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journal homepage: www.elsevier.com/locate/jasrepBronze Age agropastoral management in central Cyprus and along the Jordan Rift[☆]Patricia L. Fall^{a,*}, Steven E. Falconer^{b,*} , Elizabeth Ridder^c, Suzanne E. Pilaar Birch^d, Mary C. Metzger^e, Steven Porson^a^a Department of Earth, Environmental and Geographical Sciences, University of North Carolina, Charlotte, Charlotte, NC, USA^b Department of Anthropology, University of North Carolina, Charlotte, Charlotte, NC, USA^c Department of Liberal Studies, California State University San Marcos, San Marcos, CA, USA^d Department of Anthropology and Department of Geography, University of Georgia, Athens, GA, USA^e School of Instructor Education, Vancouver Community College, Vancouver, British Columbia, Canada

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ABSTRACT

We compare ancient landscapes and agropastoral management in a variety of environmental settings in the Eastern Mediterranean. Agropastoral practices are inferred across Early and Middle Bronze Age landscapes based on evidence excavated from four rural settlements in the northern Jordan Valley (Tell el-Hayyat, Tell Abu en-Ni'aj), the Dead Sea Basin (Zahrat adh-Dhra' 1), and the Troodos foothills of Cyprus (Politiko-Troullia). Comparative analyses using AMS dating, carbonized seed to charcoal ratios, charcoal, seed and bone frequencies, and stable isotope ratios ($\delta^{15}\text{N}$ and $\delta^{13}\text{C}$) from seeds and animal bone collagen enable discussion of contrasting natural and agrarian landscapes. Villages in the Jordan Valley burned dung fuel along with wood from riparian trees, while wood from desert trees was utilized near the Dead Sea, and pine, oak, and olive trees provided fuel in central Cyprus. Bone assemblages reveal animal husbandry based on high frequencies of sheep and goats, supplemented by domestic pigs at Tell el-Hayyat and Tell Abu en-Ni'aj. Politiko-Troullia is distinguished by the hunting of deer and feral pigs as inferred from stable isotope analysis of bone collagen. Plant cultivation strategies are inferred from $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$, which have similar values for cereals and pulses at Tell el-Hayyat and Tell Abu en-Ni'aj despite different environmental conditions and societal contexts. Values of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ from barley and wheat at Zahrat adh-Dhra' 1 suggest the greatest amount of management (irrigation and manuring), while plant cultivation at Politiko-Troullia involved olive arboriculture and little management of cereals. Ancient plants and animals illuminate the herding, hunting, and cultivation practices that helped mold ancient Eastern Mediterranean landscapes, often in response to environmental stress.

1. Introduction

We present comparative analyses of ecological data from four Bronze Age settlements in modern Jordan and Cyprus that exemplify the modestly-sized communities which formed the social foundation of ancient agrarian civilization in the Eastern Mediterranean (Fig. 1). These landscapes and practices of plant and animal exploitation illustrate dynamic contexts for Eastern Mediterranean complex society before and after the development of cities, and during their periodic abandonment. In this study, we compare village responses across time and space under different social and environmental conditions. The

earliest village, Tell Abu en-Ni'aj was occupied ~ 2500–2250 cal BCE during the first half of Early Bronze IV (Fall et al. 2021), when towns that had developed during the preceding Early Bronze I–III (~3000–2500 cal BCE) were abandoned across the Southern Levant (de Miroschedji 2014). Its habitation immediately precedes the hypothesized 4.2 ka Event (Kaniewski et al. 2018), a period of regional drought, and accordingly the abandonment of Tell Abu en-Ni'aj is potentially attributable to the effects of regional desiccation. Indeed, the end of its radiocarbon chronology is symptomatic of a dearth of radiocarbon ages in the Southern Levant in the two centuries following 2200 cal BCE (Fall et al. 2021).

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The three other settlements that we investigate here, Tell el-Hayyat, Zahrat adh-Dhra' 1 and Politiko-Troullia, were occupied over similar time periods in the early second millennium BCE (Fall et al. 2019; Fall et al. 2021; Fall et al. 2023; Falconer et al. 2023). In the Southern Levant, this temporal range encompasses the redevelopment of towns during the Middle Bronze Age (Bourke 2014; Cohen 2014). On Cyprus, this interval runs from the end of Prehistoric Bronze Age 1 through the first half of Prehistoric Bronze Age 2 (or from Early Cypriot III through the Middle Cypriot Period), before the appearance of the first cities along the coasts of Cyprus about by 1700 cal BCE (Knapp 2013; Manning 2013). Jointly, these chronologies span important environmental and cultural transitions roughly 2200–2000 cal BCE, including hypothesized regional desiccation associated with the 4.2 ka Event (Kaniewski et al. 2018) and the redevelopment of towns in the Southern Levant after about 2000 cal BCE. This timespan also covers the long pre-urban prelude to the relatively late appearance of cities on Cyprus and the flourishing of regional cultural interaction and trade across the eastern Mediterranean. In the course of these trajectories, shifts in plant and animal exploitation were key elements of social and economic responses to environmental amelioration and to periods of stress stemming from their relatively marginal agricultural settings and/or from ancient climate change. Here we investigate how the varying responses of these four communities molded agropastoral landscapes and their biotic communities in the Southern Levant and on the island of Cyprus.

2. Study sites

Our study highlights evidence from four settlements in a variety of environmental settings, which were inhabited between the mid-third and mid-second millennia BCE. Coordinated analyses of excavated plant and animal remains elucidate both parallel and divergent management practices during the waxing and waning of early agrarian civilization on landscapes ranging from arid settings that lie below modern sea level along the Jordan Rift to the wooded uplands of central Cyprus.

2.1. Tell Abu en-Ni'aj, Jordan

Tell Abu en-Ni'aj (hereafter Ni'aj) is an archaeological mound measuring 2.5 ha (32.41526 N, 35.57002, –257.1 m), which overlooks the floodplain of the Jordan River known in Arabic as the *zor*. This densely settled village of mudbrick houses was occupied continuously over roughly 250 years during the first half of Early Bronze IV, a period of pervasive abandonment of towns across the Southern Levant (Falconer & Fall 2019). The tell is situated near the perennial stream flow of the Jordan River with riparian trees, surrounded by a decidedly anthropogenic landscape of fertile agricultural fields.



Fig. 1. Map of Eastern Mediterranean showing locations of Tell Abu en-Ni'aj, Tell el-Hayyat, and Zahrat adh-Dhra' 1, Jordan, and Politiko-Troullia, Cyprus.

2.2. Tell el-Hayyat, Jordan

Tell el-Hayyat (hereafter Hayyat) is situated just 1.5 km northeast and slightly upslope of Ni'aj (32.4212 N, 35.57715 E, -237.9 m) amid rich agricultural fields on a Pleistocene alluvial terrace known in Arabic as the *ghor*, which lies just east of the modern floodplain of the Jordan River. The mound, measuring 0.5 ha, embodies a hamlet that was occupied continuously over more than 250 years through the rapid redevelopment of towns during the Middle Bronze Age of the Southern Levant (Falconer & Fall 2006; Fall et al. 2021). Hayyat is centered around a stratified series of four Canaanite temples, suggesting that this community probably was part of a local temple estate (Falconer & Fall 2022).

2.3. Zahrat adh-Dhra' 1, Jordan

Zahrat adh-Dhra' 1 (hereafter ZAD 1) consists of approximately 40 semi-subterranean stone structures dispersed over about 6 ha on the Plain of Dhra' overlooking the Dead Sea (31.26085 N, 35.56146 E, -165.3 m). The remains of ZAD 1 lie along a plateau between two deep-cut wadis that flow periodically into the Wadi el-Kerak, a major tributary of the Dead Sea Basin. Wadi erosion appears to have removed roughly half of the settlement originally measuring about 12 ha (Edwards et al. 2001; Edwards et al. 2002; Fall et al. 2019). Habitation shifted among the structures over a span of more than 300 years through the Middle Bronze Age. This site sits in a hyperarid setting on a landscape with scattered desert trees and scrub. While water flows today in wadi bottoms 20 m below ZAD 1, rarely and intermittently, the spring of 'Ain Dhra' provides a perennial water source a few kilometers upslope, which would have flowed at the elevation of ZAD 1 during its habitation.

2.4. Politiko-Troullia, Cyprus

The Middle Bronze Age settlement of Politiko-Troullia (hereafter *Troullia*) lies at the edge of the copper-bearing pillow lavas of the Troodos Mountain foothills of Cyprus (35.02047 N, 33.24322 E, 411.6 m). This site is defined by pottery, ground stone, and agricultural terraces spread over 20 ha (Ridder et al. 2017; Ridder et al. 2023), with architectural remains of buildings, courtyards and alleyways buried in modern fields measuring at least 2 ha (Fall et al. 2012; Falconer & Fall 2013). Habitation shifted across dispersed portions of the settlement over about 200 years. The modern landscape around *Troullia* is characterized by pine woodlands on surrounding hillsides just upslope from the floodplain of the now-dammed Pediaios River, which would have flowed as a perennial stream in antiquity. A spring just upstream from *Troullia* supplied water for Kamaras Creek, which would have flowed along the western edge of the settlement.

2.5. AMS chronologies

Our four modestly sized, distinctly non-urban settlements all experienced multi-phase occupational histories that are documented through Bayesian modeling of calibrated AMS ages (Fig. 2). Bayesian modeling based on 22 AMS ages situates the occupation of Ni'aj over seven phases during the first half of Early Bronze IV (Fall et al. 2021). The founding date for Ni'aj strengthens an emerging high chronology for Early Bronze IV starting by 2500 cal BCE, while the end of its habitation by 2250 cal BCE fits a regional pattern for abandonment of Early Bronze IV settlements in the Southern Levant. Indeed, very few large sedentary villages like Ni'aj date to this period in the Southern Levant. Twenty-eight calibrated AMS ages provide the chronology for Hayyat, showing that it was occupied over six stratigraphic phases. Hayyat is one of the few Middle Bronze Age settlements in the Southern Levant which, based on ceramic evidence, was also occupied during Early Bronze IV (Fall et al. 2021).

Bayesian modeling of 20 calibrated AMS ages from ZAD 1 reveals three occupational phases with initial settlement perhaps as early as 2050 cal BCE and abandonment by 1700 cal BCE (Fall et al. 2023). ZAD 1's occupation corresponds well with emerging chronologies for the Middle Bronze Age. ZAD 1 represents a culturally and environmentally marginal settlement, and as such exemplifies an important peripheral element of Bronze Age Levantine society. It is the only well-dated marginal settlement occupied during this time period in southern Jordan and the only peripheral settlement of its kind in the Southern Levant that provides a Bayesian model for habitation during the Middle Bronze Age.

The occupation of *Troullia* is based on 23 calibrated AMS ages (Falconer et al. 2023). Bayesian modeling shows that the settlement spanned six phases of occupation covering more than 200 years during the Prehistoric Bronze Age. Our analysis places the six stratified phases of occupation at *Troullia* between about 2050 and 1850 cal BCE, with the transition from Prehistoric Bronze Age 1 to 2 about 2000 cal BCE, associated with a major architectural shift at *Troullia* in response to erosion and associated downcutting. These four ancient settlements together provide a picture of local and regional occupation during the period between about 2500 and 1700 cal BCE when the region was undergoing fluctuations in rainfall, leading to periods of environmental stress.

3. Material and methods

In this paper we compare archaeobotanical and zooarchaeological data from our four focal settlements using a variety of analytical methods. Seed to charcoal ratios and relative charcoal frequencies for the four archaeological settlements have been published previously (Klinge & Fall 2010; Fall et al. 2015) and are presented here to compare

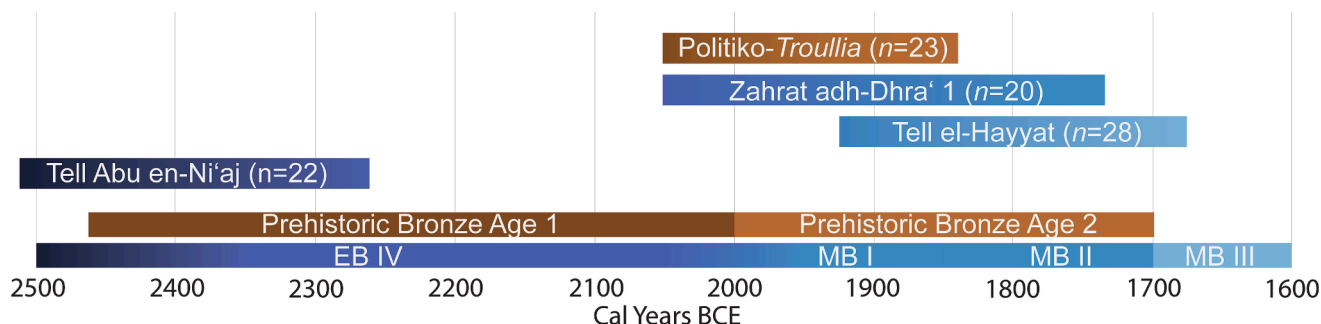


Fig. 2. Schematic comparison of the occupations of Tell Abu en-Ni'aj, Tell el-Hayyat, Zahrat adh-Dhra' 1, and Politiko-Troullia based on Bayesian modeling of calibrated AMS ^{14}C ages (Fall et al. 2021; Fall et al. 2023; Falconer et al. 2023). Age ranges based on modeled boundary medians for contiguous phases at Tell Abu en-Ni'aj, Tell el-Hayyat, and Politiko-Troullia, and according to modeled 1σ boundary confidence intervals for sequential phases at Zahrat adh-Dhra' 1. Calibration and modeling based on OxCal 4.4.4 (Bronk Ramsey 2009; Bronk Ramsey 2017) using the IntCal20 atmospheric curve (Reimer et al. 2020). Levantine chronology based on Regev et al. 2012; Fall et al. 2021; Höflmayer & Manning 2022. Cypriot chronology based on Manning 2013 and Knapp 2013: table 2.

these data to interpretations derived from other methods. The relative seed frequencies presented here represent significantly increased numbers of analyzed samples for each of the sites: Hayyat and ZAD 1 (Fall et al. 2019; Porson 2024); Ni'aj (Porson et al. 2021; Porson 2024); and *Troullia* (Klinge & Fall 2010; Supplemental Information Table S1). Relative frequencies of animal bones and teeth are updated for Hayyat (Falconer & Fall 2006: Appendices H-K), for ZAD 1 (Metzger in Edwards et al. 2001), and for *Troullia* (Metzger et al. 2021); faunal data for Ni'aj have not been published previously. Unpublished stable isotope data from seeds for the four archaeological sites come from Porson 2024. Animal bone collagen stable isotope data from Tell Abu en-Ni'aj and Tell el-Hayyat are presented in Supplemental Information Table S2. Data for Politiko-*Troullia* come from Pilaar Birch et al. 2022.

3.1. Field methods

3.1.1. Archaeological excavation

Hayyat, Ni'aj, and ZAD 1 were excavated under permits from the Department of Antiquities, Jordan, and *Troullia* was excavated under permit from the Department of Antiquities, Cyprus. These sites were excavated in 4 × 4 m units (with 1 m wide balks between the excavation units), with the exception of ZAD 1 where excavation units conformed to the visible remains of its non-contiguous stone structures. Ni'aj was excavated during an exploratory season in 1985 when 10 units were excavated in three areas, while the main two seasons of excavation (1996–1997, 2000) exposed 27 contiguous 4 × 4 m units. The cumulative area of the excavation units represents about 2.5 % of the site's area (Falconer & Fall 2019; Fall et al. 2021). Excavation of 20 units at Hayyat (1982, 1983, 1985) over 24 weeks in three seasons represents about 8 % of the tell. Excavation exposed an intact pottery kiln on the south flank of the tell, while the main excavation area of the village revealed a stratified sequence of four Canaanite temples *in antis* (Magness-Gardiner & Falconer 1994; Falconer & Fall 2006; Falconer & Fall 2022; Fall et al. 2021).

The settlement of ZAD 1 was excavated over four weeks (winter 1999–2000). Twenty-four excavation units were tailored in size and orientation to the visible stone semi-subterranean structures spread across the settlement (about 40 stone structures were mapped) (Falconer in Edwards et al. 2001; Falconer in Edwards et al. 2002; Fall et al. 2007; Fall et al. 2019). The one- and two-room structures, some with attached courtyards, are dispersed along the ridge of ZAD 1. It is estimated that only about half of the settlement remains today, while half previously had been eroded by 20 m of downcutting along the Wadi adh-Dhra'. We excavated about half of the remaining structures of ZAD 1 (with about half of the interior space for each excavated). Thus, it is estimated that about 10 % of the interior space within the stone structures of the settlement has been excavated. The settlement of *Troullia* in Cyprus (excavated in 2006–2011, 2013–2015) represents a village dispersed across about 2 ha. The site was excavated in three areas: *Troullia* East, North and West. The main excavation area of *Troullia* West exposed an area of 360 m², *Troullia* East covers about 142 m², and *Troullia* North totals 81 m² (Falconer & Fall 2013; Falconer et al. 2023). Approximately 3 % of the settlement has been excavated.

3.1.2. Recovery of carbonized seeds and charcoal

Carbonized archaeobotanical remains were collected using non-random sampling during the excavation of the four archaeological sites. All hearths, ash lenses, ovens, trash deposits and any surfaces or sediments showing evidence of burning were sampled for flotation under the supervision of PL Fall at the Deir Alla Station (Hayyat & Ni'aj), field camp by the Dead Sea (ZAD1), and the Archaeological Field Lab in Pera Orinis (*Troullia*). Flotation samples were processed using manual, non-mechanized flotation equipment (Hayyat, ZAD 1 & *Troullia*) (Fall et al. 1998; Fall et al. 2002), while the samples collected at Ni'aj (with the exception of the 1985 season, which were floated manually) were processed with a Float Tech 2000 mechanized flotation machine (Fall

et al. 1998; Fall et al. 2002). Prior to flotation, each sample volume was measured. Whether mechanized or not, the flotation methods at the four sites recovered organic remains by utilizing a large tub of water, in which a smaller basket with a 5 mm mesh bottom was suspended. Each sample was placed in the water and agitated gently to break the sediment and free the charred botanical remains, including charcoal and seeds. Light fraction remains (i.e., plant fragments) float to the surface of the water, while heavy fraction remains (i.e., heavier non-organic sediments, along with some charcoal and heavier seeds like olive pits) sink to the bottom of the basket, but do not pass through the mesh. The light fraction was skimmed from the water's surface using a fine mesh sieve (0.05 mm size mesh), and the heavy fraction was collected in the mesh-bottomed basket (5 mm). Both the heavy and light fractions were dried prior to analysis; heavy fractions were examined at the field labs and any botanical material was collected (along with small bones or artifacts like beads). Total sample volumes (liters) floated at each site are: Ni'aj (366), Hayyat (318), ZAD 1 (180), and *Troullia* (879).

3.1.3. Recovery of animal bones and teeth

All excavated sediments (other than those selected for water flotation) from all four ancient villages were dry-sieved through 0.5 cm wire mesh to recover bones and teeth (as well as other material culture, such as ceramics, stone, bone and metal tools). Animal bones and teeth were washed, identified, and quantified by MC Metzger at the 1) Deir Alla Station (Ni'aj and Hayyat), 2) field camp by the Dead Sea (ZAD 1), and 3) the Archaeological Field Lab in Pera Orinis (*Troullia*) (Falconer et al. 2004; Fall et al. 2008). The identified animal bones and teeth from Jordan (Ni'aj, Hayyat & ZAD 1) were shipped to the United States for further analyses with permission from the Department of Antiquities, Jordan; these collections are archived at Arizona State University. The zooarchaeological collections from *Troullia* are stored at the Larnaca facility by the Department of Antiquities, Cyprus. Bone and tooth samples from all four sites were selected for stable isotope analyses at the University of Georgia (UGA); samples from *Troullia* were exported from Cyprus under permission from the Department of Antiquities, Cyprus.

3.2. Laboratory analyses

3.2.1. Identification & quantification of carbonized seeds and charcoal

The main avenues for incorporating carbonized seeds and charcoal into the archaeological record include food processing waste (e.g., Fuller & Harvey 2006; van der Veen 2007; Fuller & Stevens 2009), combustion of fuelwood, and burning of dung fuel, which provides an important mechanism for carbonizing seeds of both cultivated crops and wild plants (e.g., Miller, 1984; Hastorf & Wright 1998; Shahack-Gross 2011). Archaeobotanical assemblages reflect routine events involving plant procurement and consumption (Fuller et al. 2014). While many assemblages can be interpreted in terms of food processing, they also may be influenced by collection and burning of wood and herbivore dung for fuel. While dung burning is unlikely in wet or well-wooded environments (Fuller et al. 2014; Champion & Fuller 2018), it has been a significant fuel alternative in arid regions with limited fuelwood resources (Miller 1996; Spengler 2018). Archaeobotanical studies elsewhere in southwestern Asia (e.g., Deckers et al. 2025) identify variables arising in the Bronze Age that would have contributed to increased dung fuel use, especially population pressure and depletion of wood resources. Settlements in the wooded or forested environments of Cyprus may have been less likely to incorporate dung as a fuel source, but dung could have been a vital fuel source along the Jordan Rift in the Bronze Age.

Burning of dung fuel incorporates a mixture of what livestock were fed, what they grazed on in local fields, and plant fragments (particularly chaff) introduced during the creation of dung cakes (Miller & Smart 1984; Charles 1998). In regions with greater human impacts and diminished woodlands, greater abundances of seeds compared to charcoal suggest that dung burning was a major source of carbonized plant remains (Miller 1984).

Comparable methods were employed for the processing of botanical remains from all four sites (see Fall et al. 1998; Fall et al. 2002; Fall et al. 2008; Fall et al. 2019; Fall et al. 2021; Falconer & Fall 2006; Falconer & Fall 2019). Heavy fractions were scanned for heavy seeds (e.g., *Olea*). Once dry, the light fractions were poured through 4.75 mm, 2 mm, 1 mm, and 0.5 mm sieves to aid in sorting comparably sized seeds and charcoal. A sample splitter was used for some of the larger samples from Ni'aj and Hayyat. All botanical material ≥ 0.25 mm was sorted using a binocular microscope at 6-40x magnification of charcoal, seeds, seed fragments, rachis fragments, spikelets, straw and chaff, which were identified to the lowest taxonomic level possible. Identifications of seeds, seed fragments, fruits, and other floral parts are based on external morphology through comparison with Fall's reference collection and with comparative literature (e.g., Helbaek 1958; Helbaek 1966; Martin & Barkley 1973; Zohary & Hopf 1973; Zohary & Spiegel-Roy 1975; van Zeist 1976; van Zeist & Bakker-Heeres 1982; Hubbard 1992; Jacomet 2006).

A subset of the charcoal fragments from each of the four settlements was identified by Scanning Electron Microscope (JEOL JSM6300 at Arizona State University) (Klinge & Fall 2010; Fall et al. 2015). Charcoal specimens were identified by comparing photos taken using the SEM with published keys (Fahn et al. 1986; Schweingruber et al. 2011; Akkemik & Yaman 2012). We present relative frequencies of charcoal counts by ecological groups based on today's species distributions. Charcoal from woody trees and shrubs were grouped into the following categories: desert trees, riparian trees, upland trees, shrubs, and orchard taxa (see Fall et al. 2015).

3.2.2. Seed to charcoal ratios

Seed to charcoal ratios were calculated as total weight of all seeds to weight of charcoal (g/g), for each of the four archaeological settlements (Klinge & Fall 2010; Fall et al. 2015). Following Miller (1984), we infer that increased seed to charcoal ratios indicate greater burning of animal dung relative to fuel wood burning. Lines of evidence in addition to seed to charcoal ratios are often used to determine the degree to which dung fuel was used at a settlement. For example, the presence of dung spherulites in flotation samples can verify that dung was used as fuel (Smith et al. 2019). Some studies have used abundances of weed flora to indicate "arable plant communities" rather than the natural environment (e.g., Fuller et al. 2014: 182). Other multi-proxy studies incorporate phytoliths in conjunction with macrobotanical data to determine the presence of grass phytoliths from dung or other products like fodder or matting (Fuller et al. 2014; Dunseth et al. 2019; Champion & Fuller 2018).

For each site, a subsample of flotation samples was chosen non-randomly to capture the spatial and temporal variation across the site. These subsamples represent similar proportions (13–19 %) of the total sample volume at each site. The number of subsamples (n) used and total sample volume (liters) for each site are: Ni'aj (n = 52; vol = 366), Hayyat (n = 60; vol = 318), ZAD 1 (n = 32; vol = 180), and *Troullia* (n = 110; vol = 879).

3.2.3. Identification & quantification of animal bones and teeth

For all four settlements, bone fragments which could not be identified were counted and weighed, while bones and teeth that could be identified were quantified according to the number of identifiable specimens (NISP) (Falconer et al. 2004; Fall et al. 2008; Metzger et al. 2021). All specimens were initially identified at the field labs by Metzger through comparison with published keys and drawings. Unidentified specimens in the faunal collections from Jordan were compared to collections at the Smithsonian Museum of Natural History in Washington, D.C., the Museum of Comparative Zoology at Harvard University in Cambridge, MA, and the Field Museum in Chicago. Wim Van Neer of the Royal Museum of Central Africa in Tervuren, Belgium, identified the Hayyat fish remains. Shells were identified by David Reese with reference to his own collections. Bone measurements follow von den Driesch

(1976).

3.2.4. Stable carbon and nitrogen isotope analyses of archaeological seeds

Seeds of wheat (*Triticum* spp.), barley (*Hordeum* spp.) and pulses (*Lens culinaris* and *Pisum sativum*) were chosen from each of the settlements for stable isotope analysis. Stable isotope values were derived for archaeobotanical samples from carbonized seed samples and analyzed at the Center for Applied Isotope Studies (CAIS), UGA ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$). Values were determined using a Delta-V elemental analyzer isotope ratio mass spectrometer (EA-IRMS). The archaeological plant $\delta^{13}\text{C}$ data presented in this paper have been corrected by an offset of -0.11 ‰ in accordance with experimentally determined differences between carbonized and uncarbonized seeds (Nitsch et al. 2015; Styring et al. 2016; Styring et al. 2017).

3.2.5. Stable carbon and nitrogen isotope analyses of animal bone collagen

Light stable isotope ratios ($\delta^{18}\text{O}$, $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$) reflect local climatic and environmental conditions (Rozanski et al. 1982; Merlivat & Jouzel 1979; Bowen & Wilkinson 2002; Dotsika et al. 2010) and can be extracted from archaeological seeds, bone collagen, and tooth enamel samples. As animals consume water and food, they incorporate stable isotopes into bodily tissues, recording ambient environmental conditions. We chose animal bones from secure archaeological layers and from a variety of spatial and temporal contexts at the settlements for stable isotope analysis ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$). In order to avoid sampling the same individual more than once, we chose unarticulated bones from the same skeletal element (i.e., right humeri). Bones from ZAD 1 were not sampled for stable isotope analyses due to their poor preservation. Bones of domesticated sheep (*Ovis aries*), goat (*Capra hircus*), cattle (*Bos taurus*), pig (*Sus scrofa*), along with those for wild taxa were analyzed from Ni'aj, Hayyat and *Troullia*. We sampled 100 bones from Ni'aj for stable isotopes: 23 sheep, 10 goats, 10 sheep/goat, 11 cattle, 12 pigs, and 34 from wild taxa. Samples from 119 bones from Hayyat were run for stable isotopes, including 11 sheep, 6 goats, 41 sheep/goat, 8 cattle, 16 pigs and 37 from wild taxa. We analyzed 213 bones from *Troullia*: 42 sheep, 42 goats, 11 sheep/goat, 15 cattle, 20 pigs, 76 deer, 6 foxes, and 1 owl.

Collagen was extracted from the bone samples (approximately 0.5 g per sample) at the UGA Quaternary Isotope Paleoeology (QUIP) Lab using a modified Longin method by demineralizing fragmented bone in 0.5 M HCl for several days (Ehleringer 1991). The acid was changed regularly until the sample floated and was soft. The collagen was then gelatinized by heating it in pH 3.0 water at 75C for 48 h. Each sample was filtered using an EZEE filter; then the supernatant liquid was freeze dried. The subsamples of freeze-dried collagen powder were weighed in tin capsules at the CAIS, UGA and analyzed on a Costech Elemental Analyzer coupled to a Finnigan Delta IV Plus IRMS. Stable carbon is reported relative to the standard Vienna Pee-Dee Belemnite (VPDB), and stable nitrogen is reported relative to ambient atmospheric N_2 (AIR). Standards were supplied from the National Institute of Standards & Technology (NIST). Polyethylene foil ($\delta^{13}\text{C} = -32.15$ ‰) and sucrose ($\delta^{13}\text{C} = -10.45$ ‰) were used for carbon, and ammonium sulfate ($\delta^{15}\text{N} = 20.41$ ‰) and potassium nitrate ($\delta^{15}\text{N} = 4.7$ ‰) were used for nitrogen. Two internal standards (spinach: $\delta^{15}\text{N} = -0.54$ ‰; $\delta^{13}\text{C} = -27.44$ ‰, and protein: $\delta^{15}\text{N} = 8.19$ ‰; $\delta^{13}\text{C} = -17.43$ ‰) were also used. Precision was better than ± 0.15 ‰. Long-term precision of the IRMS is ≤ 0.2 ‰ for $\delta^{15}\text{N}$ and ≤ 0.1 ‰ for $\delta^{13}\text{C}$. Success rates for the three sites are: *Troullia* 60 %; Hayyat 11 %; Ni'aj 3 %. In the case of failed samples, poor collagen preservation led to low collagen yield, low amounts of %C or %N, or C:N ratios outside the acceptable range of 2.9–3.6 ‰ (Ehleringer 1991).

Bone collagen was analyzed successfully from Ni'aj for one sheep, one Northern lapwing (*V. vanellus*), and one Eurasian coot (*Fulica atra*). From Hayyat we obtained data from 13 samples: four sheep/goat, one fox (*Vulpes vulpes*), one wild cat (*Felis silvestris*), one gazelle (*Gazella gazella*), three quail (*Coturnix coturnix*), two steppe buzzards (*Buteo buteo*

volpinus), and one wood pigeon (*Columba palumbus*). Since the majority of the processed samples were from sheep, goat, and cow, the relatively large number of successful bird bone analyses from Ni'aj and Hayyat was unexpected. For *Troullia* we obtained data from 130 individual bones, including 43 Mesopotamian fallow deer (*Dama dama mesopotamica*), 31 sheep, 27 goats, eight sheep/goat, eight cattle, eight pigs, four foxes (*Vulpes vulpes*), and one owl (most likely barn owl, *Tyto alba*).

4. Results

4.1. Relative frequencies of archaeological seeds

The three settlements along the Jordan Rift provide similar carbonized seed assemblages, based on slightly varying amounts of barley (*Hordeum* spp.) and wheat (*Triticum* spp.) among cereals, modest variation in the relative frequencies of orchard taxa (especially *Ficus*), cultivated legumes, and amounts of mostly crop-following wild plant taxa (Fig. 3). The macrofossil evidence at Ni'aj is distinguished by an abundance of cereal grains, which likely came from multiple sources, including the burning of dung as fuel, as well as from crop processing. The multi-stage sequence from crop cultivation to harvesting, storage, and consumption (e.g., see Champion & Fuller 2018) is one of multiple factors contributing to patterns of seed deposition at Ni'aj. As emphasized by Champion & Fuller (2018), seeds are commonly charred in transition from crop storage to meal preparation. This charring stage may have led to a decrease in the ratio of stem fragments to seeds, which drops from 0.45 to 0.13 midway through the occupation of Ni'aj at about 2375 BCE (Porson 2018: fig. 15). This shift suggests an increase in grains being cleaned in the end stages of crop processing, since cleaned grains tend to resist herbivore digestion (see discussion in Champion & Fuller 2018). It is also possible that diminished stem fragments could result from activities like threshing or winnowing being conducted away from the settlement (Porson 2018).

For the analyses presented here we combine the wheat species, which include bread wheat (*T. aestivum*), emmer wheat (*T. dicoccum*),

and einkorn (*T. monococcum*). Similarly, barley includes both hulled barley (*H. vulgare*) and naked barley (*H. vulgare* var. *nudum*). Among cereals, barley to wheat ratios vary from 4.01:1 at Tell Abu en-Ni'aj, to 1.36:1 at Tell el-Hayyat, and 0.72:1 at Zahrat adh-Dhra' 1. In stark contrast, the seed evidence from Politiko-*Troullia* features a strikingly predominant mix of orchard taxa – fig (*Ficus*), olive (*Olea europaea*) and grape (*Vitis vinifera*), along with terebinth (*Pistacia* sp.), which total 86 % of the site's seeds, accompanied by relatively infrequent seeds from cereals, legumes and wild plants. Relative frequencies of carbonized seed taxa provide the clearest distinction between Politiko-*Troullia* and the three settlements along the Jordan Rift.

4.2. Relative frequencies of charcoal

The charcoal assemblages from our four settlements vary in the taxa represented and in their relative abundances (Fig. 4). The most abundant wood found at Ni'aj is tamarisk (*Tamarix* spp.), accompanied by riparian trees, including poplar (*Populus* spp.) and smaller amounts of willow (*Salix* spp.) and vitex (*Vitex* sp.), which would have been available in close proximity along the Jordan River. Nearly half of the Ni'aj charcoal comes from orchard taxa, including olive, grape, pomegranate (*Punica granatum*) and especially fig. Small quantities of oak (*Quercus* sp.), pine (*Pinus* sp.), pistacia (*Pistacia* sp.) and arbutus (*Arbutus andrachne*) represent the upland trees, which are accompanied by shrub taxa. The charcoal evidence from Ni'aj reflects use of the most diverse wood resources among the four settlements, despite the arid conditions of Early Bronze IV. About two-thirds of the Hayyat charcoal represent shrubs and desert trees, perhaps from the unirrigated margins of agricultural fields, complemented with substantial frequencies of olive and upland trees (oak, pine and pistacia) similarly to Ni'aj. Although the Jordan Valley may have been characterized largely by an anthropogenic landscape of cultivated fields and pastures, its villagers were able to harvest appreciable amounts of fuel wood and construction timber from the Jordan River floodplain and from wooded slopes and the plateau above the Rift Valley. The arid setting of ZAD 1 is reflected by a

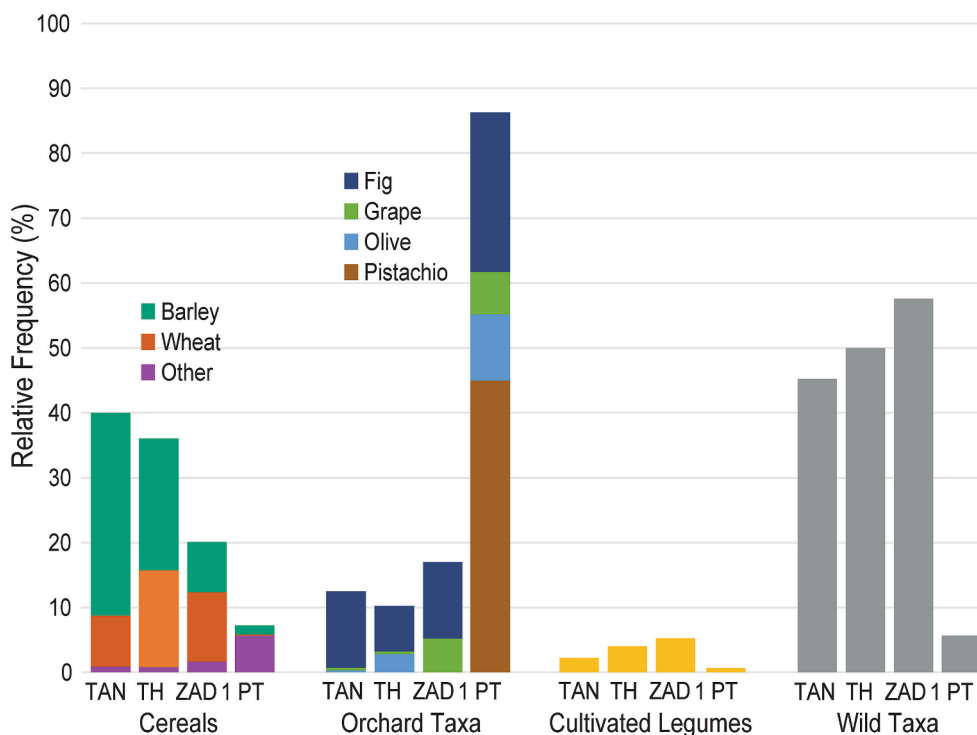


Fig. 3. Relative frequencies of carbonized seeds from Tell Abu en-Ni'aj, Tell el-Hayyat, Zahrat adh-Dhra' 1, and Politiko-*Troullia* according to plant taxa and categories (note; wild terebinth at *Troullia* included with orchard taxa). Data for Tell Abu en-Ni'aj (n = 15,303), Tell el-Hayyat (n = 18,567), and Zahrat adh-Dhra' 1 (n = 2,101) from Porson 2024: Supplemental files; data for Politiko-*Troullia* (n = 1,784) (see Supplemental Information Table S1).

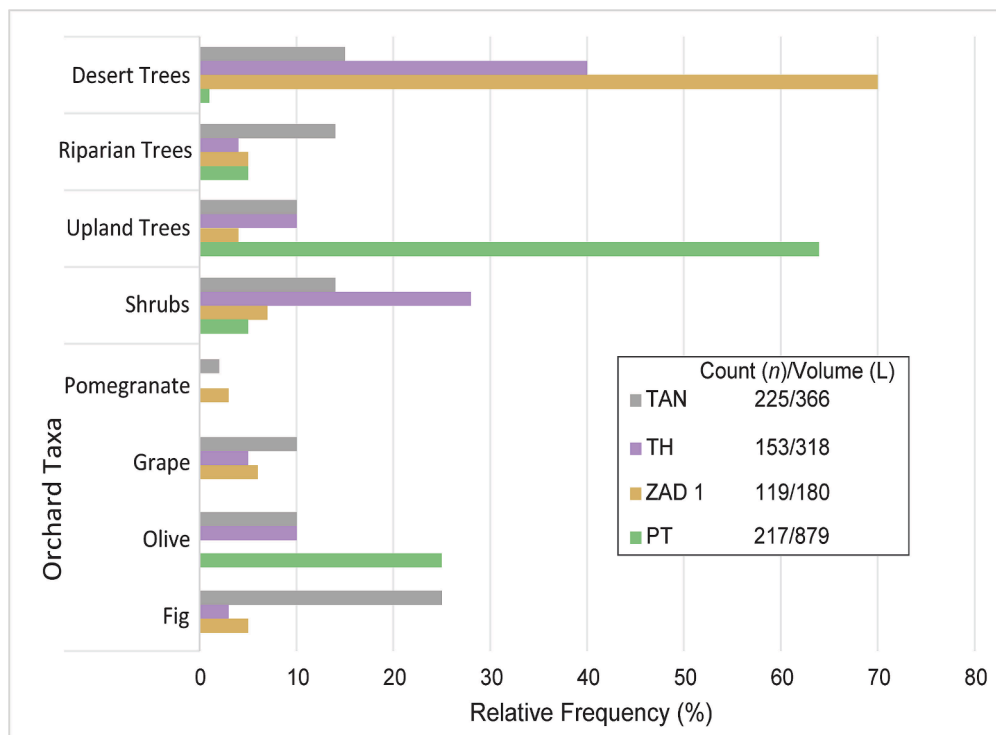


Fig. 4. Relative charcoal frequencies for woody plants from Tell Abu en-Ni’aj, Tell el-Hayyat, Zahrat adh-Dhra’ 1, and Politiko-Troullia according to plant taxa and categories (data from Fall et al. 2015).

predominance of charcoal from desert and riparian trees, especially acacia (*Acacia* spp.) and tamarisk, and the lowest frequencies of orchard taxa, including an absence of olive charcoal. Conversely, *Troullia* features the taxonomically least diverse charcoal assemblage, based on particularly substantial amounts of upland trees, including oak and especially pine, accompanied by olive, which stands alone among orchard taxa used for wood. This taxonomic combination reflects harvesting of forest resources augmented by orchard pruning, both indicative of *Troullia*’s forest verge setting and intensive olive arboriculture. The villages of Tell el-Hayyat, and especially Tell Abu en-Ni’aj, situated in the distinctively anthropogenic landscape of the Jordan Valley bottomlands, offer the most diverse charcoal assemblages, although their combinations of taxa differ. In contrast, the evidence from ZAD 1 and *Troullia*, set in less agriculturally developed landscapes, stem from much narrower variety in wood charcoal.

4.3. Seed to charcoal ratios

Seed to charcoal ratios provide proxy measures of the relative amounts of wood and dung fuel burning practiced by ancient agrarian communities (Miller 1984). Lower seed to charcoal ratios indicate greater consumption of wood resources, while higher ratios indicate landscapes with less availability of fuelwood, necessitating greater reliance on dung fuel. The seed to charcoal ratios from our four focal sites distinguish the relative amounts of dung versus wood fuel burned by the inhabitants at each settlement (Fig. 5). The archaeobotanical remains from Ni’aj provide the highest seed to charcoal ratio, and the evidence from nearby Hayyat also produces a substantial but lower ratio than is found at Ni’aj. In contrast, the settlements of ZAD 1 and *Troullia* produce much lower ratios that indicate more burning of wood than dung fuel at these settlements. These distinctions indicate that the northern Jordan Valley was characterized by a less wooded, more anthropogenic landscape. In contrast, greater availability of fuelwood is indicated in the Dead Sea Basin and in the Troodos foothills of Cyprus.

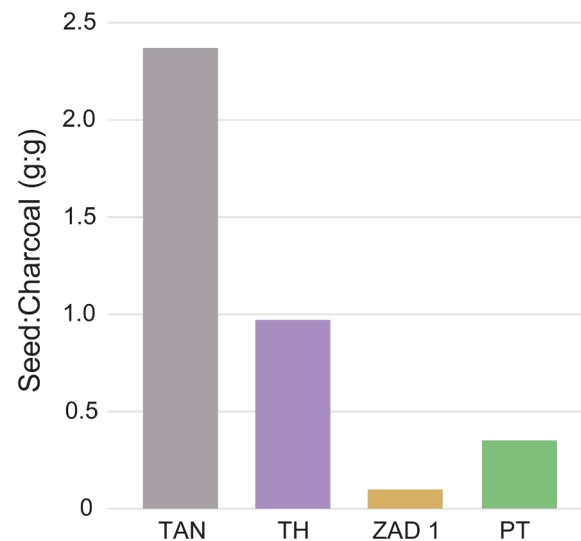


Fig. 5. Seed to charcoal ratios based on total seed and charcoal weights (g:g). Data for Tell Abu en-Ni’aj, Tell el-Hayyat, and Politiko-Troullia from Klinge & Fall 2010: table 2. Data for Zahrat adh-Dhra’ 1 from Fall et al. 2015: table 5).

4.4. Relative frequencies of animal bones and teeth

Ni’aj and Hayyat provide faunal assemblages with very similar relative taxonomic frequencies (Fig. 6). At both sites, a majority of bones and teeth represent a mix of sheep (*Ovis aries*) and goats (*Capra hircus*), which is accompanied by substantial remains of domesticated cattle (*Bos taurus*) and pigs (*Sus scrofa*), and very little evidence of equids, canids or wild animals. Sheep:goat ratios of 0.45 at Ni’aj and 0.66 at Hayyat indicate a local shift from slightly greater Early Bronze IV goat herding to a greater proportion of sheep in the Middle Bronze Age. Cattle frequencies are very similar at both sites, while remains of pig are

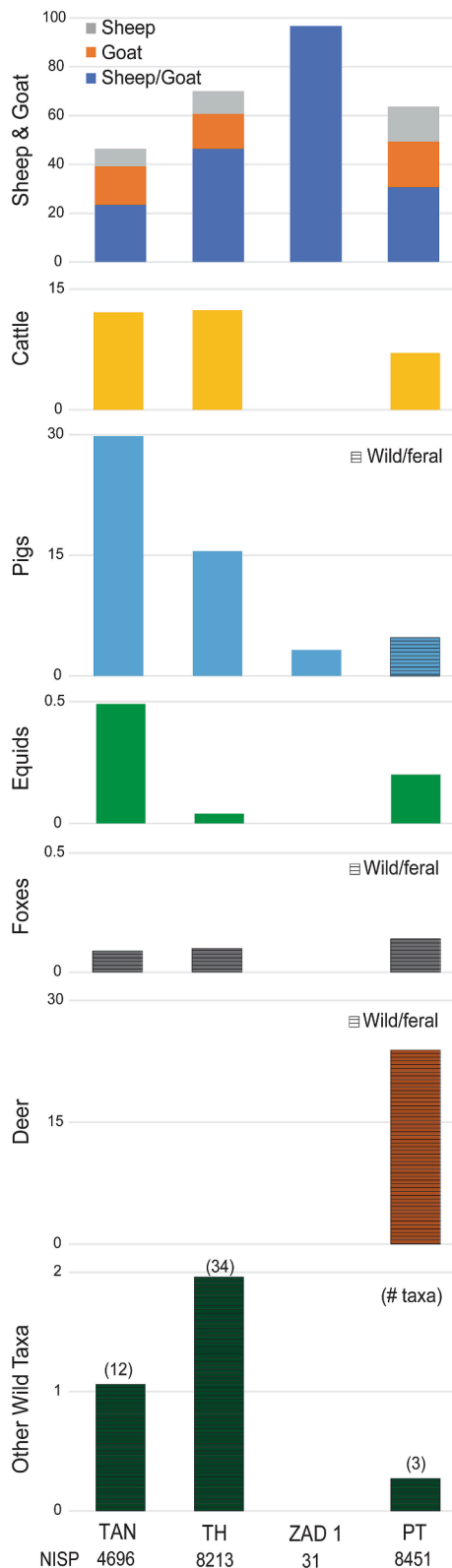


Fig. 6. Relative frequencies (%) of animal bones and teeth based on NISP from Tell Abu en-Ni'aj, Tell el-Hayyat, Zahrat adh-Dhra' 1, and Politiko-Troullia according to animal taxa and categories (note differing scales). Data for Tell el-Hayyat from Falconer & Fall 2006; data for Zahrat adh-Dhra' 1 from Metzger in Edwards et al. 2001; data for Tell Abu en-Ni'aj and Politiko-Troullia not published previously.

particularly abundant at Ni'aj, before declining in frequency at Hayyat. Although bones from wild animals are infrequent at both sites, they represent taxonomic arrays including carnivores, herbivores, birds and fish. The faunal profiles for ZAD 1 and *Troullia* are distinct from those from the northern Jordan Valley for different reasons. The small sample of bones from ZAD 1 is limited to undifferentiated ovicaprids plus a single pig bone. The evidence for animal domesticates at *Troullia* includes a mix of ovicaprids similar to that of Hayyat, with a sheep:goat ratio of 0.76, less frequent cattle bones, and modest evidence of equids. *Troullia* provides abundant remains of wild Mesopotamian fallow deer (*Dama dama mesopotamica*). The pigs from *Troullia* are hypothesized to include both feral and husbanded individuals as inferred elsewhere on prehistoric Cyprus (Croft 1991). These four settlements show contrasts in animal management, with a narrow range of domesticated species at Ni'aj, Hayyat, and ZAD 1 versus a mix of sheep/goat herding with deer hunting and a mix of hunting and husbandry of pigs at *Troullia*. The diversity of wild animal taxa varies substantially between sites, from 12 taxa at Ni'aj to 34 at Hayyat, both of which include resident and migratory birds, and just three taxa at *Troullia*, reflecting its island setting with natural lower species diversity (Table 1).

Table 1
Wild animal taxa (NISP) from Tell Abu en-Ni'aj, Tell el-Hayyat and Politiko-Troullia.

Category	Taxon	Ni'aj	Hayyat	Troullia	
Mammals	red fox (<i>Vulpes vulpes</i>)	10	8	23	
	wild cat (<i>Felis silvestris</i>)	7	2		
	caracal (<i>Felis caracal</i>)	2			
	mountain gazelle (<i>Gazella gazella</i>)	17	2		
	striped hyena (<i>Hyaena hyaena</i>)	1			
	Egyptian mongoose (<i>Herpestes ichneumon</i>)	4	1		
	gerbil (<i>Gerbillus</i> sp.)		2		
	Eurasian badger (<i>Meles meles</i>)		18		
	jird (<i>Meriones</i> sp.)		1		
	Libyan jird (<i>Meriones libycus</i>)		1		
	Sundevall's jird (<i>Meriones crassus</i>)		2		
	house mouse (<i>Mus musculus</i>)		5		
	weasel (<i>Mustela nivalis</i>)		1		
	Palestine mole rat (<i>Spalax ehrenbergi</i>)		8		
	Mesopotamian fallow deer (<i>Dama dama mesopotamica</i>)			2019	
	Birds	great bustard (<i>Otis tarda</i>)	1		
		Northern lapwing (<i>Vanellus vanellus</i>)	1		
		Eurasian coot (<i>Fulica atra</i>)	2		
		grey heron (<i>Ardea cinera</i>)	1		
sand partridge (<i>Ammoperdix heyi</i>)			2		
mallard (<i>Anas platyrhynchos</i>)			7		
long-billed pitpit (<i>Anthus similis</i>)			1		
golden eagle (<i>Aquila chrysaetos</i>)			1		
steppe buzzard (<i>Buteo buteo vulpinus</i>)			3		
common quail (<i>Coturnix coturnix</i>)			12		
rock dove (<i>Columba livia</i>)			8		
wood pigeon (<i>Columba palumbus</i>)			3		
corncrake (<i>Crex crex</i>)			2		
crested lark (<i>Galerida cristata</i>)			1		
black-headed gull (<i>Larus ridibundus</i>)			1		
mourning wheatear (<i>Oenanthe lugens</i>)			1		
Spanish sparrow (<i>Passer hispaniolensis</i>)			1		
water rail (<i>Rallus aquaticus</i>)		2			
collared dove (<i>Streptopelia decaocto</i>)		2			
Brown (Arabian) babbler (<i>Turdoides squamiceps</i>)		1			
greenfinch (<i>Carduelis chloris</i>)		1			
black francolin (<i>Francolinus francolinus</i>)		1			
moorhen (<i>Gallinula chloropus</i>)		1			
barn owl (<i>Tyto alba</i>)			1		
Fish	air-breathing catfish (Clariidae)	3	24		
	Carp/minnow (Cyprinidae)		15		
	undifferentiated fish		17		
Reptiles	freshwater turtle (<i>Mauremys capsica</i>)	1			

4.5. Stable isotope ratios from archaeological seeds

Values of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ from carbonized seeds center on a cluster of very similar means for *Hordeum* and *Triticum* at Ni'aj and Hayyat, generally with larger standard deviations for carbon than for nitrogen (especially for *Triticum* at Ni'aj) (Fig. 7). For ZAD 1, these cereals provide mean values that are higher for $\delta^{15}\text{N}$ and more negative for $\delta^{13}\text{C}$, with slightly greater standard deviations for nitrogen than for carbon. The modest number of samples from *Troullia* contribute lower nitrogen values and less negative carbon values than those from the other three sites. The analytical results for pulses describe a very different pattern based on consistently lower nitrogen values, and mean carbon values spanning a range similar to that for mean values from cereals at Ni'aj and Hayyat.

4.6. Stable isotope ratios from animal bone collagen

Our most robust bone collagen isotope data, from *Troullia*, show very similar distributions for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ from sheep and sheep/goat, suggesting that the undifferentiated ovicaprid samples from this site primarily represent sheep (Fig. 8). Goats reveal slightly less negative $\delta^{13}\text{C}$ values and lower $\delta^{15}\text{N}$ values. Cattle have similar $\delta^{13}\text{C}$ values to the sheep and goats, but slightly higher $\delta^{15}\text{N}$ values. On the other hand, swine and Mesopotamian fallow deer produce clearly lower values for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ than the sheep and goats, while a single owl and foxes are distinguished by much higher values for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$. Hayyat provides isotope concentrations for sheep/goat very similar to those for *Troullia*, while a single sheep sample from Ni'aj has an elevated $\delta^{15}\text{N}$ value accompanied by an anomalously high $\delta^{13}\text{C}$ value. Single gazelle and wood pigeon samples from Hayyat produce $\delta^{13}\text{C}$ values similar to those for the ovicaprids from *Troullia* and Hayyat, accompanied by much lower values of $\delta^{15}\text{N}$. Among the birds from Hayyat, two steppe buzzards

generate $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values that cluster with the data for pigs and wild deer from *Troullia*. A wild cat and a fox from Hayyat are distinguished by very high $\delta^{15}\text{N}$ values plus a relatively high value for $\delta^{13}\text{C}$, while three quail samples from Hayyat provide elevated values, which are distinctly higher than those for most other birds from Hayyat and Ni'aj, and most similar to those for the fox from *Troullia*. Two birds from Ni'aj have anomalously high values for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ not plotted on Fig. 8 (coot: $\delta^{13}\text{C} = -15.6$, $\delta^{15}\text{N} = 16.5$; lapwing: $\delta^{13}\text{C} = -15.6$, $\delta^{15}\text{N} = 15.7$).

5. Discussion

5.1. Plant cultivation, fuel use and crop management

Our carbonized seed and charcoal assemblages provide indirect portraits of the agropastoral regimes and plant landscapes surrounding our four focal settlements. On this basis, we infer that the farmers of Ni'aj and Hayyat cultivated very similar combinations of annual cereals (primarily wheat and barley) supplemented by less abundant legumes and orchard crops, including olive, grape and fig. Despite its markedly more arid setting, farming at ZAD 1 involved a comparable set of crops, with slightly less evidence of cereal agriculture and a greater proportion of grape and fig cultivation. High frequencies of wild, largely crop-following taxa reflect another component of the heavily cultivated landscapes around our Jordan Rift settlements. More varied charcoal assemblages indicate fuelwood preferences ranging from a mix of desert and riparian trees, shrubs, and orchard taxa at Ni'aj, to shrubs and desert trees at Hayyat, and to desert trees in particular at ZAD 1, all accompanied by little burning of upland trees at any settlement along the Rift. The occupants of Ni'aj and Hayyat were more reliant on dung as a main fuel source on the more deforested, anthropogenic landscape of the northern Jordan Valley (Fig. 9). A higher barley:wheat ratio at Ni'aj

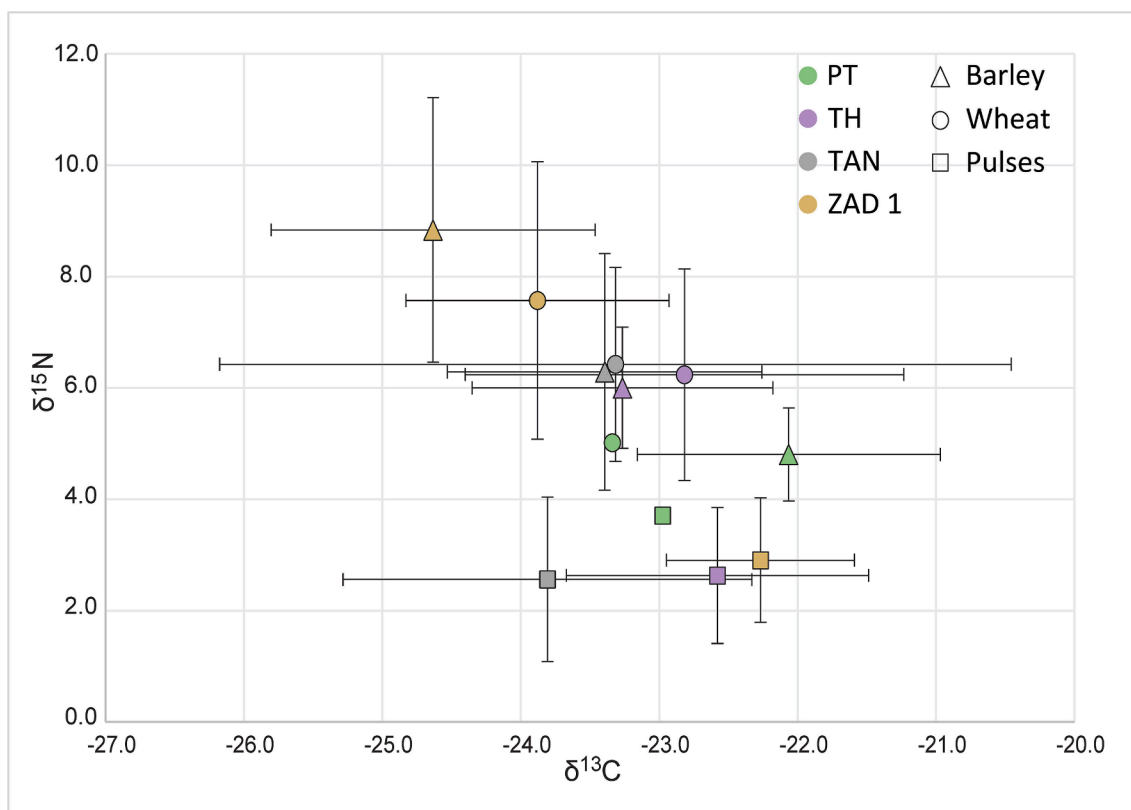


Fig. 7. Means and standard deviations for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for *Hordeum*, *Triticum* and pulse seeds from Tell Abu en-Ni'aj, Tell el-Hayyat, Zahrat adh-Dhra' 1, and Politiko-Troullia (data for Tell Abu en-Ni'aj, Tell el-Hayyat, Zahrat adh-Dhra' 1 from Porson 2024; data for Politiko-Troullia presented in Supplemental Information Table S1).

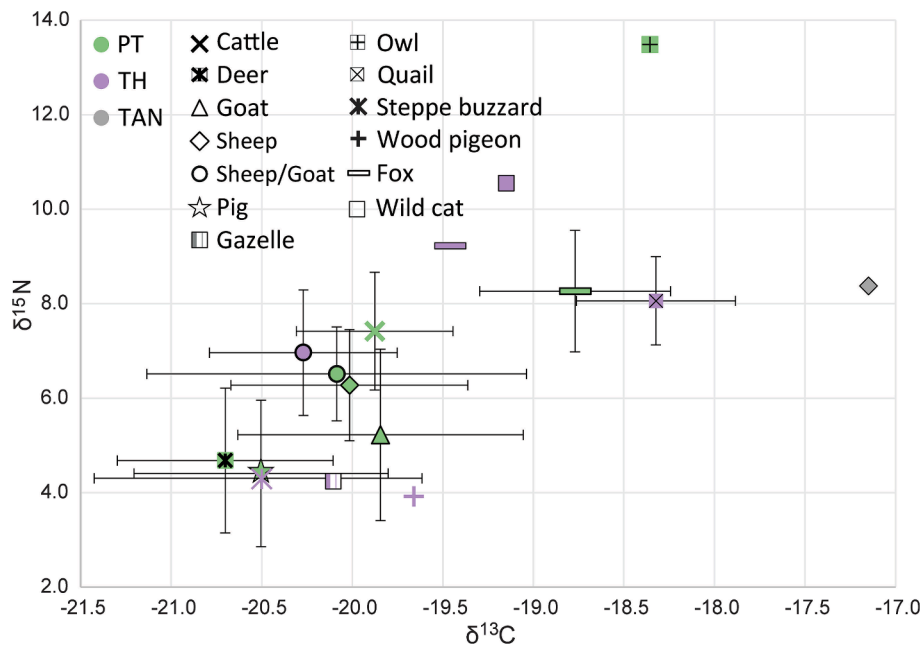


Fig. 8. Means and standard deviations for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for animal bone collagen samples from Tell Abu en-Ni'aj, Tell el-Hayyat, and Politiko-Troullia (data for Politiko-Troullia from Pilaar Birch et al. 2022).

indicates an agricultural response to greater aridity in Early Bronze IV based on intensified cultivation of barley (see discussion of wheat stable isotope evidence below). Seed to charcoal ratios are lowest at ZAD 1, on a Dead Sea landscape populated with desert trees.

The seed and charcoal evidence from *Troullia* illustrates a profoundly different landscape, which emphasized harvesting wild terebinth, as well as cultivation of olive, grape and fig, with little carbonized evidence of annual crops. The limitations of archaeobotanical evidence from Cyprus are summarized by Lucas & Fuller (2020). Relatively good rates of macrofossil recovery are reported for some sites in Cyprus (e.g., Colledge 2003; Murray 1998; Murray 2003), however, limited remains found in many settlements are attributed to poor preservation of seeds, particularly of cereals (Hansen 1991; Hansen 2005; Lucas et al. 2012). A paucity of archaeobotanical deposition also could stem from shorter site occupations and lower population densities (Croft 1991; Clarke 2007; Wasse 2007) than those in southwestern Asia, for example. At *Troullia*, a low seed to charcoal ratio underscores the availability of fuel wood from upland, as well as fruit trees, drawn from the surrounding landscape of terraced orchards and wooded hillslopes (Fig. 10). In overview, our analyses of plant remains distinguish the profoundly anthropogenic landscapes of annual croplands along the Jordan Rift at Ni'aj and Hayyat, intensively managed arid land agriculture at ZAD 1, and the modestly managed arboriculture interfaced with heavy reliance on adjacent woodland resources at *Troullia*.

5.2. Seed stable isotopes

We use $\delta^{13}\text{C}$ from seed samples as a proxy measure of water availability whereby lower (more negative) values reflect greater availability (Wallace et al. 2015). Values of $\delta^{15}\text{N}$ from non-nitrogen fixing plants reflect relative precipitation, temperature, and plant available nitrogen, with higher $\delta^{15}\text{N}$ values indicative of warmer, drier climates and greater soil N (Craine et al. 2009). Manuring supplements organic soil N, leading to increased $\delta^{15}\text{N}$ values (Amundson et al. 2003), especially in well-developed soils (Vitousek et al. 1989). As a result of their capacity to enhance soil N, nitrogen-fixing plants like pulses tend to have consistently low $\delta^{15}\text{N}$ values (Szpak et al. 2013). One general challenge of stable isotope analysis is that isotope concentrations provide proxy measures of agropastoral management involving multiple contributing

variables stemming from both natural environmental conditions and human behavior.

Our stable isotope analyses indicate similar cereal cultivation practices at Ni'aj and Hayyat. Nearly identical $\delta^{13}\text{C}$ means and standard deviations indicate very similar management of barley cultivation by both settlements, and elevated values of $\delta^{15}\text{N}$ around 6 ‰ suggest cultivation of both wheat and barley in fertilized fields. Wheat samples from Ni'aj provide a slightly more negative mean and a much greater standard deviation for $\delta^{13}\text{C}$, which may reflect diversified cultivation based on a greater mixture of wheat taxa, more varied field locations and access to water (e.g., on both the Jordan River floodplain below and the fields upslope from Ni'aj), or possibly a broader range of seasonal cultivation. Since the fields of Ni'aj were cultivated during the drier climatic conditions of EB IV in the Southern Levant, the slightly more negative $\delta^{13}\text{C}$ values from Ni'aj may reflect more watering rather than greater rainfall in comparison to farming at Hayyat during more favorable conditions in the Middle Bronze Age.

In comparison to the villages in the northern Jordan Valley, the strikingly different stable isotope signatures from ZAD 1 distinguish intensive crop management with both watering and fertilization, apparently in response to the water-stressed conditions of the Dead Sea Plain. Interestingly, despite being a drought-tolerant taxon, the $\delta^{13}\text{C}$ value for barley provides the most pronounced indication of greater water availability (presumably watered from the spring at 'Ain Dhra') among our sites and their crop taxa. This result most likely reflects enhanced watering, but could also be offset by seasonal planting and cultivation to avoid the hottest months of the year. In contrast to the settlements along the Jordan Rift, *Troullia* has the lowest $\delta^{15}\text{N}$ for both barley and wheat suggesting the least intensive soil fertilization. The more positive values for $\delta^{13}\text{C}$ at *Troullia* also may indicate less human intervention than is seen on the mainland. Our evidence for pulse cultivation is characterized by similarly low $\delta^{15}\text{N}$ values from all four settlements, but clearly more negative $\delta^{13}\text{C}$ from Ni'aj. Our stable isotope data argue for a correlation between more intensive agricultural management and increased environmental stress.

5.3. Animal husbandry, wild animal exploitation and herd management

The faunal evidence from all four settlements accords well with the

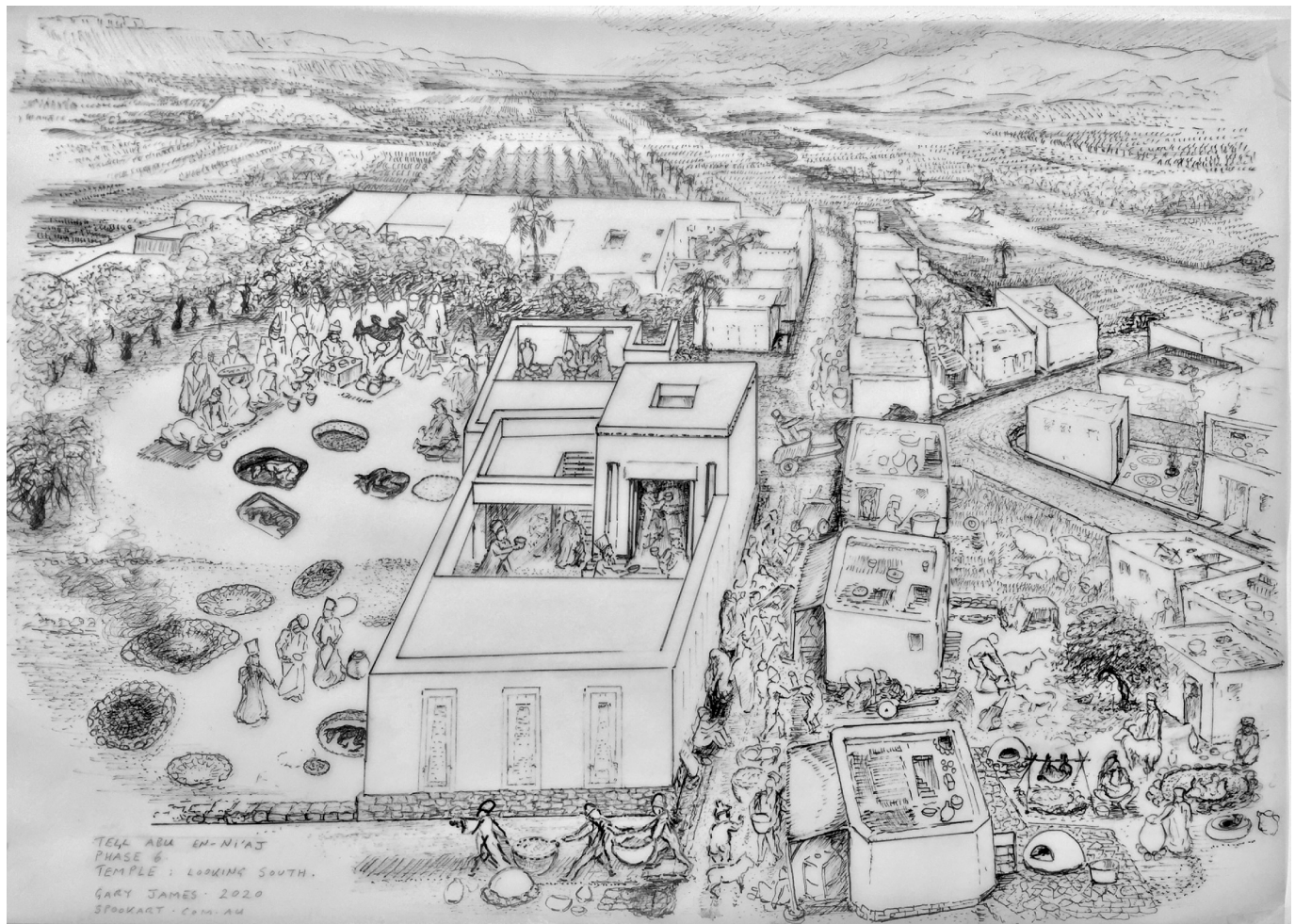


Fig. 9. Artistic illustration of the landscape around the Early Bronze IV village at Tell Abu en-Ni'aj, Jordan. View facing south depicts fields and pastures along the Jordan Rift, which is bounded by the Transjordanian Plateau to the east and the Southern Levantine Central Hills to the west. In the foreground, village houses, sherded streets, a broad room temple, and lamb burials in the temple forecourt are depicted on the basis of remains excavated from Phase 6 (modeled ~ 2483–2452 cal BCE). Artwork by Gary James.

venerable Mediterranean post-Neolithic reliance on sheep and goat husbandry for meat, dairy, and hides, augmented with management of pigs for meat, and cattle for traction. Pigs provide two insights: First, the relatively high frequency of pig bones at Ni'aj reflects the importance of this settlement's proximity to the Jordan River as a needed source for cooling, as well as watering, local swine herds (Allentuck & Rosen 2019). Second, the pig bones from *Troullia* highlight mixed management of domesticated stock (sheep, goats, cattle, and some pigs) with hunting of wild deer and feral swine. However, the most profound distinction among these communities emerges from the abundance of Mesopotamian fallow deer at *Troullia* and the dearth of wild animal bones (< 2 % NISP) at Ni'aj, Hayyat, or ZAD 1. The strikingly numerous deer remains at *Troullia* literally embody the importance of hunting and communal feasting by this community and the abundance of woodland resources available in the uplands of central Cyprus during the Bronze Age. Although wild animal bones are infrequent at Ni'aj and Hayyat, the number of wild taxa increases noticeably through time between these settlements, especially from birds along the Jordan Valley migratory flyway and fish presumably from the Jordan River. This increased taxonomic diversity may provide one of our best gauges of improved climatic conditions between Early Bronze IV and the Middle Bronze Age in the Southern Levant.

5.4. Bone collagen stable isotope analysis

We infer the diets and management of domesticated and wild animals based on stable isotope analysis of bone collagen. Lower values of $\delta^{13}\text{C}$ generally reflect increased water availability (Wallace et al. 2015), and C3 diets generate more negative values (~ -20 to -22 ‰) than C4 diets (~ -14 to -10 ‰) (Kellner & Schoeninger 2007; Lee-Thorp et al. 1989). Herbivores have $\delta^{13}\text{C}$ values about 5 ‰ higher than ingested plants (Koch et al. 1994) in comparison to omnivores and carnivores, whose $\delta^{13}\text{C}$ is about +0–2 ‰ higher than its prey (Bocherens & Drucker 2003). While values of $\delta^{15}\text{N}$ primarily indicate differences in animal diet and trophic level, elevated values also can result from increased aridity (Hartman 2010) or grazing on manured pastures or croplands (Fraser et al. 2011; Fraser et al. 2013; Kanstrup et al. 2012). Herbivores tend to produce $\delta^{15}\text{N}$ values ranging between 2 ‰ and 10 ‰ (e.g., Bocherens 2015), most commonly ~ 5–6 ‰, and an increase of 3–5 ‰ is expected for each step up in trophic level between predator and prey (Bocherens & Drucker 2003; Deniro & Epstein 1981; Schoeninger & Deniro 1984).

The distribution of our bone isotope data reveals multiple clusters indicative of multiple modes of animal management and food consumption. At *Troullia*, goats exhibit a larger range in $\delta^{13}\text{C}$ values than sheep or cattle. This pattern reflects the greater dietary flexibility of goats and suggests that they (and sheep to a lesser extent) were less intensively managed (Pilaar Birch et al. 2022). Three sheep/goat from Hayyat provide typical $\delta^{15}\text{N}$ values for herbivores around 6 ‰,

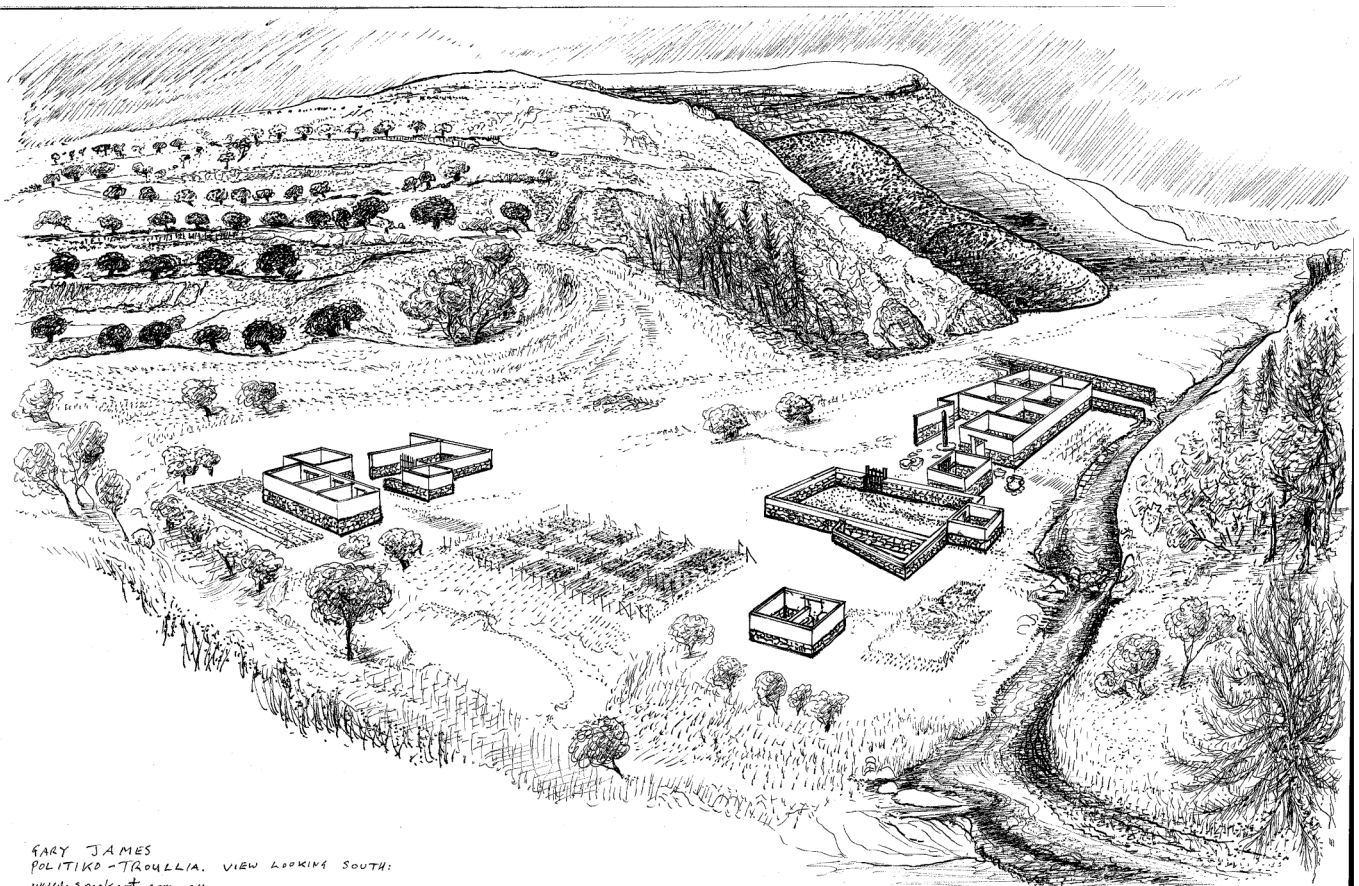


Fig. 10. Artistic illustration of the Bronze Age settlement at Politiko-Troullia, Cyprus and its surrounding landscape, facing southeast. The waters of Kamaras Creek bound the settlement to the west. The Troodos foothills to the right featured pine/oak woodlands and populations of wild Mesopotamian fallow deer (*Dama dama mesopotamica*) and feral pigs (*Sus scrofa*). The slopes of Politiko-Koliokremmos are shown planted with olive trees (*Olea europaea*). Settlement architecture is depicted on the basis of remains excavated from Phases 1a and 1b (modeled ~ 1962–1840 cal BCE), plus a gated stone enclosure inferred from soil resistivity patterning. Settlement structures are shown unroofed to provide clear views of their architectural plans. Artwork by Gary James.

suggesting consumption of wild forage and possibly some cultivated plants. The fourth produced a value of 9‰ $\delta^{15}\text{N}$, possibly due to greater consumption of nitrogen-enriched crops (e.g., wheat or barley, as suggested by the Hayyat seed isotope data). The smaller $\delta^{13}\text{C}$ range of cattle at Troullia suggests grazing on a narrower array of vegetation and the elevated $\delta^{15}\text{N}$ mean for cattle also supports their constrained management, perhaps in self-fertilized pens or with hay from manured fields. Similar stable isotope data for four sheep/goat samples from Hayyat adhere to this pattern of more constrained grazing, in contrast to more free-ranging goats and possibly sheep at Troullia. The sheep bones from Troullia could have included mouflon (*Ovis gmelini ophion*) among the wild animals hunted along with Mesopotamian fallow deer. A single sheep from Ni'aj provides a much less negative, possibly anomalous $\delta^{13}\text{C}$ value, which could reflect much lower water availability in the Levant during Early Bronze IV.

Low $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from fallow deer and pigs at Troullia suggest they foraged in wooded habitats, with little or no grazing in manured fields. Survivorship curves for deer from Troullia (Metzger et al. 2021) indicate hunting of wild individuals, rather than management of a husbanded population. The $\delta^{13}\text{C}$ data suggest that pigs consumed forage, as well as woodland vegetation. Thus, swine exploitation at Troullia combined hunting of local populations with an element of husbandry, possibly in conjunction with other domesticates. A gazelle from Hayyat contributes a $\delta^{15}\text{N}$ ratio very similar to those of the Troullia deer and pigs, and a $\delta^{13}\text{C}$ value within the range bracketed by goats and pigs at Troullia, both of which indicate browsing on wild foodstuffs. Stable isotope data from two steppe buzzards and a wood pigeon from

Hayyat also indicate feeding on wild animals and vegetation, and correspond closely with those for the gazelle from Hayyat and pigs from Troullia (which we interpret to include feral individuals), thereby completing a cluster of stable isotope fingerprints for non-domestic animals. In contrast, a set of five individual carnivores from Troullia (two foxes and an owl) and Hayyat (a fox and a wild cat) are distinguished by $\delta^{15}\text{N}$ values of ~ 9–11‰ commensurate with trophic enrichment of 2–3‰ between prey and predator. Strikingly, three Hayyat quail average ~ 8‰ $\delta^{15}\text{N}$. In conjunction with Hayyat's enriched $\delta^{15}\text{N}$ values for barley and wheat, these granivores may have enjoyed a diet based largely on cultivated cereals, either by taking advantage of fertilized crops or, more intriguingly, as animals kept for their eggs and meat (Baillieu-LeSuer 2013). Stable isotope analysis of wild animals from Ni'aj also includes two omnivorous birds (a coot and a lapwing) that provide extremely elevated values for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ that reflect trophic enrichment.

6. Conclusions

Quantified analyses of plant and animal remains, ranging from charcoal to carbonized seeds to animal bones and teeth, in conjunction with stable isotope analyses of seeds and bone collagen, provide a multifaceted avenue for inferring prehistoric agropastoral practices and anthropogenically driven landscape formation. This comparative study explores the diversity of human created or influenced landscapes that lay at the foundation of Bronze Age agrarian societies in the Eastern Mediterranean and Middle East. Archaeobotanical, faunal and stable

isotope evidence from Ni'aj, Hayyat, ZAD 1, and *Troullia* indicate strategies of intensified cultivation, herding or hunting in response to environmental stress and less intervention under more favorable agropastoral conditions. These differing contexts, and especially variability in agropastoral responses to them, led to the anthropogenic molding of differing Bronze Age agrarian landscapes across the Eastern Mediterranean and Middle East. Levantine landscapes during the waxing and waning of Bronze Age urbanism were distinctly anthropogenic, in which woody taxa commonly were cleared to make way for crops. The landscape around the Early Bronze IV village of Tell Abu en-Ni'aj was based on a mosaic of fields and pastures in the northern Jordan Valley. The occupation of Ni'aj during the arid Early Bronze IV period, plus the animal bone and charcoal evidence reflect the importance of sheep/goat husbandry on a climatically stressed anthropogenic landscape. The nearby Jordan River would have offered riparian woodland resources as well as providing a water source to meet the needs of intensified crop cultivation and management of domestic animals, especially pigs. Nearby Tell el-Hayyat sat amid fertile croplands during the more favorable environmental conditions of the Middle Bronze Age, on a more wooded landscape, with less slightly less reliance on dung fuel than was inferred for Tell Abu en-Ni'aj. Animal bone evidence offers one of the clearest direct indications of climate change, based on the significant increase in the number and diversity of wild taxa, including a wide variety of migratory birds amid the flyway of the Jordan Rift, from Early Bronze IV Tell Abu en-Ni'aj to Middle Bronze Age Tell el-Hayyat. The peripheral settlement of Zahrat adh-Dhra' 1 offers the clearest indications of intensive crop watering and fertilization to compensate for its extremely marginal agrarian setting.

In contrast, the evidence from Politiko-*Troullia* reveals a mosaic of cropland, orchards and woodlands, rather than the agricultural bottom lands along the Jordan Rift. This Cypriot Bronze Age settlement was surrounded by a mixture of fields, woodlands, olive orchards, and vineyards on the adjacent terraced hillsides of Politiko-*Koliokremmos*. The Pediaios River would have provided perennial stream flow bounded by riparian trees, while a spring fed Kamaras Creek, which in turn afforded water for the village well. Farther afield, the Troodos foothills featured oak woodlands and pine forests with populations of wild Mesopotamian fallow deer and feral pigs. Agropastoralism at Politiko-*Troullia* exemplifies a distinctly different mode of anthropogenic adaptation, featuring differing management strategies for sheep, goats and pigs, and intensified horticulture amid the local natural environment, in contrast to the clearance for dedicated croplands on a largely anthropogenic landscape along the Jordan Rift.

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CRedit authorship contribution statement

Patricia L. Fall: Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Steven E. Falconer:** Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Elizabeth Ridder:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Suzanne E. Pilaar Birch:** Investigation. **Mary C. Metzger:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Steven Porson:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jasrep.2025.105119>.

Data availability

Data will be made available on request.

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