Proceedings of the Prehistoric Society 88, 2022, pp. 155–191
doi:10.1017/ppr.2022.4 First published online 25 July 2022

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

By VALASIA ISAAKIDOU[1], PAUL HALSTEAD[2], ELIZABETH STROUD[1], ANAYA SARPAKI[3], ELENI HATZAKI[4], ERIKA NITSCH[5] *and* AMY BOGAARD[1]

In memoriam: John D. Evans, Sinclair Hood, & Mervyn Popham

Excavations at Knossos have uncovered faunal and archaeobotanical archives spanning the Neolithic and Bronze Age (7th–2nd millennia BCE), during which one of Europe's earliest known farming settlements developed into its first major urban settlement and centre of one of its oldest regional states. Through stable isotope ($\delta^{13}C$, $\delta^{15}N$) analysis of seeds and bones (as evidence for the growing conditions of cereal and pulse crops and for the types of forage consumed by livestock), land use and, ultimately, political economy are explored. Changing husbandry conditions overwrite any effects of long-term aridification. Early (7th–6th millennium BCE) Knossian farmers grew intensively managed cereals and pulses (probably in rotation) that were closely integrated (as manured sources of forage) with livestock. Through the later Neolithic and Bronze Age, settlement growth accompanied more extensive cultivation (eventually with cereals and pulses not in rotation) and greater use of rough graze and, by goats, browse. Pasture on cultivated land remained central, however, to the maintenance of sheep, cattle, and pigs. Variable diet of early sheep suggests management at the household level, while thereafter progressive dietary divergence of sheep and goats implies their separate herding. Until the Old Palace phase (early 2nd millennium BCE), urban growth was matched by increasingly extensive and probably distant cultivation and herding but somewhat more intensive conditions during the New and Final Palace phases (mid-2nd millennium BCE) perhaps reflect greater reliance on surplus from prime land of previously rival centres that now came under Knossian control.

Keywords: Knossos, Neolithic, Bronze Age, $\delta^{13}C$, $\delta^{15}N$, crop husbandry, pasture, sheep, goats

The emergence of urban settlements and strongly hierarchical societies in later prehistoric south-west Eurasia placed considerable demands on the production and mobilisation of food, triggering extensive scholarly debate on related changes in crop and livestock husbandry (eg, Childe 1950; Renfrew 1972; Gilman 1981; Sherratt 1983; Halstead 1992; Wilkinson 1994). The ERC-funded AGRICURB project has combined stable carbon and nitrogen isotope analysis of crop seeds and domestic animal bones to shed new light on farming methods in contexts ranging from the Neolithic to Iron Age and from northern Mesopotamia (Styring *et al*. 2017), through northern Greece (Nitsch *et al*. 2017) to central Europe (Styring *et al*. 2018). As a further outcome of this project, here we apply these methods to Knossos on Crete, southern Greece (Fig. 1), presenting the first such results from

[1]School of Archaeology, 1 South Parks Road, Oxford OX1 3TG, UK valasia.isaakidou@arch.ox.ac.uk
[2]20 Jarrow Rd., Sheffield S11 8YB, UK
[3]Tsikalaria 137, Chania 73100, Greece
[4]Dept of Classics, University of Cincinnati, OH 45221-0226, USA
[5]3 Cabbage Moor, Great Shelford, Cambridge CB22 5NB, UK

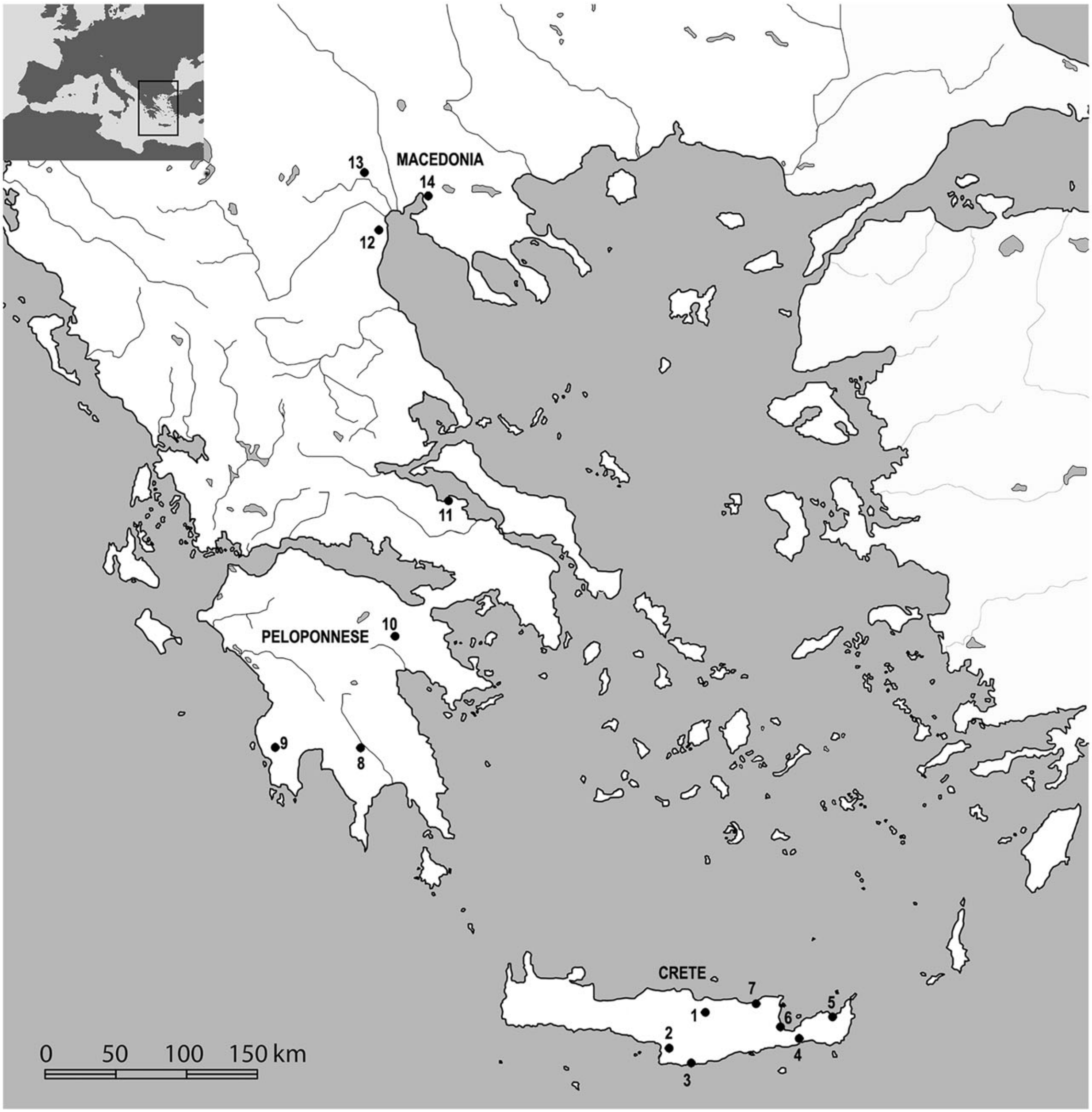

Fig. 1.
Map of Greece showing location of Knossos and other sites mentioned in the text: 1. Knossos, 2. Agia Triada & Phaistos, 3. Trypiti, 4. Schinokapsala, 5. Petras-Kefala, 6. Priniatikos Pyrgos, 7. Malia, 8. Kouphovouno, 9. Pylos, 10. Mycenae, 11. Halai, 12. Makriyalos, 13. Archontiko, 14. Toumba Thessalonikis

the site for faunal samples and new data for crop seeds, building on those reported by Nitsch *et al.* (2019) and Styring *et al.* (in press). Knossos is one of the earliest known farming settlements, earliest major urban settlement, and centre of one of the oldest regional (Minoan and Mycenaean) states in Europe (eg, Cadogan *et al.* 2004; Isaakidou & Tomkins 2008). Occupied from the early 7th to 1st millennia BCE, it offers the longest diachronic archive in Europe of domestic animal and crop remains and thus

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

an exceptional opportunity to explore the relationship of settlement growth and state formation to changing husbandry practices.

Drawing on macroscopic analysis of these archaeobotanical and faunal archives and on palatial written documents, previous studies have sought to reconstruct aspects of crop and livestock husbandry at 7th–2nd millennia BCE Knossos and of resource mobilisation by its 2nd millennium 'palace'. Here we test and refine these piecemeal and largely circumstantial reconstructions using direct evidence for husbandry conditions of 7th–2nd millennia Knossian crops and livestock, based on stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope analysis of their seeds and bones.

BACKGROUND

Knossos: from farming hamlet to urban palatial centre

Excavation and surface survey (Evans 1971; Hood & Smyth 1981; Whitelaw *et al.* 2019) have elucidated the growth of Knossos (Table 1). An Initial (IN) and Early (EN) Neolithic hamlet of perhaps 30 inhabitants developed through the Middle (MN), Late (LN), and Final Neolithic (FN) into a village of up to 250 (Tomkins 2008) or even 450 head (Whitelaw 2012, 147–8; Legarra Herrero 2019). Thereafter a suggested 'Prepalatial' (PreP) nucleated settlement of 1000–1300 grew rapidly to 4000–10,000 in the 'Late Prepalatial' (LPreP), 12,500–15,000 in the 'Old Palace' (OP) and 15,000–25,000 in the 'New Palace' (NP), before contracting to 12,000 in the 'Final Palace' (FP) and perhaps less than 3000 in the 'Postpalatial' (PostP) phase (Hatzaki 2017; Cutler & Whitelaw 2019, 15). It is debated (as for mainland Greece) whether 'households' emerged early or late in the Neolithic at Knossos, where intelligible architecture is sparse and the balance between domestic and collective control of resources was probably contested (Halstead 1995; 2019; Tomkins 2004; Kotsakis 2006). The earlier Neolithic community was small enough for egalitarian maintenance of social cohesion (cf. Forge 1972; Broodbank 1992, 42), but, from the PreP (if not later Neolithic), Knossos exceeded this limit (Legarra Herrero 2019) and the ancient core of the settlement was segregated for public or elite use (Tomkins 2012), including the later 'palaces' (cf. Whitelaw 2001).

At the inter-site level, Knossos was too small for a viable breeding population in the earlier Neolithic (Isaakidou 2008, 102; Tomkins 2008, 30–1) but had achieved potential demographic self-sufficiency by the PreP and conceivably by the later Neolithic. Ideological or economic pre-eminence of later Neolithic Knossos over the tiny settlements then widespread in the landscape (Tomkins 2008; 2020) cannot be excluded but Knossian dominance of a regional hierarchy is first evident in the palatial period. The numerous FP Linear B texts reveal selective Knossian palatial control and exploitation of agricultural, pastoral, and craft production across the central third or half of Crete (Godart 1977; Killen 1977; Bennet 1988; Halstead 1999a). Earlier (OP–NP) Hieroglyphic and Linear A texts, documenting similar resources (eg, Palmer 1995), are few and enigmatic (Bennet 2008), while some centres later subordinate to FP Knossos probably headed independent OP–early NP polities (Bennet 2012; Whitelaw 2019). The size of OP–NP urban Knossos, however, suggests its inhabitants already drew substantial resources from well beyond their immediate catchment (eg, Whitelaw 2004, 155 fig. 10.6; 2019).

The following section outlines previous models, and their underpinning evidence, of 7th–2nd millennia BCE land use and 2nd millennium palatial resource mobilisation at Knossos, as a prelude to their evaluation in the light of stable carbon and nitrogen isotope analyses of ancient crop seeds and animal bones. In conclusion, we explore how resulting insights into past land use may enrich understanding of social change at Knossos.

From archaeobotanical and faunal archives and textual records to models of changing land use

Crete has a Mediterranean climate of mild wet winters and hot dry summers, with considerable inter-annual variability in precipitation. Knossos, in lowland central Crete, with annual rainfall over the last century of ~500 mm (Tsiros *et al.* 2020), experiences more severe summer drought than most of mainland Greece (eg, Isaakidou 2008, 100 fig. 6.3). Proxy records across the Aegean and Mediterranean indicate a long-term trend to greater aridity through the 7th–2nd millennia BCE, punctuated by regionally variable (Finné *et al.* 2019) cold and dry episodes towards the end of the 7th, possibly 5th, and 3rd millennia, although their timing, nature, and severity are debated (eg, Dormoy *et al.* 2009; Aufgebauer *et al.* 2012; Clarke *et al.* 2016; Giamali *et al.* 2019). Both long-

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

TABLE 1: SITE PHASING, ABSOLUTE CHRONOLOGY & ESTIMATED SETTLEMENT AREA & POPULATION SIZE FOR PREHISTORIC KNOSSOS

Phase	*Absolute date* BC *(approx.)*	*Habitation area (ha)*	*Population estimates*
Initial Neolithic (IN)	7000–6500	0.3	30
Early Neolithic (EN)	6500–6000	0.3	30
Middle Neolithic (MN)	6000–5500	0.8	80
Late Neolithic I (LN I)	5500–5000	1.4–1.75	140–175
Late Neolithic II (LN II)	5000–4500	1.75–2.5/4.5	175–250/450
Final Neolithic (FN)	4500–3500		
Prepalatial (PreP) = EM I–EM II	3200–2500	6.5	1000–1300
Late Prepalatial (LPreP) = EM III–MM IA	2500–1900	40–65	4000–10,000
Old Palace (OP) = MM IB–MM II	1900–1750	63–76	12,500–15,000
New Palace (NP) = MM III–LM I	1750–1490	75–125	15,000–25,000
Final Palace (FP) = LM II–IIIA	1490–1300	60	12,000
Postpalatial (PostP) = LM IIIB–C	1300–1100	19	2000–3000

Phasing and chronology: for Neolithic after Tomkins (2020); for Bronze Age after Shelmerdine (2008, 4–5, figs 1.1–1.2) ('high' LBA chronology).
Settlement area: for IN–FN after Tomkins (2008, tables 3.1–3.2); for LN II–PostP after Whitelaw *et al.* (2019, fig. 19) (for LN II–FN: lower estimates after Tomkins (2007) and higher after Whitelaw *et al.* (2019)).
Population estimates assume, after Whitelaw *et al.* (2019, fig. 19): habitation densities (inferred from surviving architectural remains) of: Neolithic – 100 persons/ha; PreP – 150–200/ha; LPreP – 100-150/ha; OP-FP – 200/ha; PostP – 100–150/ha
Key: EM, MM, LM = Early, Middle and Late Minoan ceramic phases

and shorter-term changes (cf. Mauri *et al.* 2015, fig. S3) could influence the carbon and nitrogen isotope values (both generally raised by aridification) of plants and herbivorous fauna, but the principal climatic constraints on Cretan vegetation – summer drought, coupled with winter frost in the uplands – are relevant throughout this period.

The uncultivated vegetation of Crete (Zohary & Orshan 1965; Rackham & Moody 1996, 109–22) comprises a mosaic of herbaceous plants, dwarf shrubs (*phrygana*) and, below a variable tree-line, mainly broad-leafed evergreen and deciduous arboreal species (shrubs more than trees). Significant factors shaping the herbaceous-dwarf shrub-arboreal mosaic are summer drought (reflecting climate, topography, and geology), human clearance, and especially (as protective enclosures confirm) grazing/browsing by livestock. Neolithic inhabitants faced richer vegetation, judging by evidence for deciduous oaks in pollen cores from lowland south-central, and northwest Crete (Bottema 1980; Bottema & Sarpaki 2003) and in charcoal from the earliest occupation at Knossos (Badal & Ntinou 2013). Of particular relevance to carbon isotope values in animal bone, Cretan vegetation is heavily dominated by plants with C_3 photosynthesis (and thus relatively low $\delta^{13}C$ values). C_4 plants (with higher $\delta^{13}C$ values) are today restricted to a few crops (all or most being historical introductions), to summer weeds and ruderals in gardens or harvested fields or disturbed ground (Bergmeier 2008), and to saline coastal rough pasture (cf. Le Houérou 1994; Dimopoulos *et al.* 2012, 84 table 1); local tectonic and alluvial changes (eg, Ghilardi *et al.* 2018) will have affected the past extent of saline pasture. Around Knossos itself (Roberts 1979), limestone ridges immediately north and 5 km south of the settlement traditionally provided wet-season grazing but the dominant marls will have

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

supported woodland offering year-round browse until Neolithic clearance expanded seasonal grazing on cultivated land.

The distinctive insular fauna of Pleistocene Crete became extinct before the 7th millennium BCE introduction of domesticates (Jarman 1996) and the only large 'wild' terrestrial animals today are feral (escaped domestic) goats, widespread on inaccessible rocky terrain (eg, Xanthoudidis 1918, 272, ns 3, 4). Second millennium BCE figurative art apparently represents feral goats (eg, Vanschoonwinkel 1996), while biometric analysis of Knossos faunal remains may indicate feral goats and pigs by the later Neolithic (Isaakidou 2005). Badger was introduced during the Neolithic and European fallow deer during the Bronze Age (Jarman 1996; Isaakidou 2005), but the latter were conceivably enclosed, as argued by Hubbard (1995; also Palmer 2012, 380–1) for mainland Greece, rather than free-range.

The archaeobotanical archive is relatively sparse, with early excavations in the palace reporting but not retaining stored grain (Halstead 1992, 108 table 1). Of available material, a range of FP cereals and pulses comes from Storeroom P in the elite 'Unexplored Mansion' (Jones 1984; Fig. 2), while earlier samples derive from more diverse and socially inclusive contexts. At Knossos, as elsewhere on Crete, cultivated cereals and pulses were consumed throughout the period under review (Sarpaki 2013) and, in the NP and FP phases at least, included several species of both crop types (Sarpaki & Jones 1990; Sarpaki 2012; Livarda & Kotzamani 2013). Additionally, charred pips/stones, wood charcoal, and pollen suggest increasing exploitation of olive (Valamoti *et al.* 2018) and vine (Sarpaki 2012) on Crete from the PreP phase onwards and perhaps of almond at Knossos itself from the later Neolithic (Badal & Ntinou 2013; Sarpaki 2013). Lastly, two C_4 crops were *possibly* present on palatial-era Crete: common millet, *Panicum miliaceum*, is well represented archaeobotanically in northern Greece (Valamoti 2016) but not certainly on Crete (Livarda & Kotzamani 2013); and the commodity *CYP*, listed in Linear A and associated in Linear B with feasting/offerings, perfumery, and possibly also fodder, is plausibly translated as tiger nut, *Cyperus esculentus* or wild *C. rotundus* (Melena 1974), and starch grains attributed to the former are reported from palatial-era ceramic vessels on Crete (Tsafou & García-Granero 2021).

The excavated faunal archive from IN–LPreP Knossos derives from both domestic and communal contexts, but public/elite areas are overrepresented in the OP–FP assemblages. Domestic cattle, goat, sheep, and pig dominate throughout, while dog, badger, and, from the NP phase, horse and fallow deer are relatively scarce (Isaakidou 2005; 2008).

Knossian land use was shaped by its southern Aegean setting and the community's changing size, internal organisation and regional integration. Models of ancient land use in Greece have often drawn analogies with traditional 'extensive' (low-input) farming, tacitly assuming shared limitations of technology and know-how (Halstead & Isaakidou 2020). Most Neolithic settlements, however, including earlier and perhaps also later Neolithic Knossos, were small enough to have been sustained by cultivation within a few minutes' walk and thus potentially by labour-intensive, high-yielding husbandry with cereal-pulse rotation, manuring, and weeding (Halstead 1981a). Subsequent settlement growth, necessitating cultivation of more distant and less fertile land, will have impeded intensive husbandry, albeit perhaps partly offset by using cattle for tillage and bulk transport (Isaakidou 2008; Whitelaw 2012, 162–3).

Palatial Knossos drew resources from a broad region by a combination of staple and wealth finance, issuing rations of staple grains to hundreds of craft workers whose fine finished products were exchanged for other goods and services (eg, Killen 2008; Bennet & Halstead 2014). To account for production of the underpinning 'surplus' grain, both intensification (Gilman 1981; Renfrew 1982) and extensification (Halstead 1992; Whitelaw 2019, 97–8) have again been invoked, with a combination of archaeobotanical, textual, and iconographic evidence cited in support of the latter. In the palatial phases on Crete, although charred grains include multiple pulse and cereal species, Hieroglyphic, Linear A, and Linear B texts apparently record no pulses and only two (in Linear B, conceivably three) cereals (Palmer 1995; 2008; Halstead *et al.* in press). Moreover, the Linear B texts refer to production/collection of just one cereal (Killen 1995), conventionally identified as 'wheat'. FP Knossian scribes recorded its receipt in large quantities at subordinate centres (Bennet 1985) and it was arguably grown with extensive methods such as regular fallowing and tillage by oxen, the latter apparently loaned by the palace (Killen 1993), under some form

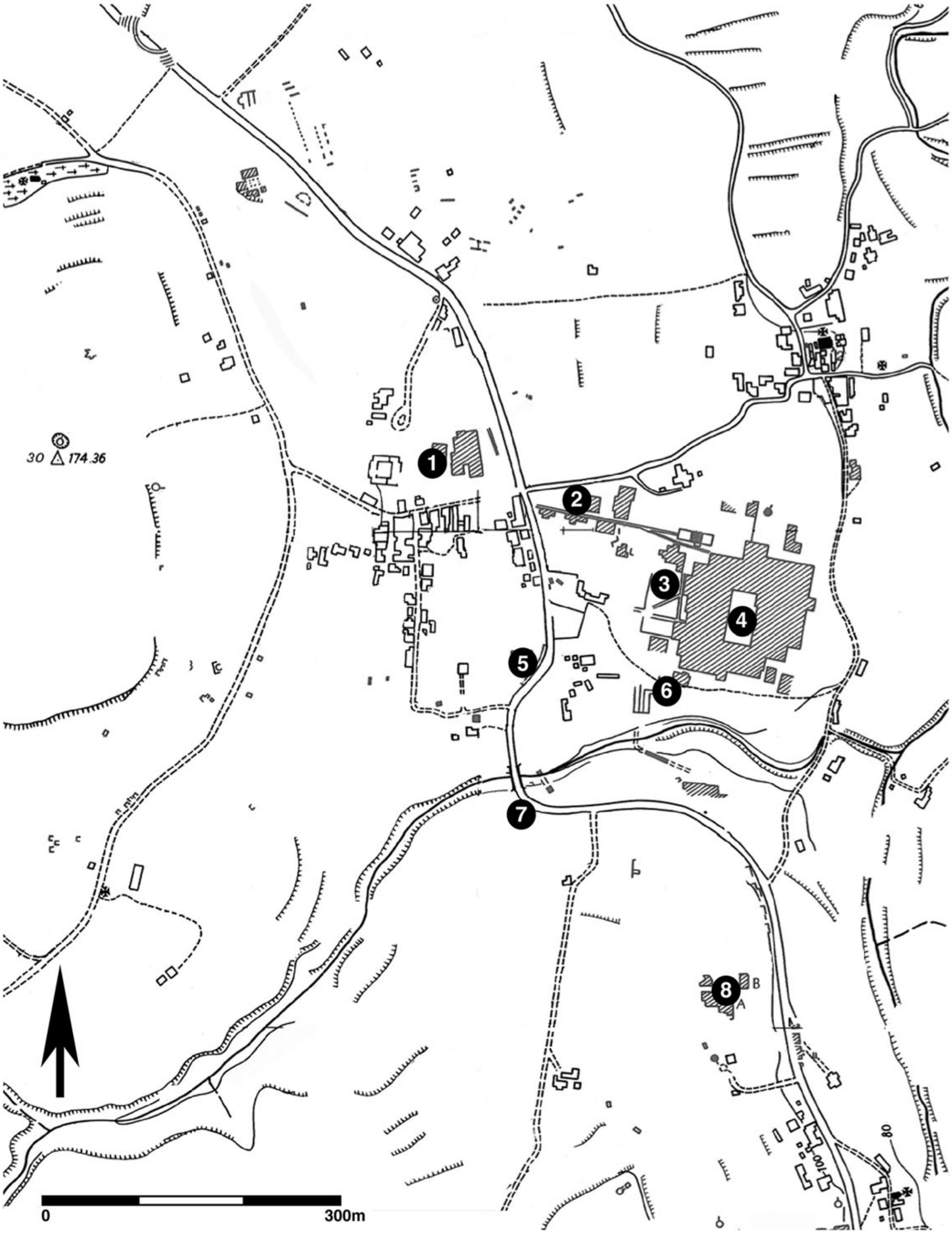

Fig. 2.
Plan of Knossos showing excavation sectors that provided seed and animal bone samples for the stable isotope analysis reported below (adapted from Hood & Smyth 1981): 1. Minoan Unexplored Mansion (MUM), 2. Royal Road (RR), 3. West Court House (WCH), 4. Central Court (CC), 5. Road Trials (RT), 6. Early Houses 93 (EH93), 7. Aqueduct Well (AW), 8. Hogarth's Houses (HH)

of share-cropping (Halstead 1999b). While textual evidence from the earlier palaces is sparser, the NP 'Harvester Rhyton', depicting a large gang of winnowers (Fig. 3a), suggests that extensive agriculture and share-cropping (Halstead & Isaakidou 2021) may likewise have contributed to filling large-scale storage facilities (eg, Christakis 2008; Privitera 2014; Fig. 3b) and financing elites. The case for palatial production of surplus 'wheat' by extensive methods rests on circumstantial evidence, however, while the contrast between specialised textual and diverse archaeobotanical records implies that palatial-era pulses and some/most cereals were produced on a different institutional basis and so potentially with more intensive husbandry (cf. Nitsch *et al*. 2019).

Throughout the Neolithic at Knossos, male sheep, goats, and cattle were slaughtered young, favouring meat yields over specialisation in milk, fibre, or traction, although skeletal 'pathologies' indicate yoking of female cattle for draught. Conversely, prepalatial Bronze Age sheep, goats, and cattle and palatial-era sheep and goats lived longer and far more males (especially of sheep) reached adulthood, consistent with greater emphasis on wool, hair, and traction, but also with selection of large adult males for conspicuous consumption in public/elite contexts (Isaakidou 2006). FP texts list working oxen and numerous wool-bearing male sheep (Fig. 3c), although it should be noted that *regional-scale husbandry* records may be unrepresentative of animals *consumed at Knossos*.

As with crop growing, alternative models of Neolithic animal keeping have proposed contrasting scales of livestock husbandry. Proponents of extensive husbandry have emphasised the scarcity of summer grazing in the lowlands (eg, for Knossos, Jarman *et al*. 1982, 147), arguing for seasonal use of upland pastures and tacitly assuming sufficient numbers of livestock to warrant such mobility. Conversely, in a largely uncultivated landscape better suited to cattle, goats, and pigs, the dominance of sheep at IN–MN Knossos (and other earlier Neolithic settlements in Greece) might reflect their close integration with cultivated land and thus maintenance in small numbers – especially so if crops were grown intensively on a small scale (Halstead 1981a; Isaakidou 2008; Halstead & Isaakidou 2020). During LN–FN, sheep remained dominant, but gave way somewhat to cattle, some at least used for draught (Isaakidou 2008; 2011), and less so to goats (Isaakidou 2008, 95 fig. 6.2). The proportional increase in goats, and their high frequencies at later Neolithic and younger sites colonising agriculturally marginal areas elsewhere on Crete (eg, Petras-Kefala, Priniatikos Pyrgos, Schinokapsala, Trypiti: Molloy *et al*. 2014; Isaakidou in prep.; Fig. 1), may reflect greater reliance on browse beyond the cultivated area. Moreover, even if Knossian livestock numbers expanded only in step with community size, economies of scale (Halstead 1996) would potentially have facilitated separate herding of sheep and goats on grazed and browsed pasture, respectively. Pigs too could have exploited woodland browse and pannage (Jarman & Jarman 1968, 260–1) and/or, as recently in northern Greece, stubble and fallow fields (Halstead & Isaakidou 2011) but, in small numbers, may largely have consumed crop by-products and food waste around the settlement. Rough (ie uncultivated) pasture suitable for cattle was probably scarcest but these large animals were better able than sheep, goats, or pigs to survive on coarse straw and stubble, perhaps supplemented by grain when their use for work prevented grazing (eg, Halstead 2014, 50–3). Dogs routinely gnawed the bones of other domesticates and so consumed at least their marrow (Isaakidou 2005) but were perhaps fed mainly with cultivated grain (or, like recent herders' dogs, bran) unless livestock were slaughtered very regularly (and thus herded on a large scale).

Through the palatial phases, urban Knossos with its monumental 'palace' probably drew livestock as well as agricultural produce from subordinate settlements, as textual (Godart 1971) and faunal isotopic (Isaakidou *et al*. 2019) evidence confirms for the FP phase. Such flows may account for the high representation in Bronze Age faunal assemblages from Knossos, compared with other sites on Crete, of cattle (Halstead & Isaakidou 2017), the largest and, in elite iconography (eg, Blakolmer 2016), most prestigious common domesticate. Livestock and their products/services dominate FP texts (Halstead 2002), that record palatial interest in goats, pigs, cattle (including working oxen), and especially male sheep and wool across central Crete. Texts also list animals earmarked for consumption, some after 'fattening' or 'finishing' (Killen 1994; 1999) but offer no indication of where livestock were pastured (Bennet 1985). Indeed, selective coverage (eg, listing too few breeding ewes to restock recorded flocks) suggests concern with palatial rights to wool rather than animal husbandry *per se* (Halstead 2001). Nonetheless, the apparent

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

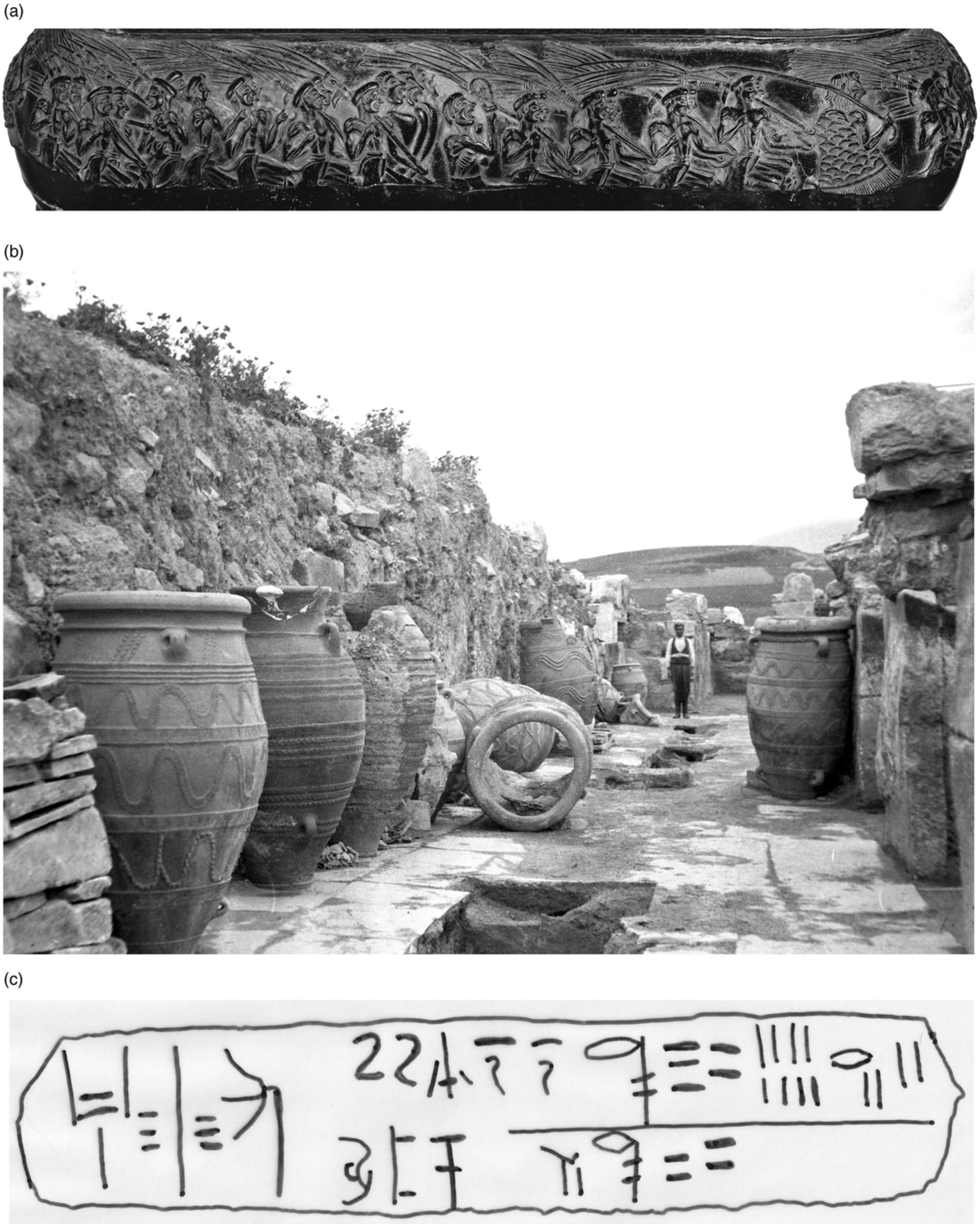

Fig. 3.
Palatial political economy: a) a large gang of winnowers depicted on the 'Harvester Vase' from NP Agia Triada, Crete (courtesy of Archaeological Museum of Heraklion; © Hellenic Ministry of Culture and Sports – Archaeological Resources Fund (TAPA)); b) palace storeroom (West Magazines) at Knossos during excavation (photograph by Ms A.M. Lloyd in 1901–04; BSA SPHS 01/2077/2566, BSA SPHS Image Collection; reproduced with permission of the British School at Athens); c) Linear B tablet De 1648 from Knossos recording (left half of tablet) two personal names and the toponym *ku-ta-to*, with which are associated (upper right) 58 male and 2 female sheep, and (lower right) 40 'missing' male sheep (horizontal strokes = 10s, vertical strokes = units; drawn after photograph at https://collections.ashmolean.org/object/476201)

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

concentration of recorded sheep at toponyms with extensive arable land suggests a major role for stubble and fallow fields (Halstead 1981b, 204), while total numbers (probably exceeding 80,000: Killen 1964) invite speculation that (like recent dairy flocks) they grazed mountain pastures in summer, as confirmed for some FP sheep, but not goats, by incremental analysis of oxygen and carbon stable isotopes in tooth enamel carbonate (Isaakidou *et al.* 2019).

Despite palatial interest in large-scale herding, especially of wool flocks, a few 'household' pigs, goats, or sheep could have been raised intensively throughout the Neolithic and Bronze Age and even by palatial-era elite households for their day-to-day provisioning, on which the texts are silent. Recent farmers of moderate means widely kept such animals for domestic consumption of preserved pork and cooking fat, young kids/lambs, and milk/cheese (Halstead 1996; Halstead & Isaakidou 2011).

While macroscopic archaeobotanical and faunal data from Knossos shed direct light on the crop and livestock species exploited over time and on the relative abundance and uses of the latter, they offer at best very indirect hints as to the scale and intensity of husbandry or the degree of integration between crops and livestock. For the palatial era, texts add a wealth of contextual detail for the husbandry and consumption especially of livestock and their products and document the farming of wheat and sheep, at least on a very large scale. The texts provide a highly selective, elite-centred perspective, however, and again shed limited light on how the recorded crops and livestock were raised. Accordingly, rival models of land use offer very different visions of the scale, intensity, and integration of Knossian land use and of the production of the staple resources that financed its palatial elite. The remainder of this paper seeks to resolve these uncertainties, using stable isotope data to clarify the conditions under which grain crops and livestock were raised at Knossos and thus the scale, intensity, and integration of land use.

CHANGING LAND USE: IMPLICATIONS FOR $\delta^{13}C$ AND $\delta^{15}N$ VALUES OF GRAIN CROPS AND LIVESTOCK

Supplementary text S1 sets out the methodological background for interpretation of C_3 grain crop $\delta^{13}C$ and $\delta^{15}N$ values in relation to changing land use. Hypothesised intensive early crop husbandry (see above) on the water-retentive soils of the Knossos valley should be associated with relatively low grain $\delta^{13}C$ values indicative of well-watered conditions, especially if the Kairatos stream was channelled for small-scale flood-irrigation (as latterly for market gardens). Subsequent expansion onto more distant and poorer/less thoroughly tilled land should be matched by lower water availability and higher $\delta^{13}C$ values. High cereal $\delta^{15}N$ values should characterise (earlier) Neolithic intensive husbandry close to Knossos, declining in the later Neolithic or prepalatial Bronze Age as cultivation over greater distances, albeit apparently facilitated by draught cows, enforced more extensive methods. In the palatial Bronze Age, low $\delta^{15}N$ values are expected for 'wheat' grown extensively, but other grains, production of which is not recorded textually, might exhibit higher values if grown more intensively.

Supplementary text S2 and Figure S1a–b set out the methodological background for interpretation of animal bone collagen $\delta^{13}C$ and $\delta^{15}N$ values in relation to changing land use. If the earliest Knossian livestock were closely tied to cultivated land on intensively managed water-retentive soils (above), their diet may have exhibited a narrow $\delta^{13}C$ range and relatively high $\delta^{15}N$ values. From the later Neolithic onwards, if more numerous livestock exploited more distant and diverse pasture, with different species herded separately, broader dietary $\delta^{13}C$ and $\delta^{15}N$ ranges would be expected, with greater divergence between species and generally lower $\delta^{15}N$ values. Yet further isotopic diversity might be introduced, at least in the palatial Bronze Age, by consumption at Knossos of animals reared elsewhere: for example, slightly higher or lower $\delta^{13}C$ values in animals reared mainly in the drier east or wetter west of Crete, respectively.

Of the forage categories modelled in Figure S1, lowland rough browse was probably available year-round but lowland rough graze relatively scarce in summer, upland rough graze normally inaccessible in winter, and pannage limited to a few autumn–winter months. C_4-rich coastal rough pasture too was traditionally exploited mainly in winter, while seasonal availability of pasture on cultivated land depended on rotation and fallowing regimes. To varying degrees, therefore, most livestock probably exploited mixtures of pastures, rather than any single modelled category, but the range of potential combinations is too large and the underpinning data currently too coarse, to warrant formal dietary mixing models.

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

Textual references to fattened or finished FP livestock may also imply consumption of isotopically enriched fodder, if this included C_4 millet or tiger nut (with very high $\delta^{13}C$ values) or C_3 grain (with slightly higher $\delta^{13}C$ and perhaps $\delta^{15}N$ than corresponding straw/chaff fodder and stubble/fallow pasture). Neolithic use of C_3 grain fodder has also been discussed in relation to livestock dental microwear (Mainland & Halstead 2005) and both macroscopic (Valamoti & Charles 2005) and isotopic (Vaiglova *et al*. 2014a) archaeobotanical data from Greece, but the bone collagen data presented below reflect long-term average diet and should be insensitive to fattening immediately before slaughter. If some livestock were reared intensively, however, fed significant quantities of grain like recent household goats, sheep, and especially pigs, their bone collagen might exhibit raised $\delta^{13}C$ and $\delta^{15}N$ values.

MATERIALS AND METHODS

We analysed carbonised cereal grains and pulse seeds from 34 samples from John Evans' 1969–70 Neolithic excavations, currently under final study by Sarpaki. Nitsch *et al*. (2019) have previously presented $\delta^{13}C$ and $\delta^{15}N$ values for four additional IN samples, including free-threshing wheat grain directly AMS-dated to the early 7th millennium cal BCE (Douka *et al*. 2017) from Evans' 1960 excavations (Evans 1968, 269), and for FP crops in Storeroom P of the Unexplored Mansion (Jones 1984; Popham 1984). Results of both new and previous analyses are presented in detail in Table S1 and in summary form in Table 2.

Samples of *c*. 5–10 grains were homogenised in an agate mortar and pestle. Pre-screening for contamination from the burial environment, using Fourier transform infrared spectroscopy (FTIR) as in Vaiglova *et al*. (2014b), detected no contamination so samples were not pre-treated. Plant data reliability was assessed by comparing $\delta^{15}N$ values to C:N ratios (Fig. S2; Supplementary text S3) and reported values from other sites in the region.

Six hundred and fifty faunal samples identifiable to species were selected for analysis from all phases of prehistoric occupation (Table S2a–b). Because faunal material has been recovered in much larger quantities than plant remains, samples from the lengthy Late Neolithic are analysed below for two separate phases, LNI and LNII (Table 1), but separate analysis of different FN subphases awaits completion of ongoing chronological work (Tomkins 2007; 2020). Due to the taxonomic composition of the assemblage, chronological coverage is good for sheep, patchier for goats, pigs, and especially cattle, restricted to the later Bronze Age for fallow deer, and sparse for dog, badger, and especially horse (one specimen). Selection of specimens, where possible from a single anatomical zone (distal humerus), sought to minimise any effects of intra-skeletal variability (Rodière *et al*. 1996, 181) and the risks of taking multiple samples from one individual or of sampling animals young enough to have been suckling at/shortly before death (and thus yielding elevated $\delta^{15}N$ values: Balasse & Tresset 2002). A few mandibles with teeth were also sampled, including some previously subjected to multi-isotope sequential analysis of enamel to explore the relationship of diet ($\delta^{13}C$) to seasonal vertical ($\delta^{18}O$) and lifetime horizontal ($^{87}Sr/^{86}Sr$) movement of FP sheep and goats (Isaakidou *et al*. 2019). For details of sampling protocol, laboratory, and quality control procedures, see Supplementary text S4.

RESULTS AND DISCUSSION: PLANT REMAINS

The results from stable isotope analysis of carbonised grains are detailed in Table S1, while summary $\delta^{13}C$ and $\delta^{15}N$ data are presented by broad crop type (cereals, pulses) and chronological period (Neolithic, Bronze Age) in Table 2 and displayed by crop taxon and chronological phase (IN, LN (including 13 cereal and two pulse samples of LN I and one pulse sample of LN II date), FN, FP) in Figure 4. The standard deviations for $\delta^{13}C$ (cereals ±0.7‰, pulses ±0.9‰) and $\delta^{15}N$ (cereals ±1.3‰, pulses ±1.0‰) values suggest that the samples overall represent a range of growing conditions (cf. Nitsch *et al*. 2015, 11 table 5), as do those of Neolithic cereals and pulses and, in part, Bronze Age cereals ($\delta^{15}N$ only) and pulses ($\delta^{13}C$ only). ANOVA and Welch two-sample t-test analysis (Table 3) highlights significant differences between broad crop types and chronological periods, especially in $\delta^{13}C$, and between some crop taxa and chronological phases.

Variability in growing conditions might in principle reflect climate/weather or husbandry practices. While pulse $\delta^{13}C$ values are lower in the Neolithic than the Bronze Age, however, and thus consistent with suggestions of long-term aridification, those for cereals

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

TABLE 2: Summary Statistics For $\delta^{13}C$ & $\delta^{15}N$ Values Of Cereal & Pulse Grains From Neolithic & Bronze Age Knossos

			$\delta^{13}C_{(VPDB)}$				$\delta^{15}N_{(AIR)}$			
		No.	*Min*	*Max*	*Average*	*SD*	*Min*	*Max*	*Average*	*SD*
Neolithic	Cereal	27	-25.0	-22.5	-23.3	0.5	1.7	8.1	4.8	1.4
	Pulse	11*	-25.0	-23.2	-24.1	0.5	0.9	4.6	2.5	1.1
Bronze Age	Cereal	14	-25.1	-23.7	-24.5	0.4	2.0	5.5	4.1	1.0
	Pulse	12	-24.5	-21.6	-23.0	0.8	0.6	2.1	1.5	0.5
All	Cereal	41	-25.1	-22.5	-23.7	0.7	1.7	8.1	4.6	1.3
	Pulse	23	-25.0	-21.6	-23.4	0.9	0.6	4.6	2.0	1.0

(*10 for $\delta^{13}C$); SD = 1 standard deviation (1σ)

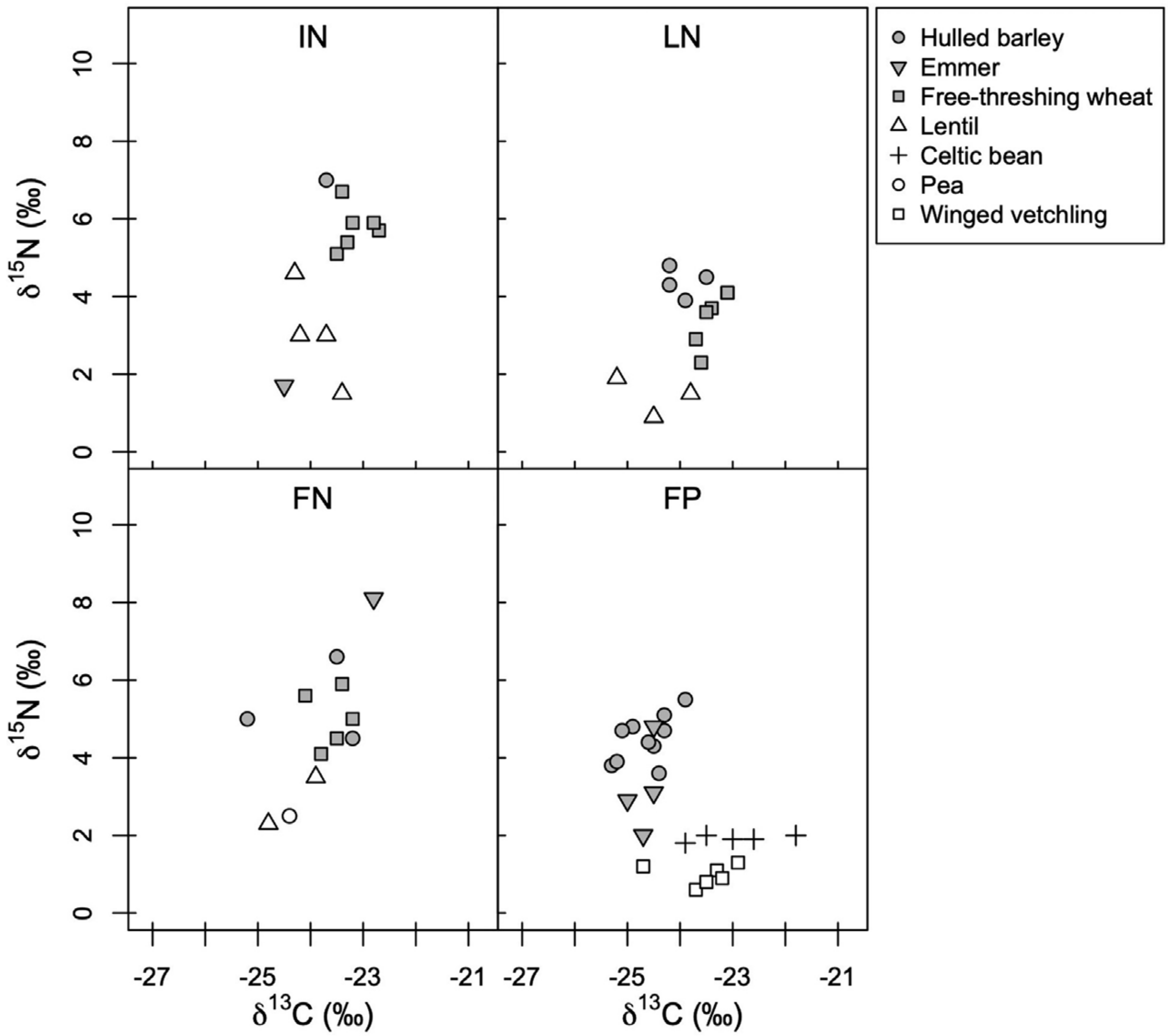

Fig. 4.
$\delta^{13}C$ and $\delta^{15}N$ values for Knossos cereal and pulse crops by phase

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

TABLE 3: RESULTS OF ANOVA & WELCH 2-SAMPLE T-TEST (DENOTED BY *) ANALYSIS OF $\delta^{13}C$ & $\delta^{15}N$ VALUES OF CEREAL & PULSE GRAINS FROM NEOLITHIC & BRONZE AGE KNOSSOS (≥3 SAMPLES PER TEST; ONLY TESTS WITH SIGNIFICANT P-VALUE SHOWN).

Species	*Phases*	*Isotope*	*df*	*F (t)*	*P-value*	*Post hoc differences*
Pulse, cereals*	All	$\delta^{15}N$	57.3	(9.07)	0.000	
Pulse, cereals*	Neolithic	$\delta^{13}C$	16.3	(3.3)	0.004	
Pulse, cereals*	Bronze Age	$\delta^{13}C$	15.3	(5.7213)	0.000	
Pulse*	Neolithic vs Bronze Age	$\delta^{13}C$	19.0	(3.607)	0.002	
Cereal*	Neolithic vs Bronze Age	$\delta^{13}C$	34.4	(7.3684)	0.000	
Barley, free-threshing wheat, lentil	Neolithic	$\delta^{13}C$	2(31)	9.62	0.001	Free-threshing wheat ≠ barley & lentil
Emmer, Celtic bean, barley, winged vetchling	Bronze Age	$\delta^{13}C$	3(22)	15.42	0.000	Celtic bean ≠ emmer & barley; winged vetchling ≠ emmer & barley
Free-threshing wheat, lentil*	IN	$\delta^{13}C$	5.35	(2.992)	0.028	
Free-threshing wheat, barley, lentil	LN vs FN	$\delta^{13}C$	2(10)	7.709	0.009	Lentil ≠ free-threshing wheat
'Wheat'*	FN vs LM II	$\delta^{13}C$	7.75	(5.4923)	0.001	
'Wheat'*	LM II vs IN	$\delta^{13}C$	8.50	(5.2703)	0.001	
'Wheat'*	LM II vs LN	$\delta^{13}C$	6.91	(8.125)	0.000	
'Wheat'*	IN vs LN	$\delta^{15}N$	8.50	(2.5778)	0.031	
'Wheat'*	LN vs FN	$\delta^{15}N$	7.37	(3.2034)	0.014	
'Wheat'*	FN vs LM II	$\delta^{15}N$	7.48	(2.8307)	0.024	
'Wheat'*	LM II vs IN	$\delta^{15}N$	8.24	(2.3613)	0.044	

Full details for post hoc test provided in Table S3
'Wheat' = emmer and free-threshing wheat combined

exhibit the opposite tendency (Table 2, Fig. 4). This suggests that any effects of such climate change (cf. Riehl *et al*. 2014) are overridden by differences in husbandry, both diachronically and between pulses and cereals.

In terms of $\delta^{13}C$ values, Figure 4 shows a striking contrast between the Neolithic and FP samples in the relative position of cereals and pulses: whereas pulses (mostly lentil) tend to be *similar to or lower than* the predominant cereal (free-threshing wheat) through the Neolithic, FP pulses are mostly *higher* than the associated cereals. Figure 5 expresses the Knossos stable carbon isotope values in terms of $\Delta^{13}C$, enabling comparison with modern baselines for poorly to well-watered cereals and pulses. Neolithic pulses all fall into the 'well-watered' band, as do most samples of the predominant Neolithic cereal, free-threshing wheat, while a few of the latter and almost all barley samples are moderately watered. By contrast, the FP cereals (emmer and barley) are mostly 'well-watered', while the associated pulses (winged vetchling and Celtic bean) are variously moderately or well-watered. These results suggest that the Neolithic free-threshing wheat and pulses grew under similar conditions as regards water availability and so were potentially rotated or inter-cropped on the same plots, a possibility further explored below in terms of nitrogen. The apparently drier growing conditions of Neolithic barley are potentially due to sowing, as was usual in recent pre-mechanised agriculture in Greece, later in the rotation cycle than wheat and thus with greater competition for moisture from weeds. Of the FP crops stored in the Unexplored Mansion, however, pulses and barley apparently experienced quite variable water availability and so cannot have been grown on the same plots of land as, and in rotation with, the strikingly well-watered emmer wheat (Nitsch *et al*. 2019).

Figure 6 also reveals diachronic variation in $\delta^{15}N$ values, which are generally higher for cereals and pulses in the IN, lower in the LN, and then again higher in the FN and lower in the FP. Manuring of

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

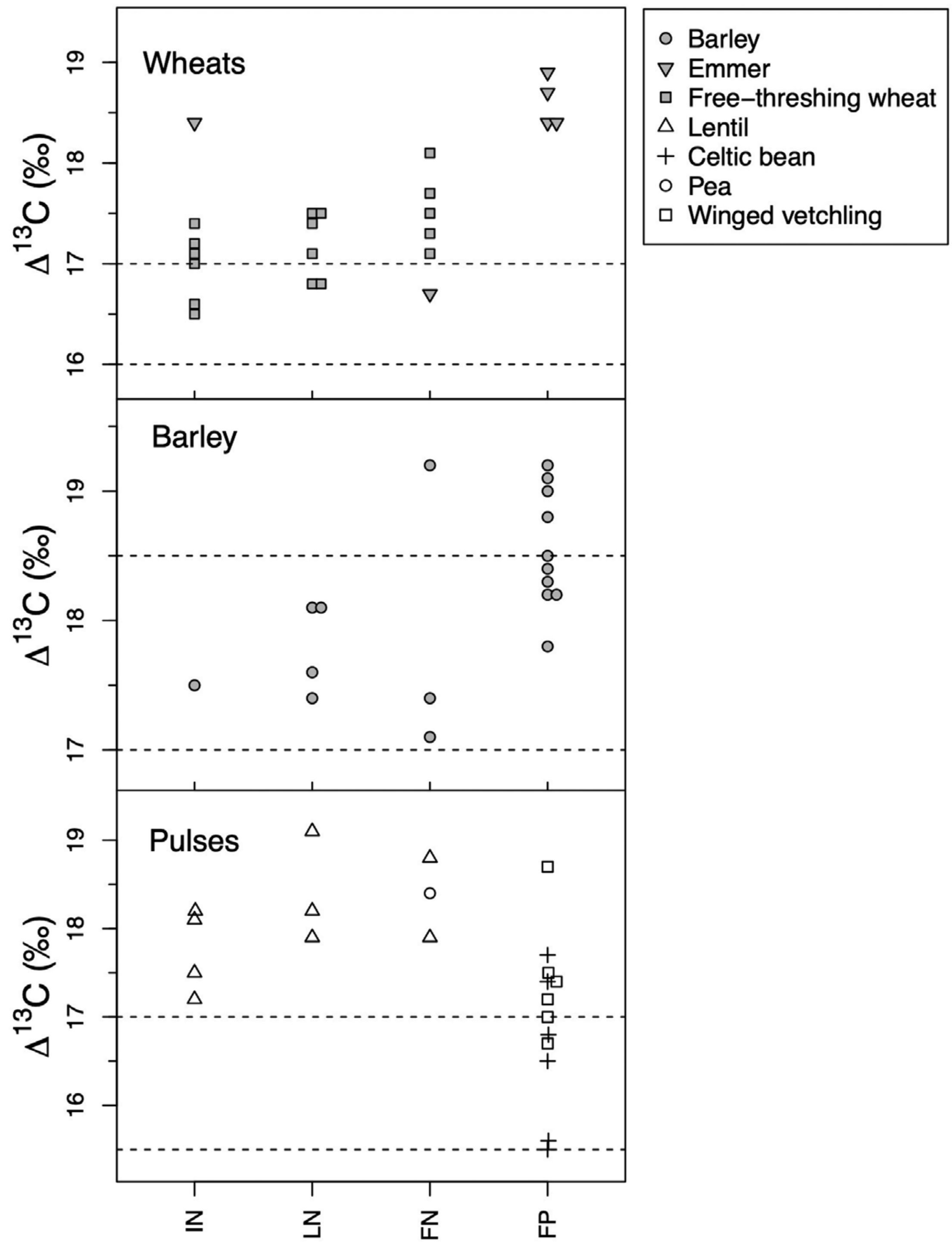

Fig. 5.
$\Delta^{13}C$ values for Knossos cereal and pulse crops by phase compared with modern reference bands (separated by dashed horizontal lines) representing 'well-watered' (uppermost), 'moderately-watered' (intermediate), and 'poorly-watered' (lowermost) growing conditions (Wallace *et al*. 2013); reference lines for barley assume a mixture of 2- and 6-row varieties

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

cereals is plausible at moderate levels throughout the Neolithic sequence, while for pulses the elevation of many $\delta^{15}N$ values well above 0‰, the value of atmospheric N_2, suggests manuring heavy enough to inhibit their fixation of nitrogen from this source. Manuring was perhaps particularly intensive when the community was very small during the IN (when one emmer sample with a strikingly low $\delta^{15}N$ value of 1.7‰ was potentially grown on a fertile newly cleared plot, manuring of which would have been counter-productive: Halstead 2018) and decreased with expanding community size during the later Neolithic. In the recent past, intensive manuring was often limited, even with animal traction, to within *c.* 500 m of the settlement (Halstead 2014, 217) and this threshold was perhaps reached (see Isaakidou 2008, 103 table 6.2) during LN II or FN if the population of Knossos approached not 250 or less but 400–500 head (Table 1). If so, the subsequent FN recovery in cereal $\delta^{15}N$ values might reflect greater use of draught cattle to promote intensive gardening, given the increase through the Neolithic in the relative abundance of cattle and the severity of traction-related skeletal remodelling/pathologies (cf. Isaakidou 2006; 2008; 2011). Either way, $\delta^{15}N$ values of LN and FP cereals and pulses suggest relatively light manuring that is consistent, for the latter phase, with the extensive agriculture anticipated on the basis of urban growth at Knossos and of Linear B textual evidence for grain production.

RESULTS AND DISCUSSION: FAUNAL REMAINS

The results from stable-isotope analysis of faunal samples are detailed in Table S2a–b. Of 645 faunal samples, 71% yielded usable results. Failure rates decline from Neolithic (42%) to Bronze Age (14%) and through successive Bronze Age phases (Table S4), inviting attribution to length of burial. Failures are particularly high in cattle, however, identifying significant observed differences between species in culinary (Isaakidou 2005, 196–203; 2007) and discard treatment (Isaakidou 2008, 95 fig. 6.2) as possible contributory factors (eg, depletion of bone collagen by prolonged boiling of intensively fractured cattle bones – cf. Roberts *et al.* 2002).

Table 4 presents summary statistics and Figure S3 scatter plots of $\delta^{13}C$ and $\delta^{15}N$ results by phase for all species, while Figure 7 displays these data as box-and-whisker plots (with outliers representing values exceeding interquartile range × 1.5 for each phase) for sheep (Fig. 7a–b), goat (Fig. 7c–d), cattle (Fig. 7e–f) and pig (Fig. 7g–h). Table 5, below, shows significant ($p<0.05$) differences (ANOVA with Tukey's post-hoc tests) in $\delta^{13}C$ and $\delta^{15}N$ values between phases for both sheep and goat (the two largest samples) and between goat and other common livestock species for individual phases.

We first consider the possible impact of long-term aridification or late 7th (EN), late 5th (FN) and late 3rd (LPreP) millennia cooler, drier episodes. Aridification should raise $\delta^{13}C$ and $\delta^{15}N$ values, but no consistent long-term trend is evident: $\delta^{13}C$ values rise in goats, but only slightly in sheep, and fluctuate in pigs; $\delta^{15}N$ values fluctuate in sheep and pigs and decline in goats; data for cattle are few and uninformative (Fig. 7). Nor are expected dry episodes mirrored in short-term peaks in $\delta^{13}C$ or $\delta^{15}N$ values. For sheep, offering the most continuous diachronic dataset, mean $\delta^{13}C$ and $\delta^{15}N$ values are strikingly low in OP, but not unusually high in EN, FN, or LPreP. For goat, the highest $\delta^{13}C$ and $\delta^{15}N$ outliers date to climatically 'normal' FP and PreP, respectively; and, while the second highest $\delta^{13}C$ outlier (-16.8‰) from a FNIB deposit *might* date to a late 5th millennium (Tomkins 2020, 56, fig. 2) dry episode, the same excavation context yielded four other goat specimens with values (-20.2 to -19.7‰) close to the Neolithic (-20.0‰) and Bronze Age (-19.8‰) means. Husbandry thus apparently overrides climate change in shaping observed variability in livestock stable isotope values, as also in crop $\delta^{13}C$ values (above). Likewise, since diachronic trends in $\delta^{13}C$ and $\delta^{15}N$ values differ between sheep, goats and pigs, husbandry practices evidently override any effects of physiological differences between species in shaping livestock stable isotope values.

Excluding the phase-by-phase outliers defined for sheep, goat, and cattle (Fig. 7), which are discussed in Supplementary text S5, we next compare the bone collagen data to modelled $\delta^{13}C$ and $\delta^{15}N$ values for Neolithic and Bronze Age forage categories to explore the dietary, and thus – indirectly – husbandry patterns, of each animal species consumed at Knossos. Modelled values for forage derived from cultivated land are based on measured values for ancient Knossian grain, while those for forage from uncultivated land are based on comparative east Mediterranean data assuming mean annual rainfall at Knossos of ~500 mm. In comparing modelled

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

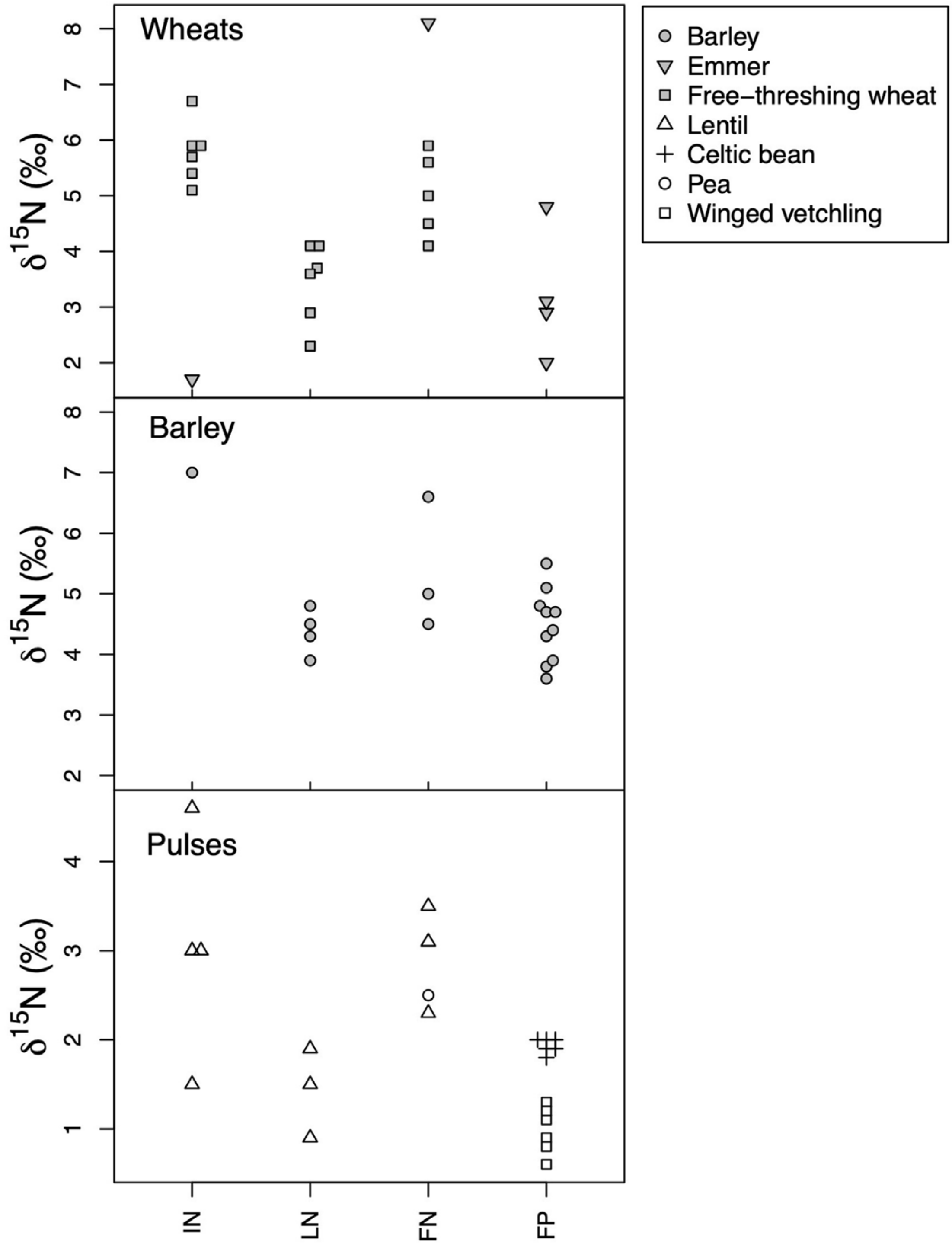

Fig. 6.
$\delta^{15}N$ values for Knossos cereal and pulse crops by phase

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

TABLE 4: SUMMARY STATISTICS FOR δ[13]C & δ[15]N VALUES OF ANIMAL BONE COLLAGEN FROM NEOLITHIC & BRONZE AGE KNOSSOS

			$\delta^{13}C_{(VPDB)}$					$\delta^{15}N_{(AIR)}$				
	Phase	*No.*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Mean*	*SD*	*Median*	*Min*	*Max*
Sheep	IN	8	−20.7	0.6	−20.5	−22.1	−20.3	6.3	1.0	6.4	4.4	7.6
	EN	8	−20.7	0.2	−20.7	−20.9	−20.4	6.0	1.3	5.7	4.8	8.7
	MN	3	−20.6	0.4	−20.5	−20.9	−20.2	4.6	0.6	4.4	4.1	5.3
	LN I	27	−20.7	0.5	−20.5	−22.0	−19.8	4.9	0.8	4.7	3.7	6.4
	LN II	13	−20.7	0.3	−20.8	−21.3	−20.1	5.9	0.8	6.0	4.8	7.1
	FN	30	−20.7	0.4	−20.7	−21.5	−19.5	5.7	0.7	5.6	4.2	7.1
	All Neolithic	*89*	*−20.7*	*0.4*	*−20.6*	*−22.1*	*−19.5*	*5.5*	*0.9*	*5.5*	*3.7*	*8.7*
	PreP	17	−20.5	0.6	−20.6	−21.3	−19.2	5.4	0.8	5.4	3.8	7.0
	LPreP	11	−20.8	0.5	−20.7	−21.8	−20.0	5.2	0.9	5.0	3.9	7.0
	OP	8	−21.0	0.5	−21.1	−21.5	−19.9	4.4	0.9	4.6	2.6	5.9
	NP	33	−20.4	0.6	−20.5	−21.5	−19.0	5.4	1.0	5.4	3.1	7.5
	FP	19	−20.3	1.0	−20.5	−21.9	−17.4	5.2	1.0	5.1	3.6	7.7
	PostP	3	−20.4	0.6	−20.4	−21.0	−19.7	5.4	1.3	4.8	4.6	7.0
	All Bronze Age	*91*	*−20.5*	*0.7*	*−20.6*	*−21.9*	*−17.4*	*5.2*	*1.0*	*5.1*	*2.6*	*7.7*
Goat	IN	2	−20.5	0.1	−20.5	−20.6	−20.4	6.9	0.8	6.9	6.3	7.5
	EN	2	−20.6	0.3	−20.6	−20.8	−20.3	6.2	0.4	6.2	5.9	6.5
	MN	2	−19.9	0.1	−19.9	−20.0	−19.8	5.6	1.2	5.6	4.7	6.4
	LN I	6	−19.8	0.7	−19.8	−20.5	−18.8	5.3	0.3	5.3	5.0	5.8
	LN II	7	−20.1	0.7	−20.2	−20.8	−18.6	5.1	0.9	5.4	3.7	6.1
	FN	29	−19.9	0.8	−20.1	−20.9	−16.8	5.6	0.7	5.4	4.2	7.5
	All Neolithic	*48*	*−20.0*	*0.7*	*−20.2*	*−21.0*	*−16.8*	*5.6*	*0.8*	*5.4*	*3.7*	*7.5*
	PreP	14	−20.0	0.4	−20.0	−20.7	−19.4	5.8	1.4	5.9	3.9	9.5
	LPreP	7	−20.4	0.5	−20.3	−21.5	−19.9	4.2	0.9	4.1	3.3	5.9
	OP	3	−19.8	0.4	−19.9	−20.1	−19.4	3.2	1.7	3.2	1.4	4.8
	NP	27	−19.9	0.6	−19.9	−21.2	−18.4	4.3	1.3	4.0	2.9	8.2
	FP	19	−19.5	1.0	−19.4	−21.2	−16.2	4.3	0.9	4.1	3.4	6.3
	PostP	1	−19.5					6.8				
	All Bronze Age	*71*	*−19.8*	*0.7*	*−19.9*	*−21.5*	*−16.2*	*4.6*	*1.4*	*4.2*	*1.4*	*9.5*
Cattle	IN	1	−21.1					6.9				
	EN	1	−21.0					4.5				
	MN	1	−21.1					4.7				
	LN I	1	−20.3					5.5				
	FN	7	−20.3	0.5	−20.6	−20.8	−19.4	5.1	0.5	5.0	4.6	6.2
	All Neolithic	*11*	*−20.5*	*0.6*	*−20.7*	*−21.1*	*−19.4*	*5.2*	*0.7*	*5.0*	*4.5*	*6.9*
	PreP	4	−19.9	0.4	−19.9	−20.5	−19.5	6.2	1.2	6.2	4.8	7.5
	LPreP	5	−20.9	0.2	−20.9	−21.0	−20.6	5.4	0.8	5.4	4.2	6.4
	OP	3	−21.1	0.2	−21.0	−21.3	−20.9	4.2	0.5	4.3	3.6	4.6
	NP	16	−20.6	0.6	−20.7	−21.2	−18.6	5.3	0.8	5.3	4.1	7.1
	FP	6	−20.2	0.8	−20.2	−21.2	−19.0	5.4	1.0	5.3	4.0	6.7
	All Bronze Age	*34*	*−20.5*	*0.6*	*−20.7*	*−21.3*	*−18.6*	*5.3*	*1.0*	*5.3*	*3.6*	*7.5*
Pig	IN	2	−20.1	1.1		−20.9	−19.4	7.6	0.3		7.4	7.7
	EN	6	−20.6	0.4	−20.7	−21.0	−20.1	5.5	0.9	5.5	4.3	6.6
	MN	7	−20.4	0.5	−20.2	−21.2	−19.9	6.1	1.0	6.1	4.7	7.3
	LN I	11	−20.7	0.5	−20.6	−21.4	−19.9	5.4	1.3	5.4	3.9	7.8
	LN II	3	−20.9	0.1	−20.9	−21.0	−20.9	4.5	0.4	4.4	4.2	5.1
	FN	12	−20.7	0.6	−20.7	−21.5	−19.9	5.6	1.3	5.9	3.1	7.0
	All Neolithic	*41*	*−20.6*	*0.5*	*−20.7*	*−21.5*	*−19.4*	*5.7*	*1.2*	*5.5*	*3.1*	*7.8*
	PreP	5	−20.6	0.4	−20.7	−21.1	−20.2	5.5	1.4	6.2	4.0	6.9
	LPreP	4	−20.8	0.5	−20.8	−21.3	−20.4	4.5	0.4	4.4	4.2	5.1
	OP	6	−20.6	0.5	−20.6	−21.1	−19.9	4.7	0.7	4.5	3.9	5.6

(Continued)

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

TABLE 4: (Continued)

			$\delta^{13}C_{(VPDB)}$					$\delta^{15}N_{(AIR)}$				
	Phase	*No.*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Mean*	*SD*	*Median*	*Min*	*Max*
	NP	13	−20.2	0.6	−20.2	−21.2	−18.9	5.7	1.1	5.4	3.9	7.7
	FP	12	−20.2	0.6	−20.2	−21.2	−19.2	6.1	1.5	6.5	2.9	8.3
	PostP	1	−20.2					4.8				
	All Bronze Age	*41*	*−20.4*	*0.6*	*−20.4*	*−21.3*	*−18.9*	*5.5*	*1.3*	*5.3*	*2.9*	*8.3*
Fallow deer	NP	7	−20.6	0.4	−20.9	−21.6	−20.3	5.0	0.6	4.9	4.1	5.9
	FP	8	−20.2	0.6	−20.3	−20.8	−19.3	4.8	1.1	4.4	3.6	6.3
	PostP	1	−21.4					5.0				
Horse	*Bronze Age*	*1*	*−20.9*					*2.7*				
Badger	*Neolithic*	*1*	*−19.8*					*5.7*				
	Bronze Age	*2*	*−19.6*	*1.6*		*−18.5*	*−20.8*	*6.8*	*2.8*		*4.8*	*8.8*
Dog	*Neolithic*	*6*	*−19.5*	*0.4*	*−19.5*	*−19.9*	*−18.9*	*8.0*	*1.2*	*7.7*	*7.1*	*10.3*
	Bronze Age	*5*	*−18.7*	*0.9*	*−18.8*	*−19.8*	*−17.4*	*7.1*	*2.8*	*8.2*	*2.4*	*9.0*

SD = 1 standard deviation (1σ)

forage values with bone collagen data, we assume trophic-level shifts between plant diet and animal tissue in herbivores and pigs of 5‰ for $\delta^{13}C$ and 4‰ for $\delta^{15}N$ (Supplementary text S2). The resulting dietary reconstructions are plausible in terms of livestock feeding preferences and Knossos' changing size and regional status. The adoption of different values for mean rainfall (~600 mm) and for trophic-level shifts ($\delta^{13}C$ – 4‰ or 6‰; $\delta^{15}N$ – 3‰ or 5‰) yields dietary reconstructions either broadly similar or less compatible with livestock feeding preferences and other known constraints (see Supplementary text S6).

Sheep

For sheep, the most abundant animal at Knossos, the range of $\delta^{13}C$ values broadens over time, implying long-term dietary diversification, while $\delta^{15}N$ values exhibit IN–LN I and LN II–OP cycles of decline interrupted by LN II and NP recovery (Fig. 7a–b, Table 4). Figure 8 displays these results, adjusting bone collagen values for trophic level shifts of ~5‰ in $\delta^{13}C$ and ~4‰ in $\delta^{15}N$, as 95% confidence ellipses overlain on modelled ellipses for different forage categories at 500 mm rainfall.

For Neolithic sheep (Fig. 8a), $\delta^{13}C_{diet}$ indicates consumption overwhelmingly of C_3 plants, as expected, and best matches the modelled ranges for C_3 forage from cultivated land and, more marginally, lowland rough pasture. Of the former, C_3 grain was apparently not of major importance, while small ruminants like sheep are ill suited to a coarse diet of cereal straw/chaff. Sheep, under traditional Mediterranean management, only consumed cereal straw/chaff if supplemented by higher-quality grain, hay, or pulse straw, but were widely and closely associated with stubble/fallow and, less so, young cereal pasture. Sheep $\delta^{15}N_{diet}$ values largely overlap the modelled range for fallow/stubble pasture, indicating the close association of Neolithic sheep with more (especially in IN and LN II, with high $\delta^{15}N_{diet}$ values) or less well-manured, cultivated land, but also extend into the range for lowland rough graze. In practice, most sheep probably exploited a mixture of cultivated and rough graze, given their partly complementary seasonal availability.

Bronze Age sheep likewise consumed a predominantly C_3 plant diet, including both forage from cultivated land and rough graze (Fig. 8b). Of the former, their $\delta^{13}C_{diet}$ overlaps most with nutritionally improbable straw/chaff, moderately with grain, and least with stubble/fallow graze, but the modelled range for stubble/fallow may be misleadingly narrow and low due to derivation exclusively from analyses of cereal grain in the FP 'Unexplored Mansion' destruction horizon. Cereals and pulses from this complex were not grown in rotation on the same land (above), so the relatively well-watered cereals represent only part of the range of FP growing conditions. Accordingly, fallow/stubble pasture was probably

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

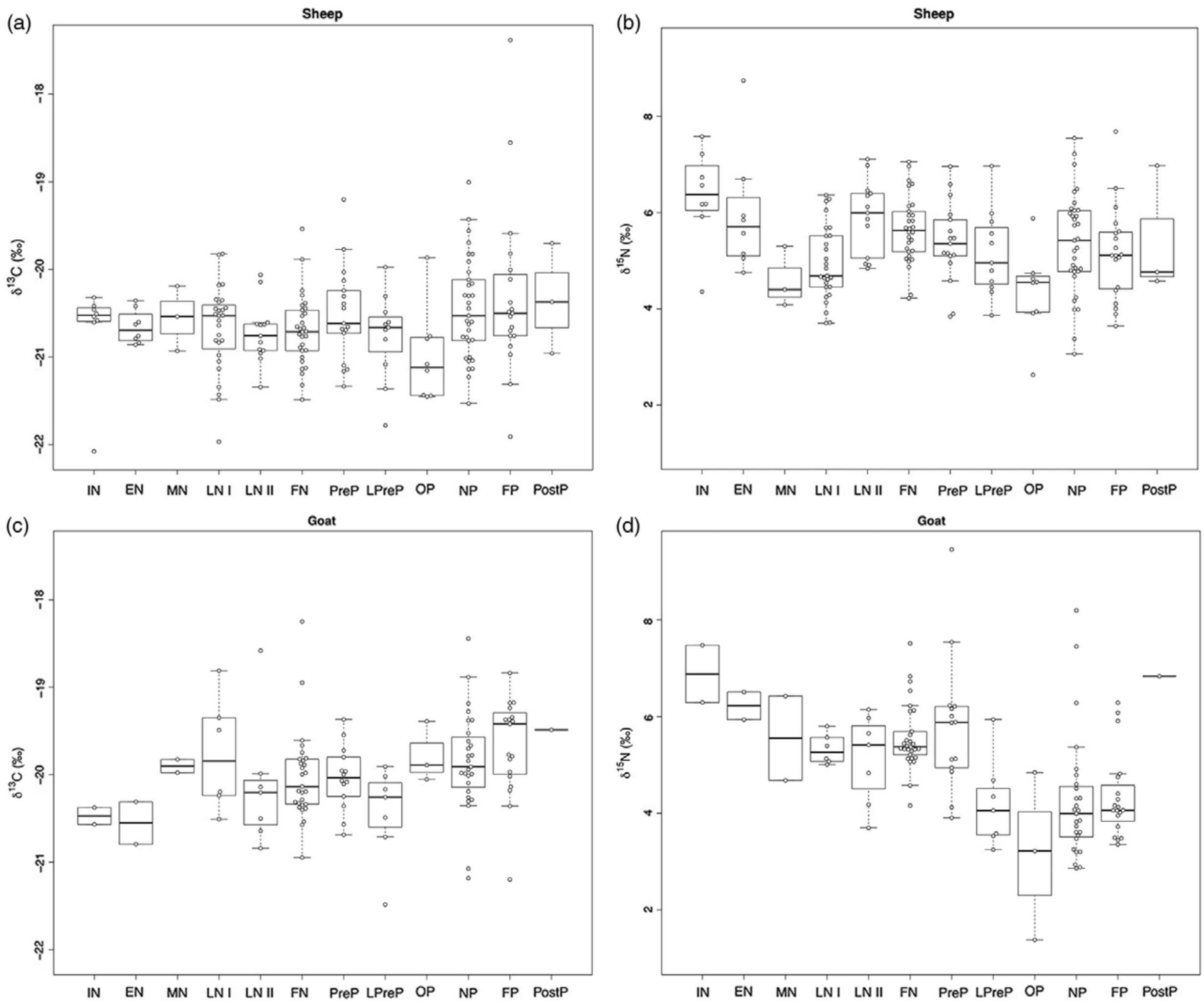

Fig. 7.
Boxplots of Knossos bone collagen $\delta^{13}C$ and $\delta^{15}N$ values by phase for a–b) sheep, c–d) goat, e–f) cattle and g–h) pig

again the primary contribution of cultivated land to Bronze Age sheep diet. Lower $\delta^{15}N_{diet}$ values than in the earlier Neolithic should partly reflect lighter manuring of cultivated land as a corollary of more extensive Bronze Age agriculture, but also suggest heavier use of rough pasture – primarily lowland C_3 rough graze, judging by $\delta^{13}C_{diet}$ values.

Sheep consumed at Neolithic–Bronze Age Knossos were thus closely associated throughout with stubble/fallow pasture on cultivated land, with some use also of lowland rough graze. Over time, stubble/fallow-grazing included more lightly manured land (mirroring more extensive cultivation) and use of C_3 rough graze expanded (mainly in the lowlands, but also – as indicated by incremental dental data – seasonally in the uplands). These changes in pasture use arguably reflect an increasing scale of herding.

Goat

For goat, less abundant than sheep throughout the Knossos sequence, the stable isotope data again reveal a broadening of diet from Neolithic to Bronze Age, but in $\delta^{15}N$ rather than $\delta^{13}C$ values (Table 4, Fig. 7c–d). Thus, while the two species share very similar IN–EN $\delta^{13}C$ and $\delta^{15}N$ values, they differ significantly in

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

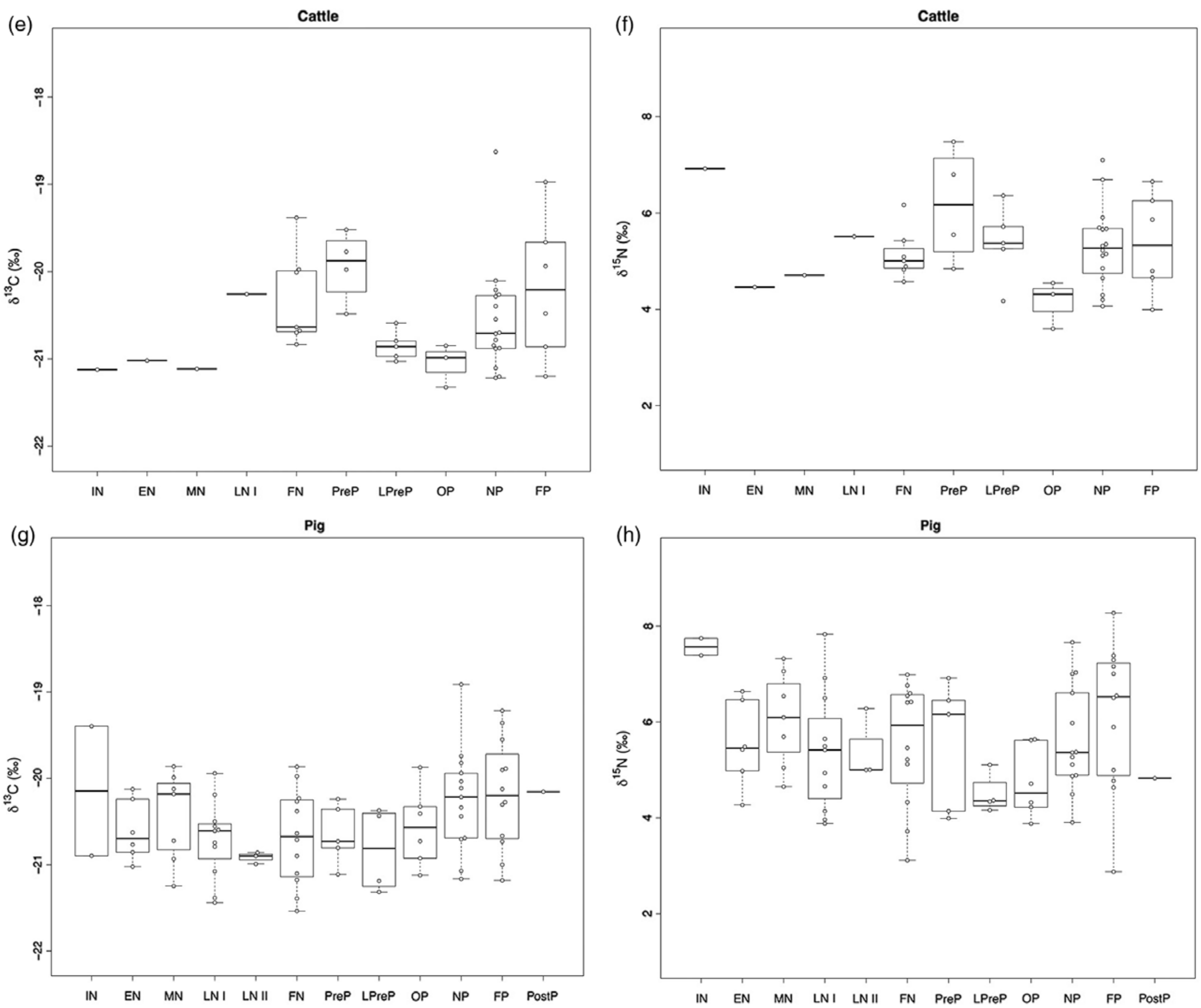

Fig. 7.
Continued

δ^{13}C values in most phases from the later Neolithic onwards and also in δ^{15}N during the NP (Table 5). This progressive dietary divergence of sheep and goat (Fig. 9a–b) matches expectations that growing livestock numbers would favour their separate herding.

Again allowing for trophic-level shifts (δ^{13}C ~5‰, δ^{15}N ~4‰), Neolithic goats share with sheep a comparable range of $\delta^{15}N_{diet}$ values (Fig. 8a), suggesting a similar association (especially in the earlier Neolithic: Fig. S3) with stubble/fallow pasture on well manured cultivated plots, but their somewhat higher $\delta^{13}C_{diet}$ values (increasingly through the later Neolithic – Fig. S3) imply intake also of browse – possibly from shrubs/trees on boundaries between cultivated plots. In mixed herds on hedged stubble fields in Greece today, while sheep graze weeds and unharvested cereal ears, goats also browse peripheral bushes and brambles (Yiakoulaki & Papanastasis 2005). Bronze Age goats (Fig. 8b) substantially overlap with sheep and with forage on cultivated land, especially in the pre-palatial phases (Fig. S3), but from LPreP onwards increasingly combine raised $\delta^{13}C_{diet}$ with low $\delta^{15}N_{diet}$ values that suggest heavy use of rough browse or possibly upland summer graze; goat feeding preferences favour browse, as do incremental dental δ^{13}C and δ^{18}O values suggesting that at least

TABLE 5: RESULTS OF ANOVA ANALYSIS OF $\delta^{13}C$ & $\delta^{15}N$ VALUES OF ANIMAL BONE COLLAGEN FROM NEOLITHIC & BRONZE AGE KNOSSOS (ONLY TESTS WITH SIGNIFICANT P-VALUE SHOWN)

Species	*Phases*	*Isotope*	*df*	*F*	*P-value*	*Post-hoc differences*
Goat***	LN II, FN, PreP, NP, FP	$\delta^{15}N$	6(100)	11.93	0.000	NP from LN I, LN II; FN from LPreP, NP, FP; PreP from LPreP, NP, FP
Sheep*	IN, EN, LN I, LN II, FN, PreP, LPreP, OP, NP, FP	$\delta^{15}N$	9(164)	4.26	0.000	LN I from IN; OP from IN, EN, LN II, FN
Sheep, goat, pig**	LN I	$\delta^{13}C$	2(41)	8.58	0.000	goat from sheep, pig
Sheep, goat, cattle, pig**	FN	$\delta^{13}C$	2(74)	9.28	0.000	goat from sheep, pig
Sheep, goat, pig**	PreP	$\delta^{13}C$	2(33)	5.38	0.009	goat from sheep, pig
Sheep, goat, cattle, pig***	NP	$\delta^{13}C$	3(83)	5.97	0.001	goat from sheep, cattle
Sheep, goat, cattle, pig***	NP	$\delta^{15}N$	3(83)	13.74	0.000	goat from sheep, cattle, pig
Sheep, goat, cattle, pig**	FP	$\delta^{13}C$	3(52)	2.80	0.049	goat from sheep
Sheep, goat, cattle, pig**	FP	$\delta^{15}N$	3(52)	6.59	0.001	goat from pig

Full details for Tukey post hoc test provided in Table S5

*≥5 samples per phase

**≥5 samples per species

***≥5 samples per phase; excluding two mandibles of unweaned goats

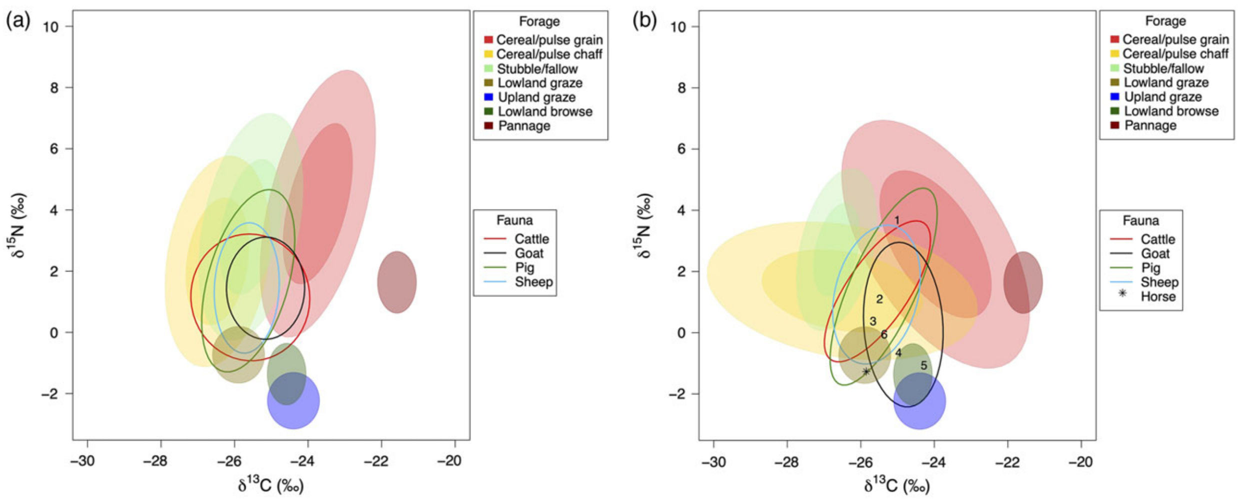

Fig. 8.
$\delta^{13}C$ and $\delta^{15}N$ values (95% confidence ellipses, excluding phase-by-phase outliers) of domestic animal species, compared with modelled forage categories (after Fig. S1) for a) Neolithic and b) Bronze Age Knossos; bone collagen values adjusted for trophic level shifts of ~5‰ in $\delta^{13}C$ and ~4‰ in $\delta^{15}N$ values; numbers in Fig. 8b denote FP mandibular specimens of sheep (1–3) and goat (4–6) discussed in the text

two FP goats (MUM78 and MUM70: Fig. 8b nos 4–5) remained year-round in the lowlands (Isaakidou *et al*. 2019, 50).

While earlier Neolithic goats were maintained mainly on well manured cultivated land, later Neolithic-PreP goats apparently combined stubble/fallow grazing with browsing, but possibly on the margins of cultivated plots and so were potentially herded with sheep. From the LPreP onwards, however, while some goats still grazed arable land, most exploited rough browse and so were herded separately from sheep (Figs 8b & 9a–b).

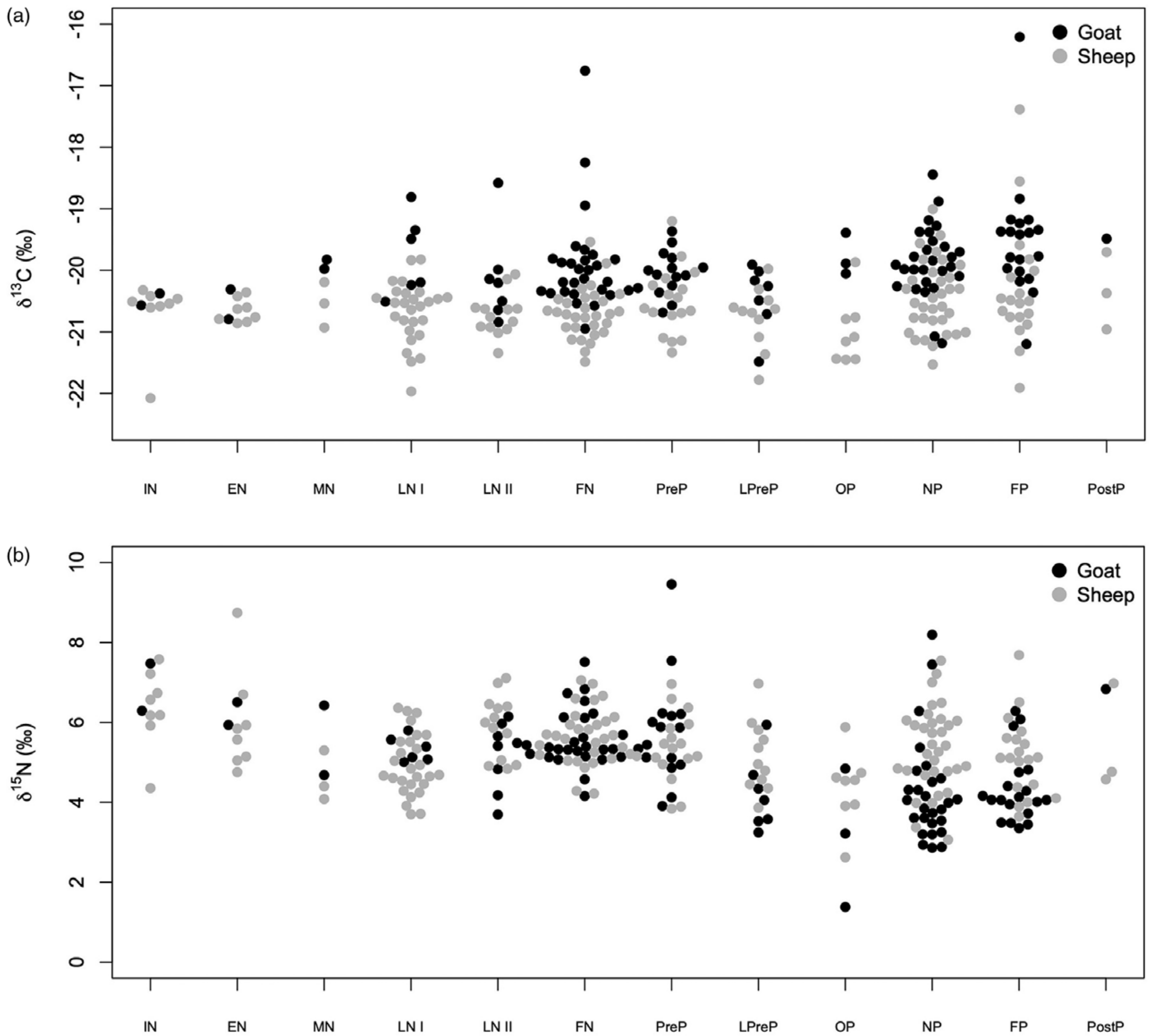

Fig. 9.
a) δ^{13}C and b) δ^{15}N values by phase for Knossos sheep and goat

Cattle

Cattle are well represented in the faunal assemblage from MN onwards, but by very fragmented (Isaakidou 2005, table 6.12) and perhaps intensively boiled specimens and thus by sparse isotopic data. Cattle diet ostensibly broadens slightly from Neolithic to Bronze Age, with lowest and highest δ^{13}C and δ^{15}N values of palatial date, but Bronze Age data are more abundant than Neolithic.

With the same trophic-level adjustments, the δ^{13}C and δ^{15}N ranges for both Neolithic and Bronze Age cattle essentially replicate those for sheep and so again indicate heavily C_3-dominated diet with reliance primarily on forage (stubble/fallow graze and/or straw/chaff fodder) from more or less manured, cultivated land, supplemented by some rough grazing (Fig. 8a–b). Among Bronze Age cattle (but not sheep), low $\delta^{13}C_{diet}$ values tend to be associated with low

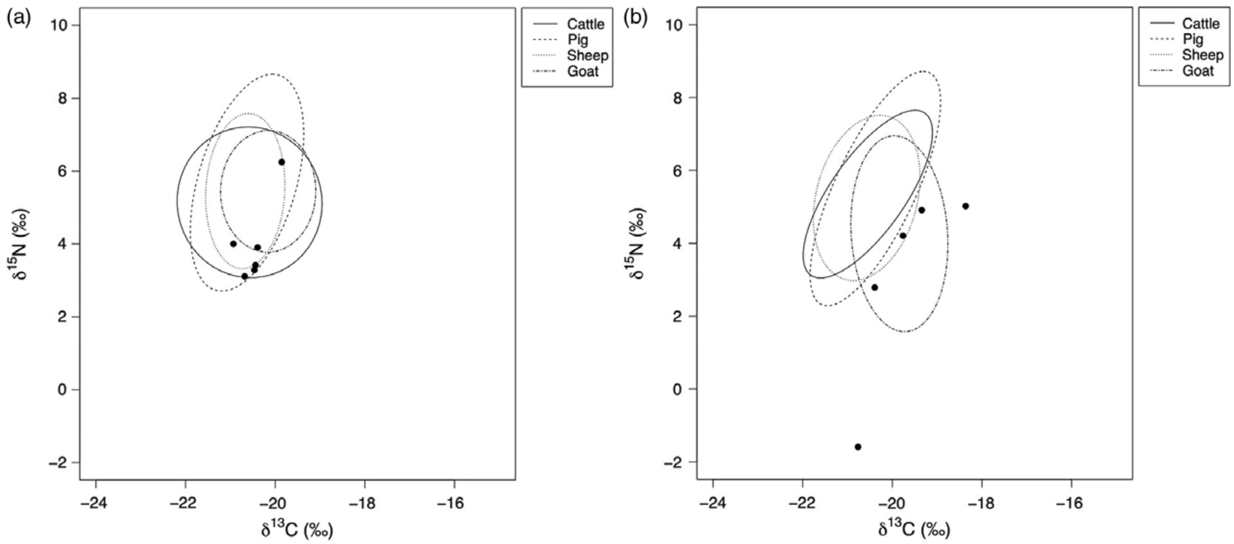

Fig. 10.
$\delta^{13}C$ and $\delta^{15}N$ values for dog (filled circles) compared with 95% confidence ellipses for sheep, goat, cattle, and pig at a) Neolithic and b) Bronze Age Knossos; bone collagen values for dog adjusted for potential carnivorous trophic level shifts of ~1‰ in $\delta^{13}C$ and ~4‰ in $\delta^{15}N$ values

$\delta^{15}N_{diet}$ and high $\delta^{13}C_{diet}$ with high $\delta^{15}N_{diet}$ (Figs 8b & S3). The former may reflect the ability of cattle (unlike sheep) to survive on a coarse diet of straw (cf. Bell 1971), while the latter may be due to feeding of C_3 grain supplements to some animals.

Pig

For both Neolithic and Bronze Age pigs, modestly represented in the assemblage, the ranges of $\delta^{13}C$ and $\delta^{15}N$ values again largely replicate those for sheep (Fig. 7g–h). Applying the same trophic-level shifts as for sheep, goats, and cattle (Fig. 8a–b), Knossos pigs consumed a diet dominated by C_3 forage from more or less manured, cultivated land (especially stubble/fallow graze) and some rough graze. C_3 browse (with relatively high $\delta^{13}C_{diet}$ and low $\delta^{15}N_{diet}$ values) and pannage (with yet higher $\delta^{13}C_{diet}$ values) were not important, but Bronze Age pigs with higher $\delta^{13}C_{diet}$ and also higher $\delta^{15}N_{diet}$ values (Figs 8b & S3) had perhaps consumed waste human food or, as suggested for some Bronze Age cattle, C_3 grain.

Horse

A single Postpalatial equid specimen (proximal metatarsal) is of a size suggesting horse (or conceivably mule, identified at coeval mainland Tiryns: von den Driesch & Boessneck 1990) rather than donkey. Assuming trophic-level shifts of 5‰ for $\delta^{13}C$ and 4‰ for $\delta^{15}N$, this animal grazed rough pasture with no hint of higher-quality fodder (Fig. 8b).

Dog

Dogs are represented by low numbers of skeletal remains in all phases. Six Neolithic samples yielded narrower ranges of both $\delta^{13}C$ and $\delta^{15}N$ values than five Bronze Age specimens (Table 4). To explore whether canine carnivory extended beyond the scavenging for bone marrow that is indicated by gnawing marks (Isaakidou 2005), a carnivorous dog diet is modelled assuming prey-predator trophic-level shifts of 1‰ for $\delta^{13}C$ and 4‰ for $\delta^{15}N$ (Supplementary text S2; Fig. 10). Most of the resulting $\delta^{13}C_{diet}$ and $\delta^{15}N_{diet}$ values are compatible with consumption of other domestic animals but would only indicate predominant carnivory if (improbably) Bronze Age dogs mainly ate goats (contrary to the evidence of gnawing traces, present on specimens of all species) and Neolithic dogs mainly ate animals that had grazed rough pasture and lightly manured stubble/fallow. Thus, Knossian dogs, and especially the Bronze Age specimen with the lowest $\delta^{15}N_{diet}$ value, probably subsisted in large measure on cultivated C_3

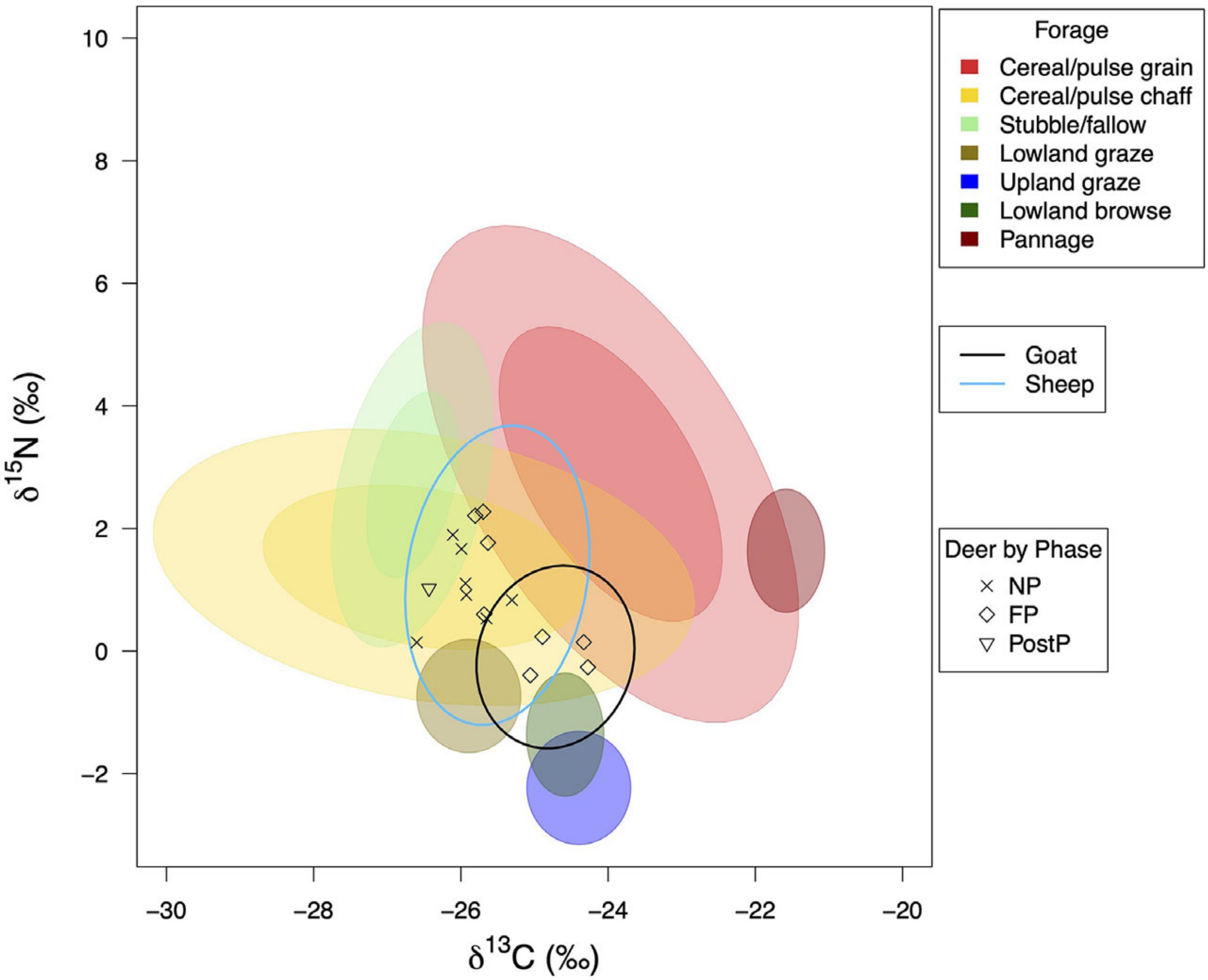

Fig. 11.
δ^{13}C and δ^{15}N values by phase for Knossos fallow deer compared with 95% confidence ellipses for Bronze Age Knossos sheep and goat and with modelled forage categories (after Fig. 8b); bone collagen values adjusted for trophic level shifts of ~5‰ in δ^{13}C and ~4‰ in δ^{15}N values

grain and perhaps mainly, as commonly in the recent past, on cereal bran with lower δ^{15}N values than whole grain (Nitsch *et al*. 2015, table 6).

Badger

Badgers are as well represented as dogs in the Neolithic, but thereafter very scarce. The δ^{13}C and δ^{15}N values of one Neolithic and two Bronze Age specimens fall largely within the ranges for dogs, consistent with the expected omnivorous diet.

Fallow deer

Fallow deer bones occur in small numbers at palatial Knossos and, albeit possibly due to excavation bias, only in elite contexts. Seven NP samples essentially fall within the δ^{13}C and δ^{15}N ranges of Knossos NP–PostP sheep, as does the single PostP specimen. Eight FP samples exhibit similar δ^{15}N values but a broader δ^{13}C spread across both sheep and goat ranges (Table 4). Assuming trophic-level shifts of 5‰ for δ^{13}C and 4‰ for δ^{15}N (Fig. 11), the NP, PostP, and four 'sheep-like' FP specimens suggest diet dominated by stubble/fallow grazing on variably manured land, perhaps with some rough grazing, while the four 'goat-like' specimens fall near the interface between arable-based forage and lowland browse. European fallow deer (*Dama dama*) in temperate Europe (Jackson 1977; Putman *et al*. 1993), like Persian fallow (*D. mesopotamica*) in the east Mediterranean (Zidon *et al*. 2017), are mixed grazers/browsers, while the former at least raid field-crops from wooded refuges (Thirgood 1995). European fallow deer on the southern Aegean island of Rhodes, however, avoid pasture and water fouled by sheep and compete more with domestic goats (Theodoridis *et al*. 2008). It is tempting, therefore, to identify the 'sheep-like' specimens as *enclosed* on farmland (as at Dudley Castle, England: Sykes *et al*. 2016, 121 fig. 8) and their 'goat-like' counterparts as free-range, whether escaped or released, and more reliant on rough browse. The suggested enclosure of this imported deer species is of considerable intrinsic importance for understanding its management on Bronze Age Crete but is also methodologically significant in precluding use of stable isotope values for fallow deer as a proxy measure for 'natural' coarse pasture, free from anthropogenic inputs.

RE-ASSESSING KNOSSIAN LAND USE AND POLITICAL ECONOMY

Mixed farming: integration of crops and livestock

Perhaps the most salient feature of the Knossos stable isotope results is the implied close interdependence of arable and pastoral farming: cultivated land was throughout the Neolithic and Bronze Age a key pasture resource for livestock, especially sheep, but also pigs, cattle, and to some extent goats; and animal manure underpinned intensive crop husbandry, especially in the earlier Neolithic. The importance of manure to early crop husbandry raises questions regarding its attendant risks, distribution, and availability. First, recent Cretan farmers spread manure very sparingly, from fear of crops 'burning' in drought years (Halstead 2014, 213–15) but a generally moister Bronze Age and, especially, Neolithic climate would have mitigated this risk. Secondly, draught cattle could have eased distribution of any stall-manure and human night-soil accumulated at the settlement (Isaakidou 2008) but mild winters and lack of predators (other than stray dogs, large raptors, and other humans) would have limited need for stalling, while delivery of dung (and urine) directly by grazing or penned livestock would have saved human labour in muck-spreading (Halstead & Isaakidou 2020). Thirdly, availability of manure depends on the scale and form of animal husbandry. Early livestock, if closely tied to small, cultivated plots, would have been few in number: a family of say 4–5 head sowing only 1–2 ha of grain crops (Halstead & Isaakidou 2020, 91–2) might maintain at most 1–2 sheep solely on stubble/fallow pasture (at 1/ha: Le Houerou 1977, 259). Penning these animals overnight on such plots (in addition to grazing stubble, fallow, and, in lean seasons, rough pasture) would have made maximum use of available manure (Halstead & Isaakidou 2020) and, thanks to deposition of both urine and faeces, may have enhanced crop $\delta^{15}N$ values more than would dry stall manure (cf. Abell *et al*. 2019), but seems unlikely to have maintained the fertility levels implied by crop $\delta^{15}N$ values (Halstead & Isaakidou 2020, 91–2). Alternatively, a family with access to working cows that sowed say twice the area of grain crops normally needed (cf. Halstead 1989) and allowed livestock to graze any growing crops that failed due to drought or weeds or lodging (stem collapse – a particular risk with heavy manuring), or were surplus to human needs, might have supported 5–10 sheep or more (cf. Le Houerou 1977, 263 table 3). Penning of animals on sown cereal pasture entails radically closer integration of early crop and livestock husbandry than is usually envisaged but would account better than more familiar husbandry regimes for the high $\delta^{15}N$ values of earlier Neolithic Knossos cereals and pulses (Halstead & Isaakidou 2020).

After the earlier Neolithic there are indications of more extensive crop husbandry and of livestock management on more distant and varied pasture that extended to lightly manured arable land, rough graze (including transfer of some palatial-era sheep to uplands in summer) and, for Bronze Age goats, arboreal browse. Use of distant rough pasture would have facilitated the escape of adventurous livestock and formation of feral populations, suspected from the later Neolithic onwards on biometric grounds (Isaakidou 2005), but stable isotope data as yet neither support nor refute this scenario.

Land use in socio-political context

Other things being equal, a likely corollary of the growth of Knossos and associated expansion of crop

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

husbandry was increasingly unequal access to good-quality, nearby land suitable for intensive cultivation, while access to draught cattle for tillage and transport would also have become more critical (Isaakidou 2008). On the other hand, communal rather than household-level production and consumption of food, as proposed by Tomkins (2004) for the earlier Neolithic, might initially have countered any such tendency. δ^{15}N values for IN cereals are quite variable, but might reflect the time elapsed since, rather than intensity of, manuring. For IN–MN sheep, however, although the narrow δ^{13}C range is compatible with shared grazing on relatively uniform pasture, variable δ^{15}N values imply these animals were not herded together across the community's stubble, fallow and perhaps sown plots, but were confined in small numbers on particular plots or holdings with contrasting manuring histories. Both livestock and cultivation plots, therefore, from early in the settlement's life, were apparently managed not collectively but by small ('household') units. Moreover, on this scenario, the broad crop δ^{15}N range probably does reflect manuring of variable intensity and thus differences between earlier Neolithic households in livestock numbers and also in area sown and the potential for surplus grain production. In turn, a differential capacity to provide 'surplus' grain to needy neighbours or meat for commensal occasions is likely to have underpinned competitive dynamics within Neolithic society (Halstead 1989; Isaakidou 2008, 105–7).

Thereafter, values for δ^{13}C (from MN) and δ^{15}N (from LN II) progressively diverge between sheep and goats (Fig. 9a–b), implying use of increasingly different and thus distant pasture, and hence active herding of the two species independently of each other, such that the increasing proportion of goats relative to sheep from the later Neolithic onwards (Isaakidou 2008, 95 fig. 6.2) arguably represents an absolute as well as relative expansion of goat numbers. Herding labour may accordingly have displaced pasture as the limiting factor on livestock numbers, while large, excavated houses at later Neolithic Knossos, if accommodating extended households (Isaakidou 2005, 64), could better have mobilised additional labour for larger and more mobile herds (cf. Halstead 2014, 292–4).

While crop and livestock stable isotope values document increasingly extensive husbandry over the early 7th–late 2nd millennia BCE, consistent with expectations from the expanding size and regional sway of Knossos, the pace of demographic and political change was uneven and the same might be expected of land use. Indeed, cereal δ^{15}N values are higher in IN (5.5–7.3‰, mean 6.3‰; excluding the low outlier discussed above) and FN (4.5–8.4‰, mean 6.0‰) than intervening LN I (2.6–5.2‰, mean 4.1‰). Cereal δ^{15}N values are not currently available for other phases of the Neolithic, but those for sheep, closely linked to arable land and thus plausible proxies for cereal growing conditions, decline from IN to LN I, before increasing in LN II-FN (Fig. 7b). The low LN I δ^{15}N values for cereals and sheep coincide with expansion of the settlement and thus its cultivated radius, apparently resulting in less intensive crop husbandry that was subsequently reversed, perhaps by FN cessation of growth (Table 1) and/or increasing LN–FN frequencies of cattle (Isaakidou 2008), some bearing stress markers consistent with draught use (Isaakidou 2006). Bronze Age crop stable isotope data are limited to the elite FP 'Unexplored Mansion', but sheep δ^{15}N values again offer a proxy for cereal growing conditions with a renewed cycle of decreasing values from LN II–FN to OP and then NP–FP increase. OP Knossos was one of at least three palatial towns in central Crete, but FP and perhaps NP Knossos had subsumed its largest 'rival' at Phaistos to the south, probably also that at Malia to the east, and many smaller centres (Bennet 1985; 2012, 239–41). A plausible reading of sheep δ^{15}N values, therefore, is that rapid urban growth at OP Knossos was supported by extensive cultivation at increasing distance, but NP–FP Knossos relied more on mobilising grain and livestock raised on subordinate centres' core rather than marginal land (as argued from FP texts for grain and sheep: Halstead 1981b; Bennet 1985).

The FP texts do not document provisioning of the ruling elite itself (cf. Lane 2004, for the mainland palace at Pylos), who presumably consumed produce from their own gardens, fields, and herds, of which the first may have occupied open spaces between urban elite buildings (Shaw 1993, 680) and the second appear in FP texts (Zurbach 2005, 325–8). The 'Unexplored Mansion' pulses, judging by their elevated δ^{15}N values, were indeed products of intensive gardens, while the cereals were grown in well-watered conditions and so probably on good land (possibly after bare fallow to eradicate weedy competitors for moisture), perhaps equivalent to that at the FP subordinate centres from which 'wheat' was centrally mobilised. Lastly, if fallow deer consumed at

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

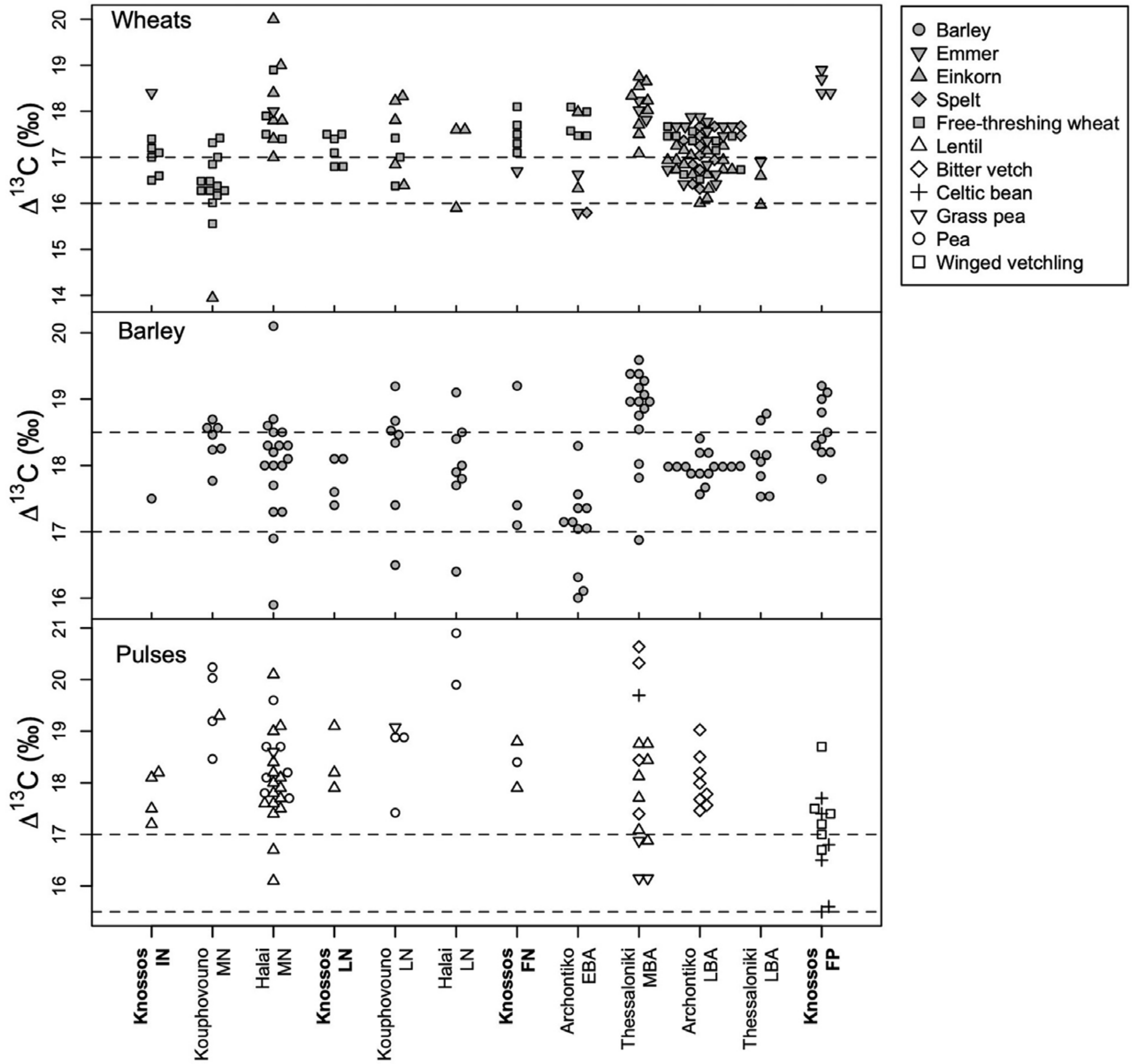

Fig. 12.
Δ^{13}C values for Knossos cereals and pulses by phase compared with those for other Neolithic and Bronze Age sites in Greece; dashed horizontal lines separate modern reference bands representing 'well-watered' (uppermost), 'moderately-watered' (intermediate) and 'poorly-watered' (lowermost) growing conditions (Wallace *et al*. 2013); reference lines for barley assume a mixture of 2- and 6-row varieties

Knossos were initially penned, as stable isotope results suggest, this would have facilitated socially restricted exploitation, consistent with their recurrence in both Cretan and mainland elite art (Palmer 2012) and reinforcing the argument that diacritical cuisine helped legitimise the palatial elite (Isaakidou 2007).

Knossos in Aegean context

Carbon and nitrogen stable isotope values for Knossos cereals and pulses largely fall within the ranges previously reported for Neolithic and Bronze sites on the Greek mainland (Figs 12–13; Vaiglova *et al*. 2014a; 2020; 2021; Styring *et al*. 2015; Nitsch *et al*. 2017),

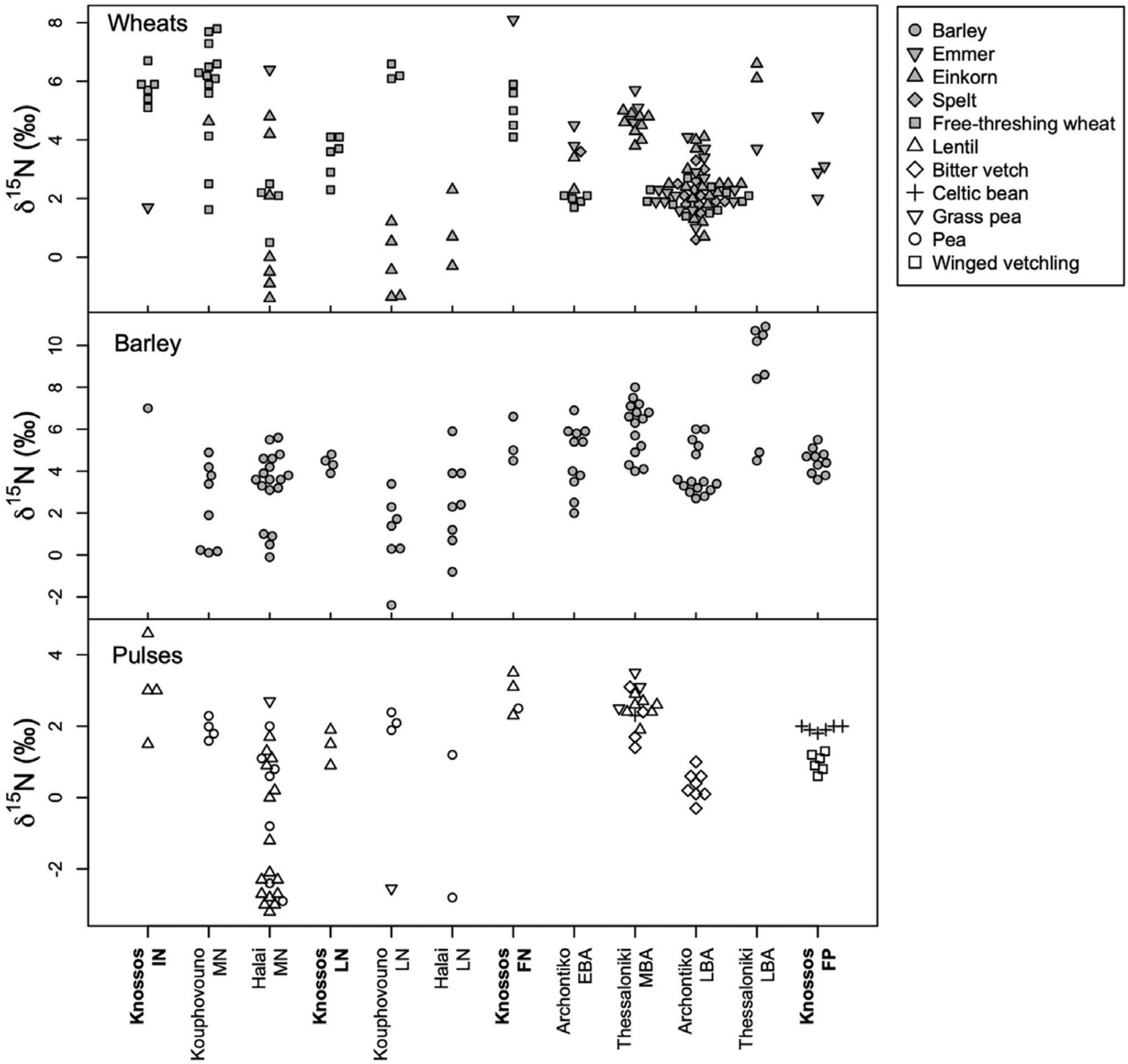

Fig. 13.
δ^{15}N values for Knossos cereals and pulses by phase compared with those for other Neolithic and Bronze Age sites in Greece

reflecting similarity in the relatively small-scale arable landscapes that early farmers created (cf. Bogaard 2005), despite regional differences in climate. Livestock display greater inter-site isotopic differences (Table S6; Fig. 14a–b), reflecting use of regionally variable pasture resources beyond (and in addition to) arable land. Most strikingly, central and north Greek cattle at EN–LN Halai (Vaiglova *et al.* 2021, 11 fig. 3), LN Makriyalos (Vaiglova *et al.* 2018, 13 table 3), late EBA-LBA Archontiko and LBA Toumba Thessalonikis (Nitsch *et al.* 2017, tables S6 & S7) exhibit some high δ^{13}C values attributable to grazing on saline coastal pasture. Conversely, in the absence of such pasture, cattle at MN–LN Kouphovouno (Vaiglova *et al.* 2014a, 209 table 2) and LBA Mycenae (Price *et al.* 2017, 121–2 tables 1–2) on the southern mainland and at Neolithic-Bronze

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

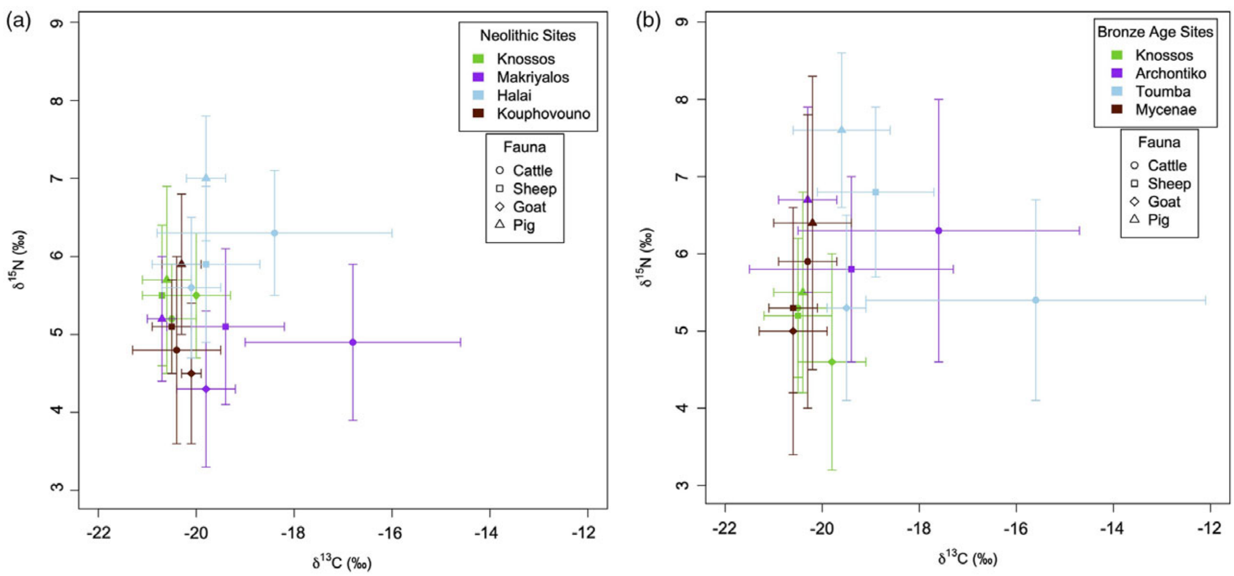

Fig. 14.
Bone collagen $\delta^{13}C$ and $\delta^{15}N$ mean values and standard deviations (± 1 σ) for Knossos sheep, goats, cattle and pigs compared with other sites in Greece: a) Neolithic and b) Bronze Age

Age Knossos exhibit $\delta^{13}C$ and $\delta^{15}N$ values close to those of sheep and probably grazed on cultivated land.

Indeed, despite the very large scale of herding in central Crete, at least in the textually rich FP phase, the isotopic ranges of the common livestock species differ much less at Knossos (with significant differences only between goats and the other three species and only from the later Neolithic onwards: Table 5) than at Neolithic Halai, Kouphovouno and Makriyalos or Bronze Age Archontiko and Toumba (Fig. 14a–b), consistent with the importance of cultivated land (implied by relatively high $\delta^{15}N$ values) to Knossos sheep, cattle and pigs and even, in part, goats. At LBA Mycenae, also a major southern Greek palatial centre, the ranges for all four common domesticates, including goats, are compatible with forage predominantly from cultivated land. Also, while $\delta^{15}N$ values of Neolithic Knossos livestock are generally higher than those for Kouphovouno and Makriyalos (but not Halai), Bronze Age values for sheep, goats and pigs, and likewise for sheep and goats from LBA Mycenae, are lower than those for Archontiko and Toumba, consistent with extensive agriculture, and thus lightly/un-manured stubble/fallow pasture, of larger scale on Crete and the southern mainland than in northern Greece, where the urban settlements and complex hierarchies of the later Bronze Age southern Aegean were lacking (Andreou 2010).

CONCLUSIONS

Large-scale stable isotope analysis of the exceptional archaeobotanical and faunal archive from early 7th–late 2nd millennium BCE Knossos has yielded significant insights at several levels. First, despite both long- and short-term climatic changes, any impact thereof on crops or livestock was not detectable isotopically and was overwritten by variation in husbandry (and, doubtless, between good and bad years), underlining the dangers (also Manning 2017) of inferring catastrophic local agricultural failures from trans-regional proxy climate records.

Secondly, in demonstrating the intensive nature of initial grain growing, the close integration therewith of livestock rearing, and the subsequent expansion through the later Neolithic and especially later Bronze Age of extensive agriculture and large-scale herding, it has provided empirical confirmation of land use models previously advanced on largely circumstantial grounds. It likewise confirms the tendency, with expanding scale of husbandry, for differential treatment of cereals and pulses and divergent

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

pasturing especially of goats from sheep, cattle, and pigs. Sheep, however, apparently maintained a close association throughout with pasture on cultivated land and so offer a useful proxy for crop growing conditions, for which direct stable-isotope data are temporally patchy and, in the palatial era, socially selective.

Moreover, a radically unexpected outcome of the apparently close integration of *all* earlier Neolithic livestock with the cultivated landscape is that apparently generous manuring of grain crops was arguably achieved only by running livestock not only on stubble/fallow plots, but also on crops sown to be harvested for grain or grazed *in situ* as circumstances dictated. In the longer term, the close association of Neolithic–Bronze Age sheep (the commonest species), but also cattle and pigs, with pasture on cultivated land implies that the number of livestock per head of human population was modest and average human levels of meat consumption consequently low, although this does not rule out a more privileged diet for elite groups or indeed for the inhabitants of Knossos in general. A more direct assessment of human diet, by stable-isotope analysis of human remains, has not been attempted because dependable interpretation of results would require comparative data for coeval and contextually representative archaeobotanical and faunal samples (as, for later Bronze Age northern Greece, by Nitsch *et al.* 2017) and no occupation phase at Knossos has yet yielded adequate samples of all three classes of bioarchaeological remains.

Thirdly, although incomplete contextual information as yet precludes meaningful spatial analysis of the archaeobotanical and faunal data, the more secure and nuanced picture of changing land use achieved for Knossos offers significant insights into the community's social fabric: for example, implied household-scale management of arable and pastoral farming from the inception of the Neolithic settlement; increasing demands on human labour from perhaps the later Neolithic onwards for herding larger livestock numbers over greater distances and on more diverse pasture; the apparent transition from relatively self-sufficient OP Knossos, maintained by often extensive and probably distant farming of its own territory, to NP–FP Knossos, mobilising produce from previously competing and now subordinate centres; the role of introduced fallow deer in elite diacritical cuisine reinforced by probable NP–FP penning; and provisioning of the FP Knossian elite from (private?) intensive gardens and high-quality fields independent of the centrally administered extensive agriculture recorded in FP texts.

Lastly, it should be emphasised that, while presenting *new* and highly informative stable isotope results, we have drawn heavily on excavation and survey evidence for the history of Knossos and its region, on written (especially Linear B) records of crop and livestock management, on previous macroscopic study of archaeobotanical and faunal remains, and on ethnographically based models of past husbandry regimes and land use. Each of these strands has played a vital part in advancing understanding of Knossian land use and political economy.

Acknowledgments Stable-isotope analysis of faunal and charred crop samples from Knossos was funded by the European Research Council (AGRICURB project, grant no. 312785, PI Bogaard). Sampling was authorised by the Greek Ministry of Culture and Sports (permit no. ΥΠΠΟΑ/ΓΔΑΠΚ/ΔΣΑΝΜ/ΤΕΕ/Φ44/207976/4405) with the support of the Heraklion Ephorate of Antiquities, the British School at Athens (BSA), and the directors of the relevant excavations: Nico Momigliano, David Wilson and the late John Evans, Sinclair Hood, and Mervyn Popham. We are indebted to the Hellenic Ministry of Culture and Sports and to the Archaeological Museum of Heraklio and its Director, Dr Stella Mandalaki, for permission to use Fig. 3a; and to John Bennet and Amalia Kakissis of the British School at Athens for permission to use Fig. 3b. We also thank Nina Kyparissi, Angelos Gkotsinas, and Amy Styring for advice and practical support during sampling; Peter Tomkins for the relative dating of Neolithic samples; Gideon Hartman and Alexandra Livarda, for kindly sharing unpublished data; Hervé Bocherens and Ehud Weiss, for access to literature otherwise inaccessible during COVID19 lockdown; John Bennet, Kostis Christakis, and Todd Whitelaw for help in preparing Figs 2–3 and Debi Harlan for drawing to our attention the photograph reproduced as Fig. 3b; and Amy Styring, Peter Tomkins, and two anonymous referees for valuable comments on an earlier draft of this paper.

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/ppr.2022.4

BIBLIOGRAPHY

Abell, J.T., Quade, J., Duru, G., Mentzer, S.M., Stiner, M.C., Uzdurum, M. & Özbaşaran, M. 2019. Urine salts elucidate Early Neolithic animal management at Aşıklı Höyük, *Turkey. Science Advances* 5(4), eaaw0038

Andreou, S. 2010. Northern Aegean. In E.H. Cline (ed.), *The Oxford Handbook of the Bronze Age Aegean*, 643–59. Oxford: Oxford University Press

Aufgebauer, A., Panagiotopoulos, K., Wagner, B., Schaebitz, F., Viehberg, F.A., Vogel, H., Zanchetta, G., Sulpizio, R., Leng, M.J. & Damaschke, M. 2012. Climate and environmental change in the Balkans over the last 17 ka recorded in sediments from Lake Prespa (Albania/F.Y.R. of Macedonia/Greece). *Quaternary International* 274, 122–35

Badal, E. & Ntinou, M. 2013. Wood charcoal analysis: The local vegetation. In N. Efstratiou, A. Karetsou & M. Ntinou (eds), *The Neolithic Settlement of Knossos in Crete: New evidence for the early occupation of Crete and the Aegean islands*, 95–118. Philadelphia PA: INSTAP Academic Press

Balasse, M. & Tresset, A. 2002. Early weaning of Neolithic domestic cattle (Bercy, France) revealed by intra-tooth variation in Nitrogen isotope ratios. *Journal of Archaeological Science* 29, 853–9

Bell, R.H.V. 1971. A grazing ecosystem in the Serengeti. *Scientific American* 225, 86–93

Bennet, J. 1985. The structure of the Linear B administration at Knossos. *American Journal of Archaeology* 89, 231–49

Bennet, J. 1988. 'Outside in the distance': problems in understanding the economic geography of Mycenaean palatial territories. In J.-P. Olivier & T.G. Palaima (eds), *Texts, Tablets and Scribes*, 19–41. Salamanca: University of Salamanca

Bennet, J. 2008. 'Now you see it; now you don't!': The disappearance of the Linear A script on Crete. In J. Baines, J. Bennet & S. Houston (eds), *The Disappearance of Writing Systems: Perspectives on literacy and communication*, 1–29. London: Equinox

Bennet, J. 2012. Bronze Age Greece. In P. Bang & W. Scheidel (eds), *The Oxford Handbook of the State in the Ancient Near East and Mediterranean*, 235–58. Oxford: Oxford University Press

Bennet, J. & Halstead, P. 2014. O-no! Writing and righting redistribution. In D. Nakassis, J. Gulizio & S.A. James (eds), *KE-RA-ME-JA: Studies presented to Cynthia Shelmerdine*, 271–82. Philadelphia PA: INSTAP Academic Press

Bergmeier, E. 2008. Diversity of aestival plant communities of irrigated garden croplands in Cretan villages. *Braunschweiger Geobotanische Arbeiten* 9, 65–80

Blakolmer, F. 2016. Il buono, il brutto, il cattivo? Character, symbolism and hierarchy of animals and supernatural creatures in Minoan and Mycenaean iconography. *Creta Antica* 17, 97–183

Bogaard, A. 2005. 'Garden agriculture' and the nature of early farming in Europe and the Near East. *World Archaeology* 37, 177–96

Bottema, S. 1980. Palynological investigations on Crete. *Review of Palaeobotany & Palynology* 31, 193–217

Bottema, S. & Sarpaki, A. 2003. Environmental change in Crete: A 9000-year record of Holocene vegetation history and the effect of the Santorini eruption. *The Holocene* 13(5), 733–49

Broodbank, C. 1992. The Neolithic labyrinth: Social change at Knossos before the Bronze Age. *Journal of Mediterranean Archaeology* 5(1), 39–75

Cadogan, G., Hatzaki, E. & Vasilakis, A. (eds) 2004. *Knossos: City, palace, state*. London: British School at Athens

Childe, V.G. 1950. The urban revolution. *Town Planning Review* 21(1), 3–17

Christakis, K.S. 2008. *The Politics of Storage: Storage and sociopolitical complexity in Neopalatial Crete*. Philadelphia PA: INSTAP Academic Press

Clarke, J., Brooks, N., Banning, E.B., Bar-Matthews, M., Campbell, S., Clare, L., Cremaschi, M., di Lernia, S., Drake, N., Gallinaro, M., Manning, S., Nicoll, K., Philip, G., Rosen, S., Schoop, U.-D., Tafuri, M.A., Weninger, B. & Zerboni, A. 2016. Climatic changes and social transformations in the Near East and North Africa during the 'long' 4th millennium BC: A comparative study of environmental and archaeological evidence. *Quaternary Science Reviews* 136, 96–121

Cutler, J. & Whitelaw, T. 2019. The Knossos Urban Landscape Project, 2005–16: Neopalatial and Mycenaean Knossos: Urban expansion and collapse. In Mitsotaki *et al.* (eds) 2019. https://12iccs.proceedings.gr/el/proceedings/category/39/35/808

Dimopoulos, P., Tsiripidis, I., Bergmeier, E., Fotiadis, G., Theodoropoulos, K., Raus, T., Panitsa, M., Kallimanis, A.S., Sýkora, K.V. & Mucina, L. 2012. Towards the Hellenic National Vegetation Database: VegHellas. *Plant Sociology* 492, 81–7

Dormoy, I., Peyron, O., Combourieu Nebout, N., Goring, S., Kotthoff, U., Magny, M., & Pross, J. 2009. Terrestrial climate variability and seasonality changes in the Mediterranean region between 15 000 and 4000 years BP deduced from marine pollen records. *Climate of the Past* 5(4), 615–32

Douka, K., Efstratiou, N., Hald, M.M., Henriksen, P.S. & Karetsou, A. 2017. Dating Knossos and the arrival of the earliest Neolithic in the southern Aegean. *Antiquity* 91, 304–21

Driesch, A. von den & Boessneck, J. 1990. Die Tierreste von der mykenischen Burg Tiryns bei Nafplion/Peloponnes. In H.-J. Weisshaar, I. Weber-Hiden, A. von den Driesch, J. Boessneck, A. Rieger & W. Böser, *Tiryns Forschungen und Berichte* 11, 87–164. Mainz am Rhein: von Zabern

Evans, J.D. 1968. Knossos Neolithic, Part ii, summary and conclusions. *Annual of the British School at Athens* 63, 267–76

Evans, J.D. 1971. Neolithic Knossos: The growth of a settlement. *Proceedings of the Prehistoric Society* 37, 95–117

Finné, M., Woodbridge, J., Labuhn, I. & Roberts, C.N. 2019. Holocene hydro-climatic variability in the Mediterranean: A synthetic multi-proxy reconstruction. *The Holocene* 29(5), 847–63

Forge, A. 1972. Normative factors in the settlement size of neolithic cultivators (New Guinea). In P.J. Ucko,

R. Tringham & G.W. Dimbleby (eds), *Man, Settlement and Urbanism*, 363–76. London: Duckworth

Ghilardi, M., Psomiadis, D., Andrieu-Ponel, V., Colleu, M., Sotiropoulos, P., Longo, F., Rossi, A., Amato, V., Gasse, F., Sinibaldi, L., Renard, M., Bicket, A., Delanghe, D., Demory, F. & Fleury, J. 2018. First evidence of a lake at ancient Phaistos (Messara plain, south-central Crete, Greece): Reconstructing paleoenvironments and differentiating the roles of human land-use and paleoclimate from Minoan to Roman times. *The Holocene* 28(8), 1225–44

Giamali, C., Koskeridou, E., Antonarakou, A., Ioakim, C., Kontakiotis, G., Karageorgis, A.P., Roussakis G. & Karakitsios, V. 2019. Multiproxy ecosystem response of abrupt holocene climatic changes in the northeastern Mediterranean sedimentary archive and hydrologic regime. *Quaternary Research (United States)* 92(3), 1–21

Gilman, A. 1981. The development of social stratification in Bronze Age Europe. *Current Anthropology* 22, 1–8

Godart, L. 1971. Les tablettes de la série Co de Cnossos. *Minos* 12, 418–24

Godart, L. 1977. Les ressources des palais mycéniens de Cnossos et Pylos. *Les Études Classiques* 45, 31–42

Halstead, P. 1981a. Counting sheep in Neolithic and Bronze Age Greece. In I. Hodder, G. Isaac & N. Hammond (eds), *Pattern of the Past: Studies in honour of David Clarke*, 307–39. Cambridge: Cambridge University Press

Halstead, P. 1981b. From determinism to uncertainty: social storage and the rise of the Minoan Palace. In A. Sheridan & G. Bailey (eds), *Economic Archaeology*, 187–213. Oxford: British Archaeological Report 96

Halstead, P. 1989. The economy has a normal surplus: economic stability and social change among early farming communities of Thessaly, Greece. In P. Halstead & J. O.'Shea (eds), *Bad Year Economics*, 68–80. Cambridge: Cambridge University Press

Halstead, P. 1992. Agriculture in the Bronze Age Aegean: Towards a model of palatial economy. In B. Wells (ed.), *Agriculture in Ancient Greece: Proceedings of the Seventh International Symposium at the Swedish Institute at Athens*, 105–16. Stockholm: Swedish Institute at Athens

Halstead, P. 1995. From sharing to hoarding: The Neolithic foundations of Aegean Bronze Age society? In R. Laffineur & W.-D. Niemeier (eds), *Politeia: Society and state in the Aegean Bronze Age*, 11–20. Liège: Aegaeum 12

Halstead, P. 1996. Pastoralism or household herding? Problems of scale and specialisation in early Greek animal husbandry. *World Archaeology* 28, 20–42

Halstead, P. 1999a. Towards a model of Mycenaean palatial mobilization. In M.L. Galaty & W.A. Parkinson (eds), *Rethinking Mycenaean Palaces*, 35–41. Los Angeles CA: Cotsen Institute of Archaeology, UCLA

Halstead, P. 1999b. Surplus and share-croppers: The grain production strategies of Mycenaean palaces. In P. Betancourt, V. Karageorghis, R. Laffineur & W.-D. Niemeier (eds), *MELETHMATA. Studies presented to Malcolm H. Wiener as he enters his 65th year*, 319–26. Liège: Aegaeum 20

Halstead, P. 2001. Mycenaean wheat, flax and sheep: Palatial intervention in farming and its implications for rural society. In S. Voutsaki & J. Killen (eds), *Economy and Politics in the Mycenaean Palace States*, 38–50. Cambridge: Cambridge Philological Society supplementary vol. 27

Halstead, P. 2002. Texts, bones and herders: Approaches to animal husbandry in Late Bronze Age Greece. *Minos* 33–4 (1998–99), 149–89

Halstead, P. 2014. *Two Oxen Ahead: Pre-mechanized farming in the Mediterranean*. Chichester: Wiley Blackwell

Halstead, P. 2018. Forest clearance and land use by early farmers in Europe: Insights from north Greek oral history. *Quaternary International* 496, 42–50

Halstead, P. 2019. This soil is mine and ours: Domestic and collective use rights in the Neolithic of Greece. In K. Kotsakis (ed.), *I Antipera Okhthi: Koinonikos khoros kai ideologia stis proistorikes koinotites*, 57–70. Thessaloniki: Aristotle University of Thessaloniki

Halstead, P. & Isaakidou, V. 2011. A pig fed by hand is worth two in the bush: ethnoarchaeology of pig husbandry in Greece and its archaeological implications. In U. Albarella & A. Trentacoste (eds), *Ethnozooarchaeology: The present and past of human–animal relationships*, 160–74. Oxford: Oxbow Books

Halstead, P. & Isaakidou, V. 2017. Sheep, sacrifices and symbols: Animals in Bronze Age Greece. In U. Albarella, M. Rizzetto, H. Russ, K. Vickers & S. Viner (eds), *Oxford Handbook of Zooarchaeology*, 113–26. Oxford: Oxford University Press

Halstead, P. & Isaakidou, V. 2020. Pioneer farming in earlier Neolithic Greece. In K.J. Gron, L. Sørensen & P. Rowley-Conwy (eds), *Farmers at the Frontier: A pan-European perspective on neolithization*, 77–100. Oxford: Oxbow Books

Halstead, P. & Isaakidou, V. 2021. Representations of palatial staple finance in the Late Bronze Age southern Aegean: The 'Harvester Vase' from Agia Triadha and the gold sheet with relief procession from Peristeria. In J. Bennet (ed.), *Representations: Material and immaterial modes of communication in the Bronze Age Aegean*, 31–51. Oxford: Sheffield Studies in Aegean Archaeology 13

Halstead, P., Bogaard, A. & Jones, G. in press. Staple grains in the southern Aegean Bronze Age: archaeobotanical, textual and ethnographic insights. In S.M. Valamoti, A. Dimoula & M. Ntinou (eds), *Cooking with Plants in Ancient Europe and Beyond: Interdisciplinary approaches to the archaeology of plant foods*. Leiden: Sidestone Press

Hatzaki, E. 2017. To be or not to be in LM IIIB Knossos. How long is a century? In C. Langohr (ed.), *Late Minoan IIIB Pottery: Relative chronology and regional differences*, 53–77. Louvain-la-Neuve: Presses universitaires de Louvain

Hood, S. & Smyth, D. 1981. *Archaeological Survey of the Knossos Area*. London: British School at Athens

Houérou, H.N. Le 1977. Plant sociology and ecology applied to grazing lands research, survey and management

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

in the Mediterranean basin. In W. Krause (ed.), *Handbook of Vegetation Science 13: Application of vegetation science to grassland husbandry*, 211–74. The Hague: Junk

Houérou, H.N. Le 1994. Forage halophytes and salt-tolerant fodder crops in the Mediterranean basin. In V.R. Squires & A.T. Ayoub (eds), *Halophytes as a Resource for Livestock and for Rehabilitation of Degraded Lands*, 123–37. Dordrecht: Kluwer

Hubbard, R.N.L.B. 1995. Fallow deer in prehistoric Greece, and the analogy between faunal spectra and pollen analyses. *Antiquity* 69, 527–38

Isaakidou, V. 2005. Bones from the Labyrinth: Faunal evidence for the management and consumption of animals at Neolithic and Bronze Age Knossos, Crete. Unpublished PhD thesis, University College London

Isaakidou, V. 2006. Ploughing with cows: Knossos and the 'secondary products revolution'. In D. Serjeantson & D. Field (eds), *Animals in the Neolithic of Britain and Europe*, 95–112. Oxford: Neolithic Studies Group Seminar Papers 7

Isaakidou, V. 2007. Cooking in the labyrinth: Exploring 'cuisine' at Bronze Age Knossos. In C. Mee & J. Renard (eds), *Cooking Up the Past: Food and culinary practices in the Neolithic and Bronze Age Aegean*, 5–24. Oxford: Oxbow Books

Isaakidou, V. 2008. The fauna and economy of Neolithic Knossos revisited. In V. Isaakidou & P. Tomkins (eds) 2008, 90–114

Isaakidou, V. 2011. Gardening with cows: Hoe and plough in prehistoric Europe. In A. Hadjikoumis, E.N. Robinson & S. Viner (eds), *The Dynamics of Neolithisation in Europe*, 90–112. Oxford: Oxbow Books

Isaakidou, V. & Tomkins, P. (eds.) 2008. *Escaping the Labyrinth: The Cretan Neolithic in context*. Oxford: Sheffield Studies in Aegean Archaeology 8

Isaakidou, V., Styring, A., Halstead, P., Nitsch, E., Stroud, E., le Roux, P., Lee-Thorp, J. & Bogaard, A. 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

Jackson, J. 1977. The annual diet of the fallow deer (*Dama dama*) in the New Forest, Hampshire, as determined by rumen content analysis. *Journal of Zoology, London* 181, 465–73

Jarman, M.R. 1996. Human influence in the development of the Cretan fauna. In D.S. Reese (ed.), *Pleistocene and Holocene Fauna of Crete and its First Settlers*, 211–29. Madison WI: Prehistory Press

Jarman, M.R. & Jarman, H.N. 1968. The fauna and economy of Early Neolithic Knossos. *Annual of the British School at Athens* 63, 241–64

Jarman, M.R., Bailey, G.N. & Jarman, H.N. (eds) 1982. *Early European Agriculture*. Cambridge: Cambridge University Press

Jones, G. 1984. Appendix 1: The LMII plant remains. In Popham, 303–6

Killen, J.T. 1964. The wool industry of Crete in the Late Bronze Age. *Annual of the British School at Athens* 59, 1–15

Killen, J.T. 1977. The Knossos texts and the geography of Mycenaean Crete. In J.L. Bintliff (ed.), *Mycenaean Geography*, 40–7. Cambridge: British Association for Mycenaean Studies

Killen, J.T. 1993. The oxen's names on the Knossos Ch tablets. *Minos* 27–8, 101–7

Killen, J.T. 1994. Thebes sealings, Knossos tablets and Mycenaean state banquets. *Bulletin of the Institute of Classical Studies* 39, 67–84

Killen, J.T. 1995. A-ma e-pi-ke-re. *Minos* 29–30, 329–33

Killen, J.T. 1999. Mycenaean *o-pa*. In S. Deger-Jalkotzy, S. Hiller, O. Panagl & G. Nightingale (eds), *Floreant Studia Mycenaea: Akten des 10 mykenologischen Kolloquiums 1995, Salzburg*, 325–41. Salzburg: Österreichische Akademie der Wissenschaften

Killen, J.T. 2008. Mycenaean economy. In Y. Duhoux & A. Morpurgo Davies (eds), *A Companion to Linear B: Mycenaean Greek texts and their world, volume 1*, 159–200. Louvain-la-Neuve: Peeters

Kotsakis, K. 2006. Settlement of discord: Sesklo and the emerging household. In N. Tasić & C. Grozdanov (eds), *Homage to Milutin Garašanin*, 207–20. Belgrade: Serbian Academy of Sciences & Arts, Macedonian Academy of Sciences & Arts

Lane, M.F. 2004. Names and Numbers: an inquiry into scribal practice at Late Bronze Age Pylos in the south-western Peloponnese. Unpublished PhD thesis, University of Sheffield

Legarra Herrero, B. 2019. The Knossos Urban Landscape Project, 2005–16: Knossos from the Neolithic to the end of the Prepalatial period. In Mitsotaki *et al.* (eds) 2019. https://12iccs.proceedings.gr/el/proceedings/category/39/35/799

Livarda, A. & Kotzamani, G. 2013. The archaeobotany of Neolithic and Bronze Age Crete: Synthesis and prospects. *Annual of the British School at Athens* 108, 1–29

Mainland, I.L. & Halstead, P. 2005. The diet and management of domestic sheep and goats at Neolithic Makriyalos. In J. Davies, M. Fabiš, I. Mainland, M. Richards & R. Thomas (eds), *Diet and Health in Past Animal Populations: Current research and future directions*, 104–12. Oxford: Oxbow Books

Manning, S.W. 2017. Comments on climate, intra-regional variations, chronology, the 2200 B.C. horizon of change in the eastern Mediterranean region, and socio-political change on Crete. In F. Höflmayer (ed.), *The Late Third Millennium in the Ancient Near East: Chronology, C14, and climate change*, 451–90. Chicago IL: Oriental Institute, University of Chicago

Mauri, A., Davis, B.A.S., Collins, P.M. & Kaplan, J.O. 2015. The climate of Europe during the Holocene: a gridded pollen-based reconstruction and its multi-proxy evaluation. *Quaternary Science Reviews* 112, 109–27

Melena, J.L. 1974. *ku-pa-ro* en las tablillas de Cnoso. *Emerita* 42, 307–36

https://doi.org/10.1017/ppr.2022.4 Published online by Cambridge University Press

Mitsotaki, C., Tzedaki-Apostolaki, L. & Giannadaki, S. (eds) 2019. *Proceedings of the 12th International Congress of Cretan Studies*. Heraklion: Society of Cretan Historical Studies. https://12iccs.proceedings.gr/en/

Molloy, B., Day, J., Bridgford, S., Isaakidou, V., Nodarou, E., Kotzamani, G., Milić, M., Carter, T., Westlake, P., Klontza-Jaklova, V., Larsson, E. & Hayden, B.J. 2014. Life and death of a Bronze Age house: Excavation of Early Minoan I levels at Priniatikos Pyrgos. *American Journal of Archaeology* 118, 307–58

Nitsch, E.K., Charles, M. & Bogaard, A. 2015. Calculating a statistically robust δ^{13}C and δ^{15}N offset for charred cereal and pulse seeds. *STAR: Science & Technology of Archaeological Research* 1(1), 1–8

Nitsch, E.K., Jones, G., Sarpaki, A., Hald, M.M. & Bogaard, A. 2019. Farming practice and land management at Knossos, Crete: new insights from δ^{13}C and δ^{15}N analysis of Neolithic and Bronze Age crop remains. In D. Garcia, R. Orgeolet, M. Pomadère & J. Zurbach (eds), *Country in the City: Agricultural functions of protohistoric urban settlements (Aegean and Western Mediterranean)*, 159–73. Oxford: Archaeopress

Nitsch, E., Andreou, S., Creuzieux, A., Gardeisen, A., Halstead, P., Isaakidou, V., Karathanou, A., Kotsachristou, D., Nikolaidou, D., Papanthimou, A., Petridou, C., Triantaphyllou, S., Valamoti, S.M., Vasileiadou, A. & Bogaard, A. 2017. A bottom-up view of food surplus: using stable carbon and nitrogen isotope analysis to investigate agricultural strategies and food webs at Bronze Age Archontiko and Thessaloniki Toumba, northern Greece. *World Archaeology* 49(1), 105–37

Palmer, R. 1995. Linear A commodities: a comparison of resources. In R. Laffineur & W.-D. Niemeier (eds), *Politeia: Society and state in the Aegean Bronze Age*, 133–55. Liège: Aegaeum 12

Palmer, R. 2008. Wheat and barley in Mycenaean society 15 years later. In A. Sacconi, M. Del Freo, L. Godart & M. Negri (eds), *Colloquium Romanum: atti del xii colloquio internazionale di micenologia, Roma, 20–25 febbraio 2006*, vol. 2, 621–39. Pisa, Roma: Fabrizio Serra

Palmer, R. 2012. Deer in the Pylos tablets. In P. Carlier, C. De Lamberterie, M. Egetmeyer, N. Guilleux, F. Rougemont & J. Zurbach (eds), *Études mycéniennes 2010. Actes du xiiie colloque international sur les textes égéens, Sèvres, Paris, Nanterre, 20–23 septembre 2010*, 357–82. Pisa, Roma: Fabrizio Serra

Popham, M.R. 1984. *The Unexplored Mansion at Knossos*. London: British School at Athens

Price, G.C., Krigbaum, J. & Shelton, K. 2017. Stable isotopes and discriminating tastes: Faunal management practices at the Late Bronze Age settlement of Mycenae, Greece. *Journal of Archaeological Science: Reports* 14, 116–26

Privitera, S. 2014. Long-term grain storage and political economy in Bronze Age Crete: Contextualising Ayia Triada's silo complexes. *American Journal of Archaeology* 118, 429–49

Putman, R.J., Culpin, S. & Thirgood, S.J. 1993. Dietary differences between male and female fallow deer in sympatry and in allopatry. *Journal of Zoology, London* 229, 267–75

Rackham, O. & Moody, J. 1996. *The Making of the Cretan Landscape*. Manchester: Manchester University Press

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 C. Renfrew & M. Wagstaff (eds.), *An Island Polity. The archaeology of exploitation in Melos*, 264–90. Cambridge: Cambridge University Press

Riehl, S., Pustovoytov, K.E., Weippert, H., Klett, S. & Hole, F. 2014. Drought stress variability in ancient Near Eastern agricultural systems evidenced by δ^{13}C in barley grain. *Proceedings of the National Academy of Sciences of the United States of America* 111(34), 12348–53

Roberts, N. 1979. The location and environment of Knossos. *Annual of the British School at Athens* 74, 231–41

Roberts, S.J., Smith, C.I., Millard, A. & Collins, M.J. 2002. The taphonomy of cooked bone: characterizing boiling and its physico-chemical effects. *Archaeometry* 44(3), 485–94

Rodière, É., Bocherens, H., Angibault, J.-M. & Mariotti, A. 1996. Particularités isotopiques de l'azote chez le chevreuil (*Capreolus capreolus* L.): Implications pour les reconstitutions paléoenvironnementales. *Comptes rendus de l'Académie des Sciences, Paris* 323, 179–85

Sarpaki, A. 2012. The taming of an island environment: Crete from dawn to noon (Neolithic to the end of the Bronze Age). In G. Cadogan, M. Iacovou, K. Kopaka & J. Whitley (eds), *Parallel Lives: Ancient island societies in Crete and Cyprus*, 35–45. London: British School at Athens Studies 20

Sarpaki, A. 2013. The economy of Neolithic Knossos: the archaeobotanical data. In N. Efstratiou, A. Karetsou & M. Ntinou (eds), *The Neolithic Settlement of Knossos in Crete: New evidence for the early occupation of Crete and the Aegean islands*, 63–94. Philadelphia PA: INSTAP Academic Press

Sarpaki, A. & Jones, G. 1990. Ancient and modern cultivation of *Lathyrus clymenum* L. in the Greek islands. *Annual of the British School at Athens* 85, 363–8

Shaw, M.C. 1993. The Aegean garden. *American Journal of Archaeology* 97(4), 661–85

Shelmerdine, C.W. 2008. Background, sources and methods. In C.W. Shelmerdine (ed.), *The Cambridge Companion to the Aegean Bronze Age*, 1–18. Cambridge: Cambridge University Press

Sherratt, A.G. 1983. The secondary exploitation of animals in the Old World. *World Archaeology* 15, 90–104

Styring, A.K., Knipper, C., Müller-Scheeßel, N., Grupe, G. & Bogaard, A. 2018. The proof is in the pudding: crop isotope analysis provides direct insights into agricultural production and consumption. *Environmental Archaeology*. doi: 10.1080/14614103.2018.1497832

Styring, A.K., Carmona, C.U., Isaakidou, V., Karathanou, A., Nicholls, G.K., Sarpaki, A. & Bogaard, A. in press. Urban form and scale shaped the agroecology of early 'cities' in northern Mesopotamia, the Aegean and central Europe. *Journal of Agrarian Change* 22

Styring, A.K., Fraser, R.A., Arbogast, R.-M., Halstead, P., Isaakidou, V., Pearson, J.A., Schäfer, M., Triantaphyllou, S., Valamoti, S.M., Wallace, M., Bogaard, A. & Evershed, R.P. 2015. Refining human palaeodietary reconstruction using amino acid $\delta^{15}N$ values of plants, animals and humans. *Journal of Archaeological Science* 53, 504–15

Styring, A.K., Charles, M., Fantone, F., Hald, M.M., McMahon, A., Meadow, R.H., Nicholls, G.K., Patel, A.K., Pitre, M.C., Smith, A., Sołtysiak, A., Stein, G., Weber, J.A., Weiss, H. & Bogaard, A. 2017. Isotope evidence for agricultural extensification reveals how the world's first cities were fed. *Nature Plants* 3, 17076

Sykes, N., Ayton, G., Bowen, F., Baker, K., Baker, P., Carden, R.F., Dicken, C., Evans, J., Hoelzel, A.R., Higham, T.F.G., Jones, R., Lamb, A., Liddiard, R., Madgwick, R., Miller, H., Rainsford, C., Sawyer, P., Thomas, R., Ward, C. & Worley, F. 2016. Wild to domestic and back again: the dynamics of fallow deer management in medieval England (*c.* 11th–16th century AD). *STAR: Science & Technology of Archaeological Research* 2(1), 113–26

Theodoridis, N., Voulgaris, K. & Papastergiou, K. 2008. Rhodian fallow deer: special characteristics, impact of wildfires, livestock grazing and poaching. In K.Th. Mantzanas & V.P. Papanastasis (eds), *Range Science and Protected Areas, Proceedings of the 6th Panhellenic Rangeland Congress in Leonidio Arcadia Peloponnesus, 2–4 October 2008*, 241–7. Thessaloniki: Hellenic Pasture & Range Society/Ministry of Rural Development & Food, Directorate General for the Development & Protection of Forests & Natural Environment

Thirgood, S.J. 1995. The effects of sex, season and habitat availability on patterns of habitat use by fallow deer (*Dama dama*). *Journal of Zoology, London* 235, 645–59

Tomkins, P. 2004. Filling in the 'Neolithic background': social life and social transformation in the Aegean before the Bronze Age. In J.C. Barrett & P. Halstead (eds), *The Emergence of Civilisation Revisited*, 38–63. Oxford: Oxbow Books

Tomkins, P. 2007. Neolithic: Strata IX–VII, VII–VIB, VIA–V, IV, IIIB, IIIA, IIB, IIA and IC groups. In N. Momigliano (ed.), *Knossos Pottery Handbook: Neolithic and Bronze Age (Minoan)*, 9–48. London: British School at Athens Studies 14

Tomkins, P. 2008. Time, space and the reinvention of the Cretan Neolithic. In Isaakidou & Tomkins (eds) 2008, 21–48

Tomkins, P. 2012. Behind the horizon: reconsidering the genesis and function of the 'First Palace' at Knossos (Final Neolithic IV–Middle Minoan IB). In I. Schoep, P. Tomkins & J. Driessen (eds), *Back to the Beginning: Reassessing social and political complexity on Crete during the Early and Middle Bronze Age*, 32–80. Oxford: Oxbow Books

Tomkins, P. 2020. About time. Rehabilitating chronology in the interpretation of settlement in east Crete between the Neolithic and Early Minoan I. *Creta Antica* 19 (2018), 45–92

Tsafou, E. & García-Granero, J.J. 2021. Beyond staple crops: exploring the use of 'invisible' plant ingredients in Minoan cuisine through starch grain analysis on ceramic vessels. *Archaeological and Anthropological Sciences* 13, 128

Tsiros, I.X., Nastos, P., Proutsos, N.D. & Tsaousidis, A. 2020. Variability of the aridity index and related drought parameters in Greece using climatological data over the last century (1900–1997). *Atmospheric Research* 240, 104914

Vaiglova, P., Bogaard, A., Collins, M., Cavanagh, W., Mee, C., Renard, J., Lamb, A., Gardeisen, A. & Fraser, R. 2014a. An integrated stable isotope study of plants and animals from Kouphovouno, southern Greece: a new look at Neolithic farming. *Journal of Archaeological Science* 42, 201–15

Vaiglova, P., Snoeck, C., Nitsch, E., Bogaard, A. & Lee-Thorp, J. 2014b. Impact of contamination and pretreatment on stable carbon and nitrogen isotopic composition of charred plant remains. *Rapid Communications in Mass Spectrometry* 28(23), 2497–510

Vaiglova, P., Halstead, P., Pappa, M., Triantaphyllou, S., Valamoti, S.M., Evans, J., Fraser, R., Karkanas, P., Kay, A., Lee-Thorp, J. & Bogaard, A. 2018. Of cattle and feasts: multi-isotope investigation of animal husbandry and communal feasting at Neolithic Makriyalos, northern Greece. *PLoS ONE* 13(6), e0194474

Vaiglova, P., Gardeisen, A., Buckley, M., Cavanagh, W., Renard, J., Lee-Thorp, J. & Bogaard, A. 2020. Further insight into Neolithic agricultural management at Kouphovouno, southern Greece: expanding the isotopic approach. *Archaeological & Anthropological Sciences* 12(2), 43

Vaiglova, P., Coleman, J., Diffey, C., Tzevelekidi, V., Fillios, M., Pappa, M., Halstead, P., Valamoti, S.M., Cavanagh, W., Renard, J., Buckley, M. & Bogaard, A. 2021. Exploring diversity in Neolithic agropastoral management in mainland Greece using stable isotope analysis. *Environmental Archaeology*. doi: 10.1080/14614103.2020.1867292

Valamoti, S.M. 2016. Millet, the late comer: on the tracks of *Panicum miliaceum* in prehistoric Greece. *Archaeological & Anthropological Sciences* 8(1), 51–63

Valamoti, S.M. & Charles, M. 2005. Distinguishing food from fodder through the study of charred plant remains: an experimental approach to dung-derived chaff. *Vegetation History & Archaeobotany* 14(4), 528–33

Valamoti, S.M., Gkatzogia, E. & Ntinou, M. 2018. Did Greek colonisation bring olive growing to the north? An integrated archaeobotanical investigation of the

spread of *Olea europaea* in Greece from the 7th to the 1st millennium BC. *Vegetation History & Archaeobotany* 27(1), 177–95
Vanschoonwinkel, J. 1996. Les animaux dans l'art Minoen. In D.S. Reese (ed.), *Pleistocene and Holocene Fauna of Crete and its First Settlers*, 351–412. Madison WI: Prehistory Press
Wallace, M., Jones, G., Charles, M., Fraser, R., Halstead, P., Heaton, T.H.E. & Bogaard, A. 2013. Stable carbon isotope analysis as a direct means of inferring crop water status and water management practices. *World Archaeology* 45(3), 388–409
Whitelaw, T. 2001. From sites to communities: defining the human dimensions of Minoan urbanism. In K. Branigan (ed.), *Urbanism in the Aegean Bronze Age*, 15–37. London: Sheffield Academic Press
Whitelaw, T. 2004. Estimating the population of Neopalatial Knossos. In Cadogan *et al.* (eds) 2004, 147–58
Whitelaw, T. 2012. The urbanisation of prehistoric Crete: settlement perspectives on Minoan state formation. In I. Schoep, P. Tomkins & J. Driessen (eds), *Back to the Beginning: Reassessing social and political complexity on Crete during the Early and Middle Bronze Age*, 114–76. Oxford: Oxbow Books
Whitelaw, T. 2019. Feeding Knossos: exploring economic and logistical implications of urbanism on prehistoric Crete. In D. Garcia, R. Orgeolet, M. Pomadère & J. Zurbach (eds), *Country in the City: Agricultural functions of protohistoric urban settlements (Aegean and Western Mediterranean)*, 88–121. Oxford: Archaeopress
Whitelaw, T., Bredaki, M. & Vasilakis, A. 2019. The long-term dynamics of Knossos in context. In Mitsotaki *et al.* (eds) 2019. https://12iccs.proceedings.gr/el/proceedings/category/39/35/816
Wilkinson, T.J. 1994. The structure and dynamics of dry-farming states in Upper Mesopotamia. *Current Anthropology* 35, 483–505
Xanthoudidis, S.A. 1918. Poimenika Kritis. *Lexigrafikon Arkheion* 5, 267–323
Yiakoulaki, M.D. & Papanastasis, V.P. 2005. Diet selection of sheep and goats grazing on cereal stubble in northern Greece. In E.M. Alcaide, H.B. Salem, K. Biala & P. Morand-Fehr (eds), *Sustainable Grazing, Nutritional Utilization and Quality of Sheep and Goat Products*, 245–50. Zaragoza: Options Méditerranéennes Série A, Séminaires Méditerranéens 67
Zidon, R., Leschner, H., Motro, U. & Saltz, D. 2017. Endozoochory by the Persian fallow deer (*Dama mesopotamica*) reintroduced in Israel: Species richness and germination success. *Israel Journal of Ecology & Evolution* 63(1), 28–34
Zohary, M. & Orshan, G. 1965. An outline of the geobotany of Crete. *Israel Journal of Botany* 14 (supplement), 1–49
Zurbach, J. 2005. Les grandes institutions et la terre dans la société mycénienne. *Cahier de recherches de l'Institut de papyrologie et d'égyptologie de Lille* 25, 313–28

RÉSUMÉ

Changements dans l'utilisation des terres et économie politique au Néolithique et à l'âge du Bronze à Cnossos, Crète : analyse des isotopes stables du carbone (δ^{13}C) et de l'azote (δ^{15}N) des graines cultivées carbonisées et du collagène des ossements animaux, par V. Isaakidou, P. Halstead, E. Stroud, A. Sarpaki, E. Hatzaki, E. Nitsch et A. Bogaard

Les fouilles de Cnossos ont mis au jour des archives fauniques et archéobotaniques couvrant le Néolithique et l'âge du Bronze (VII^{e}–II^{e} millénaires av. n. è.), au cours desquels l'un des plus anciens établissements agraires connus en Europe s'est développé en un premier centre urbain majeur et en siège de l'un des premiers états régionaux. Grâce à l'analyse des isotopes stables (δ^{13}C, δ^{15}N) des graines et des os (comme témoins des conditions de croissance des céréales et des légumineuses et des types de fourrage consommés par le bétail), l'utilisation des terres et, finalement, l'économie politique sont explorées. L'évolution des conditions de cultivation et d'élevage surpasse les effets de l'aridification à long terme. Les premiers agriculteurs de Cnossos (VII^{e}–VI^{e} millénaires av. n. è) pratiquaient la culture intensive des céréales et des légumineuses (probablement en rotation), étroitement intégrée (comme source fumée de fourrage) à l'élevage du bétail. Du Néolithique Récent à l'âge du Bronze, l'expansion de l'établissement cnossien s'accompagne d'une agriculture plus extensive (éventuellement sans rotation des céréales et des légumineuses) et d'une plus grande utilisation des pâturages naturels et, dans le cas de chèvres, du broutage. Les pâturages sur les terres cultivées restaient cependant essentiels à l'entretien des moutons, des bovins et des porcs. Le régime alimentaire variable des premiers moutons suggère une gestion au niveau du foyer, tandis que la divergence alimentaire progressive des moutons et des chèvres implique leur élevage séparé. Jusqu'à la phase du premier palais (début du II^{e} millénaire av. n. è.), l'expansion urbaine s'est accompagnée d'une agriculture et d'un élevage de plus en plus étendus et probablement éloignés, mais des con-

ditions un peu plus intensives pendant les phases du nouveau et du dernier palais (milieu du II[e] millénaire av. n. è.) reflètent peut-être une plus grande dépendance à l'égard des surplus de terres fertiles de centres autrefois rivaux et désormais sous le contrôle des habitants de Cnossos.

ZUSAMMENFASSUNG

Veränderte Landnutzung und politische Ökonomie im neolithischen und bronzezeitlichen Knossos, Kreta: Die Analyse stabiler Kohlenstoff- ($\delta^{13}C$) und Stickstoffisotope ($\delta^{15}N$) an verkohltem Körner von Kulturpflanzen und Tierknochenkollagen, von V. Isaakidou, P. Halstead, E. Stroud, A. Sarpaki, E. Hatzaki, E. Nitsch und A. Bogaard

Ausgrabungen in Knossos lieferten tierisches und archäobotanisches Material aus dem Neolithikum und der Bronzezeit (7. bis 2. Jahrtausend BCE), jenem Zeitraum, in dem sich eine der frühesten bekannten bäuerlichen Siedlungen Europas zu der ersten großen städtischen Siedlung in Europa und zum Zentrum eines seiner ältesten Regionalstaaten entwickelte. Anhand der Analyse stabiler Isotope ($\delta^{13}C$, $\delta^{15}N$) von Samen und Knochen (als Hinweis auf die Anbaubedingungen von Getreide und Hülsenfrüchten sowie für die vom Vieh verzehrten Futtermittelarten) werden die Landnutzung und letztlich die politische Ökonomie untersucht. Die veränderten Haltungsbedingungen überlagern die Auswirkungen der langfristigen Aridifizierung. Die frühen Bauern von Knossos (7.–6. Jahrtausend BCE) bauten intensiv Getreide und Hülsenfrüchte an (vermutlich in Fruchtfolge), die eng verbunden waren mit der Viehzucht (als gedüngte Futtermittel). Im Verlauf des späteren Neolithikums und der Bronzezeit ging das Siedlungswachstum einher mit einer extensiveren Bewirtschaftung (eventuell mit Getreide und Hülsenfrüchten nicht in Fruchtfolge) und einer verstärkten Nutzung von unbewirtschafteten Weideflächen sowie der Nutzung holziger Vegetation durch Ziegen. Weide auf Anbauflächen blieb jedoch zentral für die Haltung von Schafen, Rindern und Schweinen. Die variable Ernährung der frühen Schafe lässt auf eine Bewirtschaftung auf Haushaltsebene schließen, während die anschließende zunehmende Divergenz der Ernährung von Schafen und Ziegen deren getrennte Haltung impliziert. Bis zur Älteren Palastzeit (frühes 2. Jahrtausend BCE) ging das städtische Wachstum einher mit zunehmend extensivem und vermutlich räumlich distanziertem Ackerbau und Viehhaltung, aber etwas intensivere Bedingungen während der Neueren und Finalen Palastzeit (Mitte 2. Jahrtausend) reflektieren vielleicht einen größeren Rückgriff auf Überschüsse von hochwertigem Land von zuvor rivalisierenden Zentren, die nun unter die Kontrolle von Knossos gekommen waren.

RESUMEN

Modificaciones en el uso del suelo y en la política económica durante el Neolítico y la Edad del Bronce en Knossos, Creta: análisis de isótopos estables de carbono ($\delta^{13}C$) y nitrógeno ($\delta^{15}N$) de granos de cultivo carbonizados y colágeno de huesos animales, por V. Isaakidou, P. Halstead, E. Stroud, A. Sarpaki, E. Hatzaki, E. Nitsch y A. Bogaard

Las excavaciones en Knossos han permitido documentar conjuntos faunísticos y arqueobotánicos que abarcan desde el Neolítico a la Edad del Bronce (VII–II milenios BCE), durante los cuales uno de los primeros asentamientos agrícolas conocidos en Europa se convierte en el primer asentamiento urbano y centro de uno de los estados regionales más antiguos. A través del análisis de isótopos estables ($\delta^{13}C$, $\delta^{15}N$) de semillas y huesos de fauna (como evidencia de las condiciones de gestión de los cereales y legumbres cultivados y para establecer los tipos de forraje consumidos por el ganado) se exploran el uso de la tierra y, por último, la economía política. Las condiciones cambiantes del cultivo y de la ganadería sobreescriven cualquier efecto de los procesos de aridificación a largo plazo. Los primeros agricultores de Knossos (VII–VI milenio BCE) cultivaban de forma intensiva cereales y legumbres (probablemente en rotación) que fueron estrechamente integrados (como fuentes abonadas de forraje) con la ganadería. A lo largo del Neolítico final y de la Edad del Bronce, el asentamiento aumentó de tamaño acompañado de un cultivo más extensivo (eventualmente con cereales y legumbres sin

rotación) y un mayor uso de los pastizales pobres y, para las cabras, de ramoneo. El pasto en las tierras cultivadas, no obstante, fue un aspecto crucial para el mantenimiento de la oveja, el ganado vacuno y los cerdos. La variada dieta de las primeras ovejas sugiere una gestión a nivel doméstico, mientras que una progresiva divergencia en la alimentación de las ovejas y cabras implica actividades de pastoreo independientes. Hasta la fase *Old Palace* (principios del II milenio BCE), el crecimiento urbano estuvo unido a cultivo y pastoreo cada vez más extensivos y probablemente más distantes, pero de alguna manera las condiciones más intensivas durante las fases *New* y *Final Palace* (mediados del II milenio BCE) refleja quizá una mayor dependencia de los excedentes primarios de la tierra de los centros que previamente eran rivales y que ahora se encuentran bajo control de Knossos.