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Archaeobotanical proxies and archaeological interpretation: A comparative study of phytoliths, pollen and seeds in dung pellets and refuse deposits at Early Islamic Shivta, Negev, Israel

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ABSTRACT

This article presents a systematic methodological comparison of three archaeobotanical proxies (phytoliths, pollen and seeds) applied to an assemblage of dung pellets and corresponding archaeological refuse deposits from Early Islamic contexts at the site of Shivta. We set out with three main methodological questions: one, to evaluate the relative input of botanical remains from dung in refuse assemblages; two, to evaluate each archaeobotanical dataset and to test whether they are comparable, complementary or contradictory in their interpretations from dung; and three, infer herding practices at the site during the Early Islamic period. Our findings show that ovicaprine dung accumulated in Early Islamic Shivta during at least two periods: mid-7th–mid-8th centuries CE, and late-8th–mid-10th centuries CE. Methodologically, we see incomplete and incompatible reconstructions arise when each method is considered alone, with each proxy possessing its own advantages and limitations. Specifically, the amount of preserved seeds in dung pellets is low, which restricts statistical analysis and tends to emphasize small or hard-coated seeds and vegetation fruiting season; yet this method has the highest taxonomic power; pollen preserves only in uncharred pellets, emphasizes the flowering season and has an intermediate taxonomic value; phytoliths have the lowest taxonomic value yet complete the picture of livestock feeding habits by identifying leaf and stem remains, some from domestic cereals, which went unnoticed in both seed and pollen analyses. The combined archaeobotanical reconstruction from samples of the mid-7th–mid-8th centuries suggests that spring-time herding at Shivta was based on free-grazing of wild vegetation, supplemented by chaff and/or hay from domestic cereals. For the late-8th–mid-10th century samples, phytolith and pollen reconstruction indicates autumn-winter free-grazing with no evidence of foddering. Unlike the dung pellets, macrobotanical remains in the refuse deposits included domestic as well as wild taxa, the former mainly food plants that serve for human consumption. Plant remains in these refuse deposits originate primarily from domestic trash and are only partially composed of dung remains. The significance of this study is not only in its general methodological

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contribution to archaeobotany, but also to lasting discussions regarding the contribution of dung remains to archaeological deposits used for seed, pollen and phytolith analyses. We offer here a strong method for determining whether deposits derive from dung alone, are mixed, or absolutely do not contain dung. This has important ramifications for archaeological interpretation.

1. Introduction

Archaeobotany (also known as paleoethnobotany) provides insights into past human-plant interactions. It addresses topics such as diet, domestication, plant migration and environment over human evolution and history (Marston et al., 2014; Pearsall, 2016). Some of the most common archaeobotanical proxies utilized are seeds, phytoliths and pollen retrieved from excavated sediments at archaeological sites. While archaeological interpretation regarding human-plant interactions can be derived from each proxy, they are rarely used in tandem.

Addressing this issue, we tested whether the data obtained by different archaeobotanical proxies are comparable, complementary or contradictory. The study focused on botanical material retrieved from dung pellets and corresponding archaeological sediments found in refuse middens dated to the Early Islamic period (7th–10th c. CE) at the site of Shivta, Israel. We compared the macrobotanical (charred seeds and other plant material) and microbotanical (phytoliths and pollen) assemblages extracted from dung pellets and their sedimentary contexts. These analyses were complemented by geoarchaeological investigations in order to further understand the nature of the pellets and deposits, specifically the relative proportion of dung remains represented in the trash middens. Dung pellets were also directly radiocarbon dated to provide chronometric control.

1.1. Interpreting archaeobotanical finds

The impetus for this research relates to debates about the use of dung as fuel and its implications for interpreting archaeobotanical assemblages (e.g., Miller, 1984, 1996; Charles, 1998; Reddy, 1999; Sillar, 2000). Miller (1996) argued that charred seeds in Epipaleolithic and Neolithic settlements originated from animal dung fuel, and thus cannot be used for interpretation of human diet. This opinion was challenged by Hillman et al. (1997). However, only a few recent studies attempted to objectively determine if macrobotanical remains originate from dung based on geoarchaeological proxies (Baeten et al., 2018; Smith et al., 2018). Meanwhile, the debate remains largely open (Smith et al., 2018; Spengler, 2018) and most studies of macroscopic archaeobotanical assemblages still implicitly assume that charred seeds are direct indicators of human diet.

A study that combines multiple archaeobotanical proxies, accompanied by a geoarchaeological investigation of associated sediments, can address the disconnect between the archaeobotanical assemblage and its sources of origin. Specifically, a key indicator for dung, fecal (or dung) spherulites (Canti, 1997), is a microremain rarely sought by archaeobotanists, yet crucial for determining if archaeological sediments—and contexts—include or originate from degraded or burnt animal dung (Shahack-Gross, 2011). The combination of techniques we present below allows us to evaluate whether charred seeds obtained by sieving and flotation from refuse deposits excavated at Shivta originate solely from dung or from a mixture of dung and other components. This analytical combination also allows us to identify and evaluate strengths and weaknesses of different archaeobotanical methods as they relate specifically to dung by studying a sample of well-preserved dung pellets. The end result of our study presents a better understanding of livestock management during Early Islamic activity at Shivta and contributes to our understanding of its ancient economy and settlement.

This study addresses the following questions:

a) What is the botanical composition of the dung pellets and how does it reflect herd management, grazing habits and seasonality?
b) What is the botanical composition of the refuse deposits and how does it compare to the botanical composition of the dung pellets?
c) What is the origin of sediments—and in turn, the origin of botanical remains—in the refuse deposits studied; do they reflect dung, ash or mixed sources?
d) What are the methodological and broad archaeological implications of this study?

1.2. The site of Shivta

The village of Shivta (c. 9 ha, WGS84: 34.6307°E, 30.8810°N) is situated along the northern bank of Wadi Zeitan in the arid Negev Highlands, c. 40 km southwest of Beersheba (Fig. 1A–B). Average rainfall is less than 100 mm/year, with wide variation year-to-year (Israel Meteorological Service). The site was established during the Roman period (1st–3rd centuries CE), and reached its zenith during the Byzantine period (5th–6th centuries CE). During the Early Islamic period (7th–10th centuries CE, below) a smaller-scale occupation is evident before total abandonment (Segal, 1983; Hirschfeld, 2003; Tepper et al., 2018).

The rich faunal assemblage recovered during the excavation of multiple Byzantine and Early Islamic contexts reflects the livestock economy of the village, with assemblages dominated by sheep and goat (c.75%; Marom et al. submitted). Pig (3%) and camel (1%) remains were rare, and no cattle or equid remains were found in Early Islamic contexts. Additionally, the areas surrounding the village were extensively cultivated, attested by widespread dams and water channels, cisterns, dovecotes and a dense network of farms with agricultural installations (Kedar, 1957; Evenari et al., 1982; Hirschfeld and Tepper, 2006; Erickson-Gini, 2013; Ramsay et al., 2016; Tepper et al., 2018).

New excavations geared toward bioarchaeological research were conducted by G.B.-O. and Y.T. in 2015–2016 (Tepper et al., 2018). These excavations yielded several dung assemblages, including ovicaprine, equid and camel (identified macroscopically based on their distinctive shapes and sizes). We focus on ovicaprine pellets and associated sediments to learn about the Early Islamic village's livestock management and economy.

1.3. Selection of loci and materials for archaeobotanical analysis

Materials for this study originated from Areas E, K and Q, based

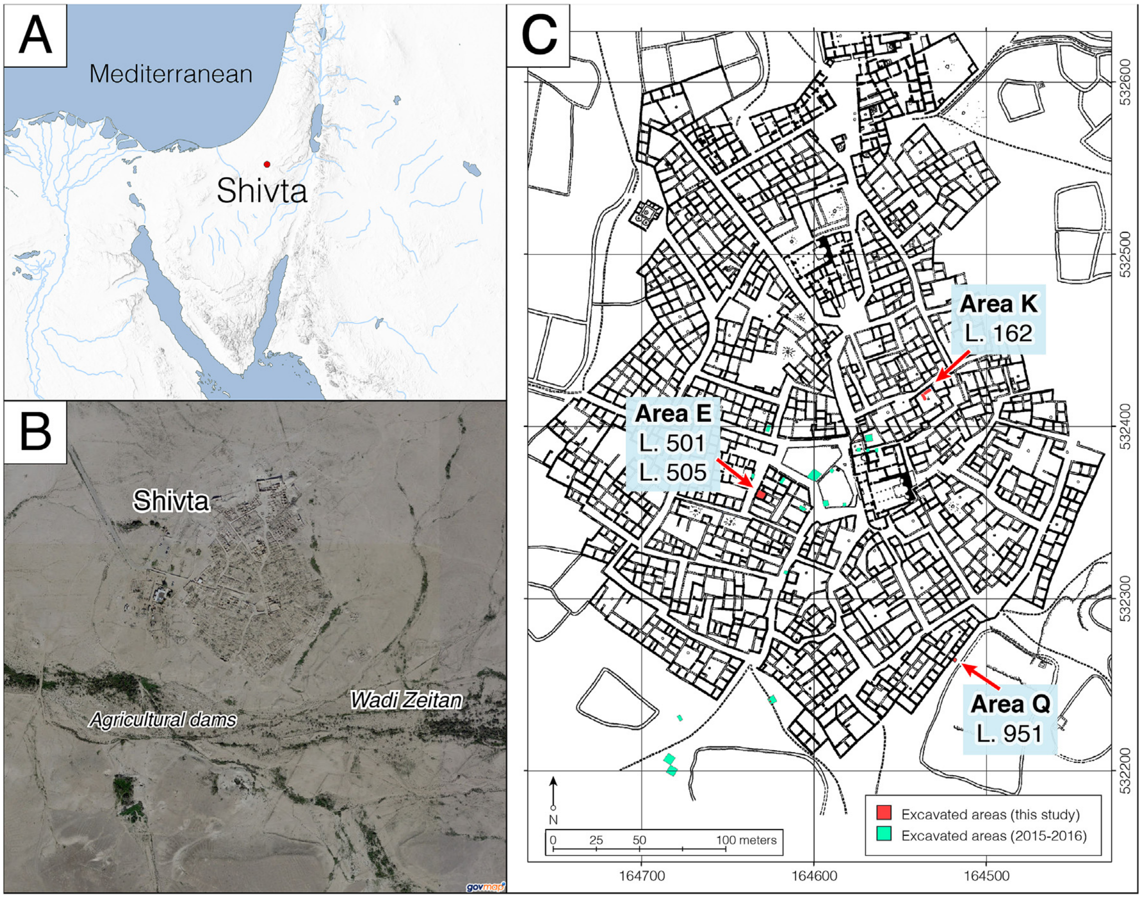

Fig. 1. A) Map of Shivta in relation to the southern Levant. B) Aerial view of Shivta and its immediate vicinity. Note location of Wadi Zeitan to the southeast (image adapted from https://www.govmap.gov.il). C) Site plan of Shivta, with loci reported in this study marked in red (adapted from Hirschfeld, 2003). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

on the quantity of intact dung pellets found during excavation. Areas E and K are located at the center of the site, and Area Q along the site's perimeter (Fig. 1C).

In Area E, dung pellets were collected from superimposed Loci 501 and 505 (Locus 501 overlay 505, separated by stone debris). Both loci were homogenous grey ashy sediment deposits with no internal layering, together approximately 1.0 m thick, which accumulated above the floor of an abandoned Byzantine house (Fig. 2A). Both loci contained Early Islamic pottery. Mainly uncharred and a few charred dung pellets were collected from both contexts. In Area K, Locus 162 consisted of an approximately 1.5 m dark-grey ashy deposit, without internal layering which accumulated on the floor of a different abandoned Byzantine house (Fig. 2B). Locus 162 also contained Early Islamic pottery (mostly cooking pots and jars). Dung pellets, all charred, were collected from its lowest part. Based on the abundance of domestic finds (e.g., pottery, glass, textile, animal bones, wood charcoal and botanical finds) and the ashy nature of the sediments, Loci 501, 505 and 162 were interpreted as domestic trash middens. The homogenous appearance of these deposits indicated rapid accumulation (possibly over a single season or year). There is no evidence that these loci were used as animal pens, nor for *in situ* burning activities.

Locus 951 (Area Q, on the site's perimeter) consisted of a post-Byzantine (based on the ceramic assemblage) yellowish-grey sediment associated with an earlier Byzantine domestic drainage channel (Fig. 2C). It was generally poor in macroarchaeological remains. Mainly uncharred and a few charred dung pellets were recovered from c. 15–20 cm below the modern surface. It may represent short-lived penning of ovicaprines.

1.4. *Livestock management and economy through dung remains*

A key question in this study regards livestock herding and foddering practices. The trash middens of this arid region are characterized by good preservation of organic materials (Fuks et al., 2016), including many charred and uncharred ovicaprine dung pellets which contain macro- and microbotanical remains. Botanical data retrieved from dung pellets can inform on livestock diet, which in turn relates to herd management practices. The botanical composition of dung pellets therefore provides data useful for determining whether animals were free-grazing on wild vegetation only (i.e., a purely pastoral herding strategy) or supplemented with agricultural byproducts (i.e., an agro-pastoral economic strategy). It can also inform on the types of vegetation consumed by animals, which in turn can be used to define the geographical and seasonal ranges of herding practices. Most previous studies addressing these issues through dung deposits relied primarily on the microbotanical record—namely on phytoliths and pollen in degraded dung deposits (Shahack-Gross et al., 2003, 2014; Babenko et al., 2007; Albert et al., 2008; Shahack-Gross and Finkelstein, 2008; Portillo et al., 2014, 2017; Dunseth et al., 2016, 2018; Ben-Yosef et al., 2017). Several studies have also been conducted on the macrobotanical remains in dung (Valamoti and Charles, 2005; Valamoti, 2013; Wallace and Charles, 2013). A few studies have

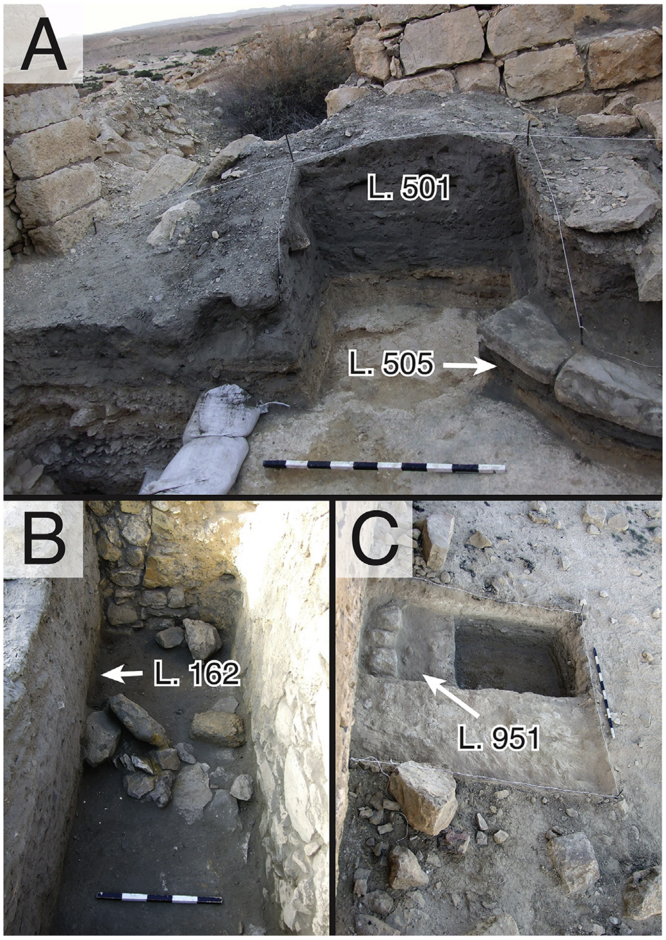

Fig. 2. Field photos of archaeological contexts where dung pellets were sampled. A) Area E, Loci 501 and 505; note superposition among loci. B) Area K, Locus 162; pellets were collected from the bottom of this locus, above the floor. C) Area Q, Locus 951.

combined micro- and macrobotanical methods (Delhon et al., 2008; Bates et al., 2017; Baeten et al., 2018; Smith et al., 2018), but as far as we are aware, none addressed the issue of dung-derived botanical remains by analyzing actual dung pellets with both macro- and microbotanical methods. Here we consider both macro- and microarchaeobotanical evidence of sediments and pellets together, to understand confluences and divergences in these data types, and to maximize what can be learned about human-plant interactions during Late Antiquity in the Negev.

2. Materials and methods

2.1. Collection strategy

Dung pellets were collected by hand and through sieving in the field. Excavated sediments were sieved at three levels of resolution: 1) all sediments were dry-sieved through 5 mm mesh; 2) from each locus approximately 20 L of archaeological sediments were wet-sieved through a 1 mm mesh to retrieve small remains including microfauna (mainly rodents, fish bones and scales), large plant remains and dung pellets; 3) 3-L sediment samples were collected from each locus for flotation and processed on site using a hand-pump system (Shelton and White, 2010).

A total of 52 archaeological ovicaprine dung pellets were selected for archaeobotanical analyses. Charred and uncharred samples were intentionally sampled from each locus except for Locus 162, which only contained charred pellets. As controls, 14 uncharred modern ovicaprine pellets from a single pile were collected from the surface of Wadi Zeitan, in the site's immediate vicinity, in December 2015 (Fig. 1B; Table 1). One dung pellet from each archaeological locus and the modern control were radiocarbon dated. Sediment samples were also collected from the studied loci for geoarchaeological evaluation.

2.2. Laboratory methods

2.2.1. Dung pellet and sediment characterization analyses

Eighteen archaeological dung pellets and three uncharred modern controls (all later used for phytolith analysis) were selected for characterization (Table 1). Both charred ($n = 9$) and uncharred ($n = 9$) archaeological pellets were chosen according to their relative representation in the archaeological assemblage. These were individually photographed, weighed, and c. 1 mg was subsampled from each for mineralogical characterization through Fourier transform infrared (FTIR) spectroscopy (below, Supplementary Table 1). Immediately after, the pellets were re-weighed, lightly homogenized using an agate mortar and pestle, and ashed at 500 °C for 4 h in a laboratory furnace (Thermo Scientific Thermolyne F6000) to remove organic material. After ashing the samples were weighed again to calculate organic matter loss on ignition (LOI). Ashed pellets were left to cool at room temperature over 48 h, after which additional FTIR analyses were carried out. Ashed dung was then used for determination of the concentrations of microremains, including phytoliths (more below) and calcitic microremains, specifically dung spherulites and ash pseudomorphs after calcium oxalate crystals originating from dicotyledonous plant tissues (Canti, 1997, 2003; Shahack-Gross and Ayalon, 2013).

Calcitic microremains were analyzed in two dung pellets from each archaeological context (one charred and one uncharred if possible) and the modern reference, as well as archaeological sediment samples (one from each locus) following the sodium polytungstate method outlined by Gur-Arieh et al. (2013). Calcitic microremains were counted systematically in 16 random fields of view at 400 × in plane-polarized (PPL) and cross-polarized light (XPL) using a Nikon Eclipse 50i POL petrographic microscope. All microremain concentrations are reported in millions per 1 g of ashed dung or sediment. A general error of c. 30% is assumed for all microremain values reported here (Albert and Weiner, 2001; Katz et al., 2010; Gur-Arieh et al., 2013). Statistical analysis (e.g., box-and-whisker graphs) was performed using IBM SPSS 24.

FTIR analysis of all dung pellet subsamples (before and after ashing) and archaeological refuse sediments followed the conventional KBr method (Weiner, 2010 and references therein). Spectra were averaged from 32 scans collected between 4000 and 400 cm^{-1} at 4 cm^{-1} resolution using a Thermo Scientific Nicolet iS5 spectrometer and Omnic 9.3 software. Spectra were compared to the extensive reference libraries of the Kimmel Center for Archaeological Science (Weizmann Institute of Science, http://www.weizmann.ac.il/kimmel-arch/infrared-spectra-library), the Laboratory for Sedimentary Archaeology (University of Haifa) and to published and unpublished experimental data. Mineralogical characterization included determining whether sediments and pellets had been exposed to heat based on the spectral attributes of clay (Berna et al., 2007; Forget et al., 2015). Alterations of the calcite component in samples (Regev et al., 2010) were not determined given the spectral properties of dung-rich sediments (Dunseth and Shahack-Gross, 2018).

2.2.2. Phytolith analysis

Phytoliths were extracted from the ashed dung pellet and sediment samples following the rapid extraction method of Katz

Table 1
Summary of archaeological and control samples utilized in the study. None of the sediment samples showed evidence for burning *in situ*. (+) indicates that the pellets from Locus 162 included four complete and fragments of at least three additional pellets. (*) indicates large 3-L samples. Detailed information can be found in Table 3 and Supplementary Tables 1–3.

		Phytoliths	Pollen	Seeds	Total per context
Controls					
Wadi Zeitan	Uncharred dung pellets	3	1	10	14
	Sediment	2	1	–	3
Archaeological Samples					
L. 505 (Area E)	Charred dung pellets	1	–	–	1
	Uncharred dung pellets	3	2	–	5
	Sediment	1	–	–	1
L. 501 (Area E)	Charred dung pellets	2	–	6	8
	Uncharred dung pellets	2	2	14	18
	Sediment	1	–	1^{*}	2
L. 162 (Area K)	Charred dung pellets	5	1	7+	13
	Sediment	1	1	1^{*}	3
L. 951 (Area Q)	Charred dung pellets	1	–	–	1
	Uncharred dung pellets	4	2	–	6
	Sediment	1	–	–	1
Archaeological Totals					*Arch. Total*
	Charred dung pellets	9	1	13	23
	Uncharred dung pellets	9	6	14	29
	Sediment	4	1	2^{*}	7

et al. (2010). Phytolith concentrations were quantified by systematically counting 16 random fields of view at 200 × using a Nikon Eclipse 50i POL petrographic microscope. All individual phytoliths in multicells were counted to avoid preservation bias. Phytolith morphologies were identified following standard literature (e.g., Twiss et al., 1969; Rapp and Mullholland, 1992; Albert and Weiner, 2001; Piperno, 2006) and a reference collection of Negev plants at the Laboratory for Sedimentary Archaeology (University of Haifa). All morphotype descriptions follow the International Code for Phytolith Nomenclature (ICPN) when possible (Madella et al., 2005). Morphological quantification was determined at 400 × under PPL by identifying at least 200 phytoliths with consistent morphologies (Albert and Weiner, 2001), and greater than 250–300 if possible (Zurro, 2018).

2.2.3. *Pollen analysis*

Ten samples were studied palynologically (Table 1). Seven intact archaeological dung pellets were divided into two: one part for pollen analysis and one for radiocarbon dating (Samples no. 1–7). Except for Sample no. 3 from Locus 162, all samples were uncharred. Materials for the palynological investigation were taken only from the inner part of the dung pellets in order to avoid contamination by external pollen that did not pass through the animal's digestive system. One archaeological sediment sample was also collected from Locus 162 (no. 9). Two samples serve as controls: a modern uncharred dung pellet (no. 8), and a surface sediment sample (no. 10) collected from Wadi Zeitan representing the recent pollen rain in the immediate landscape. Sampling strategies and techniques followed Bryant (1974a, 1974b). Pollen extraction followed the physical-chemical preparation procedure of Stockmarr (1971): one *Lycopodium clavatum* C. Linnaeus tablet (10,679 ± 953 spores in average; Batch Number 3862) was added to each sample in order to calculate pollen concentrations. Samples were immersed in 10% HCl to remove calcium carbonates, and then density separation was carried out using a $ZnBr_2$ solution (with a specific gravity of 1.95 g/ml) together with short sonication to float the organic material. After sieving (150 μm mesh) and short acetolysis, the unstained residues were homogenized and mounted onto microscope slides using glycerin. Pollen grains were identified under a Nikon ECLIPSE E100 light microscope at 200 × , 400 × and 1000 × (oil immersion) to the lowest possible systematic level. For pollen identification, a comparative reference collection of Israeli pollen flora at the Steinhardt Museum of Natural History (Tel Aviv University) was used, in addition to pollen atlases (e.g., Reille, 1995, 1998, 1999; Beug, 2004). Microcharcoal concentrations were quantified on the pollen slides following Finsinger and Tinner (2005).

2.2.4. *Macroremain analysis*

Macrobotanical remains were studied from both intact pellets and corresponding archaeological sediments. Thirty-seven ovicaprine dung pellets, including 10 uncharred modern pellets from Wadi Zeitan, 20 charred and uncharred archaeological pellets from Locus 501, and approximately seven charred archaeological pellets from Locus 162 (four complete and fragments of at least three others), were examined for identifiable plant parts (Table 1, Supplementary Table 2). Each pellet was weighed and dissected separately. In addition, the light fraction of flotation samples was sifted through stacked sieves of 4 mm, 2 mm, 1 mm, 0.5 mm mesh, and examined at each sieve size for identifiable plant parts.

Identification was performed by comparison of morphological characteristics typical to each family, genus and species with samples in the Israel National Collection of Plant Seeds and Fruits (Bar-Ilan University). The Computerized Key of Grass Grains (Kislev et al., 1995, 1997, 1999) was used for grass grain identification. Seed/fruit counts (Supplementary Table 5) were conducted on all specimens representing more than half a seed/fruit. Awn and glume fragments were not quantified, but their presence is noted below (Table 5, Supplementary Table 5). Rachis fragment counts were conducted for sieve sizes larger or equal to 1 mm; for the purposes of this study, each rachis specimen was counted as one, regardless of the number of rachis nodes.

Flowering months by species were obtained from *Flora Palaestina* (Zohary, 1966, 1972; Feinbrun-Dothan, 1978, 1986) and the updated Flora of Israel Online website (http://flora.org.il; Danin and Fragman-Sapir, 2018+). Fruiting season is estimated to be one month later than the flowering season of each species.

2.2.5. Radiocarbon dating

Five dung pellets were radiocarbon dated: one from each archaeological locus, and one modern pellet (RTD-9257). The samples were evaluated using FTIR spectroscopy and stereomicroscopy at the Kimmel Center for Archaeological Science, Weizmann Institute of Science (procedures and instrumentation the same as described in Section 2.2.1) prior to and after Acid-Base-Acid (ABA) chemical pre-treatment protocol for radiocarbon dating (cf. Boaretto et al., 2009). The samples were then measured by Accelerator Mass Spectrometry at the Dangoor Research Accelerator Mass Spectrometer (D-REAMS) at the Weizmann Institute of Science (Regev et al., 2017). All ^{14}C dates were corrected for isotopic fractionation based on the stable carbon isotope ratio ($\delta^{13}C$) in accordance with established international convention (Stuiver and Polach, 1977). Radiocarbon dates were calibrated using OxCal 4.3.2 (Bronk Ramsey, 2009) and the IntCal13 curve (Reimer et al., 2013).

3. Results

3.1. General characterization of dung pellets and associated sediments

Infrared spectra of the modern dung reference show a composition of organic matter, calcite, sodium nitrate (nitratite, $NaNO_3$), quartz and opal (Table 2, Supplementary Table 1). Spectra from the uncharred archaeological dung pellets are generally similar to the modern reference, except for the presence of gypsum in two samples. Charred archaeological dung pellets are composed of charred organic matter, heat-altered clay, calcite, opal, quartz and nitratite. The phosphate mineral carbonated hydroxylapatite is identified in 80% of the charred dung pellets.

3.1.1. Pellet characterization after ashing

Ashing at 500 °C for 4 h removed organic matter, nitratite and structural water from the clay components of all pellets (Table 2, Supplementary Table 1). Ashing also increased the visibility of carbonated hydroxylapatite peaks in the spectra, and the formation of anhydrite in various archaeological samples. Aragonite, which may form after calcite is exposed to temperatures above 600 °C (Toffolo and Boaretto, 2014), appeared in two samples (SHIV-162.2, 501.3). Since aragonite was not observed in the unashed pellets, this suggests that the ignition of organic matter raised the temperature in these samples above the target furnace temperature.

Organic matter content was calculated as a percentage of LOI (500 °C) for 18 archaeological dung pellets and three reference dung pellets (Table 2). Mean LOI for pellets from Loci 951 and 162 are similar and higher than for those from Loci 505 and 501. LOI of the modern dung is significantly higher (84 ± 1%). Charred and uncharred pellets from the same context show little difference (± a few percentage points), suggesting organic matter decayed in all archaeological samples and is not differentiated according to combustion in antiquity (Supplementary Table 1).

3.1.2. Sediment characteristics

The mineralogical composition of sediment samples from the studied loci includes clay, calcite, quartz, opal, gypsum, aragonite, nitratite, carbonated hydroxylapatite, and anhydrite (Table 2). Clay periodically appears as heat-altered. After ashing, the mineralogical compositions largely remain the same. Documented changes include the elimination of organic matter, nitratite and transformation of clay by heat, as well as transformation of gypsum into anhydrite (note though that some anhydrite is original).

Mineralogy, microremain concentrations and organic matter content are compared between the archaeological sediments and dung pellets in Table 2. While the mineralogy of the sediments and dung pellets is quite similar, significantly higher organic matter content, as well as phytolith and dung spherulite concentrations are observed in dung pellets compared to associated sediments. Ash pseudomorph concentrations are slightly higher in the sediments from Loci 501 and 505 relative to the dung pellets. The differences observed indicate that the sediment is composed of dung remains as well as other materials, such as wood/shrub ash, especially in Loci 501 and 505. The immediate implication is that botanical proxies retrieved from the refuse heap sediment originate from dung as well as other materials.

3.1.3. Radiocarbon ages of dung pellets

Infrared spectra produced before and after ABA pretreatment indicate that the modern sample is primarily composed of cellulose. The sample from Locus 162 is charred while the other archaeological samples dated are uncharred.

Table 3 gives the results of radiocarbon dating. All archaeological samples provided enough carbon for radiocarbon determination. However, the calculated efficiency is variable and the carbon

Table 2

Comparison between mineralogy, phytoliths and calcitic microremain concentrations in dung pellets and associated sediments. Microremain concentrations results given as averages in millions per 1 g of sediment or ashed dung with standard deviations. Ca = calcite, Cl = clay (a = altered, ua = unaltered), Org = organics, SN = sodium nitrate (nitratite), O = opal, Q = quartz, Ap = carbonated hydroxylapatite, Ar = aragonite, G = gypsum, An = anhydrite. Note mineralogy is presented from unashed samples. More details available in Supplementary Tables 1 and 3

Context	Type	n	Mineralogy	Organic matter content (LOI %)	Phytoliths (millions/1 g)	Dung Spherulites (millions/1 g)	Ash Pseudomorphs (millions/1 g)
Controls							
Wadi Zeitan	Uncharred dung pellets	3	Ca Cl (ua) Org SN O Q	84 ± 1	71 ± 27	667 ± 73	1.5 ± 0.3
	Sediment	2	Ca Cl (ua) Org Q	7 ± 3	0	0.07 ± 0.03	0
Archaeological Samples							
L. 505	Charred dung pellets	1	Ca Cl (a) Org SN O Q Ap	44	6	92	0.3
	Uncharred dung pellets	3	Ca Cl (ua) Org SN O Q Ap	35 ± 14	19 ± 25	121 ± 40	0.7 ± 0.5
	Sediment	1	Ca Cl (ua) SN Q	15	2	23	1
L. 501	Charred dung pellets	2	Ca Cl (a) Org SN O Q Ap	39 ± 1	13 ± 13	225	0.6
	Uncharred dung pellets	2	Ca Cl (ua) Org SN O Q Ap G	44 ± 3	13 ± 12	334	0.3
	Sediment	1	Ca Cl (a) O Q Ar An	12	9	33	0.9
L. 162	Charred dung pellets	5	Ca Cl (a) Org SN O Q Ap	55 ± 18	44 ± 30	138 ± 100	6.9 ± 8.8
	Sediment	1	Ca Cl (a) SN O Q Ar An	11	10	38	0.8
L. 951	Charred dung pellets	1	Ca Cl (ua?) Org SN O Q	58	8	299	0.3
	Uncharred dung pellets	4	Ca Cl (ua) Org SN O Q	60 ± 6	15 ± 17	290	0.2
	Sediment	1	Ca Cl (ua) SN Q G	7	0.2	2	0.1

Table 3
Radiocarbon and archaeological context data for the dung pellets from Shivta. Laboratory number, Field ID, context and material type are given in the first four columns. Analytical data refer to the percentage of material recovered after pretreatment (Eff. %) and the percentage of carbon in the purified material (C %). Radiocarbon uncalibrated age is given in years BP and the calibrated ranges for the ± 1σ and ± 2σ are given in cal CE (Oxcal 4.3.2, Bronk Ramsey, 2009; Reimer et al., 2013).

Lab #	Field ID	Area Locus Basket	Material Type	Eff. %	C %	^{14}C age (BP)	Calibrated range (cal CE)	
							±1σ (68.2%)	±2σ (95.4%)
RTD-9257	SHV #8	Wadi Zeitan (surface)	modern reference dung pellet	48.8	47.6	Modern	100.7 ± 0.27 pMC	
RTD-9290	SHV #7	Area E L. 501 B. 5099	uncharred archaeological dung pellet	19.1	16.1	1293 ± 30	670 (44.2%) 715 745 (24.0%) 765	660 (95.4%) 770
RTD-9256	SHV #4	Area E L. 505 B. 5113	uncharred archaeological dung pellet	44.5	12.9	1296 ± 23	670 (44.5%) 710 745 (23.7%) 765	665 (62.5%) 725 740 (32.9%) 770
RTD-9255	SHV #3	Area K L. 162 B. 1633	charred archaeological dung pellet	52.6	30.6	1310 ± 24	665 (48.4%) 695 745 (19.8%) 765	660 (69.5%) 720 740 (25.9%) 770
RTD-9289	SHV #2	Area Q L. 951 B. 9507	uncharred archaeological dung pellet	19.8	48.0	1161 ± 22	780 (10.5%) 790 805 (6.0%) 815 825 (10.1%) 840 860 (29.4%) 895 925 (12.2%) 945	775 (77.4%) 900 920 (18.0%) 955

percentage in the archaeological samples is lower than expected in comparison to the modern sample, reflecting not only organic carbon but also clay and quartz that could not be completely removed during pretreatment.

The modern dung sample, RTD-9257 collected in 2015, provided a modern radiocarbon value, 100.7 ± 0.27 pMC. This value is similar to several 2015 measurements of outer tree rings (101–102 pMC; Boaretto, unpublished data).

The calibrated age distribution of all the archaeological dung samples is in the range of the Early Islamic period. Three samples (RTD-9290, RTD-9256 and RTD-9255) cover the last half of the 7th century and first half of the 8th century CE. Sample RTD-9289 is later, dating to the late-8th–mid-10th century CE.

3.2. Phytoliths in dung pellets

3.2.1. Phytolith concentrations and state of preservation

Fig. 3 presents the phytolith concentrations in all dung pellets, ranging from approximately 4–83 million per 1 g of ashed archaeological dung, and 43–98 million per 1 g of ashed modern dung. There is large variability between the individual dung pellets, between all four archaeological loci and the modern reference. Although there is a large variance between the three modern samples, they fall within the ±30% error inherent in phytolith studies (Albert and Weiner, 2001; Katz et al., 2010). Two samples were counted in duplicate, showing an internal error (coefficient of variation) ranging between 15 and 23% (Supplementary Table 3).

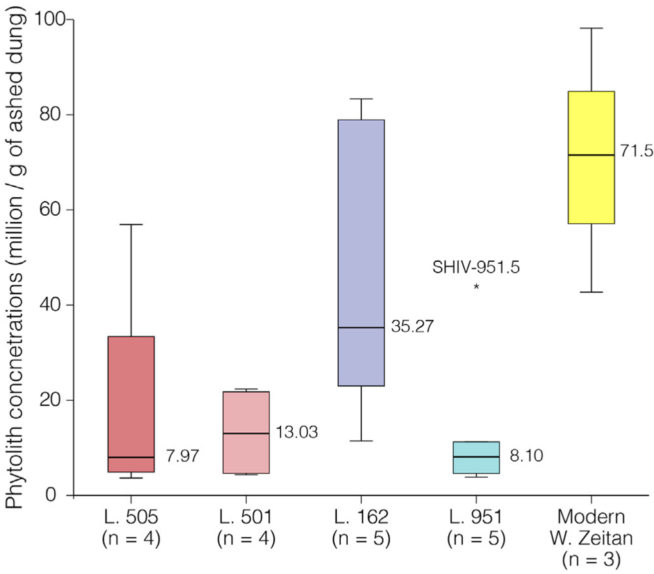

Fig. 3. Boxplot of phytolith concentrations in dung pellets by locus. Note one extreme outlier SHIV-951.5 in Locus 951.

Weathered (yet identifiable) morphologies of phytoliths occur in a range of 3–45% in the archaeological dung (Supplementary Table 3). Weathered phytoliths are slightly pitted; however delicate morphologies (e.g., hairs, dendritic long cells) are preserved in samples from all loci indicating that overall phytolith preservation is good and patterns from relative abundances of phytolith morphologies can be used to infer animal diet (Fig. 4A and B; cf. Cabanes et al., 2011).

3.2.2. Phytolith morphologies: grasses vs. dicotyledonous plants

Phytolith morphologies were analyzed for the 18 archaeological and three modern dung pellets (Fig. 5). The morphological similarities between the modern dung pellets (±1–4% in all groups) suggest they come from a single animal defecation. The high phytolith concentrations and high percentage of grass and inflorescence phytoliths in all three samples (72–77%) collected in December 2015, suggest spring-summer grazing.

Unlike the modern dung pellets, there is substantial variation in the phytolith assemblages of the samples within each archaeological locus. This raises the possibility of different individual animals, species, temporal deposition and/or defecation events. Phytoliths indicative of grasses are predominant in most archaeological samples: Loci 951 (n = 3/5, 60%), 162 (n = 4/5, 80%) and 505 (n = 3/4, 75%). Phytoliths indicative of dicots (leaves and wood/bark) dominated all samples from Locus 501. Note that due to the low concentration of phytoliths in dicots compared to monocots we assume that the actual portion of woody shrubs in the animal's diet is significantly underrepresented (Albert and Weiner, 2001; Tsartsidou et al., 2007).

3.2.3. Dendritic phytoliths as indicators of foddering with cereal byproducts

Research on modern grasses has shown that 8% dendritics are the cut-off between domestic cereals (above 8%) and wild grasses (below 8%) (Albert et al., 2008). Dendritic phytoliths were found in

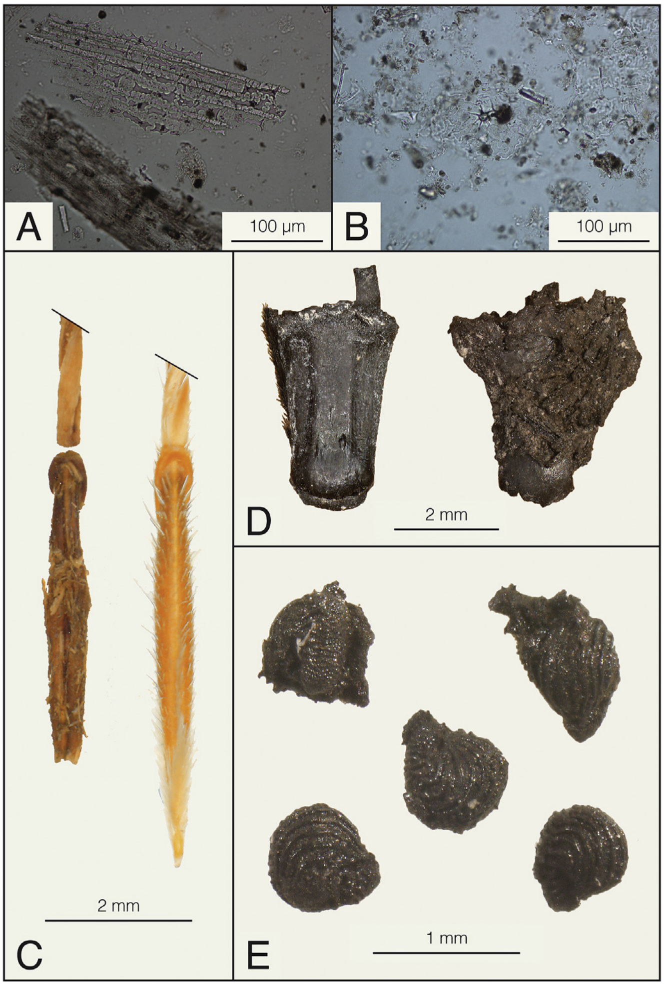

Fig. 4. Examples of archaeobotanical proxies used here. A) Two multicellular phytoliths in anatomical connection from Locus 162, including dendritics from cereal inflorescence. Note good preservation of delicate margins in this sample. B) Jigsaw multicellular phytoliths indicative of dicotyledonous leaves in Locus 951. C) *Stipa capensis* dispersal units, from a modern dung pellet collected near Shivta (Wadi Zeitan) Dec. 2015 (left) and from the Israel National Collection of Seeds and Fruits (Bar-Ilan University), collected near Netiv HaGdud, 4.4.1984 (right). Note the bristles on the latter, which did not survive in the dung pellet. The full length of the awns is not shown, hence the black cutoff lines (top). D) Six-row barley rachis segment (from Locus 501 flotation sample; left), and rachis segment covered in a fibrous matrix characteristic of dung (from Locus 162 flotation sample; right). The latter represents dung-derived plant material in the archaeological sediments. E) Five *Aizoon hispanicum* seeds retrieved from archaeological charred dung pellets, Locus 162. Visible pieces of dung matrix are attached to some of the seeds.

elevated percentages in archaeological samples from Loci 162, 505 and 501 (Fig. 6A). This suggests that, at least, the two samples with the highest percentage of dendritics from Locus 162 are unequivocal indications of animals foddered with cereals, as well as likely one sample each from Loci 505 and 501.

3.2.4. Other diagnostic phytoliths

Hat-shaped Cyperaceae (sedge) phytoliths were identified in 13 of the 18 archaeological samples (1–14% of phytolith morphologies) (Fig. 6B). Spherical echinate phytoliths, common in palm species, were observed occasionally in samples from Loci 951, 505 and 501 (Supplementary Table 3).

3.2.5. Grass leaf/stem to inflorescence ratio

Regev et al. (2015: Supplement 3: Figs. 2 and 3) showed that the leaf/stem to inflorescence phytolith ratios in modern grasses (including cultivated cereals) range between 1.2 and 3.2. Further, they showed that values with ratios >3.2 indicate overrepresentation of leaf/stem material, while values < 1.2 show overrepresentation of inflorescence material. In the dung pellets studied here, most samples were in the range between 1.2 and 3.2, indicating ingestion of whole grasses (Fig. 7). There is a dominance of leaf/stem material in three samples from Locus 951, and one from Locus 501, suggesting either foddering with straw/field stubble, or consumption of grasses in the autumn/winter (when annuals are not in bloom). Inflorescence was strongly overrepresented in three samples from Locus 162 and one from Locus 505.

3.2.6. Grass panicoid/chloridoid to festucoid ratios

Fig. 8A shows the ratios between panicoid and chloridoid short cells (bilobate and polylobate, saddle morphotypes) to festucoid phytoliths (short cell rondels and trapeziform) (cf. Regev et al., 2015: Supplement 3). Most ratios are close to 1, showing a mixture of phytoliths from all three grass families, although several samples from Loci 162, 505 and 501 show much larger ratios, suggesting dominance of panicoid/chloridoid over festucoid species.

Fig. 8B shows the relative percentages of panicoid (bilobate and polylobate), chloridoid (saddles) and festucoid (rondels and trapeziform) short cells separately. Although there are limitations because these short cell morphotypes are not exclusive to each subfamily and are produced in varying concentrations, relative frequencies can give a coarse approximation of grass subfamilies (for a thorough review see recently Esteban, 2016). Approximately half of the archaeological samples (n = 8/18, 44%) and all the reference pellets are dominated by festucoids. Individual samples from Loci 951, 505 and 501 show panicoid grasses dominating, while chloridoids dominate the remaining samples (n = 7/18, c. 39%), notably most samples from Locus 162 (n = 3/5, 60%). The dominance of saddles in these samples may be related to reeds, *Phragmites* sp. (cf. Liu et al., 2013; Ramsey et al., 2016).

Overall, the phytolith assemblages in archaeological dung pellets show variable compositions. The strongest signals suggest (a) an animal diet based on free-grazing of primarily dicotyledonous vegetation, especially in Locus 501; (b) animal diet including fodder of cultivated cereals most pronounced in Locus 162, (c) animal diet including whole grass plants except for in Locus 162, where inflorescence is overrepresented, (d) diet including sedges and possibly reeds, as well as rare consumption of palm leaves.

3.3. Pollen

3.3.1. Pollen from intact dung pellets

The results of the palynological analysis are presented in Table 4. The pollen concentration in the uncharred modern dung pellet is 0.35 million grains in 1 g of pellet material. Concentrations in archaeological pellets are variable, probably reflecting different amounts of the original pollen input as well as of varying ratios of organic and inorganic components in individual pellets (Maher, 1981). This variability does not seem to reflect a preservation bias except for the charred Sample no. 3, which is pollen barren and includes abundant microcharcoal (c. 10 million in 1 g of pellet material), indicating that this dung pellet was burned at temperatures higher than 325 °C (Sengupta, 1975), but lower than c. 450 °C because the pellet did not transform into ash (Shahack-Gross and Ayalon, 2013).

All dung pellet pollen samples are composed only of common wild desert plants. The two uncharred samples collected from Locus 951 (Samples no. 1–2) are characterized by good pollen preservation and high pollen concentrations (c. 15 and 2 million grains

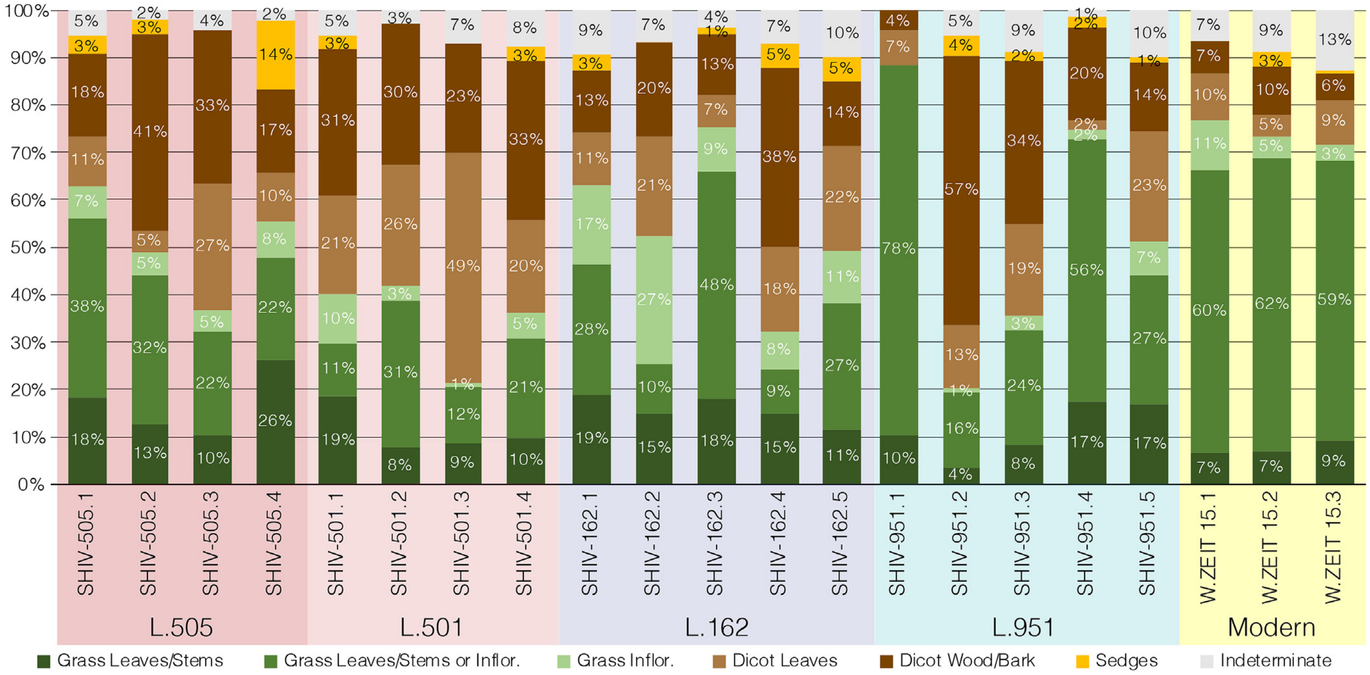

Fig. 5. Phytolith morphologies in percent of assemblage by dung pellet. Note the variability of archaeological dung within and between each locus in comparison to the similarities of modern Wadi Zeitan pellets, likely from same animal and single defecation.

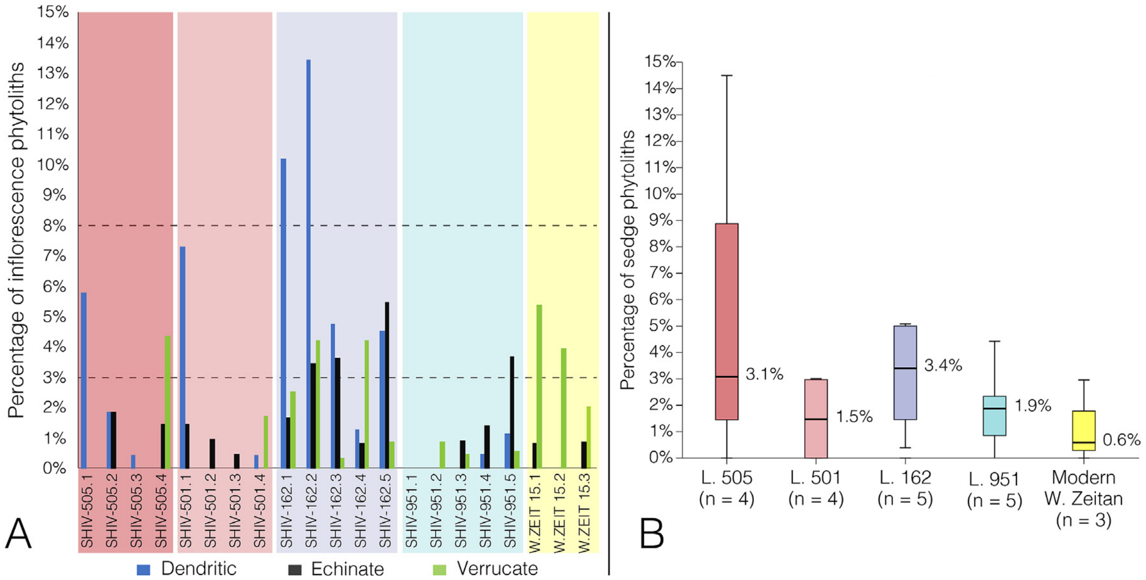

Fig. 6. A) Percentage of inflorescence phytoliths (dendritic, echinate and verrucate) by pellet. Upper dotted line indicates the 8% cutoff of dendritic phytoliths between domestic cereals and wild grasses (Albert et al., 2008). Lower dotted line indicates 3% dendritic phytoliths, which have been reconstructed as indicating some agropastoral foddering with cereal byproducts (Shahack-Gross et al., 2014). B) Boxplot of percentage of sedge phytoliths by locus.

per 1 g of pellet material, respectively). Both samples are dominated by *Artemisia*. This taxon is palynologically indistinguishable to the species level; yet based on present-day vegetation distribution in the study region, the two likely species of *Artemisia* are *A. monosperma* and *A. herba-alba*. Both species bloom during the autumn/early winter (September–December). The presence of pollen grains in clumps (i.e., pollen grains attached to one another in the flower source) in Sample no. 2 suggests that entire inflorescence were eaten. Samples no. 4–7 and the modern pellet (no. 8) are composed of similar palynological spectra. All five samples are dominated by *Atriplex* pollen and/or *Artemisia*. The flowering of the two taxa overlap in autumn/early winter. In the archaeological samples (no. 4–7) the state of preservation is good, species diversity is relatively low and the pollen concentrations are variable (c. 0.04–1.8 million grains in 1 g of pellet material). The slightly higher species diversity characterizing the modern pellet may be related to better preservation. The modern reference dung pellet also included a few clumps of Chenopodiaceae.

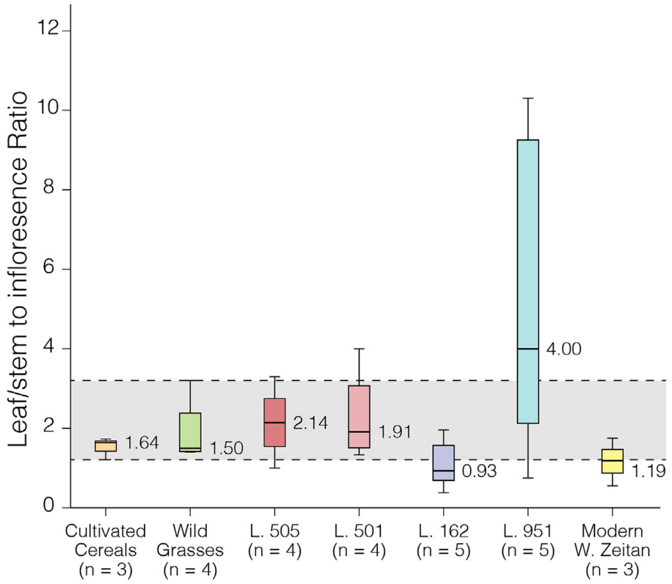

Fig. 7. Boxplots of grass leaf/stem to inflorescence ratios by locus in comparison to modern cultivated and wild grasses. Dotted lines give full range of wild and cultivated grasses. Note that inflorescence is over represented in comparison to leaf/stem phytoliths in pellets from Locus 162 (values below 1.2), while leaf/stem is over represented in half the samples from Locus 951 (values above 3.2). Data from modern cultivated and wild grasses in Regev et al. (2015: Table 1).

3.3.2. Pollen from loose sediment samples

The archaeological sediment sample (no. 9) from Locus 162 is composed of a completely different palynological spectrum in comparison to the dung pellet. It is characterized by the highest species diversity, and taxa unique to this spectrum include *Plantago* (a ruderal plant), *Pinus* (a wind-pollinated tree), *Ephedra* (a common desert element) and Cyperaceae (usually considered a water bank source) and cereal pollen type. This sample is also characterized by low pollen concentrations (c. 10,000 per 1 g of sediment) and microcharcoal (c. 150,000 per 1 g of sediment).

The surface sample (no. 10) from Wadi Zeitan serves as a control, reflecting the recent pollen rain. It includes high values of wind-pollinated trees, such as olive and cypress as well as inedible taxa, and is characterized by the lowest pollen concentrations among all samples (Table 4).

3.4. Macrobotanical remains

Macroscopic analysis yielded thousands of potentially identifiable plant specimens. Most of these derived from the sediment samples, but charred dung pellets proved to be a source of certain types of plant remains. Table 5 summarizes macrobotanical finds identified below the family taxonomic level.

3.4.1. Macrobotanical remains from intact dung pellets

A total 19 taxa were identified in the pellets, most of them to species level: 16 taxa in the uncharred modern pellets, 6 taxa in the charred pellets from Locus 162 and only 1 taxon in a single charred pellet from Locus 501 (Table 5, Supplementary Tables 2, 4, 5). Overlap in flowering season (Fig. 9) indicates that the modern pellets were produced in the month of May (allowing one month from flowering to fruiting; collection date in December 2015). Archaeological pellets from Locus 162 include taxa whose fruiting seasons overlap in the months of April–June (Fig. 9). Except for *Retama raetam*, all identified species in the pellets are low-lying annuals, mostly under 0.5 m tall. All seeds found in the dung pellets were either small (<2 mm) or hard-coated (*Retama raetam* and *Scorpiurus muricatus*). All identified taxa are wild; neither domestic grains nor fragments of cereal chaff (i.e., rachis, glume or awn fragments) were identified in the pellets. These six wild species may be found together in phytogeographic regions of the Negev, the Samarian Desert and the Lower Jordan Valley (Danin, 2004; Danin and Fragman-Sapir, 2018+).

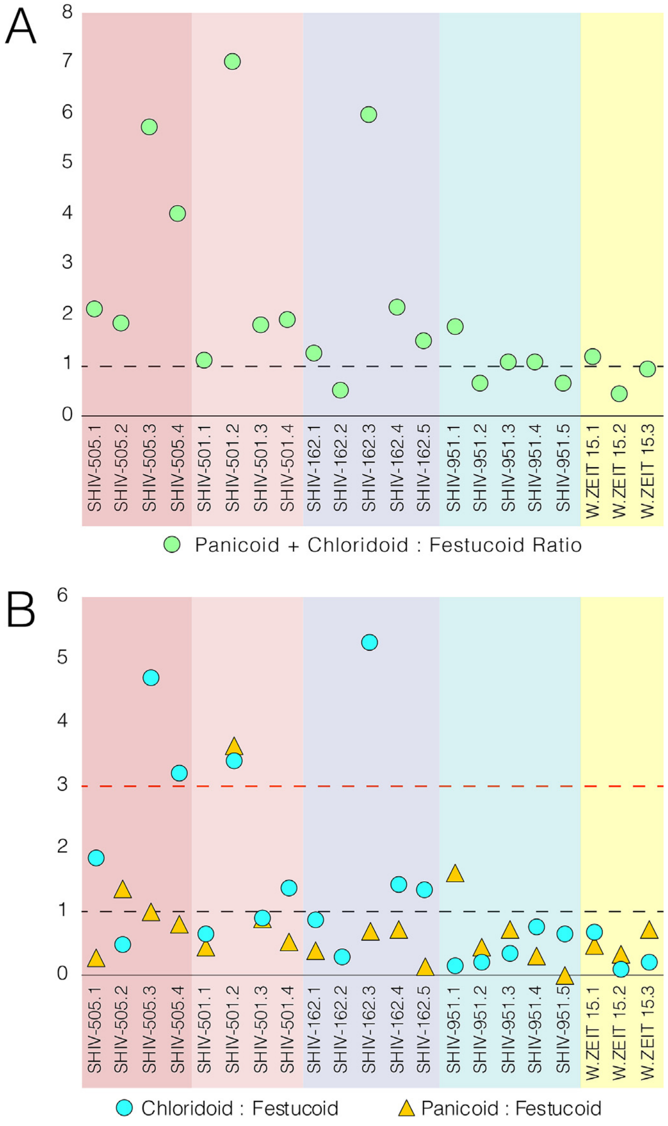

Fig. 8. A) Panicoid + chloridoid (bilobate and polylobate, saddles) to festucoid (short cell rondels and trapeziforms) ratios by dung pellet; combined values of chloridoid + panicoid below 1 shows dominance of C3 festucoid grasses in the animal dung. B) Panicoid (bilobate and polylobate) to festucoid and chloridoid (saddles) to festucoid ratios separately by dung pellet. Red dotted line refers to data in Liu et al. (2013), which shows saddles to rondels + trapeziforms ratios above 3 for modern *Phragmites* (reed) species. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

In the modern Wadi Zeitan pellets, some plant parts other than seeds were identified. Most notably, a *Stipa capensis* dispersal unit (Fig. 4C) was found, which is not considered edible for herbivores when ripe (Hillman et al., 1997: 651–652; Seligman et al., 1959: 156).

One significant difference between plant remains found in the modern pellets and those found in the charred archaeological pellets, is their quantity and quality of preservation (Supplementary Table 5). The modern pellets averaged over 13

Table 4

Pollen and microcharcoal results. (·) indicates no presence. Chenopodiaceae and unidentified clumps: presence of several pollen grains attached together, numbers indicate the number of attached grains. a.b. = absolute number.

Pollen type	Field ID	#1		#2		#3		#4		#5		#6		#7		#8		#9		#10	
	Context	L. 951 B. 9507 uncharred		L. 951 B. 9507 uncharred		L. 162 B. 1633 charred		L. 505 B. 5133 uncharred		L. 505 B.5133 uncharred		L. 501 B. 35099 uncharred		L. 501 B. 35100 uncharred		Zeitan pellet modern control uncharred		L. 162 1 cm above floor archaeological sediment		Wadi Zeitan 5 cm below surface (Sample #51) modern sediment control	
	Common name	a.b.	%	a.b.	%	a.b.	%	a.b.	%	a.b.	%	a.b.	%	a.b.	%	a.b.	%	a.b.	%	a.b.	%
Pinus	pine	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	9	2.8	·	·
Cupressus type	cypress	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	64	25.0
Artemisia	sagebrush	721	99.1	503	97.4	·	·	8	88.9	82	84.6	1	2.9	21	72.4	23	7.8	1	0.3	·	·
Asteraceae Asteroideae type	aster-like	1	0.1	·	·	·	·	·	·	4	4.1	·	·	3	10.3	9	3.1	34	10.4	125	48.6
Asteraceae Cichorioideae type	dandelion-like	·	·	·	·	·	·	·	·	·	·	·	·	·	·	11	3.7	17	5.2	·	·
Atriplex type	saltbush	3	0.4	1	0.2	·	·	·	·	8	8.2	22	62.9	·	·	209	70.8	217	66.8	22	8.6
Plantago	plantains	·	·	·	·	·	·	·	·	·	·	1	2.9	·	·	·	3.4	9	27.7	·	·
Grasses		·	·	·	·	·	·	·	·	·	·	6	17.1	·	·	·	0.7	4	12.3	·	·
Cereal type	cereals	·	·	·	·	·	·	·	·	·	·	·	·	·	·	2	0.7	17	5.2	·	·
Apiaceae	umbels	·	·	9	1.7	·	·	1	11.1	1	1.0	·	·	1	3.4	2	0.7	·	·	1	0.4
Fabaceae	legumes	·	·	·	·	·	·	·	·	·	·	1	2.9	·	·	2	0.7	·	·	·	·
Polygonaceae	knotweed	·	·	1	0.2	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Cistaceae	rockrose	·	·	·	·	·	·	·	·	·	·	1	2.9	·	·	·	·	·	·	·	·
Malvaceae	mallows	·	·	·	·	·	·	·	·	·	·	·	·	·	·	1	0.3	·	·	·	·
Rubiaceae	bedstraw	·	·	·	·	·	·	·	·	·	·	·	·	·	·	3	1.0	·	·	·	·
Brassicaceae	crucifers	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	2	0.8
Caryophyllaceae	pink family	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	3	0.9	·	·
Ephedra	Mormon-tea	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	9	3.5
Daphne type	daphne	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	6	1.8	·	·
Unidentifiable		2	0.2	2	0.4	·	·	·	·	2	2.0	3	8.6	4	13.8	23	7.8	25	7.7	34	13.2
Total pollen counted		**727**	**100**	**516**	**100**	**0**	**100**	**9**	**100**	**97**	**100**	**35**	**100**	**29**	**100**	**295**	**100**	**342**	**100**	**257**	**100**
Chenopodiaceae clump 5		·	·	3	·	·	·	·	·	·	·	·	·	·	·	1	·	·	·	·	·
Chenopodiaceae clump 6		·	·	1	·	·	·	·	·	·	·	·	·	·	·	1	·	·	·	·	·
Chenopodiaceae clump 12		·	·	1	·	·	·	·	·	·	·	·	·	·	·	1	·	·	·	·	·
Chenopodiaceae clump 15		·	·	3	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Chenopodiaceae clump 30		·	·	·	·	·	·	·	·	·	·	·	·	·	·	2	·	·	·	·	·
Unidentified clump 30		·	·	4	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Unidentified clump 15		·	·	1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Cyperaceae	sedges	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	2	·	·	·
Nymphaea	water lily	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	4	·
Spores		·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	393	·	79	·
Lycopodium		4	·	17	·	6	·	16	·	10	·	6	·	18	·	52	·	107	·	835	·
Microcharcoal		·	·	·	·	1002	·	·	·	·	·	·	·	·	·	·	·	4963	·	·	·
Weight (g)		0.11	·	0.11	·	0.15	·	0.12	·	0.05	·	0.05	·	0.05	·	0.15	·	2.8	·	4.50	·
Pollen concentrations (per 1 g of pellet/sediment)		15,283,523		2,552,406		0		43,359		1,794,500		1,079,160		298,055		349,840		10,034		632	
Microcharcoal concentrations (per 1 g of pellet/sediment)		0		0		10,298,333		0		0		0		0		0		153,230		0	

Table 5
Plant list from pellets and archaeological sediment samples; (+) indicates presence, (·) indicates absence, (*) indicates possibly cultivated species. Detailed information and counts of seeds and plant parts by context can be found in Supplementary Table 5.

Taxa	Modern Wadi Zeitan Pellets	L. 162 Pellets	L. 501 Pellets	L. 162 Sediment	L. 501 Sediment
Cereals					
Hordeum vulgare ssp. *distichum/spontaneum*	·	·	·	+	+
Hordeum vulgare ssp. *hexastichum*	·	·	·	+	+
Hordeum vulgare	·	·	·	+	+
cf. *Hordeum vulgare*	·	·	·	·	+
Triticum aestivum s.l.	·	·	·	+	+
Triticum turgidum s.l.	·	·	·	+	+
Triticum sp.	·	·	·	+	+
Triticum/Hordeum	+	·	·	+	+
cf. *Triticum/Hordeum*	+	·	·	+	+
Legumes					
Vicia ervilia	·	·	·	+	+
Lens culinaris	·	·	·	+	+
Fruit					
Ficus carica	·	·	·	+	·
Phoenix dactylifera	·	·	·	+	+
Punica granatum	·	·	·	+	·
Vitis vinifera	·	·	·	+	+
Wild/weed taxa					
Adonis dentata	·	·	·	+	+
Aizoon hispanicum	+	+	·	+	+
Anagallis arvensis	·	+	·	+	+
Andrachne telephioides	·	·	·	+	·
Anthemis pseudocotula	+	·	·	·	+
Anthemis sp.	·	·	·	+	·
Arnebia decumbens	·	·	·	+	+
Asphodelus tenuifolius/fistulosus	·	·	·	+	+
Astragalus callichrous	+	·	·	·	·
Astragalus hamosus/arpilobus	·	·	·	·	+
Astragalus tribuloides/asterias	+	·	·	·	·
Astragalus sp.	·	·	·	·	+
Astragalus/Trigonella	·	·	·	·	+
Avena barbata	·	·	·	·	+
Avena barbata/fatua	·	·	·	+	·
Avena sterilis	·	·	·	+	+
Avena sp.	·	·	·	+	+
Bassia muricata	·	·	·	+	·
Bellevalia sp.	·	·	·	+	·
Brachypodium distachyon	·	·	·	+	+
Bromus type	·	·	·	·	+
Buglossoides tenuiflora	·	·	·	·	+
Calendula sp.	·	·	·	+	+
Caylusea hexagyna	·	·	·	+	+
Centaurea pallescens	+	·	·	·	·
Chenopodium murale	+	·	·	+	·
cf. *Chenopodium murale*	·	·	·	+	·
Cutandia memphitica/dichotoma	·	·	·	·	+
Cynareae	·	·	·	+	·
Cynodon dactylon	+	+	+	+	+
Echium angustifolium	·	·	·	·	+
Emex spinosa	·	·	·	+	+
Erucaria microcarpa	·	·	·	·	+
Erucaria sp.	·	·	·	·	+
Fumaria parviflora	·	·	·	·	+
Fumaria parviflora/densiflora	·	·	·	+	+
Galium aparine	·	·	·	+	·
Galium/Asperula	·	·	·	·	+
Glebionis coronaria	·	·	·	+	·
Gypsophila capillaris	·	·	·	+	·
Hordeum glaucum	·	·	·	·	+
Hordeum glaucum/marinum	·	·	·	·	+
Hordeum marinum/geniculatum	·	·	·	·	+
Lolium rigidum	·	·	·	·	+
Lolium rigidum/perenne	·	·	·	+	+
Lolium temulentum	·	·	·	·	+
Lolium sp.	·	·	·	·	+
Malva aegyptia	·	+	·	·	·
Malva parviflora	·	·	·	+	·
Malva parviflora/oxyloba	·	·	·	+	+
Malva sp.	+	·	·	·	+

(*continued on next page*)

Table 5 (*continued*)

Taxa	Modern Wadi Zeitan Pellets	L. 162 Pellets	L. 501 Pellets	L. 162 Sediment	L. 501 Sediment
Medicago astroites	·	·	·	+	+
Medicago polymorpha/marina	·	·	·	+	+
Melilotus sulcatus	·	·	·	+	·
Mesembryanthemum nodiflorum	·	·	·	·	+
Neslia apiculata	·	·	·	+	·
Papaver sp.	·	·	·	·	+
Phalaris minor	·	·	·	+	+
Phalaris paradoxa	·	·	·	+	+
Plantago chamaepsyllium/notata	·	·	·	+	+
Plantago ovata	+	·	·	+	·
Plantago sp.	+	·	·	+	·
Pulicaria incisa	·	+	·	·	·
Retama raetam	+	·	·	·	·
Rumex sp.	·	·	·	+	·
Salsoleae	+	·	·	+	+
Schismus arabicus/barbatus	+	·	·	·	·
Scorpiurus muricatus	+	·	·	·	+
Silene colorata/decipiens	·	·	·	+	+
Silene sp.	·	·	·	+	·
Spergula fallax	·	·	·	+	·
Stipa capensis	+	·	·	·	·
Tamarix aphylla	·	·	·	+	+
Tamarix nilotica s.l.	·	·	·	+	·
Thymelaea hirsuta	·	·	·	+	+
cf. *Trifolium campestre*	·	+	·	+	+
cf. *Trifolium tomentosum*	+	·	·	·	·
Trifolium sp.	·	·	·	+	+
cf. *Trifolium*	·	·	·	·	+
Trigonella arabica	·	·	·	·	+
*Trigonella foenum-graecum/berythea**	·	·	·	+	·
Vaccaria hispanica	·	·	·	·	+
cf. *Vaccaria hispanica*	·	·	·	+	·
Vicia sativa	·	·	·	·	+
cf. *Vicia sativa*	·	·	·	+	·
*Vicia/Lathyrus**	·	·	·	+	+

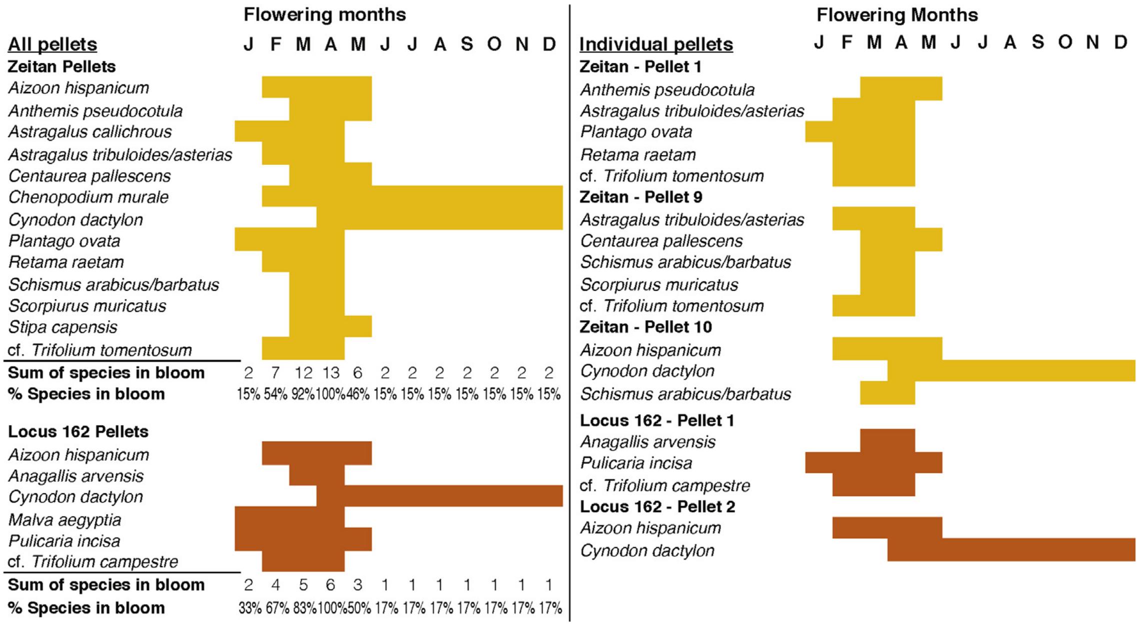

Fig. 9. Flowering months of species identified in modern and archaeological ovicaprine dung pellets (left) and selected individual pellets (right). Given estimated fruiting season one month later than the flowering season of each species, overlap of all flowering seasons in March–April suggests April–June grazing, allowing for some retention of ripe fruit/seeds on the mother plant before dispersal.

identified plant specimens per pellet, compared to less than 3 identified plant specimens per charred pellet from Locus 162. The uncharred archaeological pellets exhibited even poorer preservation. These observations suggest that seed preservation may have been affected post-depositionally, probably by bacterial activity, even under the arid conditions at the site.

3.4.2. *Macrobotanical remains from sediment samples*

The corresponding archaeological sediment samples from Loci 501 and 162 produced very rich macrobotanical assemblages, almost entirely preserved by carbonization. Each 3-L sample contained thousands of identifiable plant parts, representing approximately 50 taxa each, and some 70 distinct taxa in total (Table 5, Supplementary Tables 2, 4 and 5).

Numerically, cereal grains and chaff dominate the assemblage of plant remains in the sediment samples. Seeds originate from tetraploid (*Triticum turgidum* s.l.) and hexaploid wheat (*Triticum aestivum* s.l.) as well as six-row barley (*Hordeum vulgare* ssp. *hexastichum*) and two-row cultivated or wild barley (*Hordeum vulgare* ssp. *distichum/spontaneum*). Counts of cereal plant parts include 189 rachis segments, 89 grains, 35 culm nodes and 13 root fragments from Locus 162, and 216 rachis fragments, 135 grains, 53 culm nodes, and 8 root fragments from Locus 501. Overall, cereal plant parts exhibit excellent preservation, but a few isolated rachis segments and seeds are covered by a fibrous matrix typical of the charred dung pellets (Fig. 4D–E; Supplemental Table 5). Other domesticated species whose seeds were identified in both loci include: lentil (*Lens culinaris*), bitter vetch (*Vicia ervilia*), grape (*Vitis vinifera*), and date (*Phoenix dactylifera*). Locus 162 also contained fig (*Ficus carica*) nutlets and pomegranate (*Punica granatum*) seeds.

Although most species were identified by their seeds and fruits in the strict sense, a variety of plant parts is evident. Among the grasses, in addition to those organs mentioned above, florets, spikelets (*Cynodon doactylon*, *Avena sterilis*, *Phalaris paradoxa*), as well as numerous glume, awn, and culm internode fragments were identified. Grape skins and pedicels, lentil pod pedicels, and pomegranate rind were also found. Other plant parts identified include a *Thymelaea hirsuta* flower, a *Bassia muricata* perianth, a *Malva parviflora* receptacle, an *Anthemis pseudocotula* head, pods or siliqua (*Erucaria microcarpa*, *Melilotus sulcatus*, *Neslia apiculata*) and various stem segments and leaves (*Tamarix aphylla*, *Tamarix nilotica* s.l., *Thymelaea hirsuta,* Salsoleae).

In terms of species richness, wild annuals dominate the assemblages. Significantly, spring is the flowering season for all identified annual species from both assemblages. The flowering months of all 25 annuals identified in Locus 162 overlap in March–April, while the flowering months of all 27 annuals identified in Locus 501 overlap in April alone (Fig. 10). Grass and legume families (Poaceae and Fabaceae) are represented by the greatest number of species in these assemblages, among a total 25 plant families.

The assemblage is also diverse in habitat, including domestic, wild and weed species. Although most of the identified species have a wide geographical distribution, the combination of *Medicago astroites*, *Melilotus sulcatus* and *Tamarix aphylla* found in Locus 162 is unique to the vegetation of the Negev Highlands. Typical weed species found in the sediment samples include *Lolium temulentum, Phalaris paradoxa, Neslia apiculata* and *Vaccaria hispanica* (Zohary, 1950; Danin and Fragman-Sapir, 2018+).

4. Discussion

4.1. *Botanical reconstruction from each method*

For comparison, a discussion of each of the three methods is described below to show the similarities and differences between the interpretation resulting from each archaeobotanical proxy.

4.1.1. *Phytoliths as indicators of animal diet*

The phytolith assemblage represents a diet based on the exploitation of the immediate landscape. Phytoliths indicative of grasses dominate all dung pellet samples, except for Locus 505, which is dominated by a higher woody dicot component. This could be attributed to species differentiation, since goats more readily consume trees and shrubs than sheep (Wahed and Owen, 1986; Ngwa et al., 2000; Sanon et al., 2007). However, recent studies of traditional free-ranging sheep and goats in the Negev reveal little difference in diet selection and foraging behavior (Kam et al., 2012), i.e., sheep will also consume shrub vegetation based on forage availability. Therefore, the composition found in dung pellets in this environment cannot easily differentiate between sheep and goat.

The assemblage from Locus 505 is reminiscent of degraded dung sediments identified at earlier sites (Early–Intermediate Bronze Age: Nahal Boqer 66, Dunseth et al., 2018; Iron Age: Atar Haroa, Shahack-Gross et al., 2014: Table 4) and premodern sites (Umm Sarbut, Shahack-Gross et al., 2014: Table 4). Excluding sample SHIV-505.1, with high concentrations of dendritic phytoliths, these appear to reflect purely pastoral nomadic activities where ovicaprines feed on the local phytolith-poor shrub vegetation (Shahack-Gross and Finkelstein, 2008).

In general, the dominance of grasses in the other archaeological pellets follows patterns noted in degraded dung sediments from the Late Byzantine/Early Islamic site Wadi el-Mustayer (Shahack-Gross et al., 2014: Table 4). In some samples (those dominated by verrucate or echinate inflorescence phytoliths), this might reflect a seasonal component, as seen in the spring-summer-grazed modern reference pellets from Wadi Zeitan. The high percentage of dendritic phytoliths in the archaeological pellets from Loci 162, 505 and 501 show clear evidence for either foddering with hay (i.e., whole plants including inflorescence and grains) or cereal byproducts (i.e., chaff). In the pellets from Locus 162, the leaf/stem to inflorescence ratios below 1.2 indicate this is selective foddering with threshing byproducts (chaff), and not straw or stubble on the fields after harvest. The high leaf/stem ratios, low phytolith concentrations and low inflorescence percentages in Locus 951 most likely suggest grazing in autumn/winter, or the foddering with field stubble or straw.

4.1.2. *Pollen grains as indicators of animal diet*

The palynological assemblages in dung pellets include edible taxa only, while pollen from sediments includes both edible and inedible taxa (the latter include *Pinus* and *Cupressus* which are generally considered inedible to ruminants). The pollen spectra from dung pellets represent a diet based on animal foraging of wild vegetation typical to the arid region, probably within the immediate vicinity of Shivta. In terms of seasonality, the well-preserved pollen assemblage supports the identification of autumn/early winter grazing in Locus 951, and to a lesser extent in the pellets from Loci 501, 505 and 162. The palynological spectrum identified in the loose sediment sample from Locus 162 is distinguished from the pellet samples by its higher species diversity, not unexpected in refuse deposits as described in Section 3.1.2. The sediment from Locus 162 also contains cereal pollen.

4.1.3. *Macrobotanical remains as indicators of animal diet*

Taxa common to both the pellet and sediment samples include *Cynodon dactylon*, *Aizoon hispanicum*, *Anagallis arvensis*, cf. *Trifolium campestre*, and stem segments of local desert plants in the Salsoleae tribe of Chenopods. Two species, *Pulicaria incisa* and *Malva aegyptia*, were identified in archaeological dung pellets but not in the

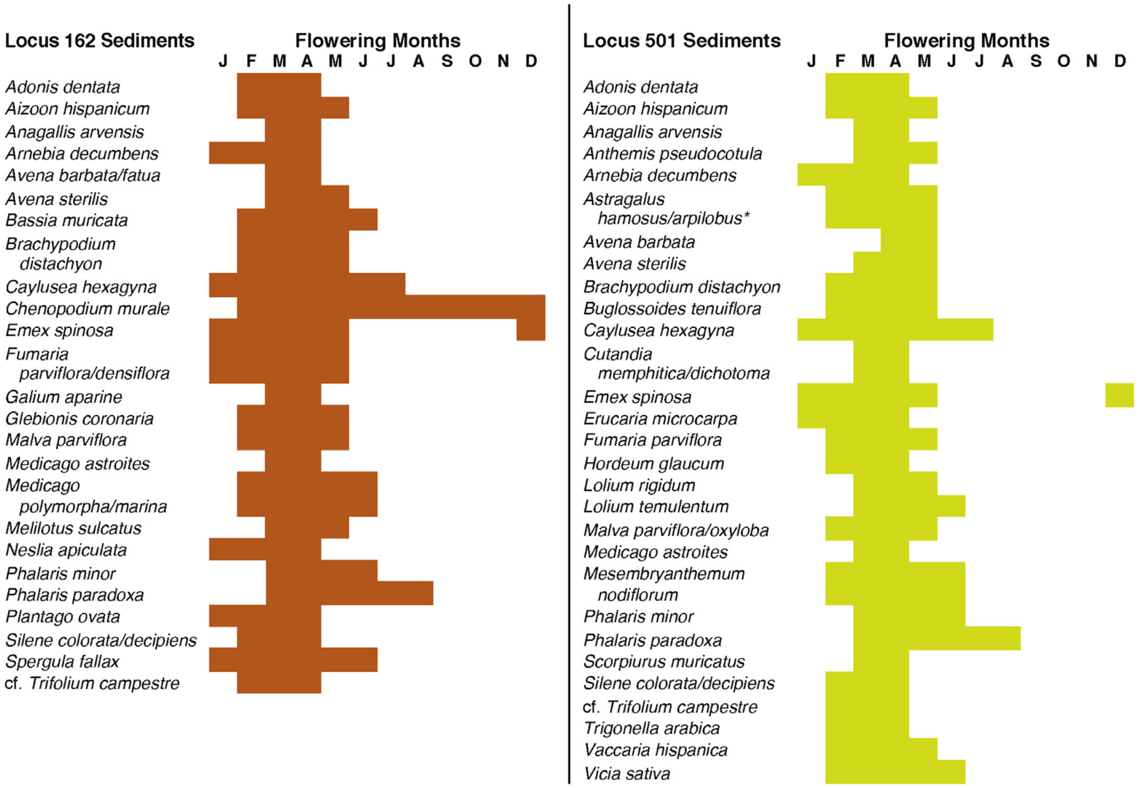

Fig. 10. Flowering months of species identified in archaeological sediments: Locus 162 (left) and Locus 501 (right). Given estimated fruiting season one month later than the flowering season of each species, overlap of all samples in March–April suggests April–June activity, allowing for some retention of ripe fruits/seeds on the mother plant before dispersal.

corresponding archaeological sediments. No definite cultivated species were found in the archaeological pellets, although in the sediments several rachis fragments were found with a characteristic fibrous matrix typical of dung attached. Hence, this absence should not be taken as evidence for the absence of foddering. Counts of macroscopic plant remains per pellet (see above and Supplementary Table 5) suggest that while charring was essential for preserving macrobotanical remains in dung, it also negatively affected their preservation. It follows that macroremains in dung pellets can only reconstruct a partial picture of animal diet.

Despite this limitation, the highly local geographic distribution and April–June fruiting season of the six wild species found in the archaeological dung pellets suggest essentially local springtime grazing/foraging. Interestingly, the macrobotanical remains from the sediments complement this picture with partial evidence for foddering.

4.1.4. Macrobotanical remains from sediments

The macroscopic plant remains—all charred—identified in the sediment samples are distinguished from those of the pellet samples by their diversity of species and plant organs (Table 5). The plant remains from the sediment samples, almost all carbonized, include the full range of agricultural products and byproducts, as well as wild species. In each 3-L sediment sample we identified some 50 taxa (to genus or species), amounting to approximately 800 identified specimens from some 1000 plant remain specimens (Supplementary Table 5).

Among cereal plant parts, prime grains (i.e., large cereal grains) are underrepresented. In Locus 162 and especially in Locus 501, many of the wheat grains are extremely small, likely representing “tail grains”, a byproduct of grain sifting following threshing (Hillman, 1984). Furthermore, the ratio of rachis segments to grains in Locus 162 is over 2:1, while the same ratio “on the stalk” would have been less than 1:2 for most cereal specimens identified. This suggests that these cereal finds are byproducts of post-harvest grain processing. In Locus 501, the same is true for the wheat (*Triticum* sp.) rachis/grain ratios (approx. 2:1), but not for barley (*Hordeum vulgare*) in which the ratios are reversed (nearly 1:2). Hence while the wheat remains apparently derive from post-harvest processing, the barley finds seem to represent unprocessed spikes. The difference in size between the barley and wheat grains supports this interpretation, which in turn strengthens the link between the archaeobotanical remains with foddering and herding practices. In Roman Palestine, as in other places, barley was considered better for fodder than for food (Safrai, 1994: 108-109).

The presence of possible dung-derived cereal rachis fragments (Fig. 4D) in the sediment samples may also be an indication of foddering. However, these are not only very poorly preserved, but also a very small minority of rachis fragments found. Despite the possible linkage between the various cereal part finds and foddering, dung and dung-derived plant remains still comprise only a subset of the macrobotanical finds in the sediment samples.

4.2. Combined botanical reconstruction

4.2.1. Reconstruction of foraging range

The wild taxa identified by all three methods indicate that the wild vegetation consumed by livestock is local to the region. Experimental and ethnographic information concerning desert-adapted ovicaprines (e.g., black Bedouin goats) can constrain the reconstructed limits of foraging-distances. The distance traveled by livestock can be estimated as a simple function of maximum distance traveled per day multiplied by total retention time (i.e., the time it takes for food to travel through an animal's digestive system). Ethnographic studies show variable distances for the foraging activities of herding ovicaprines. Modern GPS studies from the Negev with Bedouin herds average 5.46 ± 1.35 h of travel time and 5.3 ± 1.4 km per day (Arnon et al., 2011: Table 1). However, significantly longer grazing itineraries have been reported, especially in older ethnographic work: 10–11 h for Bedouin in Lebanon in the 1960s–1970s (Bhattacharya and Harb, 1973: Table 1); more recently, 9–10 h and 15–20 km per day for goatherds in Oman (Schlect et al., 2009: Table 6).

The total mean retention time of particulate matter in ovicaprine digestive systems (based on controlled feeding studies) varies considerably given different breeds and species (Silanikove et al., 1993: Table 1; Tsiplakou et al., 2011), fodder (Tisserand et al., 1991: Table 3; Coleman et al., 2003; Morand-Fehr, 2005: 28 and references therein) and watering regimens (Brosh et al., 1988; Misra and Khub, 2002). Desert-adapted breeds tend to have longer retention times in order to maximize food and water utilization from low-quality forage (Silianikove, 2000). For this study, we use an estimate based on data from local black Bedouin goats, which average 56.4 ± 1.5 h when fed a nutrient-poor mix of 90% Rhodes grass (*Chloris gayana*) and 10% alfalfa (*Medicago sativa*) (Silanikove et al., 1993: Table 1).

Based on the information above, we can reconstruct a maximum of 2.3 days of travel between ingestion and defecation at Shivta (digestion = 56.4 h/24 h = ~2.3 days) and a maximum range of 15–20 km per day. This equals approximately 35–47 km maximum transport distance of pollen, phytoliths and seeds from the original food source for unidirectional foraging, or half this range (~17–28 km) if animals were based in Shivta and returned to the site each night (Fig. 11). Theoretically, the presence of reed and sedge phytoliths could be used to constrain foraging-distances further, as they are generally known to grow near water sources (springs, wadis) or catchments (pools, cisterns, reservoirs in the winter). Sedge and reed phytoliths are also commonly used as evidence for increased water availability in paleoenvironmental studies (e.g., Ramsey et al., 2016). However, desert sedges are common in the Negev, Sinai and Jordan (e.g., *Carex pachystylis*, among others), so utilizing sedge phytoliths (or pollen) as a geographical limiter—or a paleoenvironmental proxy—in arid environments is problematic. Regardless, based on our model it is conceivable that semi-sedentary livestock raised at Shivta may have 'sampled' other phytogeographic zones such as the Western and Northern Negev. These neighboring regions have vegetation quite similar to that of the Negev Highlands (Danin, 2004).

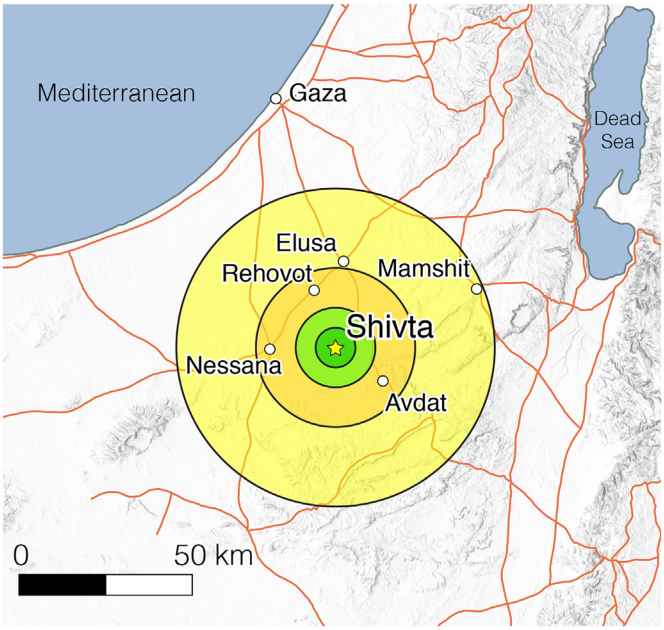

Fig. 11. Reconstructed foraging ranges of ovicaprine herds at Early Islamic Shivta. Minimum (green) and maximum (yellow) foraging-distances based on Arnon et al. (2011) and Schlect et al. (2009) respectively. Additional divisions show minimum and maximum limits if animals are based at Shivta, rather than directional excursions. Note that the maximum range includes all the important Negev sites during the Early Islamic period. Road networks (in red) from Ancient World Mapping Center (http://awmc.unc.edu/wordpress/map-files/). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.2.2. Foddering with agricultural byproducts

Only the phytolith data from the dung pellets provides direct evidence for foddering of livestock using straw, hay or byproducts of domestic cereals. This is indirectly supported by a few carbonized cereal rachis segments and seeds covered in a fibrous matrix indicative of dung, retrieved by flotation of archaeological sediments (Fig. 4D). Given the springtime season identified in the macrobotanical records, it is likely that the fodder was composed of waste from post-harvest processing (most clearly seen in Locus 162).

4.3. Methodological considerations

4.3.1. Preservation of dung pellet contents

Phytolith assemblages appear to be well-preserved in charred and uncharred pellets, as well as in the archaeological sediments. Pollen assemblages were well-preserved in the uncharred pellets, archaeological sediment and modern control sediment but absent in charred pellets. Macrobotanical assemblages were well-preserved in both modern and charred archaeological pellets, but not in uncharred archaeological pellets, which also included white mold. Poor preservation of macrobotanical remains in these pellets might result from consumption of seeds by microbial activity, which might also explain their lower weight (Supplementary Table 2).

Previous studies demonstrated that small, hard-coated seeds are more likely to survive ruminant digestive tracts than large softer-coated seeds (see review in Wallace and Charles, 2013: Table 1). This conclusion is supported by our study; the only large seeds found in the dung pellets were of *Retama raetam* and *Scorpiurus muricatus*, uniquely hard-coated seeds.

The taphonomic differences between the botanical proxies may explain discrepancies between reconstructed animal diet from dung pellet contents. Macrobotanical and pollen analyses did not identify cereals as part of the livestock diet, while phytolith analysis shows cereal chaff (and possibly hay) as a major component in the animal diet. We infer that cereal grains and chaff did not generally preserve in the pellets, while phytoliths typical of these plant parts did survive. Phytolith analysis also revealed that water-dependent plants (reeds, sedges) were probably part of the livestock diet, a component not identified by pollen or macrobotany analyses.

Overall, preservation of each botanical proxy differs within the same source material, with opaline phytoliths (an inorganic substance) having the best preservation potential.

4.3.2. Seasonality based on dung pellet contents

Seasonality is another issue that displays apparent discrepancies among the three methods. Our working assumption is that pellets from the same locus were deposited during the same season, given the rapid accumulation of the Early Islamic middens and the high resolution of locus differentiation. The seeds from the archaeological pellets from Locus 162 (B. 1634) and the modern samples demonstrates the validity of this assumption (Fig. 9).

The dominance of *Artemisia* in the well-preserved pollen spectra of Locus 951 suggests autumn-winter grazing based on the flowering season of *Artemisia* species, which flower in the study region from September–December (*A. monosperma* and *A. herba-alba*). In this case we do not have comparable macrobotanical data, but the phytolith data supports this interpretation – all of which follow the identification of autumn/winter.

Strong seasonal convergence of annual species identified among the macrobotanical remains in both dung and sediments indicates April–June grazing in Loci 162 and 501. In Locus 501, this is in contrast to one palynological spectrum (no. 7), which is dominated by *Artemisia* pollen, suggesting an autumn/winter season. However, spring-flowering *Artemisia* species also exist, such as *A. judaica*. Although this species is not known in the Negev Highlands today, it does grow in the southern Negev, southern Jordan and Sinai (Danin, 2004; Danin and Fragman-Sapir, 2018+). The inability to determine the exact species that produced the *Artemisia* pollen grains hampers the utility of palynology to deduce seasonality in this case, and the conclusions would be different without the two methods. Owing to the low state of preservation characterizing pollen sample no. 7 and the higher taxonomic resolution of macrobotany, we consider it the best indicator for seasonality.

The phytolith data has the lowest taxonomic resolution. Additionally, phytolith assemblages in this study reflect a mixed diet of grazing and supplemental foddering. Therefore, phytolith-deduced seasonality must rely on the non-cereal (and non-grass) phytoliths in these assemblages, which can only be attributed to dicotyledonous vegetation in general. Phytolith assemblages cannot be used alone—in this case study and probably in many others—to deduce seasonality.

4.3.3. *Considerations related to studies of botanical proxies in sediments*

Archaeological sediments pose several challenges when used for archaeobotanical reconstructions. In the context of sediments associated with dung, it is important to determine whether the sediments are composed primarily of degraded dung or are a mixture of dung and other components. A direct approach can be inferred through the microremain proxies of quantified dung spherulite, ash pseudomorph and phytolith concentrations (Shahack-Gross, 2011, recently also Smith et al., 2018). From the comparison between intact dung and the archaeological sediments in this study, it is clear that all studied loci are a mixture of degraded/ashed dung and other refuse components.

In reference to the question of dung-derived seeds in archaeobotanical assemblages (e.g., Miller, 1996; Hillman et al., 1997; Spengler, 2018), three lines of macrobotanical evidence suggest that a large majority of identified plant remains in the Shivta middens do not derive from dung. First, the presence of different cereal, legume and fruit crop remains, all charred, implies that domestic refuse is included in the archaeological sediments (cf. Charles, 1998). Second, the excellent preservation of plant remains from the sediments—including brush hairs from grains and rachis fragments, and the variety of other plant parts (e.g., stems, leaves, thorns, roots, pods, pedicels, florets, rachillae, dispersal units)—as well as their taxonomic diversity, contrasts starkly with the poorly preserved seeds removed from the archaeological pellets. Third, the discrepancy in seed size and hardness between the dung samples and sediment samples suggests that several large, soft seeds discovered in the sediment samples could not have survived the ovicaprine gut intact. We cannot rule out the possibility of equid or camelid dung as an additional source of seeds in the archaeological sediments. However, based on our own (unpublished) observations of plant remains from these sources, we maintain that they could not account for the excellent state of macroremain preservation in the sediments as well as their diversity.

The identification of a *Stipa capensis* dispersal unit in one of the modern dung pellets is particularly interesting in the context of the debate between Miller (1996, 1997) and Hillman et al. (1997). The latter argue that since ripe *Stipa* ssp. grains are sharp and dangerous to the ruminant digestive tract, and therefore avoided by herbivores and their keepers, they could not have originated from dung (Hillman et al., 1997: 651–652). Miller (1997: 656) retorts that, if anything, *Stipa* is more dangerous to humans than to ruminants and hence more likely to originate in ruminant dung than in human refuse. *A priori*, the *Stipa capensis* identified in a dung pellet in this study supports Miller's argument. Significantly, Seligman et al. (1959: 156) noted that avoidance of *Stipa capensis* in sheep is seasonal: it is eaten either during the winter, before ripening, or during late spring-early summer, following seed dispersal. Since the assemblage in question was also identified to late spring-early summer, the *Stipa capensis* dispersal unit may have been inadvertently ingested among mostly post-dispersal plants. In addition, it is possible that *Stipa* ssp. avoidance is specific to sheep, with hardier goats being less selective.

4.3.4. *General methodological conclusions from the study*

The above reconstructions of livestock diet and grazing season demonstrate the complementary nature of the combined methods. Pollen and macrobotanical finds point mainly to wild taxa, whereas phytoliths clearly also show foddering with cereal chaff. The unanimous convergence of annuals among macrobotanical finds from both dung pellets and sediment samples in Locus 162 and sediments from Locus 501 (mid-7th–mid-8th centuries CE) suggest that these finds originated in spring. The pollen and phytolith assemblages from Locus 951 (8th–mid-10th centuries CE) suggest autumn/early winter grazing.

While some foddering with chaff is suggested by macrobotanical finds from the sediment samples, cereal rachis, glume and awn fragments apparently did not preserve well in the pellets, while phytoliths typical of these plant parts did. Phytolith analysis also revealed that reeds and sedges were probably part of the livestock diet, a component not identified by pollen or macrobotanical analyses. Given their absence in macrobotanical and pollen remains and the low percentages within the phytolith assemblages, these must have been a small component of the diet. Perhaps they derived from opportunistic grazing near water sources.

These examples illustrate the advantages and disadvantages of each botanical proxy. Phytoliths were the best-preserved proxy in all pellets but have the lowest taxonomic power. Macrobotanical identification yielded the highest taxonomic power, which significantly enhanced reconstructions of diet and seasonality. However, the type of seeds preserved in dung pellets is skewed by ruminant digestion and post-depositional decay, and the average number of seeds per pellet is low. Pollen yielded a middle level of taxonomic identification, mostly to family or genus. Additionally, pollen preservation is limited to unburned materials. In short, there is a trade-off between preservation of plant matter type within dung pellets and taxonomic resolution of identification.

Pollen and macrobotanical finds appear to complement each other in different ways. First, they exhibit opposite preservation – charring apparently contributed to preservation of seeds within archaeological dung pellets but destroyed the pollen assemblage. Second, pollen represents flowering seasons whereas fruits/seeds represent fruiting seasons. In cases of short-term deposition, such as a dung pellet which embodies an extremely short-term time capsule, these different finds should agree and strengthen conclusions about seasonality. Unfortunately, due to limited material, in our study macrobotanical and palynological analyses were not performed on the same individual dung pellets. Third, different processes affect the deposition and identification of each type of remain. For instance, *Artemisia* seeds are extremely small and very difficult to identify, whereas *Artemisia* pollen preserves well. On the other hand, grape pollen (*Vitis vinifera*) and many other species common in the macrobotanical record rarely disperse far enough to be deposited in archaeological sediments.

Overall, the reconstruction of livestock diet benefited greatly from utilizing the three methods in tandem; had we used only one method we would have received a deficient and partial understanding of livestock diet at Early Islamic Shivta. When considering seasonality and taphonomy while interpreting results from the three methods, an image of local livestock rearing emerges. In the spring-early summer, at least, this included a mixture of foddering and free-grazing of wild plants.

5. Conclusions

This report details a multiproxy archaeobotanical investigation into dung pellets and archaeological sediments from Early Islamic Shivta. We characterized the sediment samples geoarchaeologically as mixed dung, ash and domestic refuse contents and conclude that most of the charred seeds in the sediments do not derive from animal dung. This is corroborated secondarily by the diverse macrobotanical and palynological assemblages.

Animal diet at the site consists mostly of wild plants from the local landscape, with some foddering of cereal chaff. In three contexts from the mid-7th–mid-8th centuries CE, late spring-summer pasture is suggested, based primarily on macrobotany. Based on pollen and phytolith data, in one later context from the mid-8th–10th centuries CE, an autumn-winter pasture is suggested.

In terms of the strengths and weaknesses of each proxy, there is a tradeoff between preservation and taxonomic resolution, especially within dung pellets. Of the three botanical proxies used, phytoliths are the most likely to preserve, but have the lowest taxonomic resolution. Pollen survives well in unburned contexts and may enable a higher taxonomic resolution. Macroscopic study of seeds and other plant parts has the highest taxonomic resolution, but lowest potential for preservation in dung. The seeds found in the pellets from Shivta support results from previous studies suggesting that only small or hard-coated seeds survive in sheep/goat dung pellets.

One apparent result of this tradeoff is that foddering was not directly attested by pollen or macroscopic plant remains but was evident in phytolith data. This is likely due to foddering with chaff, rather than high-quality hay. Phytolith analysis also revealed that water-dependent plants (sedges, reeds) were probably part of the livestock diet, a component not identified by pollen or macrobotany analyses. Likewise, lower taxonomic resolution of pollen and especially phytolith data yielded apparently inconsistent indicators of seasonality. Clearly, no single archaeobotanical proxy can be used alone to accurately address questions such as diet and seasonality from dung or dung-derived sediments.

The rich and diverse archaeobotanical remains from Shivta's Early Islamic trash middens represent an amalgamation of different food-production activities including local livestock rearing and mixed agriculture. Since both dung and agricultural waste are traditionally used for fuel, this find strengthens the observation based on the associated material culture that the middens are comprised of household waste. This further suggests that the Early Islamic middens may be good sources for reconstructing the full range of economic activities related to ancient daily life in Shivta.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2019.03.010.

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References

Albert, R.M., Weiner, S., 2001. Study of phytoliths in prehistoric ash layers from Kebara and Tabun Caves using a quantitative approach. In: Meunier, J.D., Colin, F. (Eds.), Phytoliths: Applications in Earth Science and Human History. Balkema, Lisse, pp. 251–266.

Albert, R.M., Shahack-Gross, R., Cabanes, D., Gilboa, A., Lev-Yadun, S., Portillo, M., Sharon, I., Boaretto, E., Weiner, S., 2008. Phytolith-rich layers from the Late Bronze and Iron Ages at Tel Dor (Israel): mode of formation and archaeological significance. J. Archaeol. Sci. 35, 57–75. https://doi.org/10.1016/j.jas.2007.02.015.

Ancient World Mapping Center. Map Files. University of North Carolina at Chapel Hill. http://awmc.unc.edu/wordpress/map-files/. (Accessed 13 October 2018).

Arnon, A., Svoray, T., Ungar, E.D., 2011. The spatial dimension of pastoral herding: a case study from the northern Negev. Israel J. Ecol. Evo. 57, 129–149. https://doi.org/10.1560/IJEE.57.1-2.129.

Babenko, A.N., Kiseleva, N.K., Plakht, I., Rosen, S., Savinetskii, A.B., Khasanov, B.F., 2007. Reconstruction of the Holocene vegetation in the central Negev Desert, Israel, on the basis of palynological data on the Atzmaut zoogenic deposit. Russ. J. Ecol. 38, 388–397. https://doi.org/10.1134/S1067413607060033.

Baeten, J., Mees, F., Marinova, E., de Dapper, M., de Vos, D., Huyge, D., van Strydonck, M., Vandenberghe, D., Linseele, V., 2018. Late Pleistocene coprolites from Qurta (Egypt) and the potential of interdisciplinary research involving micromorphology, plant macrofossil and biomarker analyses. Rev. Palaeobot. Palynol. 259, 93–111. https://doi.org/10.1016/j.revpalbo.2018.09.014.

Bates, J., Singh, R.N., Petrie, C.A., 2017. Exploring Indus crop processing: combining phytolith and macrobotanical analyses to consider the organization of agriculture in northwest India c. 3200–1500 BC. Veg. Hist. Archaeobotany 26, 25–41. https://doi.org/10.1007/s00334-016-0576-9.

Ben-Yosef, E., Langgut, D., Sapir-Hen, L., 2017. Beyond smelting: new insights on Iron Age (10th c. BCE) metalworkers community from excavations at a gatehouse and associated livestock pens in Timna, Israel. J. Archaeol. Sci. Rep. 11, 411–426. https://doi.org/10.1016/j.jasrep.2016.12.010.

Berna, F., Behar, A., Shahack-Gross, R., Berg, J., Boaretto, E., Gilboa, A., Sharon, I., Shalev, S., Shilstein, S., Yahalom-Mack, N., Zorn, J.R., Weiner, S., 2007. Sediments exposed to high temperatures: reconstructing pyrotechnological processes in Late Bronze and Iron Age strata at Tel Dor (Israel). J. Archaeol. Sci. 34, 358–373. https://doi.org/10.1016/j.jas.2006.05.011.

Beug, H.J., 2004. Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Friedrich Pfeil, Munich.

Bhattacharya, A.N., Harb, M., 1973. Sheep production on natural pasture by roaming Bedouins in Lebanon. J. Range Manag. 26, 266–269. https://doi.org/10.2307/3896573.

Boaretto, E., Wu, X., Yuan, J., Bar-Yosef, O., Chu, V., Pan, Y., Liu, K., Cohen, D., Jiao, T., Li, S., Gu, H., Goldberg, P., Weiner, S., 2009. Radiocarbon dating of charcoal and bone collagen associated with early pottery at Yuchanyan Cave, Hunan Province, China. Proc. Natl. Acad. Sci. Unit. States Am. 106, 9595–9600. https://doi.org/10.1073/pnas.0900539106.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–360. https://doi.org/10.1017/S0033822200033865.

Brosh, A., Choshniak, I., Tadmor, A., Shkolnik, A., 1988. Physio-chemical conditions in the rumen of Bedouin goats: effect of drinking, food quality and feeding time. J. Agric. Sci. 111, 147–153. https://doi.org/10.1017/S0021859600082940.

Bryant, V.M., 1974a. The role of coprolite analysis in archaeology. Bull. Tex. Archeol. Soc. 45, 1–28.

Bryant, V.M., 1974b. Prehistoric diet in southwest Texas: the coprolite evidence. Am. Antiq. 39, 407–420. https://doi.org/10.2307/279430.

Cabanes, D., Gadot, Y., Cabanes, M., Finkelstein, I., Weiner, S., Shahack-Gross, R., 2011. Human impact around settlement sites: a phytolith and mineralogical study for assessing site boundaries, phytolith preservation, and implications for spatial reconstructions using plant remains. J. Archaeol. Sci. 39, 2697–2705. https://doi.org/10.1016/j.jas.2012.04.008.

Canti, M.G., 1997. An investigation into microscopic calcareous spherulites from herbivore dungs. J. Archaeol. Sci. 23, 219–231. https://doi.org/10.1006/jasc.1996.0105.

Canti, M.G., 2003. Aspects of the chemical and microscopic characteristics of plant ashes found in archaeological soils. Catena 54, 339–361. https://doi.org/10.1016/S0341-8162(03)00127-9.

Charles, M., 1998. Fodder from dung: the recognition and interpretation of dung-derived plant material from archaeological sites. Environ. Archaeol. 1, 111–122. https://doi.org/10.1179/env.1996.1.1.111.

Coleman, S.W., Hart, S.P., Sahlu, T., 2003. Relationships among forage chemistry, rumination and retention time with intake and digestibility of hay by goats. Small Rumin. Res. 50, 129–140. https://doi.org/10.1016/S0921-4488(03)00116-0.

Danin, A., 2004. Distribution Atlas of Plants in the Flora Palaestina Area. Israel Academy of Sciences and Humanities, Jerusalem.

Danin, A., Fragman-Sapir, O., 2018+. Flora of Israel Online. http://flora.org.il/en/plants/.

Delhon, C., Martin, L., Argant, J., Thiébault, S., 2008. Sheperds and plants in the Alps: multi-proxy archaeobotanical analysis of Neolithic dung from “La Grande Rivoire” (Isère, France). J. Archaeol. Sci. 35, 2937–2952. http://doi.org/10.1016/j.jas.2008.06.007.

Dunseth, Z.C., Shahack-Gross, R., 2018. Calcitic dung spherulites and the potential for rapid identification of degraded animal dung at archaeological sites using FTIR spectroscopy. J. Archaeol. Sci. 97, 118–124. https://doi.org/10.1016/j.jas.2018.07.005.

Dunseth, Z.C., Junge, A., Fuchs, M., Finkelstein, I., Shahack-Gross, R., 2016. Geoarchaeological investigation in the Intermediate Bronze Age site of Mashabe Sade. Tel Aviv 43, 43–75. https://doi.org/10.1080/03344355.2016.1161372.

Dunseth, Z.C., Finkelstein, I., Shahack-Gross, R., 2018. Intermediate Bronze Age subsistence practices in the Negev Highlands, Israel: macro- and micro-archaeological results from the sites of Ein Ziq and Nahal Boqer 66. J. Archaeol. Sci. Rep. 19, 712–726. https://doi.org/10.1016/j.jasrep.2018.03.025.

Erickson-Gini, T., 2013. Excavations and Surveys in Israel, 125. http://www.hadashot-esi.org.il/report_detail_eng.aspx?id=5420&mag_id=120.

Esteban, I., 2016. Reconstructing Past Vegetation and Modern Human Foraging Strategies on the South Coast of South Africa. PhD Dissertation. University of Barcelona, Barcelona.

Evenari, M., Shanan, L., Tadmor, N., 1982. The Negev: the Challenge of a Desert. Harvard University Press, Cambridge, MA.

Feinbrun-Dothan, N., 1978. Flora Palaestina, vol. III. Israel Academy of Sciences and Humanities, Jerusalem.

Feinbrun-Dothan, N., 1986. Flora Palaestina, vol. IV. Israel Academy of Sciences and Humanities, Jerusalem.

Finsinger, W., Tinner, W., 2005. Minimum count sums for charcoal-concentration estimates in pollen slides: accuracy and potential errors. Holocene 15, 293–297.

Forget, M.C.L., Regev, L., Friesem, D.E., Shahack-Gross, R., 2015. Physical and mineralogical properties of experimentally heated chaff-tempered mud bricks: implications for reconstruction of environmental factors influencing the appearance of mud bricks in archaeological conflagration events. J. Archaeol. Sci. Rep. 2, 80–93. https://doi.org/10.1016/j.jasrep.2015.01.008.

Fuks, D., Weiss, E., Tepper, Y., Bar-Oz, G., 2016. Seeds of collapse? Reconstructing the ancient agricultural economy at Shivta in the Negev. Antiquity 90, 1–5. http://doi.org/10.15184/aqy.2016.167.

Gur-Arieh, S., Mintz, E., Boaretto, E., Shahack-Gross, R., 2013. An ethnoarchaeological study of cooking installations in rural Uzbekistan: development of a new method for identification of fuel sources. J. Archaeol. Sci. 40, 4331–4347. https://doi.org/10.1016/j.jas.2013.06.001.

Hillman, G.C., 1984. Interpretation of archaeological plant remains: the application of ethnographic models from Turkey. In: van Zeist, W., Casparie, W.A. (Eds.), Plants and Ancient Man: Studies in Palaeoethnobotany. Balkema, Rotterdam, pp. 1–41.

Hillman, G.C., Legge, A.J., Rowley-Conway, P.A., 1997. On the charred seeds from Epipaleolithic Abu Hureyra: food or fuel? Curr. Anthropol. 38, 651–655. https://doi.org/10.1086/204651.

Hirschfeld, Y., 2003. Social aspects of the Late-Antique village of Shivta. J. Roman Archaeol. 16, 395–408. https://doi.org/10.1017/S1047759400013210.

Hirschfeld, Y., Tepper, Y., 2006. Columbarium towers and other structures in the environs of Shivta. Tel Aviv 33, 83–116. https://doi.org/10.1179/tav.2006.2006.1.83.

Kam, M., El-Meccawi, S., Degen, A.A., 2012. Foraging behavior and diet selection of free-ranging sheep and goats in the Negev Desert, Israel. J. Agric. Sci. 150, 379–387. https://doi.org/10.1017/S0021859611000955.

Katz, O., Cabanes, D., Weiner, S., Maeir, A.M., Boaretto, E., Shahack-Gross, R., 2010. Rapid phytolith extraction for analysis of phytolith concentrations and assemblages during an excavation: an application at Tell es-Safi/Gath, Israel. J. Archaeol. Sci. 37, 1557–1563. https://doi.org/10.1016/j.jas.2010.01.016.

Kedar, Y., 1957. Ancient agriculture at Shivta in the Negev. Isr. Explor. J. 7, 178–189.

Kislev, M.E., Simchoni, O., Melamed, Y., Marmorstein, M., 1995. Computerized key for grass grains of Israel and its adjacent regions. In: Kroll, H., Pasternak, R. (Eds.), Res Archaeobotanicae: International Workgroup for Palaeoethnobotany – Proceedings of the 9th Symposium. Oetker-Voges, Kiel, pp. 69–79.

Kislev, M.E., Melamed, Y., Simchoni, O., Marmorstein, M., 1997. Computerized key of grass grains of the Mediterranean basin. Lagascalia 19 (1–2), 289–294.

Kislev, M.E., Melamed, Y., Simchoni, O., Marmorstein, M., 1999. Computerized keys for archaeological grains: first steps. In: Pike, S., Gitin, S. (Eds.), The Practical Impact of Science on Near Eastern and Aegean Archaeology. Archetype, Athens, pp. 29–31.

Liu, L., Jie, D., Liu, H., Li, N., Guo, J., 2013. Response of phytoliths in Phragmites communis to humidity in NE China. Quat. Int. 304, 193–199. https://doi.org/10.1016/j.quaint.2013.03.020.

Madella, M., Alexandre, A., Ball, T., 2005. International code for phytolith nomenclature 1.0. Ann. Bot. 96, 253–260. https://doi.org/10.1093/aob/mci172.

Maher, L.J., 1981. Statistics for microfossil concentration measurements employing samples spiked with marker grains. Rev. Palaeobot. Palynol. 32, 153–191. . https://doi.org/10.1016/0034-6667(81)90002-6.

Marom, N. Meiri, M., Tepper, Y., Erikson-Gini, T., Reshef, H., Weissbrod, L., Bar-Oz, G., submitted for publication. Zooarchaeology of the social and economic upheavals in the Late Antique-Early Islamic sequence of the Negev desert. Sci. Rep.

Marston, J.M., D'Alpoim Guedes, J., Warinner, C. (Eds.), 2014. Method and Theory in Paleoethnobotany. University Press of Colorado, Boulder.

Miller, N.F., 1984. The use of dung as fuel: an ethnographic example and an archaeological application. Paleorient 10, 71–79. https://doi.org/10.3406/paleo.1984.941.

Miller, N.F., 1996. Seed eaters of the ancient Near East: human or herbivore? Curr. Anthropol. 37, 521–528. https://doi.org/10.1086/204514.

Miller, N.F., 1997. On the charred seeds from Epipalaeolithic Abu Hureyra: food or fuel? Reply. Cur. Anthropol. 38, 655–659. https://doi.org/10.1086/204651.

Misra, A.K., Khub, S., 2002. Effect of water deprivation on dry matter intake, nutrient utilization and metabolic water production in goats under semi-arid zone of India. Small Rumin. Res. 46, 159–165. https://doi.org/10.1016/S0921-4488(02)00187-6.

Morand-Fehr, P., 2005. Recent developments in goat nutrition and application: a review. Small Rumin. Res. 60, 25–43. https://doi.org/10.1016/j.smallrumres.2005.06.004.

Ngwa, A.T., Pone, D.K., Mafeni, J.M., 2000. Feed selection and dietary preferences of forage by small ruminants grazing natural pastures in the Sahelian zone of Cameroon. Anim. Feed Sci. Technol. 88, 253–266. https://doi.org/10.1016/S0377-8401(00)00215-7.

Pearsall, D., 2016. Paleoethnobotany: A Handbook of Procedures, third ed. Routledge, New York.

Piperno, D.R., 2006. Phytoliths: A Comprehensive Guide for Archaeologists and Paleoecologists. AltaMira Press, Lanham.

Portillo, M., Kadowski, S., Nishiaki, Y., Albert, R.M., 2014. Early Neolithic household behavior at Tell Seker al-Aheimar (Upper Khabur, Syria): a comparison to ethnoarchaeological study of phytoliths and dung spherulites. J. Archaeol. Sci. 42, 107–118.

Portillo, M., Belarte, M.C., Ramon, J., Kallala, N., Sanmartí, J., Albert, R.M., 2017. An ethnoarchaeological study of livestock dung fuels from cooking installations in northern Tunisia. Quat. Int. 431, 131–144. https://doi.org/10.1016/j.quaint.2015.12.040.

Ramsay, J., Tepper, Y., Weinstein-Evron, M., Aharonovich, S., Liphschitz, N., Marom, N., Bar-Oz, G., 2016. For the birds – an environmental archaeological analysis of Byzantine pigeon towers at Shivta (Negev Desert, Israel). J. Archaeol. Sci. Rep. 9, 718–727. https://doi.org/10.1016/j.jasrep.2016.08.009.

Ramsey, M.N., Maher, L.A., Macdonald, D.A., Rosen, A., 2016. Risk, reliability and resilience: phytolith evidence for alternative ‘Neolithization’ pathways at Kharaneh IV in the Azraq Basin, Jordan. PLoS One 11 (10), e0164081. https://doi.org/10.1371/journal.pone.0164081.

Rapp, G., Mullholland, S.C. (Eds.), 1992. Phytolith Systematics. Plenum Press, New York. https://doi.org/10.1007/978-1-4899-1155-1.

Reddy, S.N., 1999. Fueling the hearths in India: the role of dung in paleoethnobotanical interpretation. Paleorient 24, 61–69. http://doi.org/10.3406/paleo.1998.4677.

Regev, L., Poduska, K.M., Addadi, L., Weiner, S., Boaretto, E., 2010. Distinguishing between calcites formed by different mechanisms using infrared spectrometry: archaeological applications. J. Archaeol. Sci. 37, 3022–3029. https://doi.org/10.1016/j.jas.2010.06.027.

Regev, L., Cabanes, D., Homsher, R., Kleiman, A., Weiner, S., Finkelstein, I., Shahack-

Gross, R., 2015. Geoarchaeological investigation in a domestic Iron Age quarter, Tel Megiddo, Israel. Bull. Am. Sch. Orient. Res. 374, 135–157. https://doi.org/10.5615/bullamerschoorie.374.0135.

Regev, L., Steier, P., Shachar, Y., Mintz, E., Wild, E.M., Kutschera, W., Boaretto, E., 2017. D-REAMS: a new compact AMS system for radiocarbon measurements at the Weizmann Institute of Science, Rehovot, Israel. Radiocarbon 59, 775–784. https://doi.org/10.1017/RDC.2016.96.

Reille, M., 1995. Pollen et Spores d'Europe et d'Afrique du Nord, supplément 1. Laboratoire de Botanique Historique et Palynologie, Marseille.

Reille, M., 1998. Pollen et Spores d'Europe et d'Afrique du Nord, supplément 2. Laboratoire de Botanique Historique et Palynologie, Marseille.

Reille, M., 1999. Pollen et Spores d'Europe et d'Afrique du Nord, II edition. Laboratoire de Botanique Historique et Palynologie, Marseille.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guikderson, T.P., Haflidason, H., Hadjas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and Marine 13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55, 1869–1887. https://doi.org/10.2458/azu_js_rc.55.16947.

Safrai, Z., 1994. The Economy of Roman Palestine. Routledge, New York. https://doi.org/10.4324/9780203204863.

Sanon, H.O., Kaboré-Zoungrana, C., Ledin, I., 2007. Behaviour of goats, sheep and cattle and their selection of browse species on natural pasture in the Sahelian area. Small Rumin. Res. 67, 64–74. https://doi.org/10.1016/j.smallrumres.2005.09.025.

Schlect, E., Dickhoefer, U., Gumpertsberger, E., Buerkert, A., 2009. Grazing itineraries and forage selection of goats in the Al Jabal al Akhdar mountain range of northern Oman. J. Arid Environ. 73, 355–363. https://doi.org/10.1016/j.jaridenv.2008.10.013.

Segal, A., 1983. The Byzantine City of Shivta (Esbeita), Negev Desert, Israel. BAR Publishing, Oxford.

Seligman, N., Rosensaft, Z., Tadmor, N., Katznelson, J., Naveh, Z., 1959. Natural Pasture of Israel: Vegetation, Carrying Capacity and Improvement (Hebrew). Sifriat Poalim, Merhavia, Israel.

Sengupta, S., 1975. Experimental alterations of the spores of Lycopodium clavatum as related to diagenesis. Rev. Palaeobot. Palynol. 19, 173–192. https://doi.org/10.1016/0034-6667(75)90039-1.

Shahack-Gross, R., 2011. Herbivorous livestock dung: formation, taphonomy, methods for identification, and archaeological significance. J. Archaeol. Sci. 38, 205–218. https://doi.org/10.1016/j.jas.2010.09.019.

Shahack-Gross, R., Ayalon, A., 2013. Stable carbon and oxygen isotopic compositions of wood ash: an experimental study with archaeological implications. J. Archaeol. Sci. 40, 570–578. https://doi.org/10.1016/j.jas.2012.06.036.

Shahack-Gross, R., Finkelstein, I., 2008. Subsistence practices in an arid environment: a geoarchaeological investigation in an Iron Age site, the Negev Highlands, Israel. J. Archaeol. Sci. 35, 965–982. https://doi.org/10.1016/j.jas.2007.06.019.

Shahack-Gross, R., Marshall, F., Weiner, S., 2003. Geo-ethnoarchaeology of pastoral sites: the identification of livestock enclosures in abandoned Maasai settlements. J. Archaeol. Sci. 30, 439–459. https://doi.org/10.1006/jasc.2002.0853.

Shahack-Gross, R., Boaretto, E., Cabanes, D., Katz, O., Finkelstein, I., 2014. Subsistence economy in the Negev Highlands: the Iron Age and the Byzantine/Early Islamic periods. Levant 46, 98–117. https://doi.org/10.1179/0075891413Z.00000000034.

Shelton, C.R., White, C.E., 2010. The hand-pump floatation system: a new method for archaeobotanical recovery. J. Field Archaeol. 35, 316–326. https://doi.org/10.1179/009346910X12707321358838.

Sillar, B., 2000. Dung by preference: the choice of fuel as an example of how Andean pottery production is embedded within wider technical, social, and economic practices. Archaeometry 42, 43–60. https://doi.org/10.1111/j.1475-4754.2000.tb00865.x.

Silanikove, N., Tagari, H., Shkolnik, A., 1993. Comparison of rate of passage, fermentation rate and efficiency of digestion of high fiber diet in desert Bedouin goats compared to Swiss Saanen goats. Small Rumin. Res. 12, 45–60. https://doi.org/10.1016/0921-4488(93)90037-I.

Silanikove, N., 2000. The physiological basis of adaptation in goats to harsh environments. Small Rumin. Res. 35, 181–193. https://doi.org/10.1016/S0921-4488(99)00096-6.

Smith, A., Proctor, L., Hart, T.C., Stein, G.J., 2018. The burning issues of dung in archaeobotanical samples: a case-study integrating macro-botanical remains, dung spherulites, and phytoliths to assess sample origin and fuel use at Tell Zeidan, Syria. Veg. Hist. Archaeobotany. https://doi.org/10.1007/s00334-018-0692-9.

Spengler, R., 2018. Dung burning in the archaeobotanical record of West Asia: where are we now? Veg. Hist. Archaeobotany. https://doi.org/10.1007/s00334-018-0669-8.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollen Spores 13, 615–621.

Stuiver, M., Polach, H.A., 1977. Discussion reporting of 14 C data. Radiocarbon 19, 355–363. https://doi.org/10.1017/S0033822200003672.

Tepper, Y., Erickson-Gini, T., Farhi, Y., Bar-Oz, G., 2018. Probing the Byzantine/Early Islamic transition in the Negev: the renewed Shivta excavations, 2015–2016. Tel Aviv 45, 120–152. https://doi.org/10.1080/03344355.2018.1412058.

Tisserand, J.L., Hadjipanayiotou, M., Gihad, E.A., 1991. Digestion in goats. In: Morand-Fehr, P. (Ed.), Goat Nutrition. Pudoc, Wageningen, pp. 46–60.

Toffolo, M.B., Boaretto, E., 2014. Nucleation of aragonite upon carbonation of calcium oxide and calcium hydroxide at ambient temperatures and pressures: a new indicator of fire-related human activities. J. Archaeol. Sci. 49, 237–248. https://doi.org/10.1016/j.jas.2014.05.020.

Tsartsidou, G., Lev-Yadun, S., Albert, R.M., Miller-Rosen, A., Efstatiou, N., Weiner, S., 2007. The phytolith archaeological record: strengths and weakness evaluation based on quantitative modern reference collection from Greece. J. Archaeol. Sci. 34, 1262–1275. https://doi.org/10.1016/j.jas.2006.10.017.

Tsiplakou, E., Hadjigeorgiou, I., Sotirakoglou, K., Zervas, G., 2011. Differences in mean retention time of sheep and goats under controlled feeding practices. Small Rumin. Res. 95, 48–53. https://doi.org/10.1016/j.smallrumres.2010.09.002.

Twiss, P.C., Suess, E., Smith, R.M., 1969. Morphological classification of grass phytoliths. Soil Sci. Soc. Am. Proc. 33, 109–115.

Valamoti, S.M., 2013. Towards a distinction between digested and undigested glume bases in the archaeobotanical record from Neolithic northern Greece: a preliminary experimental investigation. Environ. Archaeol. 18, 31–42. https://doi.org/10.1179/1461410313Z.00000000021.

Valamoti, S.M., Charles, M., 2005. Distinguishing food from fodder through the study of charred plant remains: an experimental approach to dung-derived chaff. Veg. Hist. Archaeobotany 14, 528–533. https://doi.org/10.1007/s00334-005-0090-y.

Wahed, R.A., Owen, E., 1986. Comparison of sheep and goats under stall-feeding conditions: roughage intake and selection. Anim. Sci. (Pencaitland) 42, 89–95. https://doi.org/10.1017/S0003356100017761.

Wallace, M., Charles, M., 2013. What goes in does not always come out: the impact of the ruminant digestive system of sheep on plant material, and its importance for the interpretation of dung-derived archaeobotanical assemblages. Environ. Archaeol. 18, 18–30. https://doi.org/10.1179/1461410313Z.00000000022.

Weiner, S., 2010. Microarchaeology: Beyond the Visible Archaeological Record. Cambridge University Press, Cambridge.

Zohary, M., 1950. The segetal plant communities of Palestine. Vegetatio. Acta Geobot 2, 387–411. https://doi.org/10.1007/BF00179724.

Zohary, M., 1966. Flora Palaestina, vol. I. Israel Academy of Sciences and Humanities, Jerusalem.

Zohary, M., 1972. Flora Palaestina, vol. II. Israel Academy of Sciences and Humanities, Jerusalem.

Zurro, D., 2018. One, two, three phytoliths: assessing the minimum phytolith sum for archaeological studies. Archaeol. Anthropol. Sci. 10, 1673–1691. https://doi.org/10.1007/s12520-017-0479-4.