Archaeological and Anthropological Sciences (2021) 13: 9
https://doi.org/10.1007/s12520-020-01249-1

ORIGINAL PAPER

Reconstructing animal management practices at Greek Early Iron Age Zagora (Andros) using stable isotopes

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Received: 15 June 2020 / Accepted: 1 December 2020 / Published online: 4 January 2021

Abstract

The Early Iron Age was an important period of Greek history during which the Greek city states emerged and the two earliest works of western literature, Homer's *Iliad* and *Odyssey*, were likely composed. This paper introduces the results of faunal isotope analyses (carbon and nitrogen) from the settlement of Zagora on Andros (900–700 BC), the first such study to focus on agriculture from the Greek Early Iron Age. Due to limited post-abandonment activity, Zagora provides us with a unique opportunity to investigate agricultural practices at a well-preserved settlement from the period. Amongst our findings we identify possible evidence of specialised cattle management as well as evidence that suggests agriculture may have intensified during the final decades of the settlement's occupation.

Keywords Early Iron Age · Zagora · Agriculture · Stable isotopes · Greece · Homer

Introduction

Following the collapse of the archaeologically conspicuous Mycenaean palatial system of the Late Bronze Age, the Greek Early Iron Age (EIA; ca. 1050–700 BC) is characterised for much of its duration by comparatively scant archaeological remains. This is largely owing to the tendency of successful settlements from this period to sustain continued occupation for centuries, even millennia, afterward. The relative paucity of material has traditionally earned the EIA the sobriquet 'Dark Age' (e.g. Snodgrass 1971; Dickinson 2006), although an increase in the number of excavated sites more recently has led to this label being questioned (Mazarakis Ainian 2007; Mazarakis Ainian et al. 2017). The last several decades of the EIA provide evidence of rapid population growth, an increase in trade, the birth of the Greek city state, the *polis*, and the beginning of Greek colonisation of the wider Mediterranean, so that it has been referred to as the 'Greek Renaissance' (Coldstream 1977). It is also the period especially associated with Homer's epics *Iliad* and *Odyssey* (Osborne 2004). Although the epics include an element of myth and the exact period of composition in the form now known is unclear, these works evidently contain 'some genuine memories' of EIA society (Morris 1997; Raaflaub 1997).

EIA settlements are believed to have been ruled by chiefs or elite groups such as hereditary aristocracies (Coldstream 1977; Mazarakis Ainian 1997). The large herds, such as those owned by a settlement's *basileus*, or ruler, might have been managed by specialist herders (e.g. the cowherd, Hom. *Od.* 20.209–15). Presumably there also existed smaller family herds that we typically associate with more recent small-scale rural communities (Halstead 2014). Such communities likely predominated during the EIA (Coldstream 1977). Our present knowledge of farming during the EIA is drawn from material culture along with faunal and the sparse archaeobotanical evidence. These are supplemented by anecdotes from Homer as well as from Hesiod who composed a work which discusses the agricultural calendar, *Works and Days*, ca. 700 BC (Millett 1984).

This paper uses the carbon and nitrogen stable isotopic composition (δ^{13}C and δ^{15}N) of bone collagen to examine the diets of animals recovered from the Greek EIA settlement

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of Zagora (ca. 900–700 BC) on the island of Andros (Fig. 1), with a view to assessing their management. A further aim is to explore whether any diachronic changes in animal management are visible between the early (Sub-Protogeometric, 900–850 BC and Middle Geometric, 850–750 BC; hereafter SPG/MG) and the final (Late Geometric, 750–700 BC; hereafter LG) settlement phases. Any such differences might reflect social changes that accompanied the so-called 'Greek Renaissance'.

Background

Zagora

Zagora is situated on an elevated headland on the west coast of Andros, where the climate is generally Mediterranean in character with hot, dry summers, and rainfall primarily occurring from late autumn to spring. The conditions in the island's upland mountain valleys and on the northern side of the NW-SE mountain range, however, are milder and they receive more precipitation as is evident in the watercourses and indigenous flora reflective of a more temperate climate (Snogerup et al. 2006). Archaeobotanical remains at Zagora were recovered only during the most recent field seasons (2012–2014; 2019) and their study is as of yet incomplete, so we have little evidence for the make-up of the contemporary botanical landscape. The extensive and fertile Messaria valley, located a few kilometres inland from Zagora, provides substantial arable land for growing cereals and other crops, in contrast with the steep rocky terrain surrounding the settlement.

The town of Zagora was abandoned ca. 700 BC and never re-occupied as a settlement, making it one of the best preserved of the period (Beaumont et al. 2012; Cambitoglou 1981). Thus far, approximately 10% of Zagora's 7.8 ha has been excavated, with the greatest focus of excavations being the D and H areas at the settlement's highest point as well as the J area further down the slope to the southeast (Fig. 1; Beaumont et al. 2012). While the town's political structure is unknown, the suggestion has been made that a 'chieftain' resided in a prominent location by the sacred area within the settlement (Mazarakis Ainian 1997).

Animal species recovered from Zagora include *Bos taurus* (cattle), *Ovis aries/Capra hircus* (sheep/goat - caprine), *Sus domesticus* (pig), *Canis familiaris* (dog), *Lepus europaeus* (hare) and fish, with the specific species of fish undetermined (Barnetson 1977). The majority of species identified are domestic which is typical of non-Cretan Greek EIA island sites

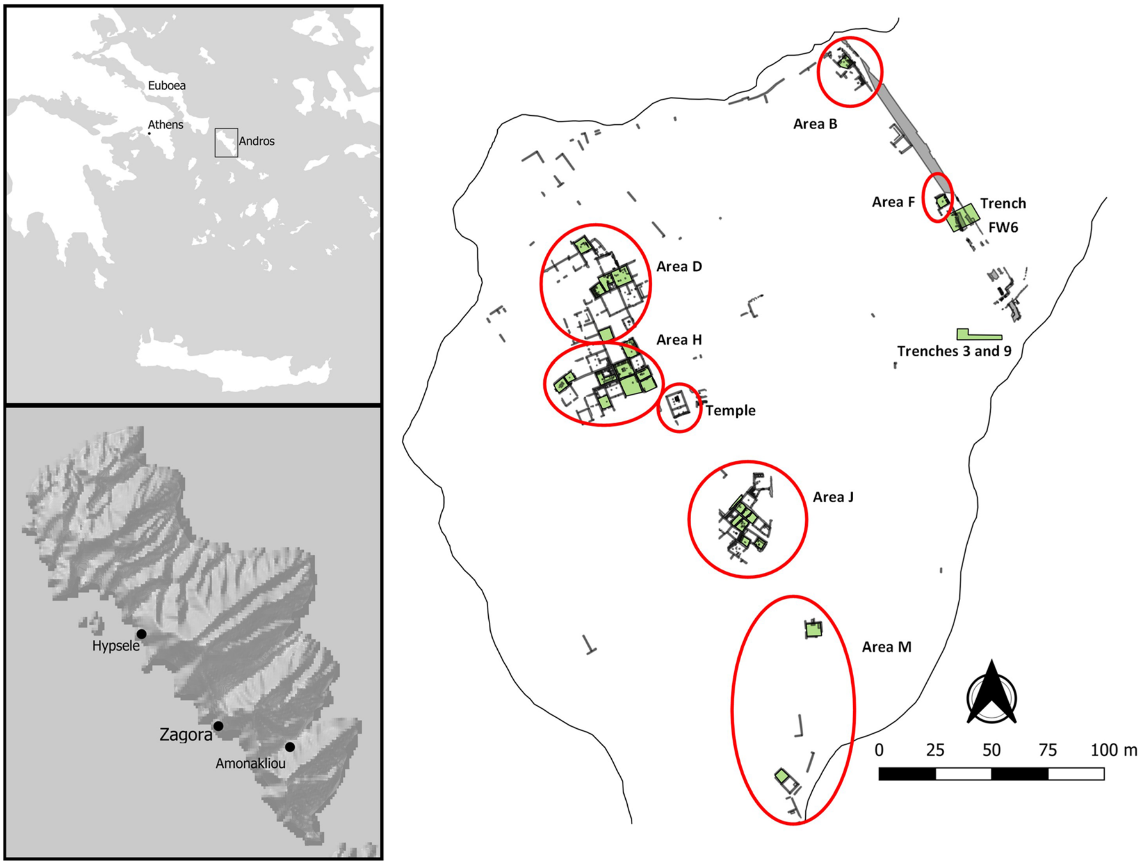

Fig. 1 Map showing the location of Zagora and settlement plan with areas sampled indicated by shading (Global Multi-resolution Terrain Elevation Data of Andros courtesy of the US Geological Survey; Zagora settlement plan after Coulton, McCallum, Anderson and Wilson)

(Trantalidou 2017). Of the caprines, goats would have outnumbered sheep since 16 of the 17 caprine samples analysed in this study that were distinguishable as either sheep or goat were attributed to goat. Goats (rather than sheep) are much better suited to the steep topography of many parts of Andros which are inappropriate for cultivation, so goats would have had a wider range of vegetation to consume than sheep.

Caprines and pigs are reported to have been killed in the 1–3 year range in 'many cases' (Barnetson 1977, p. 22), which implies an emphasis on the exploitation of caprines for meat. Our observations when selecting samples for analysis, however, suggest that for caprines this figure may well be higher, in the 4–8 year range, thereby implying that secondary products such as wool or milk could have been the main exploitation strategy. This discrepancy could be in part due to the fact that the faunal report provides animal age ranges based on bone epiphyseal fusion state and tooth eruption stages from in situ mandibular teeth while we additionally noted tooth wear stages of loose teeth. More reliable data here will only be forthcoming when the teeth and bones are aged in a systematic fashion. Only two juvenile cattle have been identified thus far at Zagora (Barnetson 1977, pp. 22–23), so it is likely that cattle were used for plough traction or transport rather than large-scale dairy production which would result in the slaughter of more infants. Based on the presence within houses of all body parts of caprines and pigs, it is believed that whole carcasses of these animals may have been prepared or consumed domestically. In contrast, cattle body parts are more widely dispersed, indicating they were more likely to have been shared between households (Barnetson 1977, p. 23).

Thus far, published dietary isotopic work on Greek EIA material has been limited to a handful of studies of human burials on the mainland (Panagiotopoulou et al. 2016; Papathanasiou et al. 2013; Triantaphyllou 2001, 2015), and those few faunal remains that were analysed were used to provide context for the composition of human diet (Panagiotopoulou et al. 2016; Papathanasiou et al. 2013). To our knowledge, this is the first isotopic study from the Greek EIA to focus specifically on agricultural practices.

Stable isotopes

Animal bone collagen $\delta^{13}C$ and $\delta^{15}N$ values primarily reflect the long-term average isotopic composition of the protein component of the food consumed by animals (Ambrose and Norr 1993; Hedges et al. 2007) and can hence provide an insight into the animal management strategies utilised at ancient sites such as Zagora. The $\delta^{13}C$ of bone collagen is offset from diet by roughly 5 ‰ due to fractionation and a small trophic level increase (Hedges 2006; van der Merwe and Vogel 1978), whereas $\delta^{15}N$ increases between 3-6 ‰ with each successive trophic level (Ambrose and DeNiro 1986; DeNiro and Epstein 1981; Hedges and Reynard 2007; O'Connell et al. 2012; Schoeninger and DeNiro 1984). Hence, the isotopic composition of an animal's collagen is dependent on the isotopic composition of primary producers at the base of the food chain.

The carbon isotopic composition of terrestrial plants is primarily influenced by their photosynthetic characteristics. On Andros, the modern vegetation is predominantly C_3 (plants that follow the Calvin cycle) but includes a number of endemic C_4 species (those that follow the Hatch-Slack pathway) (Snogerup et al. 2006). The only domesticated C_4 crop available during Zagora's period of occupation was millet, which has been cultivated in Greece since the Bronze Age (Valamoti 2016). Vegetation following the two different modes of photosynthesis are clearly distinguishable isotopically, with C_3 plants having a mean $\delta^{13}C$ of around −27 ‰ and C_4 plants −13 ‰ (Bender 1968; O'Leary 1988), with distributions around these values that do not overlap. Marine plants and algae assimilate dissolved CO_2 and bicarbonate from the water, which has a $\delta^{13}C$ value 7–8 ‰ greater than atmospheric CO_2, resulting in enriched ^{13}C values compared to land-based C_3 plants (Smith and Epstein 1971). The $\delta^{13}C$ values of contemporary C_3 plants are largely affected by water availability during growth, with dryer conditions encouraging less stomatal opening to conserve moisture resulting in minimal discrimination against the heavier isotope ^{13}C (Farquhar and Richards 1984). In contrast, in wetter conditions plants discriminate more against ^{13}C, resulting in its depletion in plant matter and hence more negative $\delta^{13}C$ values.

Plant nitrogen is derived from the soil and, in nitrogen-fixing plants, from the atmosphere, with the latter having $\delta^{15}N$ values close to that of atmospheric nitrogen (0 ‰), while the former have values closer to that of the substrate, without notable fractionation (Delwiche and Steyn 1970). Manuring of crops has been shown to increase their $\delta^{15}N$ values by as much as several per mil (Bogaard et al. 2007; Riga et al. 1971). Various other factors can also influence the $\delta^{15}N$ value of plants. The so-called 'sea spray effect' can impact plants growing close to the coast, resulting in enriched ^{15}N compositions due to marine nitrates in the sea spray (Virginia and Delwiche 1982), while waterlogged soil can also increase plant $\delta^{15}N$ due to soil denitrification (Kendall 1998). Aridity and saline soils have been linked to increased plant $\delta^{15}N$ values (Heaton 1987), although the latter could instead be due to sea spray or denitrification under wet conditions in coastal areas, since an experimental study of barley revealed a negative correlation between soil salinity and plant $\delta^{15}N$ (Handley et al. 1997). Due to the greater length of aquatic food chains compared to terrestrial ones as well as the higher $\delta^{15}N$ of sea water relative to the atmosphere, $\delta^{15}N$ tends to be higher in consumers of marine species (Peterson and Fry 1987; Schoeninger and DeNiro 1984; Sigman and Casciotti 2001).

Material and methods

Sample selection

A total of 102 bones were sampled in this study, excavated during the 1967–1974 and 2012–2014 field seasons (Table 1). Material was recovered via manual collection during excavation, dry sieving and, in the 2012–2014 campaign, from the heavy fraction after the use of a flotation tank for environmental sampling.

Species selected for analysis include the main domesticates (i.e. cattle, sheep, goat and pig) as well as hare and dog. The hare samples were analysed because they provide the only evidence for hunted fauna at Zagora; the single available dog sample was selected for measurement since dogs' diets are isotopically similar to associated humans (Guiry 2012) and so contribute useful data in the absence of having access to skeletal material from the human population (the town's necropolis has not as yet been identified).

Samples were retrieved from houses in areas B, D, F, J, H and M, and were generally taken from within the latest floors/levels of rooms and courtyards dated to the LG period, as well as from some earlier well-sealed lower floors or sub-floor levelling fills resting on bedrock. In addition, significant quantities of faunal remains were excavated from refuse dumps, namely trenches FW6, 3 and 9, that provided stratified deposits from the settlement's earliest phases, the SPG and MG periods, through to its final phase, the LG period. Due to the limited number of samples from the earlier phases, the SPG and MG periods have been considered together in the diachronic data analysis.

The bones excavated from houses were highly fragmented and, in many cases, could not be identified to species. In contrast, those bones excavated from trenches 3, 9 and FW6 were larger and more intact allowing a greater percentage of species attributions. Samples from young animals were avoided where possible to prevent measuring the nursing effect, where the mother's milk causes the nursing infant to be a trophic level above its mother (Fogel et al. 1989). This made it particularly difficult to obtain a significant number of pig samples, as most pig bones were from young individuals.

Due to the nature of the fragments available for analysis, with few presenting diagnostic features, it could not be guaranteed that all samples belonged to different individuals. To mitigate the possibility of duplicate sampling and an increased chance of a false positive when conducting statistical analyses, only one sample was used from each distinct stratigraphic unit. Where two samples were measured from the same stratigraphic unit, only the first sample inventoried for this study was used when making statistical comparisons (i.e. the sample with the lowest sample number). All statistical tests were conducted using R (v3.6.2) with parametric tests being performed when parametric assumptions were met and the non-parametric equivalent when they were not.

Sample preparation

Bones were first cleaned with a toothbrush in tap water and then air-dried. Collagen was extracted using a modified version of the Longin (1971) method, designed to remove exogenous contaminants and described as follows. Firstly, the surface along the area of bone to be sampled was mechanically abraded using a bur attached to a Dremel® hand drill, then small chunks of bone weighing approximately 200–500 mg were removed from the sample using a circular blade attached to the Dremel®. The bone chunks were then demineralised in approximately 10 ml of 0.5 M HCl at 4 °C for 1 week or until they were soft and translucent, with the acid changed twice. At the end of the demineralisation period, samples were rinsed three times with Milli-Q water. Gelatinisation of the samples was then conducted at between 70-75 °C for 48 h in approximately 10 ml of pH 3 HCl solution, after which they were filtered using an Ezee filter and freeze-dried. Collagen yields are reported as dry weight percent of the original sample extracted for processing.

Isotope analyses

Isotope analyses were conducted at the Farquhar Laboratory at the Australian National University using a Micromass IsoPrime CF-IRMS coupled to a Carlo Erba CE1110 CHN-S elemental analyser. Three mass spectrometer runs were undertaken with some samples tested in duplicate to gauge instrumental variability with the average values used. Average standard deviation of repeat measures was 0.07 (0.003–0.18) for δ^{13}C and 0.08 (0.01–0.12) for δ^{15}N.

Generally accepted indicators of good quality collagen are a C:N ratio of 2.9–3.6, carbon content of 15.3–47% and nitrogen content of 5.5–17.3% (Ambrose 1990; DeNiro 1985). An additional indicator, minimum collagen yield, is also occasionally used and here any bone yielding below 0.5% was considered low collagen bone not suitable for analyses (following van Klinken 1999).

Results

Of the 102 samples submitted, three failed to yield sufficient collagen for analysis with a further two failing collagen quality control requirements and were excluded (Table 1). Results from samples that passed quality control are shown in Fig. 2.

With the exception of caprine sample GRZG071 (δ^{13}C −18.0 ‰; δ^{15}N 6.5 ‰), caprines and cattle show little evidence of consuming considerable C_4 plant sources (with values ranging from −21.6 to −19 ‰ δ^{13}C), implying C_3

Table 1 List of samples analysed in this study. Resultant collagen yields reported as a percentage of the original bone sample. *Indicates sample failed to produce collagen that met quality requirements

Sample no.	Species	Bone element	Trench/ room	Deposit	Year excavated	Date	Collagen yield (%)	%C	%N	C:N	$\delta^{13}C$	$\delta^{15}N$	Age/bone fusion state/mandibular tooth wear stage
GRZG004	*Bos taurus*	Radius	Trench 9	4	2014	LG	1.7	37.2	13.4	3.23	−21.0	6.5	
GRZG005	*Sus scrofa dom.*	Radius	Trench 9	5	2014	LG	3.5	29.2	10.2	3.35	−20.9	6.4	
GRZG006	*Caprinae*	Tibia	Trench 9	5	2014	LG	3.2	25.4	8.7	3.39	−21.3	2.7	
GRZG010	*Caprinae*	Radius	Trench 9	6	2014	SPG	4.9	26.3	9.3	3.30	−20.6	4.5	
GRZG011	*Caprinae*	Tibia	Trench 9	6	2014	SPG	3.8	26.2	9.1	3.36	−21.3	5.6	
GRZG014	*Sus scrofa dom.*	Metacarpus IV	Trench 9	7	2014	MG	3.0	34.4	12.2	3.29	−20.4	6.4	
GRZG015	*Capra hircus*	Calcaneus	Trench 9	7	2014	MG	7.6	23.4	8.1	3.37	−21.3	5.2	Proximal epiphysis fused
GRZG017	*Capra hircus*	Scapula	Trench 9	15	2014	MG	1.9	38.1	13.9	3.19	−20.3	4.5	Proximal epiphysis fused
GRZG018	*Caprinae*	Tibia	Trench 9	15	2014	MG	1.2	38.2	13.7	3.26	−20.4	5.1	
GRZG019	*Caprinae*	Tibia	Trench 9	15	2014	MG	3.8	36.9	13.6	3.15	−20.5	4.3	
GRZG022	*Caprinae*	Tibia	Trench 9	15	2014	MG	8.2	32.9	12.1	3.17	−20.3	6.3	
GRZG023	*Caprinae*	Tibia, d	Trench 9	15	2014	MG	3.1	36.6	13.3	3.20	−19.5	5.5	Distal epiphysis fused
GRZG024	*Caprinae*	Astragalus	Trench 9	16	2014	SPG	2.5	35.0	12.5	3.26	−20.7	5.8	
GRZG025	*Caprinae*	Tibia	Trench 9	16	2014	SPG	12.5	27.9	10.1	3.21	−21.3	4.8	
GRZG026	*Sus scrofa dom.*	Ulna	Trench 9	17	2014	SPG	4.4	38.7	14.3	3.15	−21.2	5.6	Adult
GRZG027	*Caprinae*	Tibia	Trench 9	17	2014	SPG	11.6	40.0	14.9	3.13	−20.1	4.5	Adult
GRZG028	*Capra hircus*	Calcaneus, p	Trench 9	17	2014	SPG	3.5	34.5	12.7	3.17	−20.4	4.5	Proximal epiphysis fused
GRZG029	*Lepus europaeus*	Humerus, d	Trench 9	17	2014	SPG	9.1	39.2	14.6	3.13	−21.2	3.9	Distal epiphysis fused
GRZG030	*Capra hircus*	Humerus, d	Trench 9	18	2014	SPG	3.7	36.9	13.7	3.14	−19.7	4.7	Distal epiphysis fused
GRZG031	*Bos taurus*	Costa	Trench 9	18	2014	SPG	7.9	37.8	14.2	3.10	−20.3	6.2	
GRZG032	*Capra hircus*	Scapula, p	Trench 9	18	2014	SPG	2.7	37.4	14.0	3.12	−20.3	4.5	Proximal epiphysis fused
GRZG033	*Bos taurus*	Tibia	Trench 9	19	2014	SPG	7.4	40.6	15.1	3.14	−19.6	5.6	
GRZG035	*Caprinae*	Tibia	Trench 9	19	2014	SPG	6.8	39.7	14.8	3.13	−19.9	4.0	
GRZG036	*Bos taurus*	Metapodium (Metatarsus?)	Trench 9	19	2014	SPG	12.3	41.5	15.6	3.11	−19.2	6.3	
GRZG040B	*Sus scrofa dom.*	Mandible	Trench FW6	5	1974	LG	2.6	22.9	7.9	3.40	−20.6	6.3	
GRZG041	*Bos taurus*	Long bone fragment	Trench FW6	5	1974	LG	1.5	39.6	14.5	3.19	−19.7	6.0	
GRZG042	*Lepus europaeus*	Tibia, d	Trench FW6	5	1974	LG	6.8	42.6	15.7	3.16	−21.2	3.7	Distal epiphysis fused
GRZG045	*Bos taurus*	Metapodium (Metatarsus?)	Trench FW6	8	1974	LG	11.7	40.7	15.2	3.12	−20.5	8.0	
GRZG046	*Caprinae*	Scapula	Trench FW6	8	1974	LG	9.8	34.5	12.8	3.13	−19.8	6.1	Very young
GRZG047B	*Capra hircus*	Mandible	Trench FW6	8	1974	LG	12.6	41.9	15.9	3.08	−19.8	5.5	4–8 years
GRZG048	*Caprinae*	Scapula	Trench FW6	8	1974	LG	15.9	39.8	14.9	3.11	−19.4	4.2	Proximal epiphysis fused
GRZG050	*Bos taurus*	Costa	Trench FW6	12	1974	LG	2.1	37.3	13.4	3.25	−19.0	7.6	
GRZG053	*Capra hircus*	Humerus	Trench FW6	13	1974	SPG	11.3	41.9	15.0	3.26	−21.6	5.6	
GRZG055	*Caprinae*	Tibia	Trench FW6	9	1974	LG	7.2	38.9	14.4	3.15	−19.9	4.1	Distal epiphysis fused
GRZG057	*Caprinae*	Radius	Trench FW6	7	1974	LG	10.3	33.1	12.2	3.16	−20.8	5.2	
GRZG058	*Bos taurus*	Long bone fragment	Trench FW6	7	1974	LG	0.8	42.5	15.1	3.28	−20.1	6.3	
GRZG060	*Caprinae*	Humerus, d	Trench FW6	14	1974	LG	4.7	31.0	11.5	3.14	−20.2	5.2	Distal epiphysis fused
GRZG061	*Bovidae* family	Tibia	M2	49 (1C)	2014	LG	9.1	38.7	14.4	3.13	−19.1	10.4	
GRZG062	*Caprinae*	Radius	M3	44	2014	LG	0.7	39.9	13.9	3.34	−20.1	4.3	
GRZG063	*Bos taurus*	Humerus	M3	44	2014	LG	6.4	19.9	7.0	3.30	−19.8	6.0	
GRZG065	*Bos taurus*	Long bone fragment	M3	48	2014	MG	7.1	39.8	14.7	3.17	−21.0	4.8	
GRZG066	*Caprinae*	Radius	M3	48	2014	MG	4.5	37.8	14.0	3.15	−20.9	5.6	
GRZG067	*Bos taurus*	Humerus	D26	23	2014	LG	13.5	38.1	13.8	3.21	−20.6	5.7	
GRZG068	*Caprinae*	Tibia?	D26	23	2014	LG	9.6	34.2	12.4	3.21	−20.2	5.3	
GRZG071	*Caprinae*	Tibia	D26	23	2014	LG	1.9	34.5	12.6	3.20	−18.0	6.5	

Table 1 (continued)

Sample no.	Species	Bone element	Trench/ room	Deposit	Year excavated	Date	Collagen yield (%)	%C	%N	C:N	$\delta^{13}C$	$\delta^{15}N$	Age/bone fusion state/mandibular tooth wear stage
GRZG074	*Capra hircus*	Metatarsus	D26	27	2014	LG	4.9	36.4	13.7	3.11	−19.9	4.4	Proximal epiphysis fused
GRZG075	*Bos taurus*	Cranium	D26	27	2014	LG	2.4	42.6	14.4	3.45	−19.7	7.6	
GRZG076	*Caprinae*	Humerus	D26	27	2014	LG	5.2	32.9	12.0	3.20	−20.8	4.9	
GRZG077	*Caprinae*	Humerus	D26	27	2014	LG	5.4	36.7	13.7	3.12	−20.0	4.6	
GRZG078	*Caprinae*	Long bone fragment	D26	27	2014	LG	11.3	42.6	15.7	3.16	−20.3	4.2	
GRZG080	*Sus scrofa dom.*	Cranium	F1	B9	1969	LG	2.1	42.5	15.1	3.28	−20.6	6.8	
GRZG081	*Lepus europaeus*	Radius	F1	B13	1969	LG	8.8	42.3	15.5	3.19	−20.3	6.8	
GRZG084	*Bos taurus*	Long bone fragment	B2	3	1971	LG	5.1	41.9	15.6	3.14	−20.0	7.2	
GRZG085	*Capra hircus*	Humerus	J8	5	1971	LG	4.8	23.6	8.4	3.27	−21.4	7.4	
GRZG086	*Bos taurus*	First phalanx	J8	5	1971	LG	7.8	41.6	15.5	3.14	−19.6	6.7	
GRZG087	*Caprinae*	First phalanx	J6	4B-I	1971	LG	4.5	38.0	14.1	3.15	−20.8	8.4	
GRZG089	*Caprinae*	Tibia	J6	4B-I	1971	LG	5.9	43.0	15.7	3.20	−19.9	6.8	
GRZG091	*Caprinae*	Tibia	H41	B5	1969	LG	7.4	40.5	14.5	3.25	−20.9	5.9	
GRZG092	*Sus scrofa dom.*	Metacarpus IV	H41	B5	1969	LG	1.8	40.0	13.9	3.4	−21.9	6.3	
GRZG093	*Caprinae*	Astragalus	H41	B5	1969	LG	2.8	26.8	9.3	3.35	−21.3	5.0	
GRZG096	*Caprinae*	Long bone fragment	D8	A4A	1971	MG	7.1	26.5	9.6	3.21	−20.2	4.3	
GRZG098*	*Capra hircus*	Radius	D8	C5A	1971	LG	0.2	-	-	-	-	-	
GRZG099	*Bos taurus*	Humerus	H23	18Q	1969	MG	5.7	40.7	15.2	3.12	−20.7	5.3	
GRZG100	*Sus scrofa dom.*	Metapodium, d	H23	18Q	1969	MG	4.5	40.8	14.8	3.23	−20.5	7.6	Distal epiphysis unfused
GRZG102	*Sus scrofa dom.*	Metatarsus III	H23	18A	1969	LG	6.2	41.2	15.3	3.14	−20.5	7.9	
GRZG103	*Capra hircus*	First phalanx	H23	18B	1969	LG	7.4	41.7	15.6	3.12	−20.1	4.9	Proximal epiphysis fused
GRZG107	*Caprinae*	Tibia	J23	5B	1971	LG	5.1	41.3	14.8	3.25	−19.7	8.2	
GRZG108	*Caprinae*	Humerus	H18	7	1969	LG	4.6	33.8	12.3	3.21	−21.3	7.0	Adult
GRZG109	*Caprinae*	Humerus	H18	B8C	1969	LG	10.7	36.4	13.4	3.16	−20.2	6.7	
GRZG111*	*Sus scrofa dom.*	Ulna	H22	4 (B)	1969	LG	0.8	6.9	0.6	13.11	−20.1	− 14.4	
GRZG113	*Bos taurus*	Carpus/tarsus	H22	4 (B)	1969	LG	3.3	33.0	12.0	3.21	−19.8	7.2	
GRZG114*	*Capra hircus*	Metacarpus	H22	4 (B)	1969	LG	0.1	-	-	-	-	-	Proximal epiphysis fused
GRZG115	*Caprinae*	Radius	D1	4A (B)	1969	LG	8.2	34.3	12.5	3.21	−20.1	4.3	
GRZG116	*Caprinae*	Tibia	H19	13	1969	LG	8.3	37.4	13.9	3.14	−19.5	7.0	
GRZG117	*Bos taurus*	Tibia	D6	C6 (B)	1971	LG	13.3	43.0	16.0	3.13	−20.7	5.8	
GRZG118	*Capra hircus*	Radius	D6	B6B	1971	LG	9.1	39.6	14.6	3.16	−19.9	4.3	Proximal epiphysis fused
GRZG119	*Sus scrofa dom.*	Radius	D6	B4B	1971	LG	11.1	39.7	14.8	3.13	−19.6	8.6	
GRZG120	*Bos taurus*	Tibia	H21	12B	1969	LG	1.4	39.1	13.8	3.32	−20.3	6.7	
GRZG122	*Sus scrofa dom.*	Mandible	J21	8	1971	LG	6.2	38.1	14.2	3.13	−19.6	7.8	$M_2 = l$, $M_3 = f$
GRZG123	*Lepus europaeus*	Innominate	J21	8	1971	LG	2.2	39.1	14.1	3.24	−21.2	3.9	
GRZG124	*Capra hircus*	Second phalanx	J21	8	1971	LG	8.3	42.0	15.6	3.14	−20.4	4.0	
GRZG125	*Sus scrofa dom.*	Mandible	J17	7 (B)	1971	LG	4.5	30.6	10.6	3.37	−21.1	6.3	$P_4 = e$, $M_1 = j$
GRZG127	*Caprinae*	Humerus	D27	8 (B)	1971	LG	8.7	37.7	14.1	3.11	−19.7	3.6	
GRZG128	*Bos taurus*	Long bone fragment	D27	8 (B)	1971	LG	1.6	32.8	11.9	3.21	−20.6	6.4	
GRZG129	*Capra hircus*	Cranium	H35	7 (B)	1971	LG	1.0	37.6	13.2	3.32	−19.9	3.5	
GRZG132	*Bos taurus*	Tibia	J9	7	1971	LG	13.0	39.5	14.9	3.09	−19.3	7.3	
GRZG133	*Capra hircus*	Scapula	J9	7	1971	LG	12.7	35.7	13.2	3.15	−20.7	6.1	
GRZG134	*Ovis aries*	Ulna	J9	7	1971	LG	12.5	40.3	14.8	3.17	−20.2	5.8	
GRZG135	*Bos taurus*	Tibia	H22	6 (B)	1969	LG	6.7	25.8	9.6	3.15	−21.3	5.7	
GRZG136*	*Capra hircus*	Metatarsus	H22	6 (B)	1969	LG	0.1	-	-	-	-	-	

Table 1 (continued)

Sample no.	Species	Bone element	Trench/ room	Deposit	Year excavated	Date	Collagen yield (%)	%C	%N	C:N	$\delta^{13}C$	$\delta^{15}N$	Age/bone fusion state/mandibular tooth wear stage
GRZG137	*Bos taurus*	Humerus	J2	5 (B)	1971	LG	2.2	26.5	9.2	3.35	−21.3	5.2	
GRZG138	*Sus scrofa dom.*	Humerus	J22	11 (B)	1971	LG	4.2	42.0	15.4	3.18	−20.3	7.4	Distal epiphysis fused
GRZG139	*Sus scrofa dom.*	Mandible	J22	5 (B)	1971	LG	3.6	29.4	10.5	3.28	−20.9	8.2	
GRZG140	*Capra hircus*	Calcaneus	H27	5A	1969	LG	9.1	33.3	12.1	3.21	−20.2	6.6	
GRZG142	*Bos taurus*	Metatarsus	H19	22 (B)	1969	MG	11.8	34.2	12.9	3.09	−20.6	6.0	Proximal/distal epiphysis fused
GRZG144*	*Caprinae*	First phalanx	H19	22 (B)	1969	MG	1.9	24.5	7.8	3.65	−20.2	2.5	
GRZG145	*Caprinae*	Long bone fragment	H19	17	1969	LG	7.6	29.0	10.8	3.13	−21.3	6.4	
GRZG146	*Caprinae*	Femur	H40	15 (B)	1969	LG	6.4	24.7	9.0	3.20	−20.0	4.2	
GRZG147	*Capra hircus*	Humerus, d	H22	5 (B)	1969	LG	5.2	31.6	11.5	3.21	−19.9	4.6	Distal epiphysis fused
GRZG148	*Bos taurus*	Radius, p	H22	5 (B)	1969	LG	10.3	30.5	11.3	3.15	−21.5	5.7	Proximal epiphysis fused
GRZG151	*Bos taurus*	First phalanx	H22	5 (B)	1969	LG	6.1	25.5	9.5	3.13	−20.5	7.0	
GRZG152	*Canis* familiaris	Mandible	Trench 3	30	2013	SPG	7.3	34.7	12.9	3.14	−19.5	7.5	Adult

plants provided the majority of their protein intake. Similarly, the pig samples' $\delta^{13}C$ values range between −21.2 and −19.6 ‰ and do not exhibit evidence of significant C_4 consumption in their diets, nor do they appear to have consumed significant amounts of marine protein, which could also cause bone collagen carbon isotopic compositions to be higher (Tauber 1981).

For inter-species comparisons a one-way ANOVA test was conducted to test for the effect of species on mean collagen $\delta^{13}C$ values. The result found no effect of species on $\delta^{13}C$ ($F_{(4,77)} = 1.9, p = .13$). For nitrogen, the data are not normally distributed hence a Kruskal-Wallis test was performed to test the effects of species on mean collagen $\delta^{15}N$ values. The results found a significant effect of species on mean $\delta^{15}N$ ($H(4) = 26.6$, $p < .001$). A Mann-Whitney *U* test with Holm's sequential Bonferroni correction post hoc test was conducted to determine which inter-species differences were statistically significant. The results reveal that the mean goat nitrogen isotopic composition is significantly lower than that of both the cattle and pig ($p < .001$ for both). When excluding those samples identified as sheep or goats, mean caprine nitrogen isotopic composition values are also significantly lower than those of both cattle ($p = .04$) and pig ($p = .005$).

Between the earlier (SPG/MG) and later (LG) periods, an increase in the mean $\delta^{13}C$ and $\delta^{15}N$ values of the main domesticates' bone collagen is observed. The increase is not statistically significant for goat $\delta^{13}C$ ($p = .31$) and $\delta^{15}N$ ($p = .54$), caprine $\delta^{13}C$ ($p = .65$) and $\delta^{15}N$ ($p = .15$), pig $\delta^{13}C$ ($p = .72$) and $\delta^{15}N$ ($p = .39$), and cattle $\delta^{13}C$ ($p = .53$). However, the increase in mean cattle $\delta^{15}N$ values is statistically significant ($p = .01$).

Pearson's correlation indicates that there is a moderate positive correlation between pig $\delta^{13}C$ and $\delta^{15}N$ values ($r = .64$, $p = .02$) and between cattle $\delta^{13}C$ and $\delta^{15}N$ values ($r = .60$, $p = .002$), while caprine $\delta^{13}C$ and $\delta^{15}N$ values exhibit no correlation ($r = .009$, $p = .96$). The goat $\delta^{13}C$ data are not normally distributed and so a Spearman's correlation was instead used. The results indicate that goat bone collagen $\delta^{13}C$ and $\delta^{15}N$ values are not correlated ($r_s = -0.39$, $p = .14$).

Discussion

Caprines

The caprines exhibit a broad range of isotopic compositions implying that their diets were quite varied. With the limited available evidence there does not appear to be any difference between the diets of the sheep and the goats (Fig. 3). Based on most of the caprines being identified as goats in this study as well as the predominance of goats relative to sheep in other EIA Cycladic assemblages (Trantalidou 2012, table 1c), it is expected that very few of the remaining caprine specimens are in fact sheep. The topography of Andros and its different

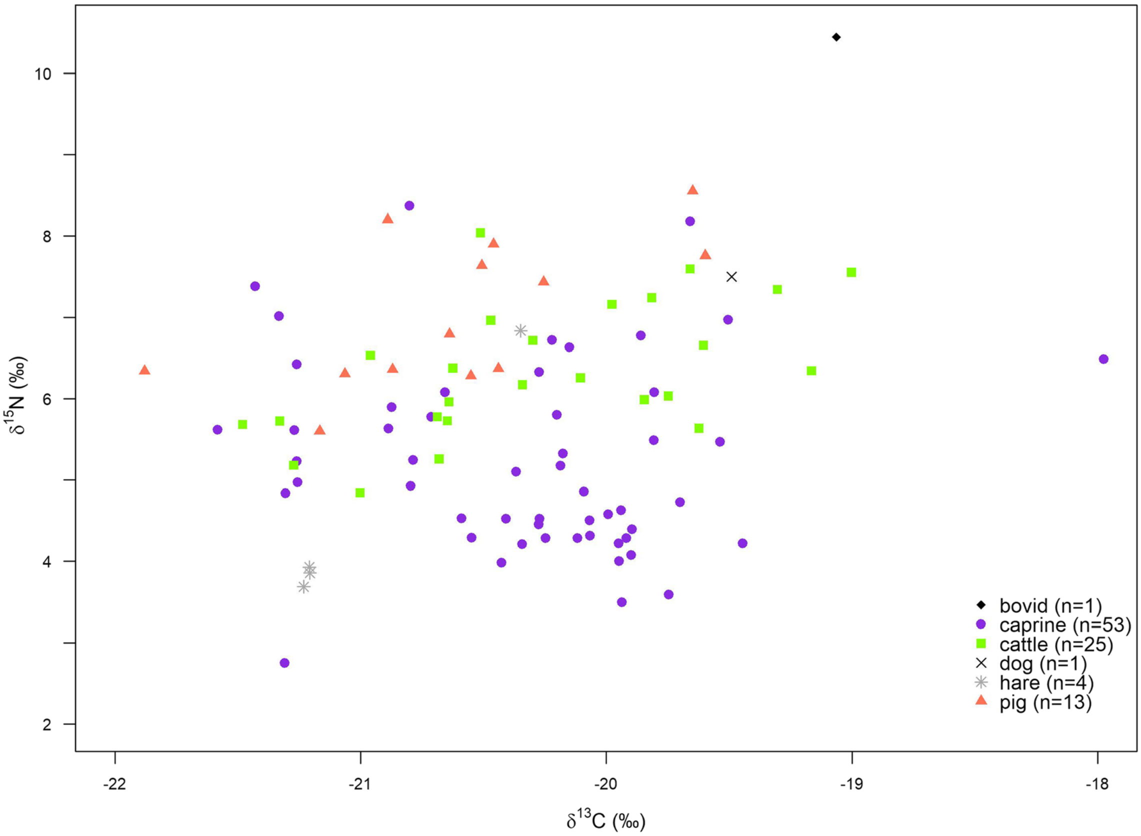

Fig. 2 Plot of δ^{13}C and δ^{15}N values

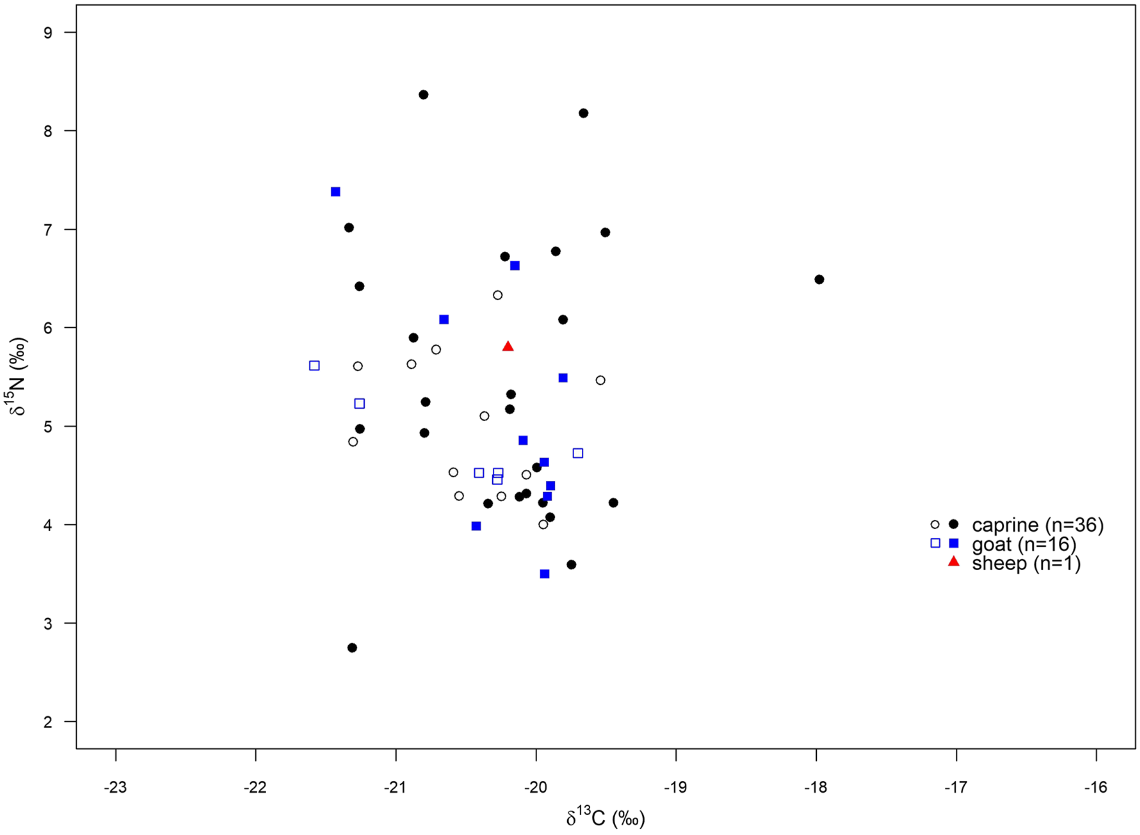

Fig. 3 Plot of caprine δ^{13}C and δ^{15}N values. Closed shapes represent LG period samples and open shapes SPG/MG period samples

microclimates (Snogerup et al. 2006) would allow goats a more isotopically diverse diet, possibly explaining the wide variety in isotopic compositions.

Overall, the caprine carbon isotopic compositions are quite constrained in range compared to the nitrogen. Based upon this observation, we can make some assumptions regarding the vegetation consumed by the caprines with higher $\delta^{15}N$ values. Typically, when the $\delta^{15}N$ of vegetation is affected by water stress or salinity there tends to be a corresponding shift in $\delta^{13}C$ (Farquhar et al. 1982; Isla et al. 1998), which does not appear to be the case for the plants consumed by the caprines due to the limited range in caprine $\delta^{13}C$. Similarly soil denitrification due to the actions of groundwater, as in wetland environments, would also impact plant $\delta^{13}C$ due to greater water availability. Plants growing in soils with high organic matter content (such as soil treated with manure) can have elevated $\delta^{15}N$ values without significantly impacting $\delta^{13}C$ (Bogaard et al. 2013). Land cleared by burning can also increase vegetation $\delta^{15}N$, and modern Greek farmers have reported higher yields when sowing crops on land cleared in this way (Halstead 2014). However, the effect on plant $\delta^{15}N$ is only temporary with values returning to normal after about a decade (Szpak 2014).

The caprines at Zagora that exhibit the highest $\delta^{15}N$ values therefore quite possibly consumed a diet primarily consisting of vegetation growing in nutrient-rich soils, such as by grazing on crop stubble or weeds growing in fallow fields subjected to manuring, or they may have been foddered on the crops themselves and their by-products. Those caprines (especially goats) with lower $\delta^{15}N$ values may have spent more time exploiting the vegetation growing in the mountainous rocky terrain away from the arable valleys and Zagora.

Pigs

The linear relationship exhibited by the pigs' $\delta^{13}C$ and $\delta^{15}N$ values can be explained using a linear mixing model and the consumption by pigs of two food sources, with one source comprising elevated, and the other lower, $\delta^{13}C$ and $\delta^{15}N$ (Fig. 4; see Schwarcz 1991, Fig. 2). As illustrated by Richards and Hedges (1999), each of the two dietary sources need not comprise a single food and may include a mixture of different foods but in the same proportions for each individual. The consumption of varying quantities of these two sources, as well as the ad hoc consumption of other foods, can account for individual variability along the regression line as expected in a sample population whose individual lives may not have overlapped significantly, if at all.

The correlation between $\delta^{13}C$ and $\delta^{15}N$ values in populations is commonly explained to be related to their consumption of varying proportions of a distinct marine and terrestrial food source (e.g. Lubell et al. 1994; Richards and Hedges 1999). A primarily or even purely terrestrial diet, likewise with two isotopically distinct sources, is also possible (e.g. Prowse et al. 2004; Reitsema et al. 2010). The pig collagen $\delta^{13}C$ values are not elevated enough to indicate a clear marine signal; however, this does not preclude a marine contribution to diet since the effect on collagen $\delta^{13}C$ values may be too subtle in animals on a low protein diet consuming small quantities (up to 20%) of marine protein (Hedges 2004). Likewise, a negligible enrichment of pig ^{15}N has been observed in pigs that consumed diets comprising less than 25% marine protein (Webb et al. 2016).

Food sources at the high end of the $\delta^{13}C$ and $\delta^{15}N$ distribution could have included marine foods, terrestrial animal protein or C_3 cereal grains grown in fields subjected to manuring. Significant consumption of C_4 vegetation was unlikely given the slope of the regression line (0.96). This would require a C_4 plant to have high $\delta^{15}N$, in the order of 15 ‰, to be a plausible significant dietary source, assuming a C_4 plant mean $\delta^{13}C$ of −13 ‰ (O'Leary 1988), and a diet to collagen spacing of 5 ‰ for $\delta^{13}C$ and 4 ‰ for $\delta^{15}N$. Lower $\delta^{13}C$ and $\delta^{15}N$ foods may have consisted of forage or fodder such as pasture, acorns, roots or nitrogen-fixing legumes.

Cattle

As with pigs, the correlation between the $\delta^{13}C$ and $\delta^{15}N$ values of cattle implies their diets primarily comprised of varying proportions of two food sources; in this case a terrestrial C_3 source such as pasture and another plant source enriched in both ^{13}C and ^{15}N. The cattle regression line is shallower than that of the pigs (0.8), making the contribution of C_4 vegetation to the diet a more plausible explanation than for pigs (Fig. 5). While cattle may have consumed one of the endemic C_4 species growing on Andros, they may have also been occasionally foddered on millet, although it is as yet uncertain if this crop was cultivated by the inhabitants of Zagora.

Another possible contributor to the elevated isotopic compositions in cattle is marine plants such as macroalgae. Marine plants tend to be enriched in ^{13}C and ^{15}N relative to terrestrial C_3 vegetation growing under conditions that do not enrich their ^{15}N (Jennings et al. 1997; Sigman and Casciotti 2001). A correlation in the carbon and nitrogen isotopic compositions of sheep from Neolithic Quanterness in Scotland led Schulting et al. (2017) to suggest this linear relationship was a result of the animals' consumption of seaweed, agreeing with earlier tooth enamel carbonate isotope data from the region (e.g. Balasse et al. 2005). In more recent times, it is not unheard of for cattle to consume seaweed as fodder (Newton 1951), while rare references in the classical world to livestock eating seaweed imply it was used during unfavourable circumstances (Plutarch, *Caes.* 52.6; Caesar, *BAfr.* 24). Given that overall cattle bone collagen is not highly enriched in ^{13}C, C_4 or marine plants would not have been significant contributors to diet

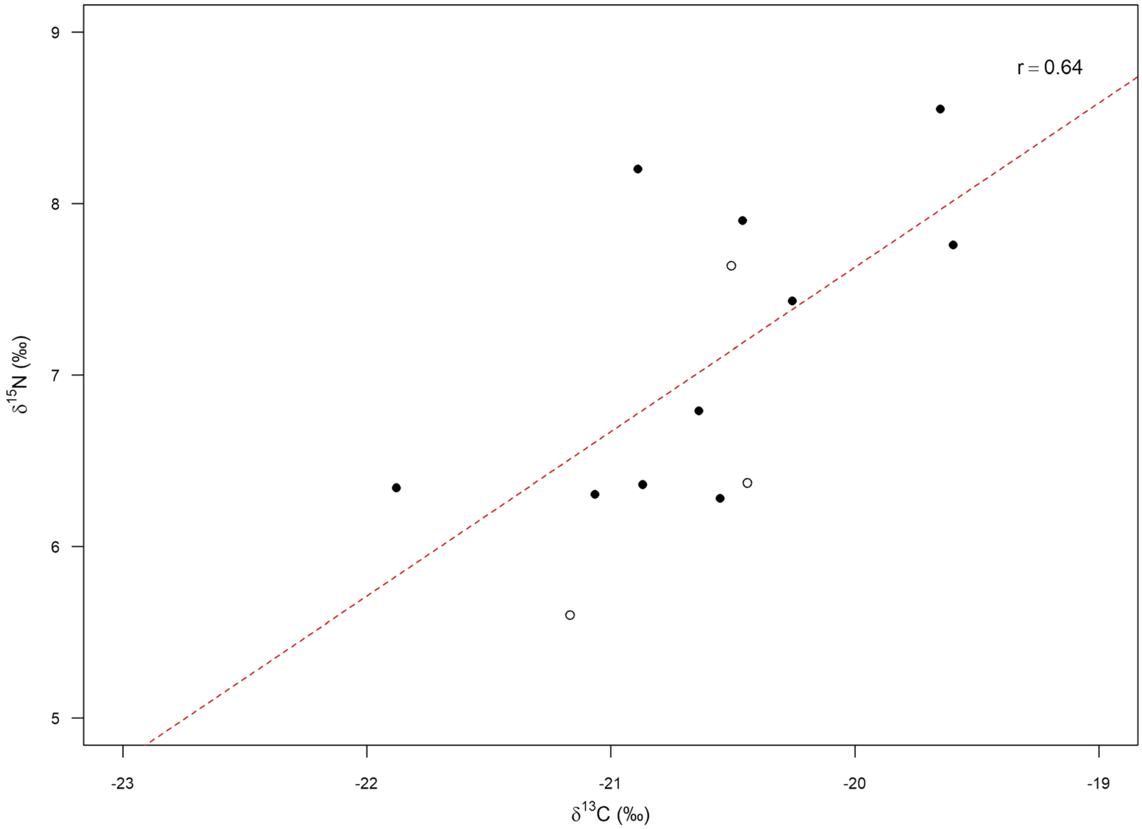

Fig. 4 Plot of pig δ^{13}C and δ^{15}N values. Closed shapes represent LG period samples and open shapes SPG/MG period samples

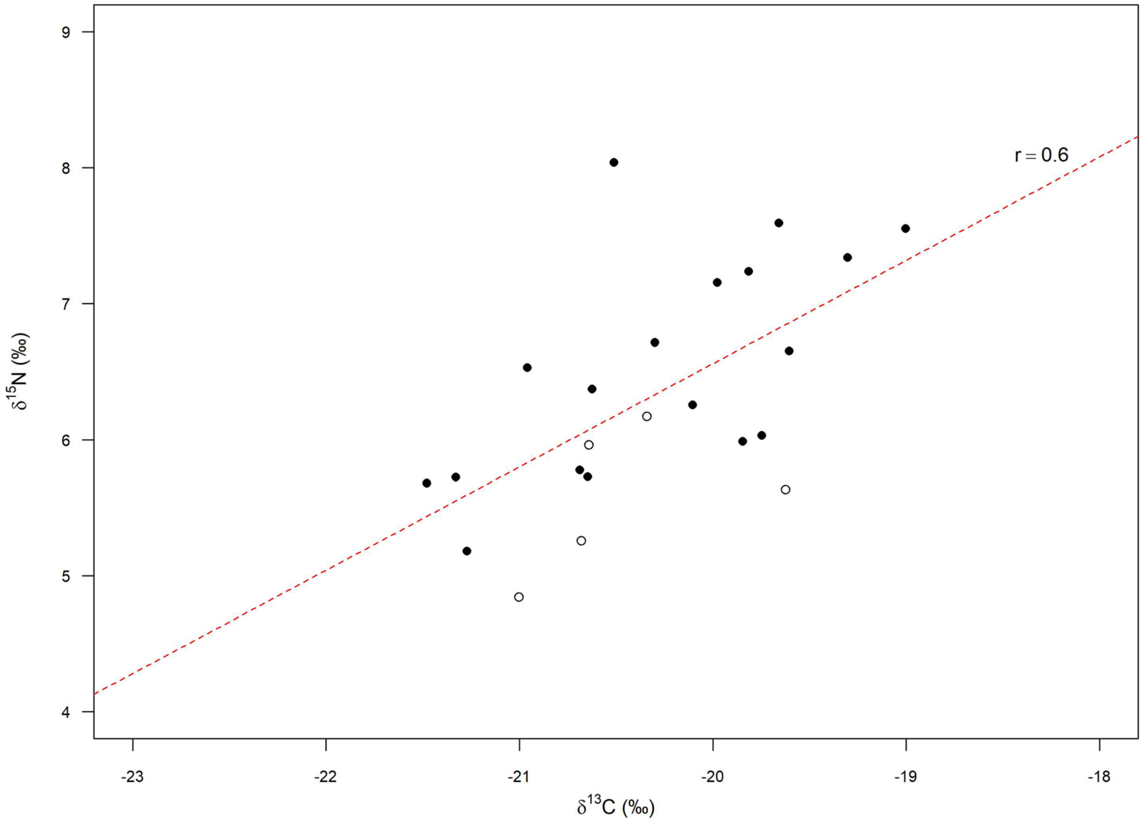

Fig. 5 Plot of cattle δ^{13}C and δ^{15}N values. Closed shapes represent LG period samples and open shapes SPG/MG period samples

and perhaps may have been seasonal in nature, such as during short dry spells in summer.

Other species

The only wild species analysed in this study is hare. European hares' preferred habitat is agricultural land and their diet consists of weeds, grasses and cultivated crops (Smith et al. 2018, pp. 188–189). The Zagora hare collagen isotopic compositions range from −21.2 to −20.3 ‰ ($\overline{X} = -21$ ‰) for δ^{13}C and 3.7 to 6.8 ‰ ($\overline{X} = 4.6$ ‰) for δ^{15}N, with three of the four samples exhibiting almost identical values (Fig. 2).

These three analogous hare samples were recovered from three different areas of the site across two different phases (J21 and trench FW6 dating to LG; and trench 9 dating to SPG). Due to their wide dispersion across time and space, it is not likely that they belonged to a single individual disturbed by post-depositional processes, nor is it likely that such a small animal was shared amongst different households. While the number of samples is very few, their constrained values do hint at a specific landscape 'zone' within which hares were regularly hunted.

The one dog sample analysed in this study reflects a terrestrial C_3-based diet, although its ^{13}C and ^{15}N are both enriched above the mean values of the main domesticates as might be expected for an animal that consumes a diet similar to humans. As with pigs, the consumption of small quantities of marine protein is possible.

The fragment of a bovid bone that could not be identified to a specific species was the only 'identifiable' specimen recovered from the house located at the far southern end of the settlement and so it was thought pertinent to include it in the present study. This sample exhibits the highest δ^{15}N value of all samples and its δ^{13}C is also amongst the highest. While it cannot be confirmed, it is possible that this sample belonged to a juvenile animal implying the enriched ^{13}C and ^{15}N could be due to the nursing effect.

Animal management practices at Zagora

Up until the beginning of the LG period, there were fewer houses and more open space within the confines of Zagora than at the close of the period when construction was more densely packed (Beaumont et al. 2012; Cambitoglou et al. 1988). The settlement flourished during this final phase when the population was at its largest (Cambitoglou 1981). An increase in population would have placed added pressure on the immediate hinterland surrounding the settlement to feed the growing populace.

Coincident with this period of settlement growth is the increase in the range of herbivore nitrogen isotopic compositions. For caprines and (to a lesser extent) cattle, the samples' δ^{15}N range increases from the SPG/MG periods to the LG

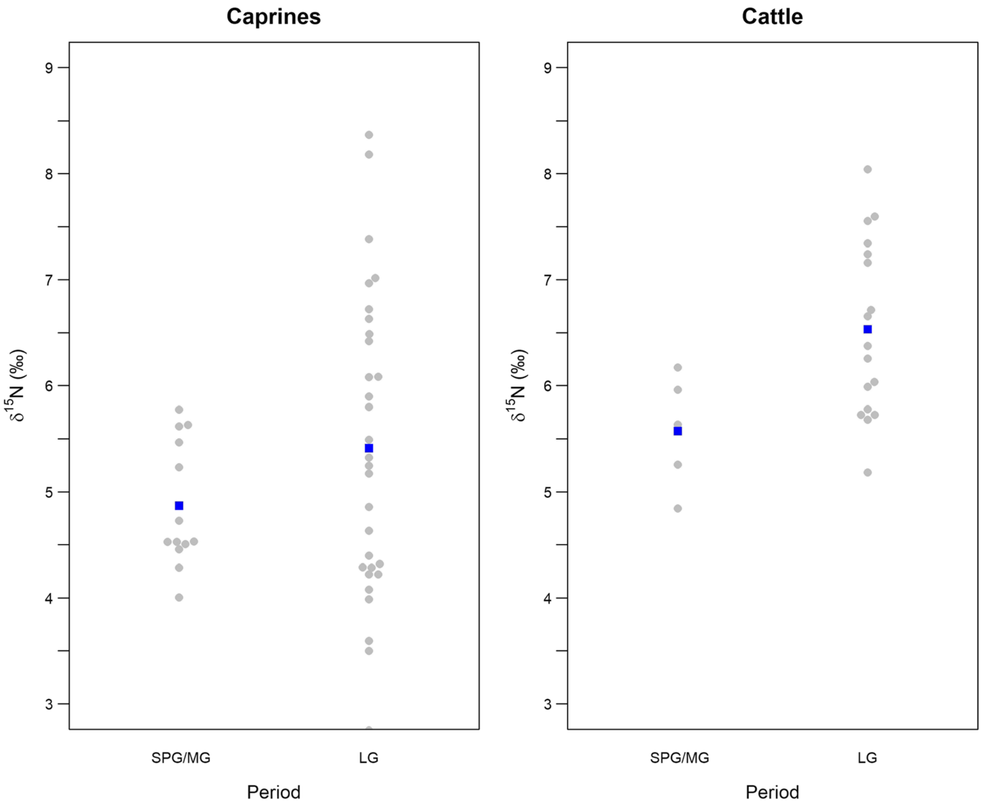

Fig. 6 Plot of caprine and cattle δ^{15}N values for the SPG/MG and LG periods created using the R Beeswarm package. Blue squares represent period mean values

period (Fig. 6). Although the increase in mean caprine δ^{15}N is not statistically significant, the increased range of values perhaps suggests that pasture on the island with relatively low δ^{15}N was still being exploited, while agriculture also intensified in certain areas during the LG period when Zagora's population was at its largest. Intensive agricultural practice is characterised by greater soil disturbance along with the application of organic matter such as manure to the soil to increase the soil's agricultural output, also resulting in higher δ^{15}N values in plants (Styring et al. 2017).

The statistically significant higher mean δ^{15}N value of cattle when compared to caprines is an indication that on the whole cattle consumed foods that were more enriched in ^{15}N. This could be the result of cattle spending time grazing in areas where they were used for ploughing, consuming weeds and crop stubble that were growing in fields treated with manure, while caprine flocks mostly roamed the uncultivated landscape. It is also possible that the cattle and those caprines with elevated δ^{15}N grazed frequently on vegetation in areas close to the settlement or in paddocks previously densely occupied by animals. Hedges et al. (2005) found that the wool of sheep grazing in restricted urban areas had higher δ^{15}N than sheep living in more open environments but comparable δ^{13}C, probably due to the higher quantity of organic input into the soil from manure, urine or plant refuse. If this were the case at Zagora, it may indicate that these animals grazing around the settlement were stalled within its confines, as has already been suggested (Cambitoglou 1981, p. 34). In more recent history, it was common for people in rural Greece to keep farm animals within their houses, even adjacent to living areas (Gallant 2015).

The increase in the range of cattle nitrogen isotopic compositions over time is not as pronounced as with the caprines, supporting the idea of a tighter management regime with cattle as is reflected in the correlation of their δ^{13}C and δ^{15}N values. At Zagora the number of families who owned cattle was likely limited since cattle were the most valued of the main domesticates. In Homeric epic cattle were so valuable that they functioned as a unit of currency (e.g. Hom. *Il.* 6.235-6, 23.700-5). The value of cattle at Zagora may be visible in the distribution of the various cattle bone elements across the settlement that suggests cattle carcasses were being shared between households. The isotopic and osteological patterns exhibited by cattle at Zagora could be the result of the sharing of joints of meat that originated from animals under limited ownership and/or control or from animals in smaller family herds that were managed as a single large herd when not being used for draught. In modern times when a family's livestock numbers are small, a range of strategies can be adopted to make their management more economical such as employing a herder or joining the animals into larger village-wide or extended kin herds (e.g. Franić 1935; Halstead 2014; Kenna 1990). If cattle were managed at the individual household level, then the isotopic evidence suggesting a two-source diet implies that each family grazed their cattle on isotopically similar pastures or provided them with isotopically similar fodder.

In exhibiting a linear relationship between their δ^{13}C and δ^{15}N values, the pigs can also be suggested as having likely been subjected to a specific feeding protocol. Unlike cattle, however, it is more difficult to conceive a restricted diet for pigs. Pigs are generalist feeders and would have consumed any organic waste that households had available, which is unlikely to have been the same across the settlement given that rates of food spoilage would differ. Furthermore, the specific crops grown as 'famine food' or animal fodder would have depended on individual choices and plot location (Halstead 2014, pp. 291–294). The enriched ^{15}N of pigs suggests they did not subsist entirely on free-range foods; if they were completely free-roaming, they would have had highly individualised diets. The most plausible explanation is that pigs were managed by a relatively small number of people who specialised in their rearing and implemented similar herding and/or feeding strategies. It is certainly possible that pig management was a specialisation practiced at Zagora, paralleling Homer's mention of the existence of swineherds in Greece during the proto-historic period. Homer specifically details the operation of Odysseus' swineherd Eumaeus and his fellow herders throughout Book 14 of the *Odyssey*, providing us with an insight into how such an operation may have been run at the time. In it he describes Eumaeus' pigsties being amply provisioned with pigs and situated outside of the main settlement (Hom. *Od.* 14.1–17). Despite the isotopic data suggesting pig diets may have been based on a specific feeding protocol, we lack further evidence for specialised pig management at Zagora. Whether or not swineherds existed here must remain an open question.

Agricultural production was not necessarily Zagora's primary function as a settlement and it has been proposed that control of, or involvement in, local maritime trade was instead its main economic role (Cambitoglou et al. 1988; Coldstream 1977). The possibility that at least some of the animals consumed at Zagora may have been imported from other villages or towns should thus not be excluded. Such a scenario could account for the isotopic heterogeneity of the caprines and even the homogeneity of the cattle and pigs if they were sourced from a specialised external producer(s). The only contemporaneous settlement on Andros that has been excavated thus far is Hypsele, a fortified town located on the west coast some 12 km to the north of Zagora (Televantou 2012), although the existence of other EIA settlements on the island is indicated by surface scatters of pottery sherds (Koutsoukou 1992) and a grave found near the village of Amonakliou situated in a large arable valley about 10 km ESE of Zagora (Desborough 1972, pp. 128–129). Future studies on animals from these areas may provide insight into the possibility of animal trade.

It is worth comparing the results from Zagora with the published faunal isotopic data from other Greek EIA sites even though the data are limited. These other studies produced faunal samples from the coastal settlement of Kynos in Lokris (Papathanasiou et al. 2013) and from the cemeteries of Halos on the coast of the Pagasetic Gulf in Thessaly (Panagiotopoulou et al. 2016). Three of the four cattle samples from these two sites (mean $\delta^{13}C = -19.1$ ‰, $\delta^{15}N = 7.4$ ‰) are similar in isotopic composition to the most ^{13}C- and ^{15}N-enriched Zagora cattle samples, while the fourth cattle sample, from Halos, is enriched in ^{13}C relative to all others ($\delta^{13}C = -17.5$ ‰, $\delta^{15}N = 6$ ‰). The five Kynos (mean $\delta^{13}C = -19$ ‰, $\delta^{15}N = 5.7$ ‰) and three Halos (mean $\delta^{13}C = -19.9$ ‰, $\delta^{15}N = 3.3$ ‰) caprine samples are slightly enriched in ^{13}C relative to the mean Zagora caprine ^{13}C composition. The mean Kynos caprine nitrogen isotopic composition is similar to that of the Zagora caprines, while the Halos caprines are slightly depleted in ^{15}N relative to the Zagora samples. The $\delta^{13}C$ (−21.0 ‰) and $\delta^{15}N$ (7.4 ‰) of the single pig sample, from Kynos, are similar to the mean Zagora pig isotopic composition. The slightly enriched ^{13}C of some of the caprines and cattle from these other sites relative to those from Zagora probably indicates the greater availability of C_4 pasture in these areas on the mainland coast or the provisioning of millet as fodder here. It could also suggest that the mainland herbivores consumed C_3 vegetation growing under slightly dryer conditions. The lower Halos caprine $\delta^{15}N$ values could be a reflection of caprines here consuming vegetation growing in soils with greater salinity, such as in coastal areas, or in soils with less organic matter content, such as in more open pasture. When larger faunal isotopic data sets from other EIA Greek sites become available, more detailed comparisons of animal management can be undertaken.

Conclusions

The faunal isotope results from Zagora provide new evidence for animal management from the Greek EIA. The correlation between the $\delta^{13}C$ and $\delta^{15}N$ values of the cattle suggests that they consumed diets comprising largely of two main food sources, with proportions of these two sources varying between individuals. Considering the high value of cattle during this period in Greece, together with the widespread distribution of cattle body parts at Zagora, this suggests that cattle may have been under limited ownership and belonged to a small number of herds. The enriched cattle ^{15}N relative to the caprines could be the result of the cattle grazing on vegetation growing in manured fields in areas where they were used for ploughing. The data for caprine diet is quite different to that of the cattle, with their isotopic compositions indicating a greater diversity of diets, possibly the result of caprines (particularly goats) ranging further across Andros' rugged terrain and foraging in different microenvironments. On the available evidence at present, there is no indication of homogeneous management of these animals. Like the cattle, the pig $\delta^{13}C$ and $\delta^{15}N$ values correlate, hinting that they also consumed a diet comprising primarily of varying quantities of two main food sources.

From the earliest phases (SPG/MG) to the final phase (LG) at Zagora, we see an increase in the dietary range of caprines and cattle. The isotopic shifts towards higher $\delta^{15}N$ values imply that a greater consumption of plants growing in soils exposed to higher organic matter content is most likely responsible for this change. The increase during the 'Greek Renaissance' at a time when Zagora reached its maximum extent could imply there was growing pressure on the surrounding hinterland, forcing the expanding population to intensify agricultural production or herd animals in areas close to human settlement. Although there is a lack of evidence for any settlement boundaries during this period, these isotope results may also suggest that certain members of the community had restricted access to land or perhaps that agricultural land may have been in short supply during Zagora's final phase.

Acknowledgements The authors wish to thank the Cycladic Ephorate of Antiquities and the Greek Ministry of Culture and Sport for permission to study and analyse the material. We would also like to thank the Archaeological Society at Athens, the Australian Archaeological Institute at Athens and its former director Alexander Cambitoglou† and director Stavros Paspalas, and the Zagora Archaeological Project and its directors Lesley Beaumont, Paul Donnelly, Margaret Miller and Stavros Paspalas for approving access to the material for analysis. Isotope analyses were funded by the University of Sydney's Carlyle Greenwell Fund. We are grateful to Stavros Paspalas for his feedback on an earlier draft of the manuscript and to Beatrice McLoughlin for making the legacy Zagora faunal report publicly accessible. We would also like to thank the three anonymous reviewers whose suggestions helped improve this article.

References

Ambrose SH (1990) Preparation and characterization of bone and tooth collagen for isotopic analysis. J Archaeol Sci 17:431–451

Ambrose SH, DeNiro MJ (1986) The isotopic ecology of East African mammals. Oecologia 69:395–406

Ambrose SH, Norr L (1993) Experimental evidence for the relationship of the carbon isotope ratios of whole diet and dietary protein to those of bone collagen and carbonate. In: Lambert JB, Grupe G (eds) Prehistoric human bone: archaeology at the molecular level. Springer Verlag, Berlin/Heidelberg, pp 1–37

Balasse M, Tresset A, Dobney K, Ambrose SH (2005) The use of isotope ratios to test for seaweed eating in sheep. J Zool 266:283–291

Barnetson L (1977) Report on the animal bones from Zagora, Andros, Greece, 1977. Unpublished faunal report. https://aaia.sydney.edu.au/wp-content/uploads/2020/10/Barnetson_1980_Zagora_Bone_Report_1977.pdf. Accessed 22 October 2020.

Beaumont LA, Miller MC, Paspalas SA (2012) New investigations at Zagora (Andros): the Zagora Archaeological Project 2012. Mediterr Archaeol 25:43–66

Bender MM (1968) Mass spectrometric studies of carbon 13 variations in corn and other grasses. Radiocarbon 10(2):468–472

Bogaard A, Heaton THE, Poulton P, Merbach I (2007) The impact of manuring on nitrogen isotope ratios in cereals: archaeological implications for reconstruction of diet and crop management practices. J Archaeol Sci 34:335–343

Bogaard A, Fraser R, Heaton THE, Wallace M, Vaiglova P, Charles M, Jones G, Evershed RP, Styring AK, Andersen NH, Arbogast R-M, Bartosiewicz L, Gardeisen A, Kanstrup M, Maier U, Marinova E, Ninov L, Schäfer M, Stephan E (2013) Crop manuring and intensive land management by Europe's first farmers. PNAS 110:12589–12594

Cambitoglou A (1981) Guide to the finds from the excavations of the Geometric town at Zagora. Archaeological Museum of Andros, Athens

Cambitoglou A, Birchall A, Coulton JJ, Green JR (1988) Zagora 2: excavation of a geometric town on the island of Andros. In: Excavation season 1969; study season 1969-1970. Athens Archaeological Society, Athens

Coldstream JN (1977) Geometric Greece. Ernest Benn, London

Delwiche CC, Steyn PL (1970) Nitrogen isotope fractionation in soils and microbial reactions. Environ Sci Technol 4:929–935

DeNiro MJ (1985) Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeodietary reconstruction. Nature 317:806–809

DeNiro MJ, Epstein S (1981) Influence of diet on the distribution of nitrogen isotopes in animals. Geochim Cosmochim Acta 45:341–351

Desborough VRDA (1972) The Greek Dark Ages. Ernest Benn, London

Dickinson OTPK (2006) The Aegean from Bronze Age to Iron Age: continuity and change between the twelfth and eighth centuries BC. Routledge, Abingdon

Farquhar GD, Richards RA (1984) Isotopic composition of plant carbon correlates with water-use efficiency of wheat genotypes. Aust J Plant Physiol 11:539–552

Farquhar GD, O'Leary MH, Berry JA (1982) On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. Aust J Plant Physiol 9:121–137

Fogel M, Tuross N, Owsley D (1989) Nitrogen isotope tracers of human lactation in modern and archaeological populations. In: Annual Report to the Director, Geophysical Laboratory, 1988–1989 edn. Carnegie Institution, Washington DC, pp 111–117

Franić I (1935) Obnovljena porodična zajednica (zadruga) Filipa Kraljičkovića u selu Palanjek, sreza Sisak, banovine savske. Vjesnik Etnografskog Muzeja u Zagrebu 1–2:49–68

Gallant TW (2015) The Edinburgh history of the Greeks, 1768 to 1913. The Long Nineteenth Century. Edinburgh University Press, Edinburgh

Guiry EJ (2012) Dogs as analogs in stable isotope-based human paleodietary reconstructions: a review and considerations for future use. J Arch Method Theory 19:351–376

Halstead P (2014) Two oxen ahead: pre-mechanized farming in the Mediterranean. Wiley Blackwell, Chichester

Handley LL, Robinson D, Scrimgeour CM, Gordon D, Forster BP, Ellis RP, Nevo E (1997) Correlating molecular markers with physiological expression in Hordeum, a developing approach using stable isotopes. New Phytol 137:159–163

Heaton THE (1987) The $^{15}N/^{14}N$ ratios of plants in South Africa and Namibia: relationship to climate and coastal/saline environments. Oecologia 74:236–246

Hedges R (2004) Isotopes and red herrings: comments on Milner et al. and Lidén et al. Antiquity 78(299):34–37

Hedges R (2006) Where does our protein carbon come from? Br J Nutr 95:1031–1032

Hedges R, Reynard L (2007) Nitrogen isotopes and the trophic level of humans in archaeology. J Archaeol Sci 34:1240–1251

Hedges REM, Thompson JMA, Hull BD (2005) Stable isotope variation in wool as a means to establish Turkish carpet provenance. Rapid Commun Mass Spectrom 19:3187–3191

Hedges REM, Clement JG, Thomas DL, O'Connell TC (2007) Collagen turnover in the adult femoral mid-shaft: modelled from anthropogenic radiocarbon tracer measurements. Am J Phys Anthropol 133:808–816

Isla R, Aragüés R, Royo A (1998) Validity of various physiological traits as screening criteria for salt tolerance in barley. Field Crop Res 58:97–107

Jennings S, Reñones O, Morales-Nin B, Polunin NVC, Moranta J, Coll J (1997) Spatial variation in the ^{15}N and ^{13}C stable isotope composition of plants, invertebrates and fishes on Mediterranean reefs: implications for the study of trophic pathways. Mar Ecol Prog Ser 146:109–116

Kendall C (1998) Tracing nitrogen sources and cycling in catchments. In: Kendall C, McDonnell JJ (eds) Isotope tracers in catchment hydrology. Elsevier Science, Amsterdam, pp 519–576

Kenna ME (1990) Family, economy and community on a Greek island. In: Harris CC (ed) Family, economy and community. University of Wales Press, Cardiff, pp 143–163

Koutsoukou A (1992) An archaeological survey in north-west Andros, Cyclades. Unpublished PhD dissertation, University of Edinburgh.

Longin R (1971) New method of collagen extraction for radiocarbon dating. Nature 230:241–242

Lubell D, Jackes M, Schwarcz H, Knyf M, Meiklejohn C (1994) The Mesolithic-Neolithic transition in Portugal: isotopic and dental evidence of diet. J Archaeol Sci 21:201–216

Mazarakis Ainian A (1997) From rulers' dwellings to temples: architecture, religion and society in Early Iron Age Greece (1100-700 B.C.). Paul Åströms Förlag, Jonsered.

Mazarakis Ainian A (ed) (2007) Oropos and Euboea in the Early Iron Age. University of Thessaly Publications, Volos

Mazarakis Ainian A, Alexandridou A, Charalambidou X (eds) (2017) Regional stories towards a new perception of the early Greek world. University of Thessaly Press, Volos

Millett P (1984) Hesiod and his world. Proc Camb Philol Soc 30:84–115

Morris I (1997) Homer and the Iron Age. In: Morris I, Powell B (eds) A new companion to Homer. Brill, Leiden, pp 535–559

Newton L (1951) Seaweed Utilisation. Sampson Low, London

O'Connell TC, Kneale CJ, Tasevska N, Kuhnle GGC (2012) The diet-body offset in human nitrogen isotopic values: a controlled dietary study. Am J Phys Anthropol 149:426–434

O'Leary MH (1988) Carbon isotopes in photosynthesis. BioScience 38(5):328–336

Osborne R (2004) Homer's society. In: Fowler R (ed) The Cambridge companion to Homer. Cambridge University Press, Cambridge, pp 206–219

Panagiotopoulou E, van der Plicht J, Papathanasiou A, Voutsaki S, Nikolaou E, Tsiouka F (2016) Isotopic (^{13}C, ^{15}N) investigation of diet and social structure in Early Iron Age Halos, Greece. J Archaeol Sci Rep 10:212–220

Papathanasiou A, Panagiotopoulou E, Beltsios K, Papakonstantinou M-F, Sipsi M (2013) Inferences from the human skeletal material of the Early Iron Age cemetery at Agios Dimitrios, Fthiotis, Central Greece. J Archaeol Sci 40:2924–2933

Peterson BJ, Fry B (1987) Stable isotopes in ecosystem studies. Annu Rev Ecol Evol Syst 18:293–320

Prowse T, Schwarcz HP, Saunders S, Macchiarelli R, Bondioli L (2004) Isotopic paleodiet studies of skeletons from the Imperial Roman-age cemetery of Isola Sacra, Rome, Italy. J Archaeol Sci 31:259–272

Raaflaub KA (1997) Homeric society. In: Morris I, Powell B (eds) A new companion to Homer. Brill, Leiden, pp 624–648

Reitsema LJ, Crews DE, Polcyn M (2010) Preliminary evidence for medieval Polish diet from carbon and nitrogen stable isotopes. J Archaeol Sci 37:1413–1423

Richards MP, Hedges REM (1999) Stable isotope evidence for similarities in the types of marine foods used by Late Mesolithic humans at sites along the Atlantic coast of Europe. J Archaeol Sci 26:717–722

Riga A, van Praag HJ, Brigode N (1971) Rapport isotopique naturel de l'azote dans quelques sols forrestiers et agricoles de Belgique soumis à divers traitements culturaux. Geoderma 6:213–222

Schoeninger MJ, Deniro MJ (1984) Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. Geochim Cosmochim Acta 48:625–639

Schulting RJ, Vaiglova P, Crozier R, Reimer PJ (2017) Further isotopic evidence for seaweed-eating sheep from Neolithic Orkney. J Archaeol Sci Rep 11:463–470

Schwarcz HP (1991) Some theoretical aspects of isotope paleodiet studies. J Archaeol Sci 18:261–275

Sigman DM, Casciotti KL (2001) Nitrogen isotopes in the ocean. In: Encyclopedia of ocean sciences. Academic Press, London, pp 1884–1894

Smith BN, Epstein S (1971) Two categories of $^{13}C/^{12}C$ ratios for higher plants. Plant Physiol 47:380–384

Smith AT, Johnston CH, Alves PC, Hackländer K (eds.) (2018) Lagomorphs. Pikas, rabbits, and hares of the world. Johns Hopkins University Press, Baltimore

Snodgrass AM (1971) The Dark Age of Greece: an archaeological survey of the eleventh to the eighth centuries BC. Edinburgh University Press, Edinburgh

Snogerup S, Snogerup B, Stamatiadou E, von Bothmer R, Gustafsson M (2006) Flora and vegetation of Andros, Kikladhes, Greece. Annales Musei Goulandris 11:85–270

Styring A, Rösch M, Stephan E, Stika H, Fischer E, Sillmann M, Bogaard A (2017) Centralisation and long-term change in farming regimes: comparing agricultural practices in Neolithic and Iron Age southwest Germany. Proc Prehist Soc 83:357–381

Szpak P (2014) Complexities of nitrogen isotope biogeochemistry in plant-soil systems: implications for the study of ancient agricultural and animal management practices. Front Plant Sci 5(288):1–19

Tauber H (1981) ^{13}C evidence for dietary habits of prehistoric man in Denmark. Nature 292:332–333

Televantou CA (2012) Hypsele on Andros: the geometric phase. Mediterr Archaeol 25:83–87

Trantalidou K (2012) Animal remains related to sacred areas on the Cycladic islands Amorgos and Tenos, during the Geometric Period: two distinct examples bearing evidence of sacrificial rites and bone working activities. In: Mazarakis Ainian A (ed) The 'Dark Ages' revisited. University of Thessaly Press, Volos, pp 1059–1105

Trantalidou K (2017) Active responses of Early Iron Age Aegean communities to their natural and social environment: the evidence from the animal bones. In: Mazarakis Ainian A, Alexandridou A, Charalambidou X (eds) Regional stories towards a new perception of the early Greek world. University of Thessaly Press, Volos, pp 633–667

Triantaphyllou S (2001) A bioarchaeological approach to prehistoric cemetery populations from central and western Greek Macedonia. British Archaeological Reports (International Series), Oxford

Triantaphyllou S (2015) Stable isotope analysis of skeletal assemblages from prehistoric northern Greece. In: Papathanasiou A, Richards MP, Fox SC (eds) Archaeodiet in the Greek world: dietary reconstruction from stable isotope analysis. American School of Classical Studies at Athens, Princeton, pp 57–76

Valamoti SM (2016) Millet, the late comer: on the tracks of Panicum miliaceum in prehistoric Greece. Archaeol Anthropol Sci 8:51–63

Van der Merwe NJ, Vogel JC (1978) ^{13}C content of human collagen as a measure of prehistoric diet in woodland North America. Nature 276: 815–816

Van Klinken GJ (1999) Bone collagen quality indicators for palaeodietary and radiocarbon measurements. J Archaeol Sci 26: 687–695

Virginia RA, Delwiche CC (1982) Natural 15N abundance of presumed N2-fixing and non-N2-fixing plants from selected ecosystems. Oecologia 54:317–325

Webb EC, Stewart A, Miller BG, Tarlton JF, Evershed RP (2016) Age effects and the influence of varying proportions of terrestrial and marine dietary protein on the stable nitrogen-isotope compositions of pig bone collagen and soft tissues from a controlled feeding experiment. STAR 2(1):54–66