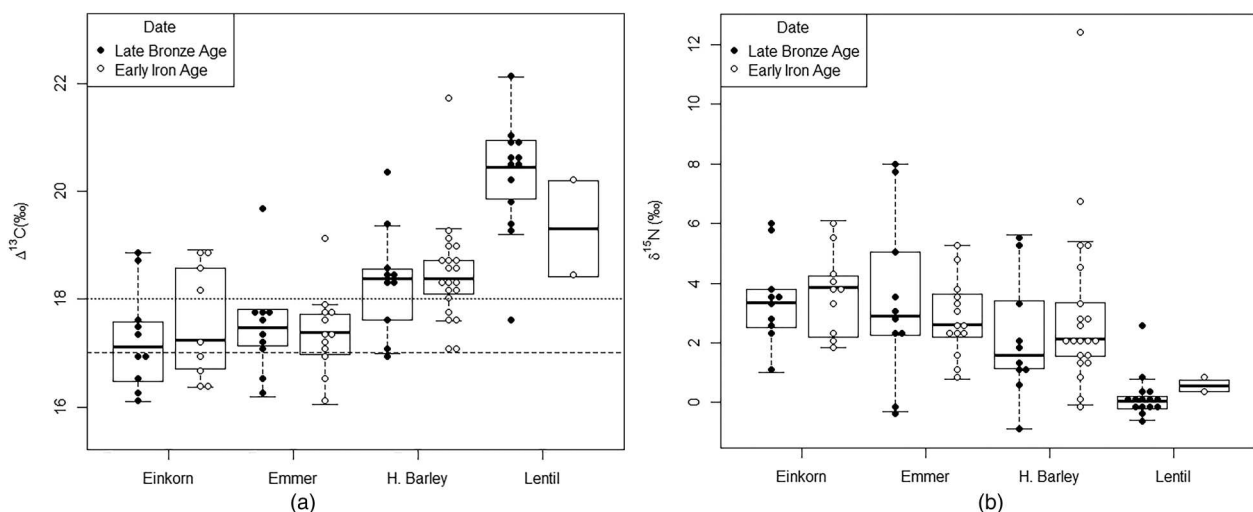


Figure 8. (a) $\Delta^{13}\text{C}$ values of the four crop species, coded by chronological period. The lower dashed line indicates the lower limit of the ‘adequate water provision’ zone for wheat. The upper dotted line indicates the lower limit of the ‘adequate water provision’ zone for hulled barley. (b) $\delta^{15}\text{N}$ values of the four crop species, coded by chronological period.

Table 5. Results of Wilcoxon Signed-Rank tests between all species and chronological period.

Statistical Test	Isotopic Analysis	Species	Results
Wilcoxon Signed-Rank	Carbon	All	$W = 1061.5, p = 0.33$
Wilcoxon Signed-Rank	Carbon	H. Barley	$W = 113.5, p = 0.74$
Wilcoxon Signed-Rank	Carbon	Emmer	$W = 56, p = 0.82$
Wilcoxon Signed-Rank	Carbon	Einkorn	$W = 50, p = 0.71$
Wilcoxon Signed-Rank	Carbon	Lentil	$W = 5, p = 0.23$
Wilcoxon Signed-Rank	Nitrogen	All	$W = 1346.5, p = 0.02$
Wilcoxon Signed-Rank	Nitrogen	H. Barley	$W = 131.5, p = 0.27$
Wilcoxon Signed-Rank	Nitrogen	Emmer	$W = 61, p = 0.63$
Wilcoxon Signed-Rank	Nitrogen	Einkorn	$W = 58, p = 0.58$
Wilcoxon Signed-Rank	Nitrogen	Lentil	$W = 25, p = 0.16$

Similarly, Figure 9(a,b) show crop $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values coded by contextual category (tombs, settlement, Hypogeion). Again, there does not appear to exist any correlation between context, crop species and stable carbon or nitrogen isotope values. The only exception to this are the $\Delta^{13}\text{C}$ einkorn values from the settlement and the Hypogeion which do show a 1‰ difference between the average means (settlement – 16.7 ± 0.4 , Hypogeion – 18.3 ± 0.7). The results of a factorial 2-way ANOVA test performed on all $\Delta^{13}\text{C}$ values ($F(2, 66) = 2.51, p = 0.08$) and $\delta^{15}\text{N}$ values ($F(2, 69) = 0.85, p = 0.43$), however, do not indicate any statistical differences between excavation contexts by crop species.

Discussion

Crop Management at Methone

The stable $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values obtained for the cereal grains analysed in this study indicate that cereal crops cultivated at the site of Methone were generally grown under a range of low intensity management systems, similar to those seen at other Late Bronze Age urban settlements in the eastern Mediterranean (e.g. Diffey et al. 2020; Nitsch et al. 2017). This type of husbandry

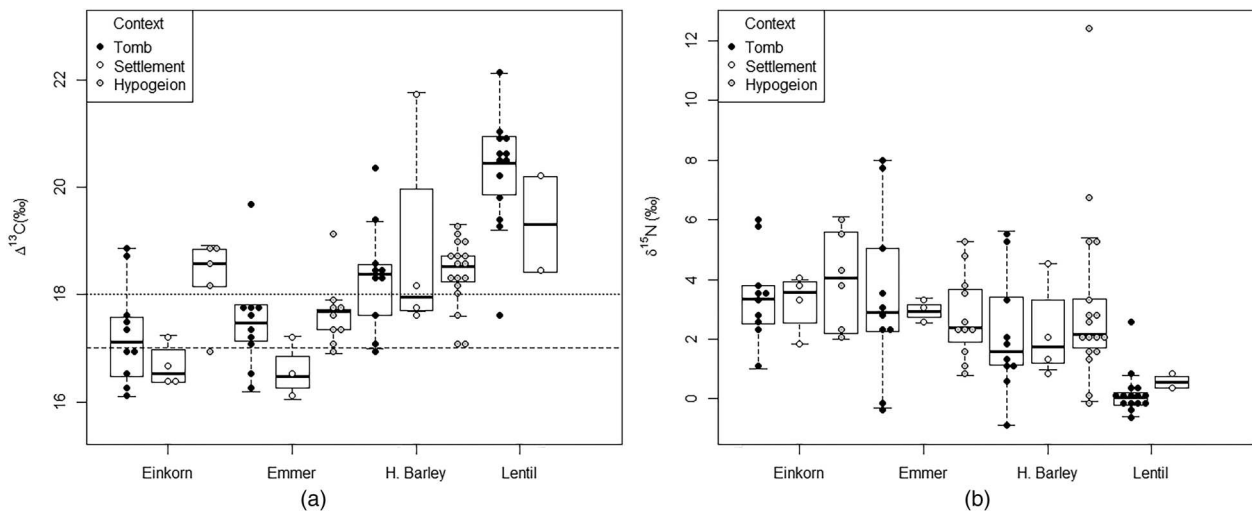


Figure 9. (a) $\Delta^{13}\text{C}$ values of the four crop species, coded by contextual category. The lower dashed line indicates the lower limit of the 'adequate water provision' zone for wheat. The upper dotted line indicates the lower limit of 'adequate water provision' zone for hulled barley. (b) $\delta^{15}\text{N}$ values of the four crop species, coded by contextual category.

seems to have continued without significant changes, based on current isotopic data, between the Late Bronze Age and the Early Iron Age. Variable and relatively high $\Delta^{13}\text{C}$ values of cereals suggest that these systems would have relied on the high annual rainfall experienced in this region to provide water for cereal cultivation rather than using irrigation schemes (cf. Wallace et al. 2013). In contrast, the $\Delta^{13}\text{C}$ values of lentil were markedly higher than those of the cereals, indicating that lentil was cultivated under different conditions. These conditions are likely to have been significantly *wetter* than those experienced by the cereals, possibly due to hand watering by local households. Ethnographic evidence from various regions in Greece suggests that pulse crops are often grown in vegetable gardens near the house, whilst cereals are cultivated in outfields farther from the settlement (Halstead 2014, 206). The carbon isotope results from Methone potentially indicate a similar cropping pattern present in the Late Bronze Age – Early Iron Age periods, with lentil possibly grown in more 'garden-like' infield plots near the main settlement so that they could be tended to and watered regularly, whilst cereals could have been grown in larger outfields farther away from the settlement.

Relatively low nitrogen stable isotope values indicate that crops may not have been grown in artificially enriched soils and that manure/middening material was not applied regularly to the arable fields. Certainly, the similarity in nitrogen stable isotope values between the three cereal species would suggest that there was no significant difference in terms of soil enrichment or modification by crop type. Likewise, the intra-species variability in terms of nitrogen stable isotope values indicates that all cereals were grown in variable conditions. Lentil also exhibited low $\delta^{15}\text{N}$ values contingent with a lack of soil enrichment or amendment. Soil enrichment through use of animal manure has

been widely documented from Neolithic and Bronze Age communities in southern Europe (e.g. Bogaard et al. 2013; Vaiglova et al. 2021) and the Middle East (Diffey et al. 2024; Styring et al. 2017). Ethnographic studies show that there are several factors influencing the decision to use manure or not (and how) in agricultural systems, including first of all its availability, and secondly its qualities in relation to transport, being a heavy and difficult resource to move (e.g. Halstead 2014). Because of these factors, the use of manure tends to be generally more plentiful in the immediate environs of a domestic settlement where livestock are kept or kitchen midden material is disposed of (Wilkinson, 1994). At Methone, the interpretation of manuring/middening practices is difficult to elucidate directly from nitrogen stable isotope values without an unmanured baseline⁴. On the basis of the results presented above, the stable nitrogen isotope results can be interpreted as an indication that the cereal crops and lentil were not being grown in soils that were consistently enriched through the application of manure/middening material. This could be because the cereals were cultivated away from the main settlement area or that domesticated animals were herded far away from the crop fields, making the transport of manure to the fields difficult or undesired.

Overall, the variable nature of the results of carbon and nitrogen stable isotope analysis from Methone indicate that there was a range of low intensity crop husbandry systems in use at the site, with some preferential treatment of lentil which appears to have been cultivated under significantly *wetter* conditions to those of the cereal crops.

Methone in Context

The relatively few well-preserved bioarchaeological assemblages and lack of other stable isotopic studies

on crops from northern Greece dated to the Early Iron Age render the results of this study particularly important within their wider geographical and chronological context, whilst results from the Late Bronze Age add important detail to the mosaic of practices in the north Aegean.

For the Late Bronze Age, previous stable isotopic work by Nitsch et al. (2017) has suggested that farming strategies in northern Greece were fairly variable, with some sites adopting intensive arable land management systems with the close integration of crops and livestock, whilst others used more extensive systems with herding and crop production kept fairly separate. This was likely due to the relative importance of different resources and their economic significance within the wider socio-economy of these settlements, as well as the variable landscapes present in northern Greece. The Late Bronze Age cereal carbon stable isotope results from Methone correlate broadly with the corresponding values from nearby Archontiko, central Macedonia and Toumba Thessalonikis (Nitsch et al. 2017), all of which would have had similar climates to Methone. When assessed together, these results indicate that wheat and barley crops received moderate to adequate water (rain-fed) provision throughout the region during this period. At both Archontiko and Toumba Thessalonikis, however, Nitsch et al. (2017) noted that wheat appears to be better watered than barley, a pattern that was also recognised at Late Bronze Age (LBA) Assiros Toumba (Wallace et al. 2015). However, this difference between species is not observed at Late Bronze Age Methone, suggesting that the wheats and barley were grown under similar watering conditions. Instead, the $\Delta^{13}\text{C}$ values of lentil at Methone are significantly higher than those recorded for the cereals, and importantly, are higher than any of the $\Delta^{13}\text{C}$ values documented at Archontiko (no LBA stable isotope data for lentil are available from Toumba Thessalonikis; Nitsch et al. 2017), which are within the moderate-adequate water provision levels. This would suggest that lentil at Methone was cultivated under *wetter* conditions than those indicated by the stable carbon isotope results from the other Late Bronze Age site with comparable data in the northern Aegean and may indicate the use of distinct agricultural management systems by different LBA societies.

Similarly, the nitrogen isotope values of cereals and pulses at LBA Archontiko are roughly similar to those seen for Methone, with most $\delta^{15}\text{N}$ values from Archontiko above 2‰. When compared with the unmanured faunal baseline inferred for the site, this would indicate that the cereals were grown using low-medium levels of artificial soil enrichment, but that pulses were unmanured. Comparisons between the Methone nitrogen stable isotope values and the Archontiko faunal baseline,

although purely exploratory, would suggest the same pattern in general soil amendment at both sites. At both Archontiko and Toumba Thessalonikis, however, hulled barley $\delta^{15}\text{N}$ values tend to be higher than those of the glume wheats. This has been interpreted as potentially reflecting the importance of barley within the human diet (Nitsch et al. 2017), or as a mechanism to ensure the availability of ‘early bite’ pasture for grazing animals (Halstead 2006). Again, however, this is not a pattern that is evident from the Methone stable nitrogen isotope results, where most taxa exhibit a comparable range of $\delta^{15}\text{N}$ values. Furthermore, the nitrogen isotope values from LBA Toumba Thessalonikis are significantly higher than those at Methone and are indicative of a comparatively more intensive manuring regime. Nitsch et al. (2017) state that these values are representative of a closely integrated relationship between crop and livestock production at the site linked to the creation of surplus crop staples that act as a risk buffering mechanism for times of economic hardship or harvest failure. By comparison, the scarcity of intensively manured crops from LBA (but also EIA) Methone is likely representative of a different crop production strategy in use at the site. Furthermore, the relative lack of available (animal) manure, as indicated by the low stable nitrogen isotopic values from Methone, may suggest that domestic animals were not being grazed near the site, and were instead herded to the south on the Katerini plain or further west in upland areas.

The stable isotope results for the Early Iron Age at Methone point to a continuity of practices with the previous period (Figure 8(a)). However, no other stable isotope studies are available for this period of northern Greece to allow comparisons between the agricultural strategies across the region. Traditional archaeobotanical analyses from other Early Iron Age sites are available and these indicate that domesticated crops continued being commonly cultivated across the Aegean (e.g. Livarda 2012; Margaritis 2017; Valamoti et al. 2018). A variety of cereals and pulses, such as hulled barley, glume and free-threshing wheats, lentil and bitter vetch, along with a range of other food plants, have been identified from various of northern Greek sites, such as Karabournaki and Toumba Thessalonikis (Valamoti et al. 2018). Similarly, zooarchaeological studies from the LBA–EIA show a heterogenous animal economy, with a range of domestic herbivores, indicating that mixed agropastoral farming practices were still in use at many sites (Dibble and Finné 2021). Finally, stable isotope analyses of human bones from Late Bronze Age and IA Geometric sites in the Aegean do not show a significant change in human consumption practices but instead suggest that diets were based mainly on

terrestrial plant and animal proteins throughout these periods (Dotsika et al. 2022).

The Late Bronze Age – Early Iron Age Agro-economy

Recent studies into the nature of Bronze Age agriculture in southern Greece and the Middle East (e.g. Diffey et al. 2020, 2024; Isaakidou et al. 2022; Styring et al. 2017) have indicated that this period was generally characterised by low-input, extensive cereal crop farming regimes, alongside large-scale herding. However, studies from the Aegean have showed that these patterns were not entirely homogenous, and instead there was some species-specific treatment of both plants and domesticated animals throughout the palatial era (Isaakidou et al. 2019, 2022). It has been suggested that the extensive agricultural systems were intended to maximise arable yields through the cultivation of larger plots of land rather than higher labour contributions, thus establishing *land* as the greatest source of wealth (Bogaard et al. 2018, 2019). Over time this type of farming may have led to the formation of land ‘monopolies’ whereby one family or social group controlled large tracts of arable land and therefore the agricultural economy (Halstead 1992). Certainly, during the Late Bronze Age in southern Greece large-scale agriculture was controlled by an elite bureaucracy with palaces acting as central places for administration and resource storage (Halstead 1999; Killen 2008). The collapse of these systems has led to debate over to what extent the agro-economies they controlled also disintegrated. In the north, a different socio-economic trajectory was followed and the few studies available so far show variation in the regimes, with both extensive and intensive systems adopted at sites such as Archontiko and Toumba Thessalonikis respectively (Nitsch et al. 2017). The evidence from Methone points to a continuation of the use of a relatively low-input system from the Late Bronze through to the Early Iron Age.

Overall, the archaeobotanical (Livarda et al. 2023; Livarda and Bouchard-Perron 2020) and crop stable isotopic data from Methone (this paper) do not support the traditional view of Early Iron Age agriculture proposed by Snodgrass (1987) that farming had been largely abandoned as populations turned to a more pastoral-based economy. Similarly, the results do not align with Cherry’s (1988) suggestion that agriculture returned to more intensive mixed strategies similar to those seen during the Neolithic period. Instead, the results largely indicate that from the Late Bronze Age – Early Iron Age farmers continued to use generally low-input but variable agricultural strategies. Within this context, however, there is evidence that individual sites in this region, including Methone, and likely throughout Greece in the Early Iron Age,

pursued agricultural systems that were adapted to specific local settings and environmental conditions. Foxhall (1995) suggests that in southern Greece, the collapse of palatial administration structures and of the centralised mobilisation of goods allowed smaller local communities to focus on their own subsistence economies. Due to the lack of those elite bureaucracies in the north, it is possible that similar systems of *localised* low-input agriculture may have been practiced throughout the Late Bronze Age and into the Early Iron Age. Certainly, the isotope results from Methone do not suggest that there was any radical change in agricultural practice between these periods and that even with a potentially drying climate (e.g. Kaniewski et al. 2013; Manning et al. 2023), communities in this region continued to rely on rain-fed cereal cultivation as a main-stay of their agro-economy, supplemented by more intensively managed pulses.

Conclusions

The results of crop stable isotope analysis from Methone have provided new insights into a Late Bronze Age – Early Iron Age agro-economy in northern Greece. Overall, the variable nature of the results from the site indicates that there was a range of low intensity crop husbandry systems in use at Methone, with different, preferential management of lentil in comparison to the cereals. Well-preserved bioarchaeological material is scarce in this region and period, and this paper represents the first crop stable isotope study of Early Iron Age material from the area. The results highlight the need to proceed with further isotopic analyses to increase the number of available samples by archaeological context and period. Going forward, more studies from sites in both northern and southern Greece will help to elaborate further the picture of agricultural heterogeneity during a crucial transition period as populations grappled with, and adapted to, changing local and regional, social and environmental conditions.

Notes

1. <https://www.weather-atlas.com/en/greece>
2. Involving researchers from the Pieria Archaeological Service, the Cotsen Institute of Archaeology, UCLA, Aristotle University, Thessaloniki, the Catalan Institute of Classical Archaeology (ICAC), University College Dublin, and the University of the Balearic Islands. See Morris et al. 2020 for full list of researchers and funding sources.
3. Lentil has been removed for this part of the analysis due to the lack of samples dated to the Early Iron Age and recovered from the Hypogeion.
4. Faunal stable isotope analysis work is ongoing.

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References

- Alagich, R., K. Trantalidou, M. C. Miller, and C. Smith. 2021. "Reconstructing Animal Management Practices at Greek Early Iron Age Zagora (Andros) Using Stable Isotopes." *Journal of Archaeological and Anthropological Sciences* 13 (1): 9. <https://doi.org/10.1007/s12520-020-01249-1>.
- Andreou, S. 2019. "The Thermaic Gulf." In *A Companion to the Archaeology of Early Greece and the Mediterranean*, edited by I. Lemos and A. Kotsonas, 913–938. Hoboken: Wiley and Sons.
- Andreou, S., and K. Kotsakis. 2000. "Counting People in an Artefact-Poor Landscape: The Langadas Case, Macedonia, Greece." In *Reconstructing Past Population Trends in Mediterranean Europe (3000 BC-AD 1800)*, edited by J. Bintliff, and K. Sbonias, 35–44. Oxford: Oxbow.
- Araus, J. L., A. Febrero, R. Buxo, M. Camalich, D. Martin, F. Molina, M. Rodriguez-Ariza, and I. Romagosa. 1997. "Changes in Carbon Isotope Discrimination in Grain Cereals from Different Regions of the Western Mediterranean Basin during the Past Seven Millennia. Palaeoenvironmental Evidence of a Differential Change in Aridity during the Late Holocene." *Global Change Biology* 3 (2): 107–118. <https://doi.org/10.1046/j.1365-2486.1997.00056.x>.
- Bessios, M. 2010. *Περίδων Στέφανος: Πύδνα, Μεθώνη και οι αρχαιότητες της βόρειας Πιερίας*, Κατερίνη. Εκδόσεις Α.Φ.Ε.
- Bessios, M. 2023. "The Excavation of the Hypogeion." In *Excavations at Ancient Methone, 2003-2011. Conducted by Matthaios Bessios, Athena Athanassiadou, and Konstantinos Noulas*, edited by S. P. Morris and J. K. Papadopoulou, 387–406. Los Angeles: Cotsen Institute of Archaeology. <http://www.ioa.ucla.edu/ancientmethone>.
- Bessios, M., A. Athanassiadou, and K. Noulas. 2023. "Excavations at Methone (2003–2013)." In *Excavations at Ancient Methone, 2003-2011. Conducted by Matthaios Bessios, Athena Athanassiadou, and Konstantinos Noulas*, edited by S. P. Morris and J. K.

- Papadopoulos, 19–48. Los Angeles: Cotsen Institute of Archaeology. <http://www.ioa.ucla.edu/ancientmethone>.
- Bogaard, A., M. Fochesato, and S. Bowles. 2019. “The Farming-Inequality Nexus: New Insights from Ancient Western Eurasia.” *Antiquity* 93 (371): 1129–1143. <https://doi.org/10.15184/aqy.2019.105>.
- Bogaard, A., R. A. Fraser, T. H. E. Heaton, M. Wallace, P. Vaiglova, M. Charles, G. Jones, et al. 2013. “Crop Manuring and Intensive Land Management by Europe’s First Farmers.” *Proceedings of the National Academy of Sciences* 110 (31): 12589–12594. <https://doi.org/10.1073/pnas.1305918110>.
- Bogaard, A., T. H. E. Heaton, P. Poulton, and I. Merbach. 2007. “The Impact of Manuring on Nitrogen Isotope Ratios in Cereals: Archaeological Implications for Reconstruction of Diet and Crop Management Practices.” *Journal of Archaeological Science* 34 (3): 335–343. <https://doi.org/10.1016/j.jas.2006.04.009>.
- Bogaard, A., A. Styring, M. Ater, Y. Hmimsa, L. Green, E. Stroud, J. Whitlam, et al. 2018. “From Traditional Farming in Morocco to Early Urban Agroecology in Northern Mesopotamia: Combining Present-day Arable Weed Surveys and Crop ‘Isoscapes’ to Reconstruct Past Agrosystems in (Semi-)Arid Regions.” *Environmental Archaeology* 23 (4): 303–322. <https://doi.org/10.1080/14614103.2016.1261217>.
- Charles, M., E. Forster, M. Wallace, and G. Jones. 2015. ““Nor Ever Lightning Char Thy Grain”: Establishing Archaeologically Relevant Charring Conditions and Their Effect on Glume Wheat Grain Morphology.” *STAR: Science and Technology of Archaeological Research* 1 (1): 1–6. <https://doi.org/10.1179/2054892315Y.0000000008>.
- Cherry, J. F. 1988. “Pastoralism and the Role of Animals in the pre- and Protohistoric Economies of the Aegean.” In *Pastoral Economies in Classical Antiquity*, edited by C. R. Whittaker, 6–34. Cambridge: Philological Society.
- Cleveland, W. S. 1979. “Robust Locally Weighted Regression and Smoothing Scatterplots.” *Journal of the American Statistical Association* 74 (368): 829–836. <https://doi.org/10.1080/01621459.1979.10481038>.
- Desborough, V. R. 1972. *The Greek Dark Ages*. London: Benn Publisher.
- Dibble, F., and M. Finné. 2021. “Socioenvironmental Change as a Process: Changing Foodways as Adaptation to Climate Change in South Greece from the Late Bronze Age to the Early Iron Age.” *Quaternary International* 597:50–62. <https://doi.org/10.1016/j.quaint.2021.04.024>.
- Diffey, C., G. Emberling, A. Bogaard, and M. Charles. 2024. “Cropping the Margins: New Evidence for Urban Agriculture at mid-3rd Millennium B.C.E. Tell Brak, Syria.” *Iraq* 85:151–178. <https://doi.org/10.1017/irq.2023.3>.
- Diffey, C., R. Neef, J. Seeher, and A. Bogaard. 2020. “The Agroecology of an Early State: New Results from Hattusha.” *Antiquity* 94 (377): 1204–1223. <https://doi.org/10.15184/aqy.2020.172>.
- Dotsika, E., M. Tassi, P. Karalis, S. Gougoura, E. F. Kranioti, D. E. Michael, M. Kazou, A. E. Poutouki, and G. Diamantopoulos. 2022. “Reconstruction of Greek Population Diet from Neolithic Period to Modern Times.” *American Journal of Biological Anthropology* 178 (2): 328–346. <https://doi.org/10.1002/ajpa.24516>.
- Drake, B. L. 2012. “The Influence of Climate Change on the Late Bronze Age Collapse and the Greek Dark Ages.” *Journal of Archaeological Science* 39 (6): 1862–1870. <https://doi.org/10.1016/j.jas.2012.01.029>.
- Farquhar, G. D., J. R. Ehleringer, and K. T. Hubick. 1989. “Carbon Isotope Discrimination and Photosynthesis.” *Annual Review of Plant Physiology and Plant Molecular Biology* 40 (1): 503–537. <https://doi.org/10.1146/annurev.pp.40.060189.002443>.
- Ferrio, J. P., J. L. Araus, R. Buxó, J. Voltas, and J. Bort. 2005. “Water Management Practices and Climate in Ancient Agriculture: Inferences for the Stable Isotope Composition of Archaeobotanical Remains.” *Vegetation History and Archaeobotany* 14 (4): 510–517. <https://doi.org/10.1007/s00334-005-0062-2>.
- Fiorentino, G., J. P. Ferrio, A. Bogaard, J. L. Araus, and S. Riehl. 2015. “Stable Isotopes in Archaeobotanical Research.” *Vegetation History and Archaeobotany* 24 (1): 215–227. <https://doi.org/10.1007/s00334-014-0492-9>.
- Foxhall, L. 1995. “Bronze to Iron: Agricultural Systems and Political Structures in Late Bronze Age and Early Iron Age Greece.” *Annual of the British School at Athens* 90:239–250. <https://doi.org/10.1017/S006824540001618X>.
- Francey, R. J., C. E. Allison, D. M. Etheridge, C. M. Trudinger, I. G. Enting, M. Leuenberger, R. L. Langenfelds, E. Michel, and L. P. Steele. 1999. “A 1000-Year High Precision Record of Delta C-13 in Atmospheric CO₂.” *Tellus B* 51 (2): 170–193. <https://doi.org/10.3402/tellusb.v51i2.16269>.
- Fraser, R., A. Bogaard, T. H. E. Heaton, M. Charles, G. Jones, B. T. Christensen, P. Halstead, et al. 2011. “Manuring and Stable Nitrogen Isotope Ratios in Cereals and Pulses: Towards a new Archaeobotanical Approach to the Inference of Land use and Dietary Practices.” *Journal of Archaeological Science* 38 (10): 2790–2804. <https://doi.org/10.1016/j.jas.2011.06.024>.
- Fraser, R., A. Bogaard, M. Schäfer, R. Arbogast, and T. H. E. Heaton. 2013. “Integrating Botanical, Faunal and Human Stable Carbon and Nitrogen Isotope Values to Reconstruct Land Use and Palaeodiet at LBK Vaihingen an der Enz, Baden-Württemberg.” *World Archaeology* 45 (3): 492–517. <https://doi.org/10.1080/00438243.2013.820649>.
- Godefroy, L., A. Salavert, and E. Margaritis. 2023. “Enlightening the Darkness: The Potential of Charcoal Analysis for the Study of Vegetation Dynamics and Relative Exploitation at Krania during the Iron Age Greece.” *Quaternary International* 659:24–33. <https://doi.org/10.1016/j.quaint.2022.08.002>.
- Halstead, P. 1981. “From Determinism to Uncertainty: Social Storage and the Rise of the Minoan Palace.” In *Economic Archaeology: Towards an Interpretation of Ecological and Social Approaches*, BAR-IS 96, edited by A. Sheridan, and G. N. Bailey, 187–213. Oxford: Archaeopress.
- Halstead, P. 1992. “Agriculture in the Bronze age Aegean: Towards a Model of Palatial Economy.” In *Agriculture in Ancient Greece: Proceedings of the Seventh International Symposium at the Swedish Institute at Athens*, edited by B. Wells, 105–117. Stockholm: Swedish Institute at Athens.
- Halstead, P. 1999. “Surplus and Share-Croppers: The Grain Production Strategies of Mycenaean Palaces.” In *MELETHMATA. Studies Presented to Malcolm H. Weiner as He Enters His 65th Year*, edited by P. Betancourt, V. Karageorghis, R. Laffineur, and W.-D. Niemeier, 19–26. Liege: Aegaeum.
- Halstead, P. 2006. *What’s Ours Is Mine? Village and Household in Early Farming Society in Greece. Achtentwintigste Kroon-Voordracht*. Stichting

- Nederlands Museum voor Anthropogic en Praehistorie: Amsterdam.
- Halstead, P. 2014. *Two Oxen Ahead: Pre-mechanized Farming in the Mediterranean*. Oxford: Oxford University Press.
- Indermühle, A., T. F. Stocker, F. Joos, H. Fischer, H. J. Smith, M. Wahlen, B. Deck, et al. 1999. "Holocene Carbon-Cycle Dynamics Based on CO₂ Trapped in ice at Taylor Dome, Antarctica." *Nature* 398 (6723): 121–126. <https://doi.org/10.1038/18158>.
- Isaakidou, V., P. Halstead, E. Stroud, A. Sarpaki, E. Hatzaki, E. Nitsch, and A. Bogaard. 2022. "Changing Land Use and Political Economy at Neolithic and Bronze Age Knossos, Crete: Stable Carbon ($\delta^{13}\text{C}$) and Nitrogen ($\delta^{15}\text{N}$) Isotope Analysis of Charred Crop Grains and Faunal Bone Collagen." *Proceedings of the Prehistoric Society* 88:155–191. <https://doi.org/10.1017/ppr.2022.4>.
- Isaakidou, V., A. Styring, P. Halstead, E. Nitsch, E. Stroud, P. le Roux, J. Lee-Thorp, and A. Bogaard. 2019. "From Texts to Teeth: A Multi-isotope Study of Sheep and Goat Herding Practices in the Late Bronze Age ('Mycenaean') Polity of Knossos, Crete." *Journal of Archaeological Science: Reports* 23:36–56. <https://doi.org/10.1016/j.jasrep.2018.09.019>.
- Kaniewski, D., E. V. Campo, J. Guiot, S. L. Burel, T. Otto, and C. Baeteman. 2013. "Environmental Roots of the Late Bronze Age Crisis." *PLoS One* 8 (8): e71004. <https://doi.org/10.1371/journal.pone.0071004>.
- Killen, J. T. 2008. "Mycenaean Economy." In *A Companion to Linear B: Mycenaean Greek Texts and Their World, Volume 1*, edited by Y. Duhoux, and A. Morpurgo Davies, 159–200. Louvain-la-Neuve: Peeters.
- Knodell, A. R. 2021. *Societies in Transition in Early Greece: An Archaeological History*. Oakland: University of California Press.
- Koukouli-Chrysanthaki, X. 2014. 'Η αρχαιολογική έρευνα στην Μακεδονία της Πρώιμης Εποχής του Σιδήρου. Απολογισμός και προοπτικές', In Στεφανή, Ε., Μερούσης, Ν., Δημουλά, Α. (eds.), *Εκατό Χρόνια Έρευνας στην Προϊστορική Μακεδονία 1912–2012*. Πρακτικά Διεθνούς Συνεδρίου, Αρχαιολογικό Μουσείο Θεσσαλονίκης, 22–24 Νοεμβρίου 2012, Thessaloniki, pp. 153–177.
- Krahtopoulou, A. 2010. *The Geoarchaeology of Northern Pieria, Macedonia, Greece*. Katerini: Mati Publications.
- Larsson, M., J. Bergman, and P. Lagerås. 2019. "Manuring Practices in the First Millennium AD in Southern Sweden Inferred from Isotopic Analysis of Crop Remains." *PLoS One* 14:e0215578.
- Lemos, I. 2002. *The Protogeometric Aegean: The Archaeology of the Late Eleventh and Tenth Centuries BC*. Oxford: Oxford University Press.
- Lemos, I. 2010. "The Excavation at Lefkandi-Xeropolis (2003–2009): Summary of the Mycenaean Seminar, 12 May 2010." *Bulletin of the Institute of Classical Studies of the University of London* 53:134–136.
- Leuenberger, M., U. Siegenthaler, and C. C. Langway. 1992. "Carbon Isotope Composition of Atmospheric CO₂ during the Last ice age from an Antarctic ice Core." *Nature* 357 (6378): 488–490. <https://doi.org/10.1038/357488a0>.
- Livarda, A. 2008. "Knossos, the Little Palace North Project, Part I: The Early Greek Periods." *Annual of the British School at Athens*, 103: 259–271.
- Livarda, A. 2012. "The Archaeobotanical Evidence of the Late Bronze Age and Protogeometric Occupation under the Roman Villa Dionysus, Knossos, Crete, and an Overview of the Protogeometric Data of Greece." *Annual of the British School at Athens* 107:189–209. <https://doi.org/10.1017/S0068245412000068>.
- Livarda, A. 2014. "Archaeobotany in Greece." *Archaeological Reports* 60:106–116. <https://doi.org/10.1017/S057060841400012X>.
- Livarda, A., and J.-A. Bouchard-Perron. 2020. "The Ancient Methone Archaeological Project: A Preliminary Report on Fieldwork, 2014–2017." *Hesperia*, 89(4), 659–723.
- Livarda, A., and G. Kotzamani. 2013. "The Archaeobotany of Neolithic and Bronze Age Crete: Synthesis and Prospects." *The Annual of the British School at Athens* 108:1–29. <https://doi.org/10.1017/S0068245413000063>.
- Livarda, A., R. Veropoulidou, A. Vasileiadou, and L. Picornell Gelabert. 2023. "Lifeways and Foodways in Iron Age Methone: A Perishable Material Culture Approach." In *Excavations at Ancient Methone, 2003–2011. Conducted by Matthaios Bessios, Athena Athanassiadou, and Konstantinos Noulas*, edited by S. P. Morris and J. K. Papadopoulos, 471–486. Los Angeles: Cotsen Institute of Archaeology. <http://www.ioa.ucla.edu/ancientmethone>.
- Manning, S. W., C. Kocik, B. Lorentzen, and J. P. Sparks. 2023. "Severe Multi-year Drought Coincident with Hittite Collapse around 1198–1196 BC." *Nature* 614 (7949): 719–724. <https://doi.org/10.1038/s41586-022-05693-y>.
- Margaritis, E. 2017. "Domestic and Ritual use of Plants in Early Iron Age Greece." In *Regional Stories towards a New Perception of the Early Greek World: Acts of an International Symposium in Honour of Professor Jan Bouzek, Volos 18–21*, edited by A. M. Ainian, A. Alexandridrou, and X. Charalambidou, 735–746. Thessaly: Volos University Press.
- Morgan, C. 2009. "The Early Iron Age." In *A Companion to Archaic Greece*, edited by K. A. Raaflaub, and H. van Wees, 41–63. Oxford: Blackwell Publishing.
- Morris, S., J. Papadopoulos, M. Bessios, A. Athanassiadou, and K. Noulas. 2020. "The Ancient Methone Archaeological Project: A Preliminary Report on Fieldwork, 2014–2017." *Hesperia* 89 (4): 659–723. <https://doi.org/10.2972/hesperia.89.4.0659>.
- Morris, S. P., S. Triantaphyllou, V. Papanthasiou, B. N. Damiata, and J. Southon. 2023. "The Late Bronze Age Cemetery." In *Excavations at Ancient Methone, 2003–2011. Conducted by Matthaios Bessios, Athena Athanassiadou, and Konstantinos Noulas*, edited by S. P. Morris and J. K. Papadopoulos, 239–322. Los Angeles: Cotsen Institute of Archaeology. <http://www.ioa.ucla.edu/ancientmethone>.
- Nitsch, E. K., S. Andreou, A. Creuzieux, A. Gardeisen, P. Halstead, V. Isaakidou, A. Karathanou, et al. 2017. "A Bottom-up View of Food Surplus: Using Stable Carbon and Nitrogen Isotope Analysis to Investigate Agricultural Strategies and Diet at Bronze Age Archontiko and Thessaloniki Toumba, Northern Greece." *World Archaeology* 49 (1): 105–137. <https://doi.org/10.1080/00438243.2016.1271745>.
- Nitsch, E. K., M. Charles, and A. Bogaard. 2015. "Calculating a Statistically Robust $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ Offset for Charred Cereal and Pulse Seeds." *Science and Technology of Archaeological Research* 1 (1): 1–4. <https://doi.org/10.1179/2054892315Y.0000000001>.
- Papadopoulos, J. K. 1996. "Dark Age Greece." In *The Oxford Companion to Archaeology*, edited by B. M. Fagan, 253–255. Oxford: Oxford University Press.

- Papadopoulos, J. K. 2023. "The Early Iron Age Settlement and Pottery: An Overview." In *Excavations at Ancient Methone, 2003-2011. Conducted by Matthaios Bessios, Athena Athanassiadou, and Konstantinos Noulas*, edited by S. P. Morris, and J. K. Papadopoulos, 323–384. Los Angeles: Cotsen Institute of Archaeology. <http://www.ioa.ucla.edu/ancientmethone>.
- Polunin, O., B. Everard, P. Halliday, and J. Callow. 1987. *Flowers of Greece and the Balkans: A Field Guide*. Oxford: Oxford University Press.
- Poulaki-Pantermali, E. 2013. Μακεδονικός Όλυμπος: Μύθος-ιστορία αρχαιολογία, Thessaloniki: Ministry of Culture and Sports, KZ' Ephorate of Prehistoric and Classical Antiquities.
- Raven, J. A., M. Andrews, and A. Quigg. 2005. "The Evolution of Oligotrophy: Implications for the Breeding of Crops Plants for low Input Agricultural Systems." *Annals of Applied Biology* 146 (3): 261–280. <https://doi.org/10.1111/j.1744-7348.2005.040138.x>.
- Renfrew, C. 1972. *The Emergence of Civilisation: The Cyclades and the Aegean in the Third Millennium BC*. London: Methuen.
- Renfrew, C. 1982. "Polity and Power." In *An Island Polity. The Archaeology of Exploitation in Melos*, edited by C. Renfrew, and M. Wagstaff, 264–290. Cambridge: Cambridge University Press.
- Snodgrass, A. M. 1971. *The Dark Age of Greece: An Archaeological Survey of the Eleventh to the Eighth Centuries BC*. 2nd ed. New York: Routledge.
- Snodgrass, A. M. 1987. *An Archaeology of Greece: The Present State and Future Scope of the Discipline*. Berkeley: University of California Press.
- Stroud, E., M. Charles, A. Bogaard, and H. Hamerow. 2023. "Turning up the Heat: Assessing the Impact of Charring Regime on the Morphology and Stable Isotopic Values of Cereal Grains." *Journal of Archaeological Science* 153:105754. <https://doi.org/10.1016/j.jas.2023.105754>.
- Styring, A. K., M. Charles, F. Fantone, M. M. Hald, A. McMahon, R. H. Meadow, G. K. Nicholls, et al. 2017. "Isotope Evidence for Agricultural Extensification Reveals How the World's First Cities Were Fed." *Nature Plants* 3:1–11. <https://doi.org/10.1038/nplants.2017.76>.
- Styring, A. K., P. Vaiglova, A. Bogaard, M. J. Church, D. R. Gröcke, M. Larsson, X. Liu, E. Stroud, P. Szpak, and M. P. Wallace. 2024. "Recommendations for Stable Isotope Analysis of Charred Archaeological Crop Remains." *Frontiers in Environmental Archaeology* 3:1470375. <https://doi.org/10.3389/fearc.2024.1470375>.
- Szpak, P., and K. L. Chiou. 2020. "A Comparison of Nitrogen Isotope Compositions of Charred and Desiccated Botanical Remains from Northern Peru." *Vegetation History and Archaeobotany* 29 (5): 527–538. <https://doi.org/10.1007/s00334-019-00761-2>.
- Szpak, P., J. Metcalfe, and R. Macdonald. 2017. "Best Practices for Calibrating and Reporting Stable Isotope Measurements in Archaeology." *Journal of Archaeological Science: Reports* 13:609–616. <https://doi.org/10.1016/j.jasrep.2017.05.007>.
- Thomas, C. G. 2009. "The Mediterranean World in the Early Iron Age." In *A Companion to Archaic Greece*, edited by K. A. Raaflaub, and H. van Wees, 22–40. Oxford: Blackwell Publishing.
- Treasure, E. R., M. J. Church, and D. R. Gröcke. 2016. "The Influence of Manuring on Stable Isotopes ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) in Celtic Bean (*Vicia faba* L.): Archaeobotanical and Palaeodietary Implications." *Archaeological and Anthropological Sciences* 8 (3): 555–562. <https://doi.org/10.1007/s12520-015-0243-6>.
- Vaiglova, P., J. Coleman, C. Diffey, V. Tzevelekidi, M. Fillios, M. Pappa, P. Halstead, et al. 2021. "Exploring Diversity in Neolithic Agropastoral Management in Mainland Greece Using Stable Isotope Analysis." *Environmental Archaeology* 28 (2): 62–85. <https://doi.org/10.1080/14614103.2020.1867292>.
- Vaiglova, P., C. Snoeck, E. Nitsch, A. Bogaard, and J. Lee-Thorp. 2014. "Impact of Contamination and pre-Treatment on Stable Carbon and Nitrogen Isotopic Composition of Charred Plant Remains." *Rapid Communications in Mass Spectrometry* 28 (23): 2497–2510. <https://doi.org/10.1002/rcm.7044>.
- Valamoti, S. M. 2023. *Plant Foods of Greece: A Culinary Journey to the Neolithic and Bronze Ages*. Tuscaloosa: The University of Alabama Press.
- Valamoti, S. M., E. Gkatzogia, I. Hristova, and E. Marinova. 2018. "Iron Age Cultural Interactions, Plant Subsistence and Land Use in Southeastern Europe Inferred from Archaeobotanical Evidence of Greece and Bulgaria." In *Archaeology across Frontiers and Borderlands: Fragmentation and Connectivity in the North Aegean and the Central Balkans from the Bronze Age to the Iron Age*, edited by S. Gimatzidis, and M. Pieniążek, 269–290. Vienna: Austrian Academy of Sciences Press.
- Valamoti, S. M., and C. Petridou. 2022. "Cooking with Cereals in the Early Bronze Age Kitchens of Archondiko Giannitson (Northern Greece): An Archaeobotanical Investigation of Phase IV (2135-2020 cal BC)." In *Cooking with Plants in Ancient Europe and Beyond: Interdisciplinary Approaches to the Archaeology of Plants Foods*, edited by S. M. Valamoti, A. Dimoula, and M. Ntinou, 43–56. Sidestone Press: Leiden.
- Veropoulidou and Krahtopoulou. Forthcoming. *Changing Landscapes, Constant Tastes: Land and Time Crossings in Pieria, Northern Greece*.
- Wallace, M., G. Jones, M. Charles, R. Fraser, P. Halstead, T. H. E. Heaton, and A. Bogaard. 2013. "Stable Carbon Isotopes Analysis as a Direct Means of Inferring Crop Water Status and Water Management Practices." *World Archaeology* 45 (3): 388–409. <https://doi.org/10.1080/00438243.2013.821671>.
- Wallace, M. P., G. Jones, M. Charles, R. Fraser, T. H. E. Heaton, and A. Bogaard. 2015. "Stable Carbon Isotope Evidence for Neolithic and Bronze Age Crop Water Management in the Eastern Mediterranean and Southwest Asia." *PLoS One* 10 (6). <https://doi.org/10.1371/journal.pone.0127085>.
- Whitelaw, T. 2012. "The Urbanisation of Prehistoric Crete: Settlement Perspectives on Minoan State Formation." In *Back to the Beginning: Reassessing Social and Political Complexity on Crete during the Early and Middle Bronze Age*, edited by I. Schoep, P. Tomkins, and J. Driessen, 114–176. Oxford: Oxbow Books.
- Wilkinson, T. J. 1994. "The Structure and Dynamics of dry-Farming States in Upper Mesopotamia [and Comments and Reply]." *Current Anthropology* 35 (5): 483–520. <https://doi.org/10.1086/204314>.