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Fuel use in ancient Southwest Asia based on wood charcoal and seed data from fire installations☆

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ABSTRACT

This study synthesizes a large dataset of published and new charcoal and seed data from archaeological fire installations in southwest Asia to gain an understanding in regional and temporal variation in fuel use through the last 10,000 years. It considers wood (charcoal) fuel, and its underlying selection and management, as well as agropastoral by-products, and the role of population pressure. It focusses on regional diachronic trends, as well as zooms in on three regions: The Middle Euphrates, Faynan and Kinet Höyük region.

From the late 4th millennium BC onwards, marked changes in fuel use took place, with alternative fuels like dung and jift/pomace increasingly used. This change coincides with population pressure, which seems to have caused the progressive exhaustion of local wood resources, and economic changes, which may have made wood fuel alternatives more plentiful. The Southern Middle Euphrates, for example, saw a shift towards increased use of imported, possibly reused or remnant, coniferous fuel wood in the 2nd millennium BC. In the long term, we do not see much evidence for sustainability of exploitation, but there are some indications for possible intentional sustainable behavior like coppicing and/or pollarding in the Middle Euphrates during the Early Bronze Age, using pruning remains especially in the Levant, and more centrally organized woodland management in Southern Mesopotamia.

We found indications for 'least effort' and 'opportunistic' behavior in former fuel collection but also of selection towards higher quality fuels when choice was possible. Our results demonstrate the capacity for large scale comparative analyses of this type to shed light on the complex decision-making processes underlying fuel use.

1. Introduction

Over millennia, fire installations in Southwest Asia have been fueled under changing social, climatic, and vegetation conditions. In the face of the current political crises in the region, which has limited access to fossil fuels (Makdesi et al. 2022), people have returned to traditional fuels, with attendant problems of landscape pressure and long-term deforestation. Of the traditional fuels, wood is often preferred since it burns with greater steadiness and reaches higher temperatures than dung (Miller and Marston 2012). Collecting a kilogram of dung is typically more time-consuming than collecting a kilogram of wood (Mekonnen and Köhlin 2008), while at the same time dung normally produces somewhat less energy per kilogram than wood (e.g. 11.95 MJ/kg for sheep and goat dung, 14 MJ/kg for dried cow dung in India as in Vaňkát et al. 2010; Kaur et al. 2017 compared to 21.8 MJ/kg on average for wood cf. Table Appendix Table 1). Dung fuel, however, is sometimes preferred over wood for specific activities (Sillar 2000; Peña et al. 2003). Such preference is predominantly found in livestock-dependent societies, where dung use is strongly embedded in their cultural traditions (Mekonnen and Köhlin 2008; Sillar 2000). In traditional agriculture,

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dung fuel use has also contributed to diminished agricultural productivity due to soil nutrient depletion, since it reduces the availability of dung as manure as has been established through qualitative and quantitative data, including econometric analyses (e.g., Eckholm 1977; Mekonnen and Köhlin 2008). However, ashes can still be used as manure to improve the soil quality (Wilkinson 1989). Where wood resources are available in Southwest Asia, the partial return to wood as fuel for cooking, baking, heating, lighting, and craft production has caused extensive logging (Raydan 2022). In Lebanon, legal and illegal logging is reported to cause significant deforestation (Pita 2023). In Syria, even ancient olive groves have been felled for heating (Pesce 2014). Wood fuel is no longer available to many poor communities (Ahmed 2022), which revives the use of alternative fuels, such as dung fuel cakes, pistachio shells, and olive pressing remains (pomace/jift), depending on local availability. These were common fuels in this region before fossil fuels became popular in the late 20th century (Ball 2021; Iqtissad 2016; Makdesi et al. 2022). The present-day fuel crisis raises questions about the past that are pivotal for the present regarding how ancient societies in Southwest Asia tackled their fuel needs under changing climates, environments, and socio-economic structures. In this study, we investigate how past societies used and managed their fuel sources in light of local environmental conditions.

1.1. Geography, climate and vegetation of the region

Diverse climatic and topographic conditions shape the vegetation cover in Southwest Asia, creating varied opportunities to exploit fuel resources. Typical sclerophyllous woodlands and maquis mark the low-lying coastal areas of the Mediterranean-influenced Levant, which includes evergreen oak (*Quercus*), pistachio (*Pistacia*), buckthorn (*Rhamnus*), mock privet (*Phillyrea*) and olive (*Olea*) (Zohary 1973). Towards higher elevations, such as in the Amanus Mountains, rainfall is between 600 mm and 1000 mm per year, and dense and diverse forest vegetation occurs that varies over elevation. Large parts of the Amanus are covered by pine (*Pinus*)-oak (*Quercus*) forests, such as e.g. the Kinet Höyük region, while at higher elevations, the famous cedar (*Cedrus*) occur (Aytaç and Semenderoğlu 2011; Zohary 1973; Meiggs 1982). In contrast, other regions of the Levant, such as the Faynan in the Southern Levant, receive as little as 30 mm annually. Phytogeographically, the Faynan region is part of the Saharo-Arabian region, with hyper-arid desert-like vegetation mainly consisting of open saxaul shrub (*Haloxylon persicum*), open *Vachellia* woodland including dwarf shrub-like bean caper (*Zygophyllum*) (Albert et al. 2004). Remains of metallurgical smelting in this region suggest that vegetation may have been lusher in the past (Albert et al. 2004). In Mesopotamia, along the Euphrates and Tigris, patches of riverine woodland occur, mainly of poplar (*Populus*), willow (*Salix*), and tamarisk (*Tamarix*). These are the remains of a once denser riverine gallery forest. Away from the rivers, in Northern Mesopotamia, where rainfall is above 300 mm annually, dryland cultivation takes up a large part of the landscape. In the past, woodland (steppe) extended further into these areas (e.g., Deckers and Pessin 2010). Further south, below the 300 mm isohyet and away from the major rivers, increasingly desert-adapted species occur with decreasing rainfall, i.e. halophytic plants and drought-resistant shrubs (Zohary 1973). In the transition zone, between 300–180 mm of rainfall, crop dryland cultivation is possible, often combined with pastoralism. However, crop failure is common, and this region has been labeled the 'Zone of Uncertainty' (Wilkinson 2000). In this zone and below 180 mm rainfall, wood resources are scarce. East of Mesopotamia, the Zagros Mountains in Iran feature distinctive vegetation dominated by oak-pistachio-almond woodlands at lower elevations and a greater variety of deciduous trees at the higher, more humid environments (Zohary 1973). The vegetation of Central Anatolia consists today mainly of steppe shrubs and grasses with some woodland in areas with greater moisture (Zohary 1973), though this region also used to be more wooded in the past (Ocakverdi and Unal 1991; Woldring and Bottema 2003). Present-day vegetation results from millennia of human activities.

1.2. General insights into the history of fuel use

Southwest Asia has a longstanding history of fuel exploitation. The earliest possible hearths date back to about 790 000 years BP at Gesher Benot Ya'Aqov (Alperson-Afil et al. 2007) and 300 000 years BP (at Qesem Cave) (Alperson-Afil et al. 2007) and belonged to hunter-gatherer camps. Since then, fireplaces have become central to human societies. After sedentarisation (from 16,000 years ago) and neolithization (from 12,000 years ago), the hearth reflects the 'domestication of society' and became a focal point of the house (Fuchs-Khakhar 2019). Over time, fireplaces evolved from simple forms, such as fire pits and hearths, to more complex constructions, like ovens (Baird 2012; Salonen 1964). The increasing diversification of fire installations also reflects innovations in craft production, including the introduction of ceramics (from 10,000 years ago in Southwest Asia), lime production (10th/9th millennium BC), metallurgical smelting (late 6th millennium BC), glazing (late 5th millennium BC) and glass production (mid/late 3rd millennium BC) (Fenn 2015; Gibbs 2015; Mignardi et al. 2021). Social developments were often associated with increasing fuel needs. The craft specialization connected with increasing social differentiation and urbanization from the 5th millennium BC onwards (Ur 2010) was likely correlated to pyrotechnological advances. Urbanization occurred at different times across North and South Mesopotamia and the Levant (Lawrence et al. 2021b) and appears to coincide with more economic specialization, including, for example, the pastoral sector (Ur 2010). The 3rd millennium BC urban expansion (Ur 2010; Wilkinson et al. 2014) further increased the need for fuel. With expanding trade networks and large-scale production of transport containers, e.g., for olive oil trade in the Levant, more fuel was needed (Badreshany et al. 2020). The second and first millennium BC are often characterized as periods of increased internationalization, with the rise of territorial empires from 1600 BC onwards (Van de Mieroop 2016). The expansion of international trade networks and progress in metallurgical technology promoted a further demand for wood and other fuels. Fuel use became more efficient through improved kiln designs and increased wood charcoal use (Erb-Satullo 2019; Iamoni 2015).

1.3. Previous approaches to identify fuel use and outcome

Ancient fuel use in Southwest Asia has been investigated through several methods and approaches. Anthracological studies have documented the use of wood fuel, mainly through identifying wood charcoals from secondary refuse deposits, though also sometimes from the direct contents of hearths and ovens (Deckers 2016; Wright 2016). Diameter measurements, combined with ring width measurements, have allowed us to understand fuel wood procurement strategies such as cutting branches (e.g., coppicing or pollarding) and/or harvesting entire trees (e.g., Wright 2018; Deckers et al. 2024a). Additionally, the investigation of ratios in charred botanical assemblages has provided insights, since high ratios of charred wild plant seeds to wood in combination with high ratios of wild to cultivated seeds are indicative of the use of dung as fuel. This is because dung contains a mix of seeds, typically from wild plants (Miller 1984). Multiproxy studies, including geoarchaeological techniques, have shown the potential to detect dung fuel use and to gain insight into the proportion of dung versus wood fuel used in the past, especially through the ash pseudomorph to dung spherulite ratio (Fuks and Dunseth 2021). Excreted dung spherulites formed during the digestion of calcium-rich food by animals serve as evidence of dung in their own right (e.g., Fuks and Dunseth 2021; Gur-Arieh et al. 2014; Smith et al. 2019, Smith et al. 2022; Proctor et al. 2022; Proctor et al. 2024), while ash pseudomorphs, which are calcite crystals created during the combustion of wood containing calcium oxalate crystals, are a proxy for wood fuel (Fuks and Dunseth 2021). Attempts have also been made to identify the use of pomace/jift as a fuel by studying the remains of olive oil pressing (Marinova et al. 2011). Pomace/jift typically may be differentiated from food remains based on fragments versus complete seeds, though not all archaobotanists have recorded whether seeds were complete or fragmented. However, a high volume of carbonized olive seed fragments in archaeobotanical assemblages remains the most reliable criterion in identifying former pomace/jift as fuel (Rowan 2015).

Previous work to understand fuel use in Southwest Asia delivered valuable insights. For example, darkened spherulites from combustion features at Abu Hureyra indicate that dung was used as a fuel since the 11th millennium BC. However, its use decreased there from 7350 BC perhaps because animal herding moving further away from the site (Smith et al. 2022). Dung spherulites from a 6th millennium BC pyrotechnic feature at Tell Zeidan indicate dung used as fuel, though it appears in variable quantities within the site (Smith et al. 2019). In the 3rd and 2nd millennium BC, the seed-to-wood charcoal ratio and wild seed-to-cultivated seed proportions indicate that dung fuel gained importance at several sites, such as Kurban Höyük (Türkiye), Umm el-Marra (Syria), Malyan (Iran), Mozan (Syria), Emar (Syria), Tell Abu en-Nia‘j (Jordan), Tell el-Hayyat (Jordan) (Deckers 2011, 2016a; Fall et al. 2015; Miller 1985; Miller and Marston 2012). In the cases of Malyan, Mozan, Tell Abu en-Nia‘j, and Tell el-Hayyat, wood charcoal analysis suggests the use of dung fuel was an adaptation prompted by deforestation or vegetation degradation (Deckers 2011; Deckers et al. 2024a; Fall et al. 2015; Miller 1985). Wood charcoal studies are increasingly undertaken in Southwest Asia and have provided valuable insights into local wood fuel exploitation at the site level (cf. Appendix Table 1), with fewer regional syntheses (although see Deckers and Pessin 2010; Fall et al. 2015). Preliminary diameter measurement studies on wood charcoals provided variable results regarding the possible application of coppicing or pollarding in support of a sustainable fuel supply (Deckers et al. 2024a; Wright 2018 versus Kabukcu 2018), though the dataset is still small. In the Mediterranean zone, pruning remains from fruit tree crops seem to have contributed significantly to the fuel supply in the 4th- to 2nd millennium BC (e.g., Deckers et al. 2021; Fall et al. 2015; Liphschitz 2007). There is some evidence for pomace/jift being used as fuel during the 3rd/2nd millennium BC in the Mediterranean zone, for example at Yarmouth (Israel) and Tweini (Syria) (Rowan 2015 and references therein). Research into the reasons specific fuels may have been selected is very limited in Southwest Asia. Marston (2009) and Wright (2016) have addressed wood qualities as a factor in fuel selection at Gordion (Turkey) and Kaman-Kalehöyük (Turkey), although they could not detect evidence of consistent selection of wood with optimal qualities.

Hence, while much has been published regarding ancient fuel use in Southwest Asia, a systematic supra-regional investigation of the archaeobotanical contents of fire installations has yet to be undertaken. Moreover, conclusions regarding former fuel use are often based on secondary refuse deposits since they are typically believed to contain the remains of repeated dumping of hearth/oven waste. However, in these contexts, it is not possible to differentiate between fuel waste and the remains of burning events impacting structural timber, roofing material, furniture, or wooden artifacts. Here, we use the latest version of the Archaeobotanical Database of Eastern Mediterranean and Near Eastern Sites (ADEMNES 2015) to systematically investigate archaeobotanical remains from oven, hearth, and firepit contexts across Southwest Asia dating to the last 10,000 years, with additional new charcoal identifications and diameter and ring-width measurements. In many previous fuel studies, settlement dynamics, particularly population density, have been recognized and discussed as an essential factor impacting fuel availability, but studies have not integrated reconstructions of population into their analyses. We explicitly include settlement dynamics, providing insight into the impact of population growth on fuel availability and use. We also investigate factors that may have influenced fuel selection, such as caloric values and land use practices, and whether resources were managed to make wood fuel exploitation more sustainable. Table 1 summarizes the major questions the manuscript addresses with approach and methodology used.

Table 1
Summary of major questions the manuscript focuses on with applied approach and methodology.

Questions	Approach	Method
Can we find a proxy for dung fuel use in large seed datasets that lack systematic mention of dung pellet presence?	Investigate the difference between seed samples with and without dung pellets in terms of overgrazing proportions	Kruskal Wallis test on overgrazing % (according to YES, NO, NA) and Dunn's follow-up test in JMP
	Investigate individual associations of taxa related with the factor yes/no dung pellets	CCA analysis on cleaned seed dataset with dung presence as factor (YES/NO) in the program CANOCO
	Search for supporting evidence that the overgrazing taxa do not systematically relate with crop processing	Depict overgrazing % over cereal chaff % and test for significant linear correlation
Where and when was dung used?	Map overgrazing percentages, where available, using coordinates and temporal information	Bubble plot according to time slices, use background map in JMP
	Investigate the overgrazing seed percentages over time	Plot overgrazing % over time in JMP –Display smoothed curves over the dataset to see the trend
Where and when was jift/pomace used?	Map olive seed %, where available, using coordinates and temporal information	Bubble plot according to time slices, use background map in JMP. 30 % olive seeds amongst seed data are assumed to represent jift/pomace.
	Investigate the olive seed percentages over time	Depict overgrazing % over time in JMP. Display smoothed curves over the dataset to see the trend
What was the role of population pressure on alternative fuel use (i.e. dung and jift/pomace)?	Use a population density proxy over time, such as Summed Probability Distribution of radiocarbon dates (SPD) (NERD database) to compare the trends in alternative fuel	Plot SPD on a time scale over overgrazing % and olive seed % in JMP
Was dung sole fuel or used as additional fuel?	Compare samples from which seed and wood charcoal remains were investigated	Check whether samples with possible dung also contained wood fuel
What wood fuel was used? Does wood fuel use differ regionally, possibly related with 'principle of least effort' behaviour?	Search for regional patterning in the wood identification results of the samples.	Identify samples. Assign anthracological fuel samples to vegetation zones. Perform CCA analysis on the cleaned wood charcoal dataset with region as factor in the program CANOCO
	In our study region areas receiving more rainfall are expected to have a higher taxon availability. In case people were selecting extremely towards one particular fuel, this pattern would no longer be visible	Depict number of taxa per sample over palaeorainfall in JMP. Calculate palaeorainfall based on present day rainfall, e.g. extrapolation of Soreq Cave stable isotopic data. Perform linear regression and test for its statistical significance
Does wood fuel use change over time and why?	Investigate diachronic changes in fuel use in smaller regions, which allows to hold the locational parameter constant. Select examples from regions that show differences on the CCA	Plot the major results over time in JMP, i.e. evolution of used wood taxa or wood taxa groups, caloric values, rainfall data, and alternative fuel data if available

(*continued on next page*)

Table 1 (*continued*)

Questions	Approach	Method
Can we find indications for sustainable tree management practices contributing to fuel supply? Were trees completely removed or are there indications for sustainable tree management like coppicing or pollarding, that caused fast growth of branchwood? Were pruning remains used?	It is assumed that grape vine and olive charcoal remains typically reflect pruning or tree management remains. Pruning is beneficial for the productivity and health of these plants. The percentages of pruning remains provide information as to the intensity of fruit tree cultivation.	Depict grape vine and olive charcoal % per sample over time in JMP – Display smoothed curves over the dataset to see the trend
	In case of coppicing and pollarding, small diameters with young cambial ages would be expected in the anthracological record, opposed to large diameters and older cambial ages for trunk wood. In an unmanaged tree, trunk wood is growing faster than branch wood (use threshold based on present day data, here lower quartile of GenTree data from trunks).	Measure maximal diameter of *Populus/Salix* charcoal fragments in combination with ring width measurements. Use AD model to reconstruct the original wood diameter. Reconstruct minimal cambial age represented by the fragment and plot over diameter in JMP, after correcting for shrinking (24 %). Compare with coppiced and pollarded willow. Plot over natural growth data for poplar (e.g. GenTree database data) in JMP.
Were people selecting better quality fuel preferentially or did they collect randomly?	Investigate the caloric values of mixtures of wood per oven/hearth context	Collect caloric values for wood species and average them out per genus. Calculate caloric values for wood mixtures. Search for trends in the whole dataset by using the factor palaeorainfall in JMP; plot results over rainfall. Perform linear regression and test for its statistical significance. Search for diachronic trends in smaller regions; plot results over time; display as smoothed curves.
Did people select fuel differently for different fire installation types?	Investigate olive seed percentages, overgrazing percentages, and caloric percentages according to oven/tannur versus fireplace/hearth; analyse conifer percentage distributions over the ovens, hearths and kilns	Statistical analysis to detect significant differences between oven/tannur, fireplace/hearth, and kiln contents in JMP. Select statistic tests according to characteristics of the dataset with regards to dependency, homogeneity of variance, and distribution

2. Materials and methods

2.1. Investigated fire installations

We extracted the non-woody macrobotanical records from 241 fire installations, such as ovens, hearths, and fire pits, represented by more than 91,580 identifications from 42 sites (Fig. 1 and Appendix Tables 2 and 3). We found fewer published wood charcoal than seed samples from fire (related) installations, which is due to the typical focus of anthracologists on secondary refuse deposits to gain insight into long-term vegetation changes (cf. Asouti and Austin 2005) and the overall smaller number of wood charcoal studies compared to seed studies in Southwest Asia (cf., e.g., Deckers et al. 2024b: Appendix Table 1). We added our new wood charcoal identifications from selected oven/hearth contexts to the dataset, comprising 35 new wood charcoal contexts and approximately 6,070 wood charcoal fragments. This results in a dataset of 88 oven/hearth/fire pit/slag heap contexts, represented by more than 23,719 identifications from 28 sites (Fig. 1 and Appendix Table 2). Only 15 contexts included both non-woody macrobotanical records and wood charcoals.

2.2. Pomace use detection

Although pomace/jift might be differentiated from food remains based on fragments versus complete seeds, it is a problem that complete seeds and fragments are not listed separately in publications. Therefore, following Rowan (2015), we assume high proportions of olive seed fragments from fuel contexts indicate the use of pomace/jift (as in Rowan 2015); we set the threshold at 30 %.

2.3. Dung fuel use identification in large seed datasets

Dung pellets have been regularly, though not consistently, recorded in archaeobotanical reports from Southwest Asia (Appendix Table 3a). Their presence or absence was reported for 59 out of 241contexts; more specifically, 13 contained pellets, while 46 showed no pellets. If found in combustion contexts, dung pellets are indicative of dung used as fuel. However, since dung pellets may not be recorded or may be disintegrated through taphonomic processes, we investigate the seed taxa present in oven/hearth/fire pit contexts where dung pellets were recorded. Our assumption is that these may serve as a proxy for indicating dung even in cases where pellets were not found or not recorded. Since overgrazing is often associated with the diminution of wood resources and correlates with increased dung use (e.g., Reddy 1983; Anderson and Fishwick 1984; Barnes 1990), we hypothesize overgrazing signature seed taxa may be a proxy for dung fuel use. Of the list of possible overgrazing signature taxa, *Adonis*, *Anthemis*, *Centaurea*, and *Verbascum* were represented within the samples (cf. Appendix Table 4 with references). Even though some of those may also be frequent in crop fields, these plants expand under intense grazing and are non-desirable plants to the animals but when ubiquitous have a higher chance of being eaten. Regions that cannot produce much wood for climatic reasons are particularly sensitive to grazing (e.g., Abdelsalam 2021). Since there were unequal variances and one group was too small to establish reliably normality of the data, a Kruskal Wallis test was applied using JMP statistical discovery software to detect whether significant differences in rank distribution exist in the proportions of seeds related to overgrazing in archaeobotanical flotation samples with dung pellets and those without, but the third group of 'unknown' was included into the analysis as well. A Dunn's follow-up test then highlighted the specific pairs of groups that show significant differences in their rank distributions (with a significance level of 0.05).

Additionally, Canonical Correspondence Analysis (CCA) was undertaken on the non-woody macrobotanical content of the samples after cleaning the raw dataset, which was as follows: All taxa with less than 12 counts, indeterminate taxa (such as Cereals indeterminate), the Boraginaceae, which likely contained some modern uncharred specimens, and taxa represented in less than four samples were excluded. All samples with less than 30 remaining counts were excluded as well. The analysis was then performed on the percentage values (Appendix Table 3b). We used the program CANOCO to search for patterns of seed/chaff remains associated with dung. A permutation test was undertaken to establish the significance of the relationship.

To investigate whether our assumed overgrazing proxy did not instead represent weeds from crop fields, and entered the record as crop processing by-products, we searched for a relationship between our overgrazing proxy and cereal chaff and culm remains (for list of cereal

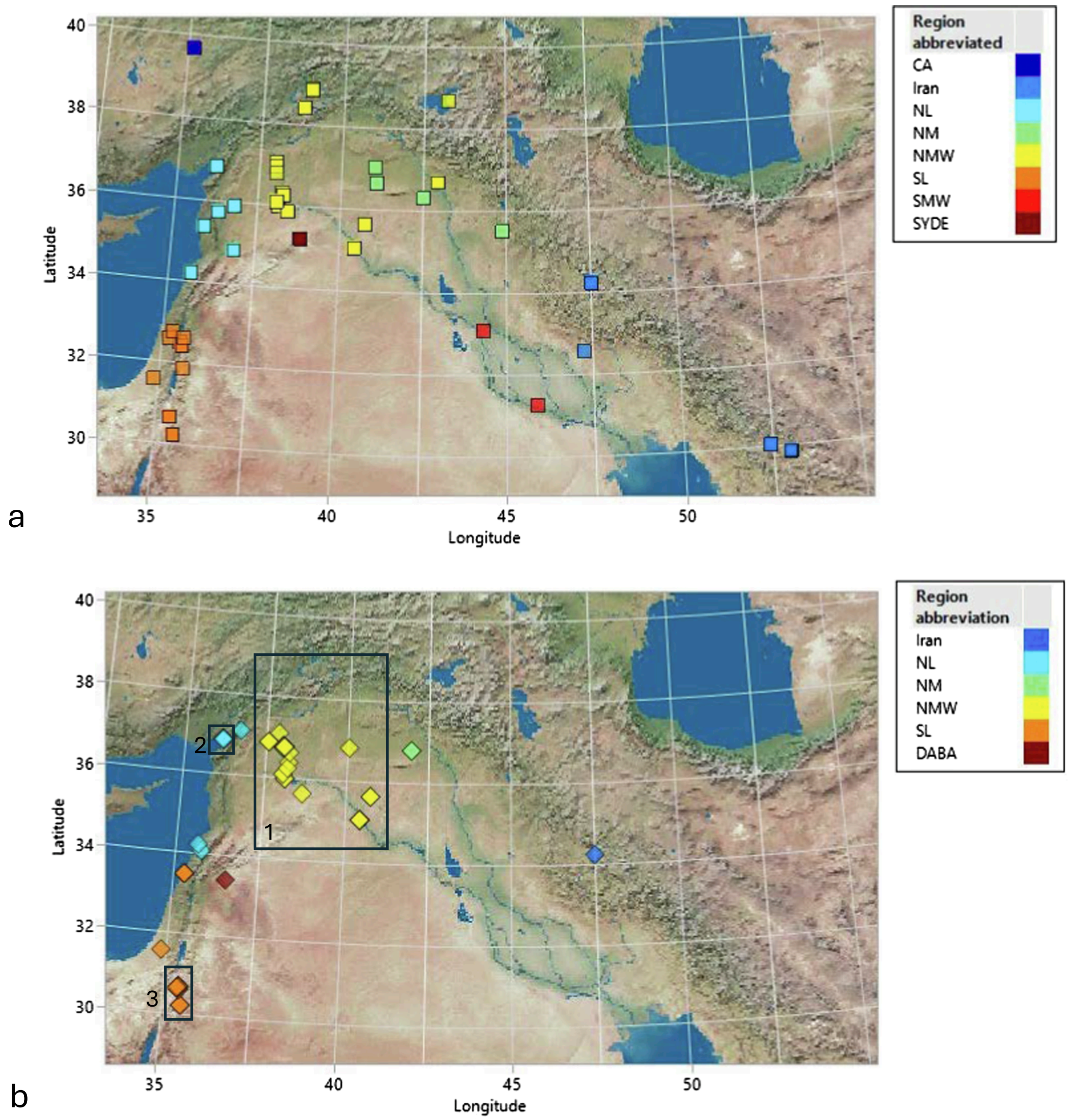

Fig. 1. Map depicting the location of the archaeological sites with a) seed (squares) and b) charcoal (diamond) data from fire installations and slag heaps used in the analysis. The color of the site shows the regional assignment used in this publication. Abbreviations: CA: Central Anatolia, NL: Northern Levant, NM: Northern Mesopotamia, NMW: Northern Mesopotamia along major water body, SL: Southern Levant, DABA: Damascus Basin, SYDE: Syrian Desert, SMW: Southern Mesopotamia along major water. Background map from program JMP. For coordinates of the individual sites cf. Appendix Table 2 and 3. Regions and sites of special interest are indicated in b: 1. Middle Euphrates system (only sites along the major rivers included in this subregion – yellow sites), 2. Kinet Höyük at the foot of the Amanus Mountains, 3. Faynan region.

chaff remain taxa used, cf. Appendix Table 5), though it cannot be excluded that chaff may also have been fed to the animals. We would expect higher proportions of cereal chaff to correlate with higher percentages of our assumed overgrazing proxy if they were weeds in those crop fields. A linear regression test was combined with a variance analysis test (with a significance level of 0.05) in JMP.

To better understand whether dung was used as additional fuel besides wood, we checked the 15 fire installations for which both seeds and wood charcoals were investigated (compare Appendix Tables 2 and 3).

2.4. Approach to understand the role of population pressure on fuel use

To understand population pressure through time, we use the Summed Probability Distribution (SPD) of radiocarbon dates as a proxy for population density derived from Palmisano et al. (2022). This approach assumes that the presence of more people is associated with the occurrence of more datable material, such as food or structures and that their measurement collection is random, which is likely when large datasets are aggregated. The dataset consists of over 11,000 dates from 1020 sites. Given the assumptions, we interpret this curve cautiously and validate it with independent data (Palmisano et al. 2021). We compare the population density proxy with smoothed curves over dung (overgrazing percentage) and pomace/jift (olive percentage), proxies for wood fuel alternatives, using cubic spline smoothing with a low smoothing parameter (lamba = 0.05), which allows for more flexibility in the fit using JMP. This enabled us to reveal underlying trends without too much noise.

2.5. Recognition of regional differences in fuel use

As indicated in Fig. 1 and Appendix Tables 2 and 3, we assigned each site to a geographical region, including Southern Levant, Northern Levant, Northern Mesopotamia, Southern Mesopotamia, Iran, and Damascus Basin. Additionally, within Mesopotamia, we included subregions centered around major water bodies, such as the Euphrates or Khabur Rivers. These regions are marked by different environments, reflecting differences in vegetation today. We then conducted CCA on the taxa wood charcoal percentages of all fire installation and slag heap samples, with the region as the explanatory variable, to understand the local differences in wood/charcoal fuel use. A permutation test was undertaken to evaluate the significance of this relationship. For the CCA we cleaned the charts from noise by deleting taxa that had an extremely low representation or were not exactly identified (like indeterminate, conifer or *Quercus* sp.). Subsequently, taxa that were represented in less than 4 samples were also excluded from the CCA, as well as samples of which hardly anything remained after cleaning. The CCA analysis was undertaken on the newly calculated percentages of the cleaned dataset (Appendix Table 2b).

Furthermore, the contribution of possible pruning remains to fuel wood was also considered to gain insight into the role of land use and social and economic decisions in fuel provisioning by comparing percentages of olive and grape wood between the Levant and Mesopotamia through time (cf. also Deckers et al. 2024b) as both are routinely pruned today.

2.6. The role of human selection of fuel

2.6.1. Investigating possible selection towards burning properties

The preferential selection of wood with higher caloric values was investigated, assuming that greater energy per wood unit would have been desirable for past populations. This is one of several factors that often play a role in market-driven as well as tradition-guided decisions associated with wood as fuel nowadays, along with for example ease of ignition, burn duration, smoke and spark production (e.g., Bahru et al. 2021; Cardosa 2015; Wright 2016). It tends to relate to energy, time and labor efficiency. However, preferences may also depend on specific cultural thermal requirements and particular cultural practices.

Results of empirically measured caloric data in MJ/kg (Appendix Table 1, including references) were collected for the different wood genera. Species-specific data was averaged at the genus level, since we mostly cannot identify wood charcoals at the species level. We calculated the weighted average energy output per kilogram of the wood/charcoal mixture found in the fire installation and slag heap contexts (Appendix Table 1). This was done by considering the contributions of the different types of wood/charcoal present in the sample based on their proportions. For those calculations, we excluded unspecific taxa like Dicotyledon, Chenopodiaceae, Leguminosae, indeterminate wood and taxa for which no caloric data was found, such as *Haloxylon*, and rare minor taxa such as *Ficus*, *Punica*, *Celtis, Zilla spinosa, Ephedra, Moringa,* and *Paliurus/Ziziphus*. For slag heaps, we assume that charcoal was used as fuel and therefore multiplied the caloric values by 1.6 (rounded average of values from MacLeod et al. 2023; Ruiz-Aquino et al. 2019). A linear regression analysis was combined with an analysis of variance (with a significance level of 0.05) to investigate whether more rainfall/lusher vegetation are associated with higher caloric values using JMP. To investigate further the issue of strong selection towards, for example wood with higher caloric values, we also undertook a linear regression analysis to determine whether more rainfall is associated with more taxa. We use reconstructed palaeorainfall as in Hewett et al. (2022), also throughout the publication (cf. modern and reconstructed values in Appendix Table 2).

2.6.2. Investigating functional fuel selection

Additionally, we investigated the role of selective fuel use for different purposes, as in differences in fuel use between fireplaces/hearths and ovens/tannurs. With a Wilcoxon rank-sum test (as non-normal distribution and equal variance characteristics), we checked for significant differences between the two groups of fire installations regarding olive seed percentages, a proxy for jift/pomace and overgrazing taxa, a proxy we establish for dung. While we applied the analysis on the whole dataset for dung, for jift/pomace we only applied it on the Levantine dataset with an additional sample from Tell Taya that contained olive seeds.

We tested for possible statistically significant differences between the caloric values of wood mixtures of ovens/tannurs and fireplaces/hearths with a Wilcoxon rank-sum test (since there is no normal distribution but equal variance). Subsequently, we tested the same for smaller regions, such as Kinet Höyük, the Middle Euphrates with > 400 mm palaeorainfall, and the Middle Euphrates region with < 300 mm palaeorainfall. Respectively, a Welch test was applied for Kinet and the Middle Euphrates dataset > 400 mm (since normal distribution of datasets and unequal variance) and a Wilcoxon rank-sum test for the Middle Euphrates dataset < 300 mm (since non-normal distribution of datasets and equal variance) to detect significant differences in the central tendency, with the Welch test focusing on means and the Wilcoxon rank-sum test on rank distributions.

We also analyzed for Kinet Höyük whether conifers could have been used more in kilns and ovens, than in hearths, which was checked with a Kruskal-Wallis test (as equal variances and insufficient sample size to reliably assess normality). All tests were performed in JMP again at a significance level of 0.05.

2.6.3. Gaining insight into possible wood size selection

We investigated the wood charcoal datasets from the Middle Euphrates region to search for possible indications of management of fuel wood, such as coppicing and pollarding, which would have resulted in the use of wood of mainly small, more uniform diameters since such practices involve the rotational cutting back of twigs to ground level or a stump.

Therefore, where the size of the charcoal fragments allowed it, diameter measurements of the last annual ring on *Populus/Salix* charcoal fragments were measured (cf. Müller 2023) using the digital circle tool. This new data can be found in Appendix Table 6. The circle tool method was applied with a digital Keyence microscope on 110 *Populus/Salix* fragments from fire installation contexts of the Middle Euphrates region. Due to the thin rays of *Populus/Salix*, it was impossible to apply trigonometric measurements, which are known to provide better results (Paradis-Grenouillet et al. 2013).

To reconstruct the diameter of the original wood used in the fire installation contexts, the AD model was used as detailed in Dufraisse (2006). Ring widths were also measured, where possible (n = 288) (cf. Müller 2023). We used the average ring width per fragment to calculate an approximate cambial age for the last ring represented on the charcoal fragments (using the methodology as in Deckers et al. 2024a) (Appendix Table 6). Furthermore, we used cambial age and diameter data from unmanaged, coppiced, and pollarded poplar wood from Out et al. (2013) and unmanaged black poplar trees from the GenTree database to compare our approximate cambial ages over diameters (Martínez-Sancho et al. 2020). To compare the charcoal with fresh wood data, we took a shrinking factor of 24 % into account (Paradis-Grenouilet and Dufraisse 2018). The corrected archaeological data did not overlap with any of the *Populus nigra* values likely due to slower growth in the Syrian Middle Euphrates; we divided the GenTree annual growth data by 2.6 to make the data fit. This is the lowest factor to achieve overlap of the two datasets. We only used datasets overlapping in diameter with the archaeological values for reconstructed cambial ages between 10 and 30 years. Testing the methodology by reconstructing cambial ages using the GenTree dataset showed that values between 0 and 30 years gave better results than those > 30 years. This is due to the reduction of growth as the trunk gets broader/older, which causes an overestimation of the reconstructed cambial age. We did not include the first ten years of cambial ages for matching the datasets since if coppiced and pollarded samples or small branches are represented; they would be mainly in this group. This way, we included the growth data from FRPO0603, FRPO0637, FRPO0702, FRPO0711, FRPO0715, FRPO0718, FRPO0604, FRPO0701, FRPO0712, FRPO0714, FRPO0723, FRPO0601, FRPO0605, FRPO0609, FRPO0638, FRPO0704, FRPO0705, FRPO2046, FRPO0722, FRPO0721, FRPO0638, FRPO0724 (Martínez-Sancho et al. 2020).

We also attempted to differentiate between branches and trunk wood, since unmanaged branches would have typically grown slower than the trunk (Dufraisse et al. 2018). For this purpose, we used a threshold set by the lower quartile value of 685 ring width measurements from *Populus nigra* trunks from southern Europe, also derived from the GenTree dataset. Without the 2.6-factor correction mentioned above, this value was 1.12 mm/year, whereas it was 0.431 mm/year applying it. We tested both.

Additionally, where wood charcoal fragments allowed it for Kinet Höyük, diameters were measured from all possible taxa, using the paper stencil method to give insight into the size of the wood used as fuel (Appendix Table 7). Research by Müller (2023) demonstrated that this method provides results comparable to those of the digital circle tool.

2.7. Determining local diachronic changes in fuel use

We focused on three regions with abundant diachronic data to understand fuel use in greater detail over time: the Middle Euphrates, Kinet Höyük at the foot of the Amanus, and the Faynan region (Fig. 1b, respectively, areas 1, 2, and 3). Zooming in on these regions allows us to hold the locational parameter constant.

2.7.1. Approach for the Middle Euphrates region

The Middle Euphrates region (Fig. 1b area 1) saw substantial settlement expansion in the 3rd millennium BC (Wilkinson et al. 2012). Rainfall reaches from 530 mm in the north to 160 mm in the south.

The wood charcoal identification results for the Middle Euphrates system are summarized according to environmental groups such as riverine forest, woodland (steppe), imported, and *Olea/Vitis*, with taxon attribution to an environmental group as detailed in de Gruchy et al. (2016, Appendix B). We divided our datasets between the Northern Middle Euphrates and Southern Middle Euphrates to consider the rainfall gradient, with the dividing line at 300 mm reconstructed annual rainfall since this is known to correlate with differences in land use and vegetation (Wilkinson et al. 2014). We also compared the data with local proxies for wood fuel alternatives, including overgrazing taxa and olive percentages. All results for the different groups are depicted as smoothed curves over the diachronic samples using cubic spline with lambda set to 0.05 in JMP.

For this region, we additionally also investigated in greater detail possible fuel selection factors, such as heating quality of wood, woodland management, and functional differences as described in 2.6.1, 2.6.2 and 2.6.3.

2.7.2. Approach for Kinet Höyük at the foot of the Amanus in the Northern Levant

In the Northern Levant, we investigated wood fuel use at the site of Kinet Höyük at the foot of the Amanus (Fig. 1b area 2), which is known for its rich and diverse woody vegetation (Aytaç and Semenderoğlu 2011; Zohary 1973; Meiggs 1982) and receives rainfall up to 695 mm annually today. Kinet Höyük was likely a significant center for exporting precious wood in the Bronze and Iron Age (Akar 2009; Watson-Treumann 2000).

We use palaeorainfall data calculated as in Hewett et al. (2022) to understand the relationship between diachronic changes in rainfall amount and fuel, reflecting possible changes in vegetation. We also include diameter results as described in 2.6.3 to gain insight into the size of fuel wood exploited. To understand the evolution of the heating quality of the wood used, we depict the weighted average caloric values of the mixtures of wood charcoal found (cf. 2.6.1).

2.7.3. Approach for the Faynan region in Jordan

A third zone of focus is the hyperarid Faynan region in Jordan (Fig. 1b area 3), receiving only ca. 30 mm rainfall annually today and with very scarce woody vegetation cover. However, there is substantial evidence for intensive copper production, which would have required large amounts of wood charcoal.

We mainly focused on diachronic changes in fuel use based on wood charcoals from slag heaps between 2700 and 500 BC, as published in Engel (1993) and Baierle et al. (1989).

We investigated the heating value of the charcoal mixtures used over time and again compared our results to changing rainfall patterns.

3. Results

3.1. Dung fuel use

A Kruskal Wallis test indicates significant differences in the rank distributions of proportions of overgrazing percentages for the fire installations with dung pellets, without dung pellets, and those where it was not recorded (unknown) (X^2 for overgrazing %= 27.826, p = 0.0001=, df = 2). More specifically, Dunn's follow-up test showed significant differences in rank distributions between those samples with and without dung pellets ($p = 0.0001$). Those with pellets have a higher median than those without and unknown dung pellets, however, the greater variability and spread of those with dung pellets also contributed to the observed significant differences in their rank distribution. Hence, higher grazing levels are associated with dung as fuel/overgrazing taxa in fuel contents.

The CCA (Fig. 2) shows a fairly strong pseudo-canonical correlation of 0.710 between the species composition and the presence of dung on axis 1, which indicates a relationship between the species composition and recorded dung pellet presence/absence, but only a small percentage of the total variation is explained by this (3.86 % − adjusted explained variation when taking the degrees of freedom into account = 1.7 %). The relationship between the species composition for the samples and dung presence/absence is statistically significant, as indicated through a permutation test (pseudo-F = 1.8, p = 0.006). Notably, *Anthemis* (ANTHSPE), *Adonis* (ADONSPE) and *Verbascum* (VERBSPE), taxa typically considered indicative of overgrazing seem to be associated with dung in the CCA diagram. *Centaurea* (CENTTYP) takes a position in between dung and no dung pellets in the samples, suggesting it may also have been introduced into the contexts through the cereal harvest. Therefore, the dung/overgrazing proxy should be interpreted with care.

Wheat and barley chaff (TRITCHA and HORDIR) also seem to take a position in between with dung pellets and without, suggesting they may have been fed to the animals in some cases. *Avena* sp. (AVENSPE), *Vitis* sp. (VITISPE) and *Olea* sp. (OLEASPE) finds show a close association with absence of dung pellets, suggesting they were not typically used as fodder or preserved in dung. The major weeds (*Lolium* LOLISPE, *Bromus* BROMSPE, etc.) also show a closer association with installations without dung pellets, whereas geophytes and 'anti-agricultual' weeds (salinity indicators) show a closer association with dung pellet presence.

The analysis did not indicate a statistically significant linear relationship between overgrazing taxa percentages and cereal chaff (Fig. 3) (F (1, 217) = 0.331, p = 0.566), which is in support of them being a proxy for dung. While there is one sample from Tell Brak with dung pellets that shows high percentages of cereal chaff and culms associated with high overgrazing percentages, quite some samples with high overgrazing taxa show rather low percentages of cereal processing waste (Fig. 3). Fig. 4 depicts all sites with overgrazing indicators and dung pellets, i.e., those with possible dung fuel use. Dung fuel appears to be represented in most of the settled regions of Southwest Asia. Northern Mesopotamia has some early indications for dung use along the

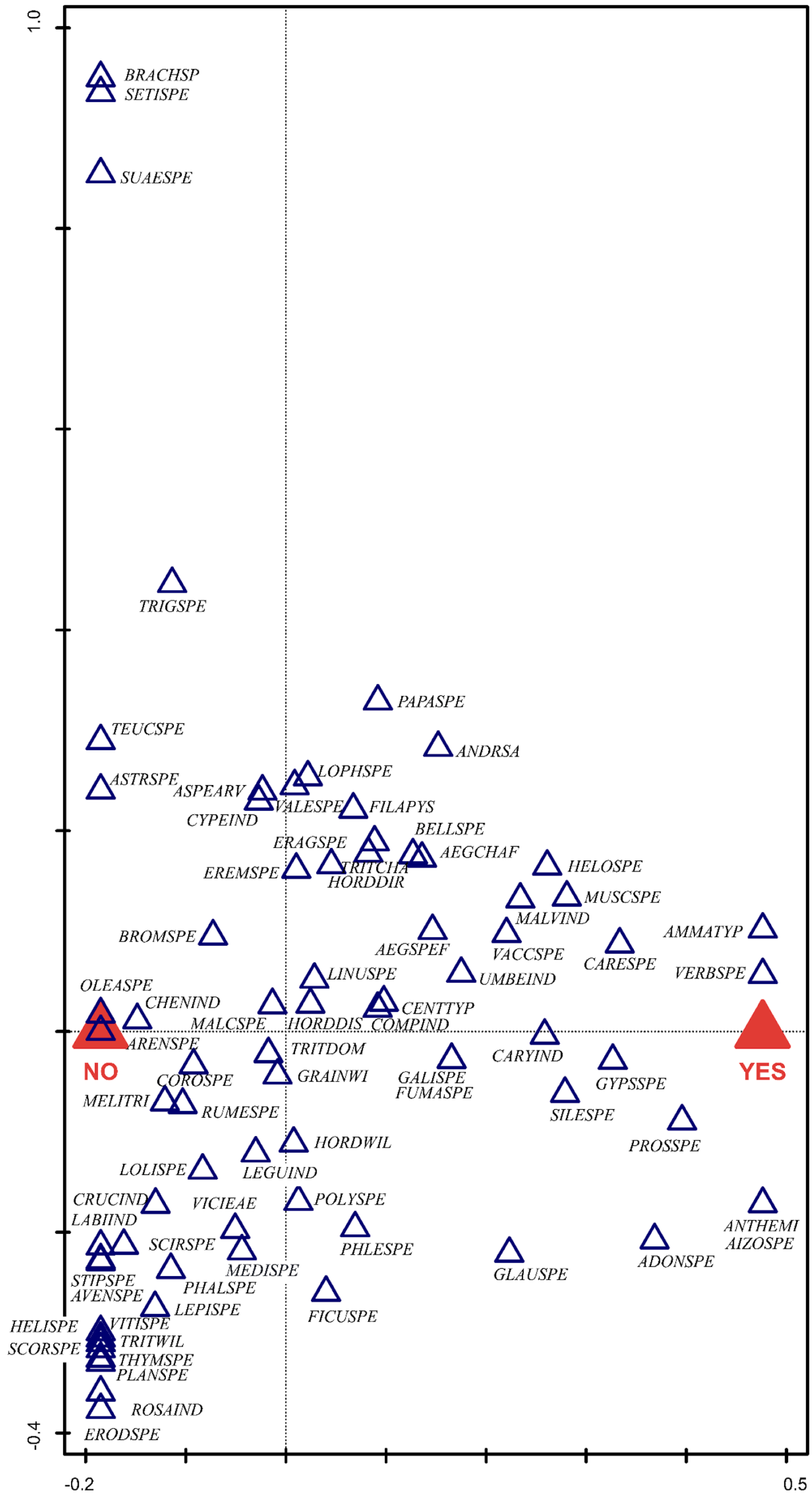

Fig. 2. CCA diagram depicting the species distribution for non-woody macrobotanical samples from fire installation contexts with (yes) or without dung pellets (no) based on data as in Appendix Table 3b.

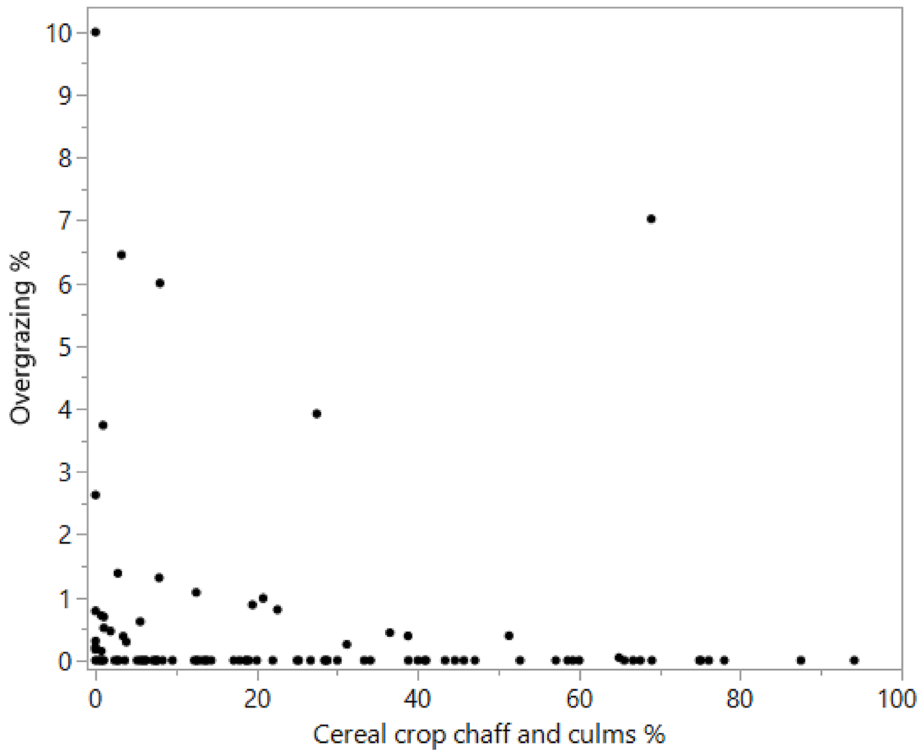

Fig. 3. Depiction of overgrazing taxa percentages over cereal chaff and culm percentages of non-woody macrobotanical remains for the different oven, hearth, fire pit samples (as in Appendix Table 3a).

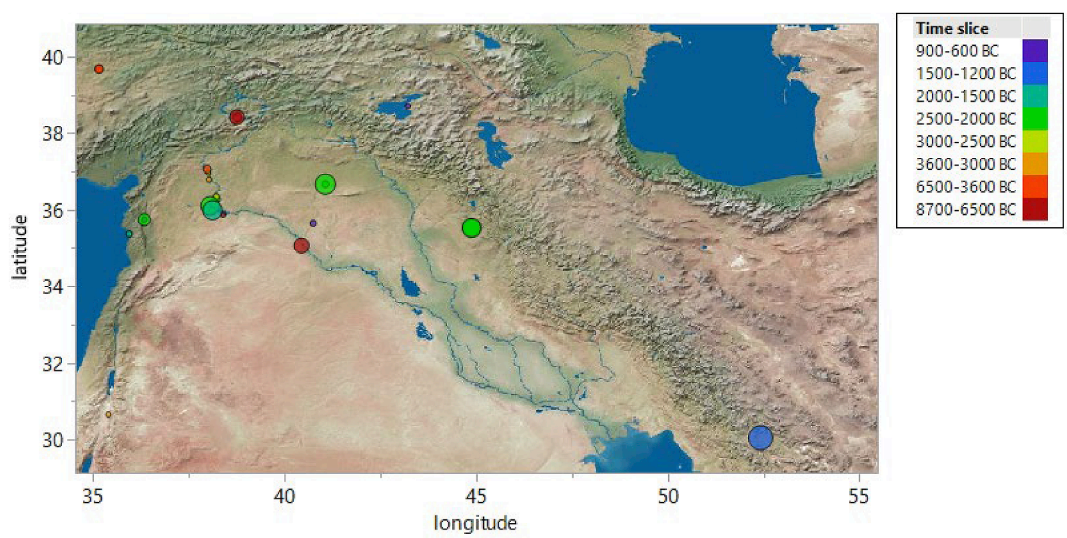

Fig. 4. Distribution of sites with dung proxy indicators in fire installation contexts (overgrazing taxa and dung pellets for one site without overgrazing indicators). Color scale indicates chronology, while size scale reflects the percentage of overgrazing taxa (For exact % values cf. Appendix 2). One site mapped did not have overgrazing indicators, but instead dung pellet presence (Tell Jerablus, the smallest orange dot). Background map from program JMP.

Euphrates system (period 8700–3600 BC). In the period between 2500 and 1500 BC, overgrazing becomes visible at sites towards the steppe zone at the center of the Fertile Crescent. There is less data for the later periods, but there is a remarkably high value for overgrazing indicators at Malyan in Iran in 1500–1200 BC.

For the 15 samples where both seed and chaff and wood charcoal were investigated (Appendix Table 2 and 3), those with indicators for dung as fuel also contained wood charcoal, indicative of a mixture of wood and dung as fuel. There is a research bias causing an overall lack of samples for which both wood charcoal and seed results are published, which is related to different specialists working on the samples and a longer tradition of seed investigation.

3.2. Pomace/jift fuel use

The distribution of olive seeds in fuel samples, which may indicate pomace/jift, shows a particularly high proportion in the Levant (Fig. 5). However, evidence of this type is completely absent from the northernmost part of the Northern Levant. Olive seeds start to occur in larger proportions in fuel from 3000 BC onwards, mainly in the Levant. Of note

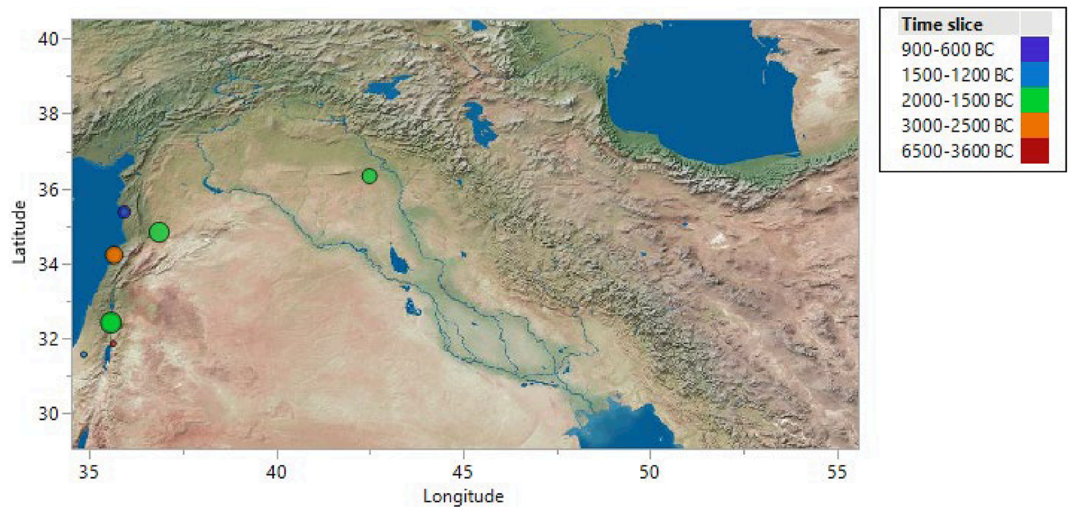

Fig. 5. Sites with olive seed proportions in their fuel contexts. Except for the smallest scale of dot, that is < 5 %, all dots represent > 30 % olive seeds in a hearth/ oven/ context (for exact % values cf. Appendix Table 3a). The size of the dots indicates its relative proportion while the color indicates the period of occurrence. Background map from program JMP.

is the 2000–1500 BC distribution near the inner part of the Fertile Crescent, i.e., in a more arid environment (Fig. 5).

3.3. The role of population pressure in dung and pomace/jift fuel use

Fig. 6 depicts the proxies for dung and pomace/jift and population levels (SPD of radiocarbon dates) over time. There are similarities between the population density curve and the dung and pomace/jift. The dung proxy appears to follow the population density proxy remarkably, with a sharp increase around the 3rd millennium BC and higher values until around 500 BC. While the 3rd millennium BC rise in calibrated radiocarbon curve is corroborated by archaeological survey, the 500 BC decrease is not and is likely a product of archaeologists taking fewer radiocarbon dates (Palmisano et al. 2022). The dung proxy also shows a slight increase in the sixth millennium and 4th millennium BC (Fig. 6). However, a more substantial increase occurs in the 3rd millennium BC

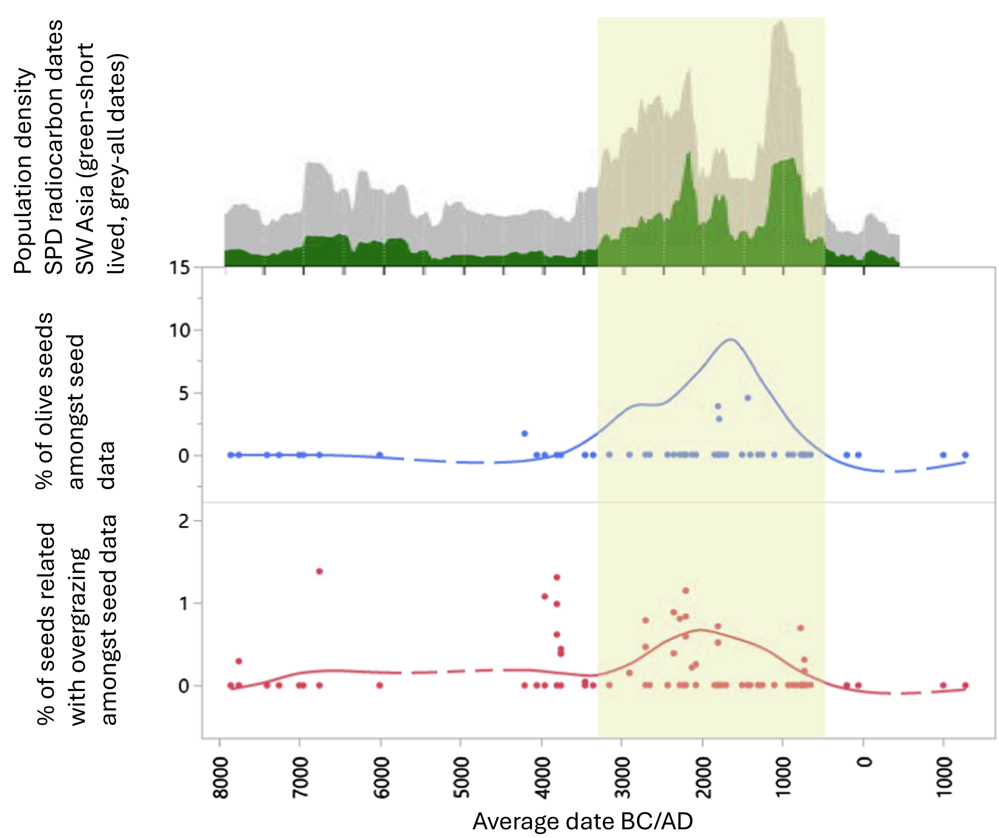

Fig. 6. Depiction of trends of proxies for population density (after Palmisano et al. 2022) and proxies for alternative fuels, such as smoothed curves for jift/pomace and dung, respectively *Olea* seed % and overgrazing seed % (based on 241 contexts for the dung proxy and 219 for the jift/pomace proxy, cf. data Appendix Table 3a). Note that we zoomed in on the smoothed curves and therefore, fire installations with higher percentages of olive seeds and dung proxies were cut off from the graph.

with a peak around 2000 BC and seems to decrease again by 400 BC. The pomace/jift proxy increases in the 4th millennium BC, peaks around 1500 BC, and declines again until ca. 500 BC.

3.4. Regional differences in wood (charcoal) fuel use

The CCA on the wood charcoal data from all oven/hearth/slag heap samples indicates that the regional location had a significant influence on the composition of the sample (Fig. 7). The variable region explains 30.4 % of the total variation in charcoal taxa (26 % when taking the degrees of freedom into account). 18.57 % of the variation is depicted in the first two axes (Fig. 7). The high pseudo-canonical correlation coefficients (0.922 (Axis 1), 0.878 (Axis 2), 0.877 (Axis 3), 0.911 (Axis 4)) indicate a strong relation between charcoal taxa and region. The permutation test results back the statistical significance of the model with a pseudo-F value of 7 and *p*-value of 0.002, indicating that the observed correlations are unlikely to have occurred by chance. Especially the Southern Levant, Northern Levant and Northern Mesopotamia along major water bodies show a different grouping (Fig. 7b). Local regional conditions, like the availability of wood in general and particular species such as olive, seem to have strongly influenced fuel use. For example, in Northern Mesopotamia along the Euphrates and Khabur (cf. NMW Fig. 7), the samples strongly associate with riverine species (*Populus/Salix*, *Ulmus*, *Alnus*, *Phragmites*), and *Lycium*. In the Northern Levant there is the strongest association with *Pinus* (Fig. 7a), that is a considerable vegetation component of the Amanus Mountains and foothills. The Southern Levant shows a strong exclusive association with saline and irrigated conditions typical for the Jordanian region, like *Vachellia*, *Phoenix*, *Retama raetam*. While the Northern and Southern Levantine samples are different in their composition (Fig. 7b), there is a continuum of typical Mediterranean taxa common to both regions that are plotted between both regions, with in the north a stronger association with *Vitis*, *Arbutus* and *Olea*, while in the south a stronger association with *Pistacia* and evergreen *Quercus*, and *Rhamnus/Phillyrea* located exactly in the middle (Fig. 7a).

Iran and Northern Mesopotamia show an association with deciduous *Quercus* and *Prunus* subgenus *Amygdalus*, *Prunus* and Maloideae (Fig. 7a).

The contribution of olive and grape wood to fuel through time in the Levant and Mesopotamia is detailed in Fig. 8. Both olive and grape wood made a more significant contribution to fire installations in the Levant compared to Mesopotamia, with olive especially having a notable contribution to fuel wood in the Levant. At the same time, this firing material appears relatively unimportant for Mesopotamia. However, diachronic changes are visible, with olive wood charcoal increasingly represented from 3000 BC in the Levant and 2000 BC in Mesopotamia onwards. In most cases, grape wood has not played a significant role in the fuel wood of Southwest Asia. There is, however, an increase in its presence in the Levant after 1000 BC. The latter signal derives primarily from the Northern Levant, specifically the site of Kinet Höyük, located in a region with access to considerable wood resources.

3.5. Local diachronic changes in fuel use

3.5.1. Kinet Höyük at the foot of the Amanus in the Northern Levant

Fig. 9 summarizes the evolution of the major taxa represented in fuel

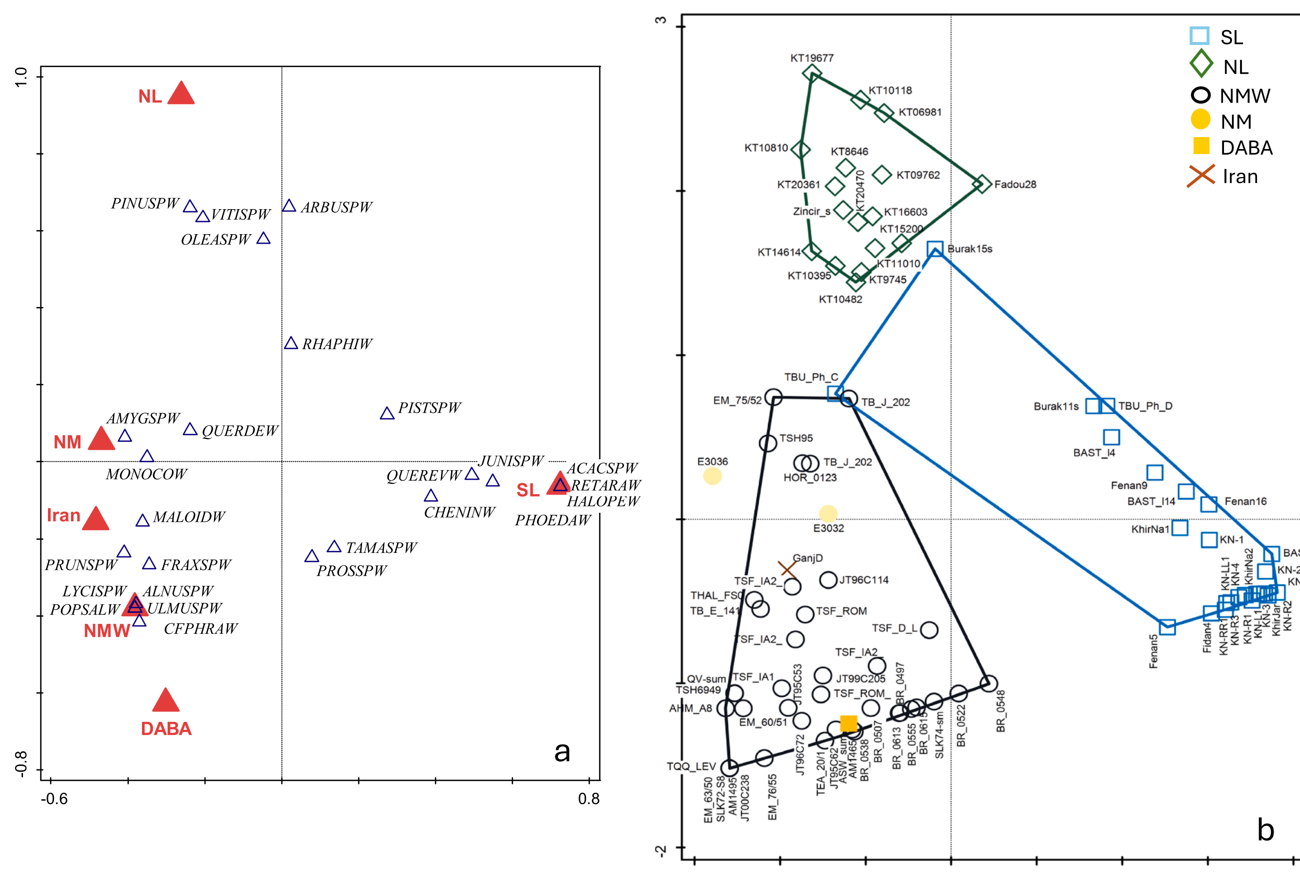

Fig. 7. CCA results of wood charcoal taxa representation in archaeological fire installation contexts and slag heaps from Southwest Asia. a. Associations of species with regions, b. Plot that shows the delineation of the regions with their individual samples (Shortened sample labels as in Appendix Table 2b, cleaned file). Abbreviations for regions: NL = Northern Levant, SL = Southern Levant, NMW = Northern Mesopotamia near considerable water body, NM = Northern Mesopotamia, DABA = Damascus Basin and Iran.

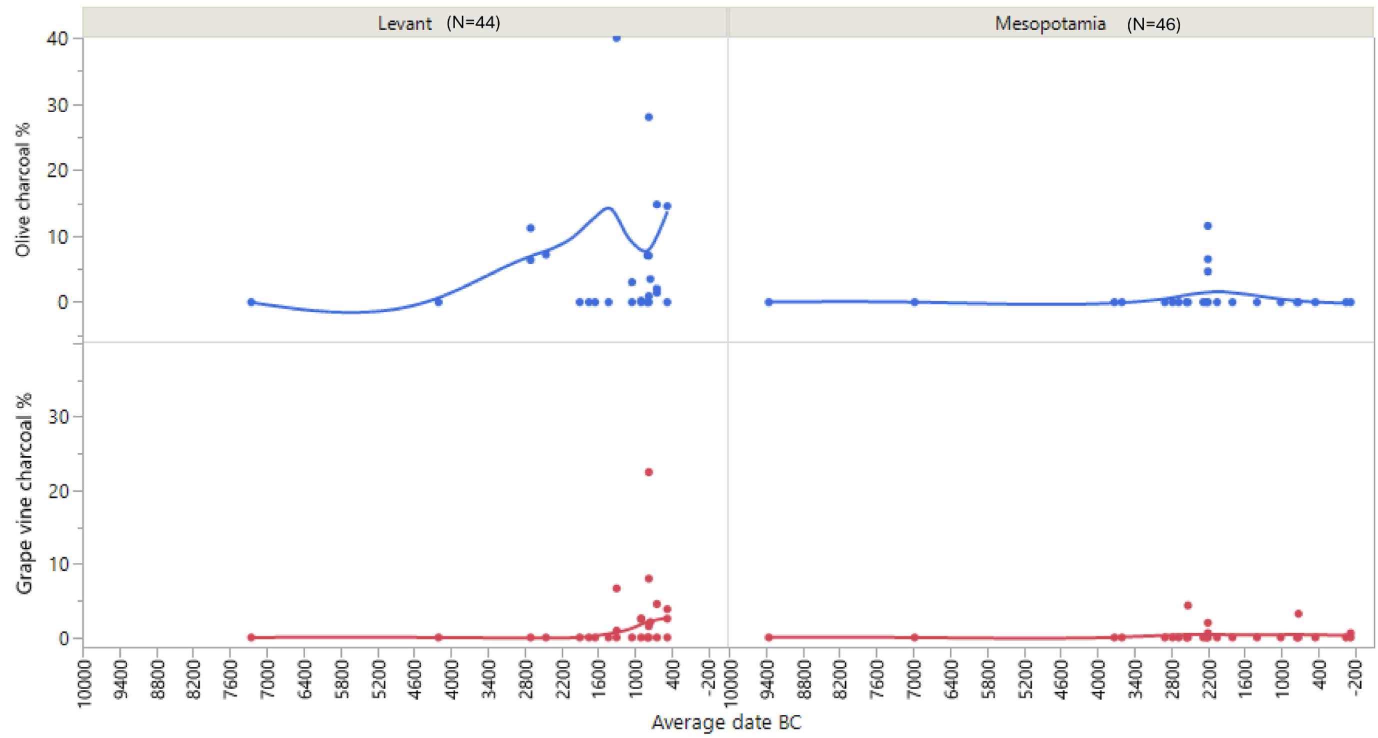

Fig. 8. Comparison of grape and olive wood charcoal proportions over time in fire installation contexts in the Levant versus Mesopotamia with smoothed curves over the dataset (data as in Appendix Table 2a).

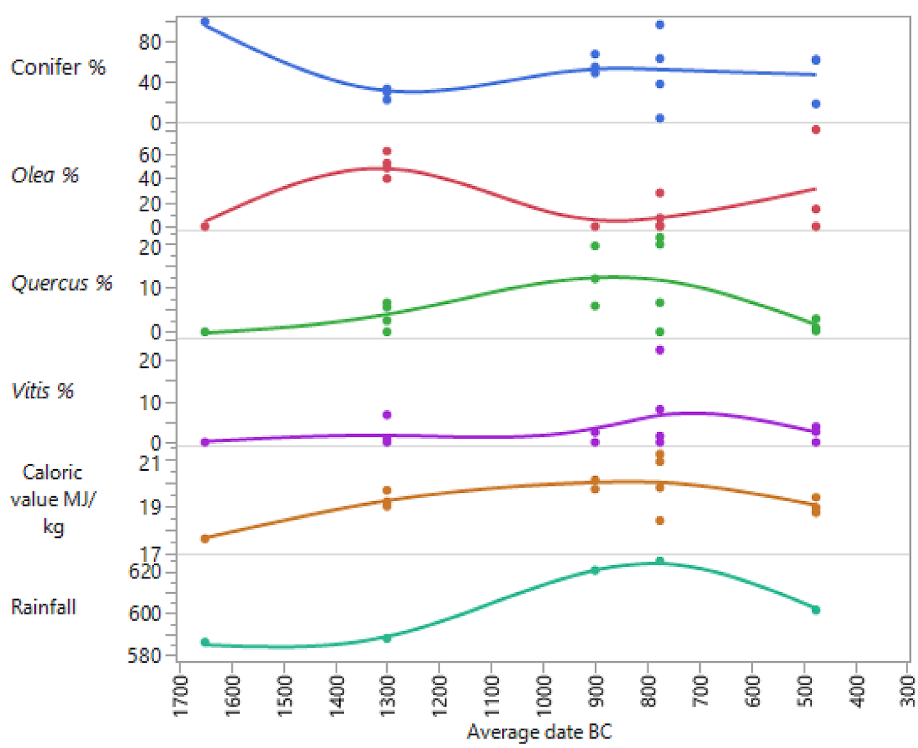

Fig. 9. Major lines of fuel use through time at Kinet Höyük near the Amanus Mountains in the Northern Levant depicted against paleorainfall in mm (methodology as in Hewett et al. 2022). For details of the individual samples and all taxa, see Appendix Table 2a.

contexts through time at this site. In the first half of the second millennium BC, conifers in the sample dominated. Around 1300 BC, *Olea* wood started to contribute strongly to the fuel wood, while conifers reduced somewhat in importance but remained strongly represented between 1300 and 400 BC. *Olea* wood charcoal percentages decrease again from 900 BC in favor of oak, and there is a slight increase in grape vine charcoal. Around 500 BC, *Olea* wood charcoal again increased somewhat while oak decreased. While there is some variability in caloric values of the oven/hearth contents, there appears to be a trend towards fuel with higher caloric values from 1700 to 800 BC, related to increased

Quercus and *Olea* wood, which decreases again around 475 BC.

3.5.2. The Faynan region in Jordan

The main wood taxa coming from slag heap contexts of the Southern Levant dated between 2800 and 400 BC are indicated in Fig. 10. These contexts represent fire installation refuse related to metallurgy. Of note is the similarity in the curves of *Juniperus*, the average reconstructed rainfall, and caloric values of the wood combination through time. Fig. 10 shows high percentages of *Juniperus* and a small proportion of *Olea* in the 3rd millennium BC samples, parallel with higher rainfall and caloric values compared to later samples. The *Juniperus* and *Olea* percentages decrease through time, parallelled by lower rainfall values, while *Tamarix* and *Retama* become strongly represented, although implying lower caloric values. Of note is the low contribution of *Phoenix* in some later contexts, i.e., from 1050 to 475 BC (center point of phase).

3.5.3. The Middle Euphrates region

For the Middle Euphrates region, the large amount of data regarding the diachronic evolution of fuel use is summarized in Fig. 11, where the moister Northern part (>300 mm) and the more arid Southern part (<300 mm) are separated. Riverine woodland is strongly represented amongst wood charcoals. However, in the north, non-riverine woodland, such as woodland (steppe) taxa, including oak and olive/grape wood, make up a certain proportion between 3000 BC and 50 AD. In the Southern Middle Euphrates, on the contrary, non-riverine woodland taxa are rare, as are olive and grape pruning remains. However, from the 2nd millennium BC onwards, the use of imported conifers increased, with a peak in the 1st millennium BC. Amongst the seeds from the more arid Middle Euphrates, from the later 3rd millennium BC onwards we also observe a higher percentage of seeds related to overgrazing and possibly dung fuel use, while in the moister Middle Euphrates, no such increase is visible. Jift/pomace does not seem to have played a role as fuel in the Middle Euphrates region, as indicated by extremely low olive stone percentages in fuel contexts. There is, however, little seed data from fire installations from the second and first millennium BC in the Northern Middle Euphrates region which partially relates to the less dense occupation compared to the 3rd millennium BC (Wilkinson et al. 2012) and the archaeobotanical focus on later and earlier periods.

3.6. Human selection in fuel quality or purpose?

3.6.1. Selection for heating quality?

There is a significant linear relationship between reconstructed rainfall and caloric values considering all fuel contents from Southwest Asia (Fig. 12a), with higher caloric values in zones with more rainfall. However, it is a weak relationship as only 7.66 % of the variance in caloric values is explained by rainfall ($F (1,64) = 5.313$, $p = 0.024$). This pattern is strongly influenced by the inclusion of oak, that has a high caloric value but also tendentially occurs more in moister zones of this region.

Regarding the reconstructed caloric values for the wood contents of ovens/hearths from the Middle Euphrates region, there appears to be some variability, though also an overall trend with lower caloric values in zones of lower rainfall, as indicated by the linear regression (Fig. 12b) that shows a weak but statistically significant linear relationship ($p = 0.014$), explaining ca. 16 % of the variation of the caloric values ($F (1, 37) = 6.690$).

We also found a slight but significant linear relationship between the number of taxa and the reconstructed rainfall for Southwest Asia (Fig. 12c), with more different taxa in the sample upon higher rainfall. Only 8.13 % of the variability in the number of taxa can be explained by rainfall, with $F (1,85) = 7.522$, $p = 0.007$).

3.6.2. Selection for functional differences?

As for the possible selection of fuel for fire installation-specific purposes, no statistically significant difference in rank distributions could

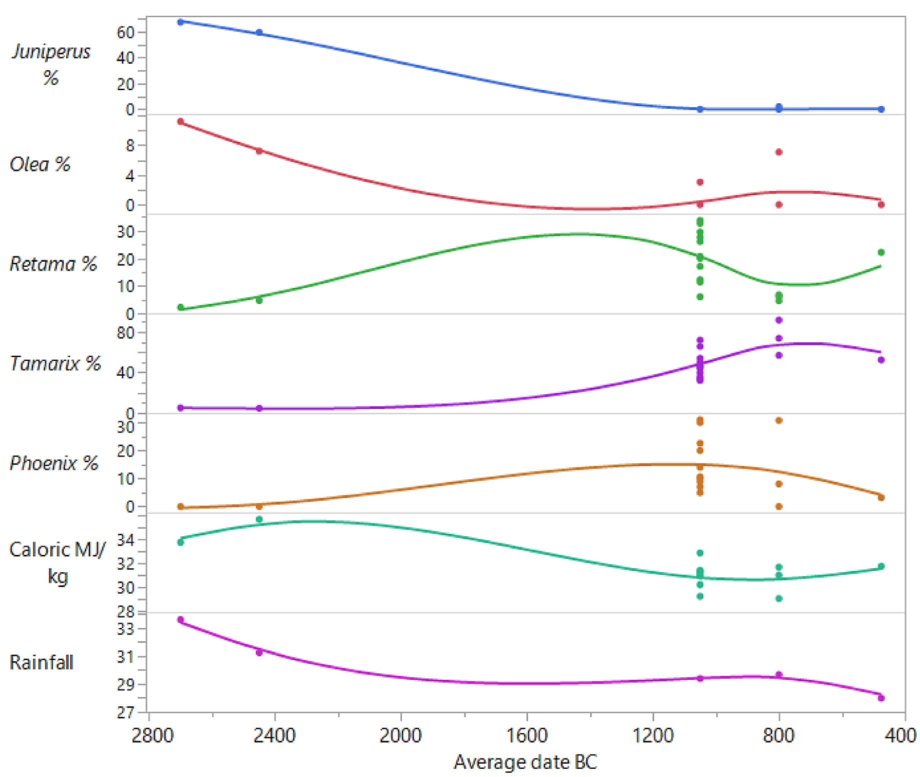

Fig. 10. Summary of some major results regarding fuel use related with metallurgical production in the Faynan region of the southern Levant, depicted against paleorainfall in mm (methodology as in Hewett et al. 2022). Data included from the sites Fenan, Khirbet en-Nahas and Khirbet el-Jariye (cf. also Appendix Table 2a with references).

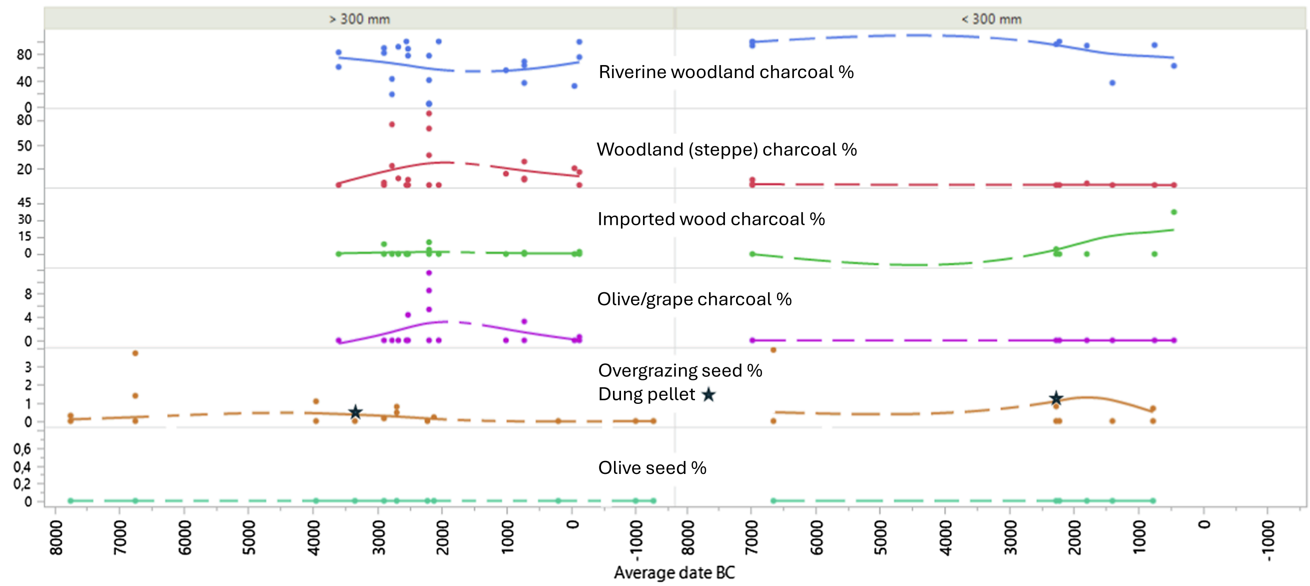

Fig. 11. Summary of wood charcoal and seed data from fire installation contexts for the Middle Euphrates system, divided by sites that received more than 300 mm (reconstructed) rainfall and those receiving less than 300 mm.

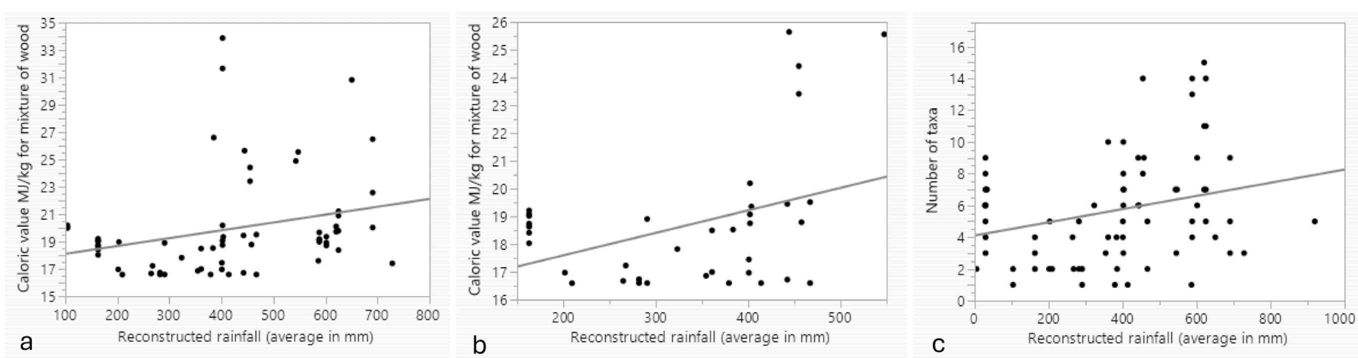

Fig. 12. Reconstructed average caloric value for wood of fuel contexts depicted against the reconstructed average rainfall (after Hewett et al. 2022) (Data as in Appendix Table 1). a. for all samples from Southwest Asia. No slag heap data was depicted, c. for the Middle Euphrates. The rainfall gradient is from high in the north to low in the south in this region. b. Number of wood/charcoal taxa over reconstructed annual average rainfall (after Hewett et al. 2022) (cf. raw data Appendix Table 2). Slag heap data is included. Linear regression line is indicated.

be detected between the overgrazing percentages, i.e., dung proxy percentages in ovens/tannurs and fireplaces/hearths ($Z = -0.901$, $p = 0.368$). However, a significant difference was detected in rank distributions between fireplaces/hearths and ovens/tannurs regarding olive seed percentage ($Z = -2.576$, $p = 0.010$). Notably, olive stones were present only in oven/tannur contexts. This indicates a tendency for higher olive percentages in oven/tannur contexts compared to fireplaces/hearths.

Furthermore, no statistically significant differences could be determined between the distributions of caloric values of ovens/tannurs and fireplaces/hearths based on a Wilcoxon rank-sum test ($Z = -1.583$, $p = 0.114$). However, for the Middle Euphrates region with $>$ 400 mm palaeorainfall a Welch's *t*-test revealed a significant difference in the means of the caloric values of fireplaces/hearths and ovens/tannurs ($F(1, 9.353) = 12.516$, $p = 0.006$), notwithstanding/though the sample is small, with fireplace/hearth contexts showing a tendency for higher means of wood mixtures of fireplaces/hearths compared to oven/tannurs. In the Middle Euphrates $<$ 300 mm palaeorainfall, no significant differences in rank distributions of caloric values in ovens/tannurs and fireplaces/hearths were found using a Wilcoxon rank-sum test ($Z = -1.381$, $p = 0.167$). Also, at Kinet Höyük, no significant differences between the mean caloric values of the fuel in ovens and hearths were visible using a Welch test ($F(1, 8.61) = 0.003$, $p = 0.959$), despite differences in the variability.

Additionally, no significant differences could be detected in the rank distribution of conifer wood percentages in kiln, oven or fireplace/hearth contexts at Kinet Höyük ($\chi^2 = 0.160$, $df = 2$, $p = 0.923$), though interpretation is limited due to the small sample number.

3.6.3. *Wood size selection?*

Appendix Table 6 presents the results of the diameter and ring width measurements of *Populus/Salix* charcoal fragments from the Middle Euphrates region, including the approximate calculation of the maximal cambial age represented on the charcoal fragment. Primarily, *Populus* was measured. The corrected results of the Early Bronze Age Middle Euphrates show an exploitation of mainly smaller diameters, especially within the groups 4–7 and 2–4 cm. However, there is also evidence for utilizing larger diameters (Fig. 13).

Shrinking corrected *Populus/Salix* diameter measurements from Early Bronze Age oven/hearth contexts are plotted on Fig. 14 against their estimated cambial age, alongside reference data from Out et al. (2013) for unmanaged, coppiced, and pollarded European willow. For the Middle Euphrates wood charcoals, we observe a cluster of cambial ages between 5 and 7 for diameters around 4 to 5 cm, possibly indicative

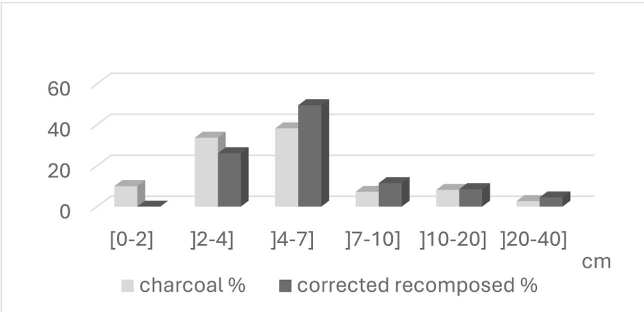

Fig. 13. Reconstruction of the original wood diameters (in cm) of Early and Middle Bronze Age wood charcoal samples from oven/hearth contexts from the Middle Euphrates, as calculated with the analysis Diameter Tool, the AD model applied to 110 *Populus/Salix* charcoal fragments (Dufraisse et al. 2006 and https://dendrac.mnhn.fr/spip.php?rubrique70, Accessed 7.3.2024). 104 samples were from the Early Bronze Age, while 6 were from the Middle Bronze Age.

of coppicing or pollarding, though with a slightly slower growth than the European *Salix*, and somewhat longer rotation. Note that this reference is based on roundwood, whereas the Middle Euphrates wood charcoal data is based on minimal diameters. We may therefore underestimate the diameters and cambial age of the ancient data. The ash deposit wood charcoal data, which may also include unintentional fuel remains like conflagration remains, shows a mixed pattern, with some fragments overlapping with the coppicing and pollarding references, and others with unmanaged wood (Fig. 14).

The shrinkage-corrected ancient *Populus/Salix* data from the Middle Euphrates are also compared with the present-day dendro-measured *Populus nigra* data from the GenTree database (Martínez-Sancho et al. 2020). As described in the methods section, we divided GenTree diameter data by 2.6 to make the data fit approximately. Fig. 15 shows transformed datasets that overlap with the archaeological values for reconstructed cambial ages between 10 and 30. The resulting pattern of the archaeological data for the Middle Euphrates in Fig. 15 is less clear than in Fig. 14. Some wood charcoals show large diameters for their

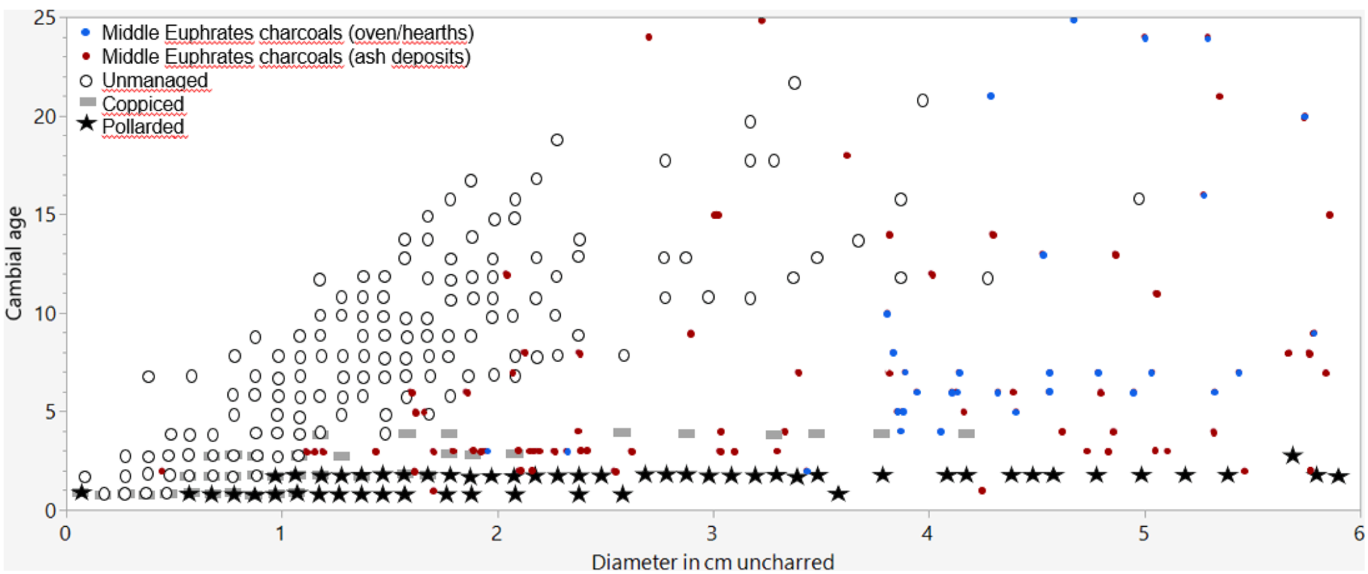

Fig. 14. Cambial age plotted over diameter for Middle Euphrates *Populus/Salix* charcoals from Early Bronze Age fire installation and ash deposit contexts compared with present day *Salix* branch data from the Netherlands and Denmark for unmanaged, coppiced, and pollarded trees as published in Out et al. (2013). Raw data for Middle Euphrates region see Appendix Table 6.

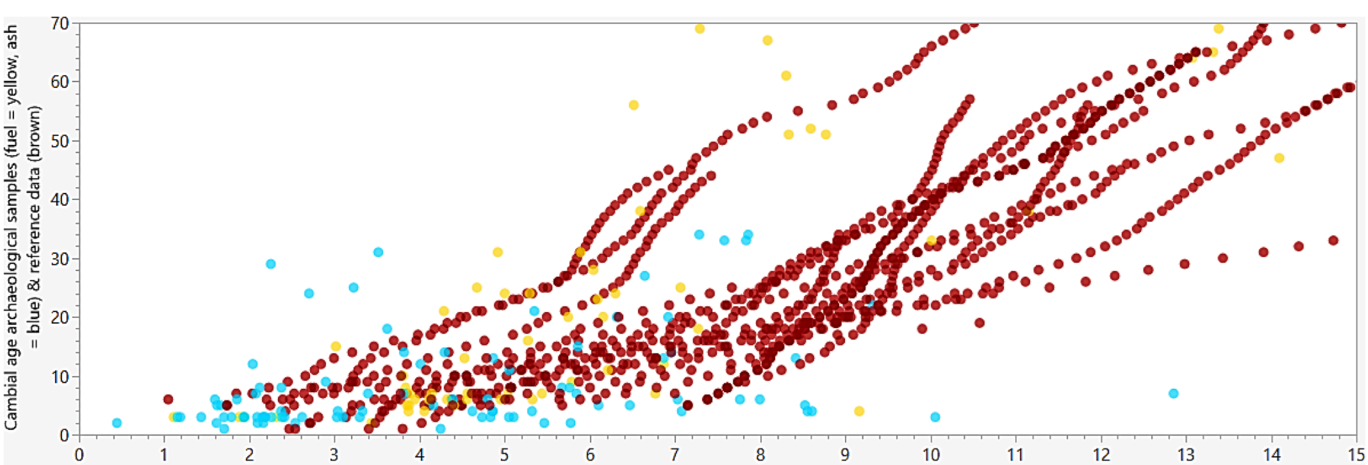

Fig. 15. Cambial age for measured and transformed (divided by a factor 2.6) reference *Populus nigra* (grey) from southern Europe compared to the archaeological *Populus/Salix* data from Early Bronze Age oven/hearth contexts (yellow) and other ash fill contexts (blue). Raw data for Middle Euphrates region see Appendix Table 6.

young reconstructed cambial ages, which implies fast annual growth compared to the transformed (divided by 2.6) reference, possibly indicative of the use of coppicing or pollarding. However, it cannot be excluded that this wood may have grown in better environmental conditions compared to the other ancient samples.

Of the 64 possible poplar fragments from fuel contexts of which ring widths were measured, there are hardly any indications of the use of unmanaged branchwood. In fact, there are no unmanaged branches if the lower quartile value of transformed ring width data from trunk wood is used as the boundary, and only eight if the untransformed lower quartile value is applied. If we assume that poplar coppicing rotation cycles were maximally 20 years (Appendix Table 6), then approximately half of these fragments were likely from trunk wood, while most of the other half may represent coppiced/pollarded branchwood (Fig. 14).

Appendix Table 7 details the diameter measurement results from Kinet Höyük. It shows that larger-diameter pine charcoal is represented in all measured contexts. Of note is the presence of large-diameter *Vitis* and *Olea* wood at 775 BC and 475 BC (center point of phase), respectively.

4. Discussion

4.1. Wood fuel alternatives

4.1.1. Dung fuel proxy based on seed data

The statistically significant difference in known overgrazing taxa like *Anthemis*, *Adonis*, *Centaurea*, and *Verbascum* found in oven/hearth/fire pit contexts with and without dung pellets, as well as the close association of most of these taxa with dung presence in the CCA (Fig. 2), indicates they may be a proxy for dung use as fuel. The placement of *Centaurea* between dung or absence of dung suggests that *Centaurea* may also have been introduced into the contexts through the cereal harvest. Therefore, the dung/overgrazing proxy should be interpreted with care.

Most of these taxa could also have been disposed of in the fire as part of crop processing since they could have grown as weeds in fields and been harvested with the crops (Davis 1965-2000). However, the lack of a linear relationship between cereal chaff and culm remains and overgrazing percentages indicates they were mostly not part of the same process (Fig. 3), though chaff is often part of ruminant fodder, and also survives in the digestion tract of the animal (Valamoti and Charles 2005), like e.g. in the case of Tell Brak (Fig. 3; the dot reflecting ca. 7 % overgrazing taxa). The high percentage of 'overgrazing indicators' in that context in fact represents crop weeds.

The overgrazing taxa do not represent regular grazing forage, due to their bitter taste (*Anthemis*) (Center for Invasive Species Solutions 2024), their tough and hairy leaves (*Verbascum*) (Gross and Werner 1978), spininess (*Centaurea*), or toxicity (*Adonis*) (Woods et al. 2011). However, these plants tend to expand upon overgrazing since the more palatable plants are eaten first, allowing the less palatable to proliferate. The increase in less palatable plants then increases the chance that they are eaten accidentally. *Anthemis*, *Adonis*, *Centaurea*, and *Verbascum* have been reported to be eaten by animals, and even found in dung (e.g., Amini et al. 2022; Dunseth et al. 2019; Martinez et al. 1985). The consumption of small amounts of *Adonis* by sheep has been reported not to cause their death or illness (Woods et al. 2011). *Verbascum* even made it on a list of weeds palatable to goats (Rosa García et al. 2012), while *Anthemis ruthenica* additive to sheep hay has been reported as promising in improving milk performance (Fedenko 2023), and *Anthemis cotula* was concluded to hold some potential as forage, though low quality compared to other plants of the Asteraceae family (Basbag and Sayar 2023). While these plants do not represent the animals' preferred food, they can be consumed in small amounts and are frequent in a degraded landscape, but they may also have grown in the crop fields, which is somehow also part of a degraded landscape. Therefore, we apply the overgrazing taxa as indicators of dung use, especially in areas where wood resources were scarce.

4.1.1.1. Regions and trends in alternatives to wood fuel use.

Our research suggests that dung has been used as fuel in many regions of Southwest Asia (Fig. 4) and we could not detect differences as to its use in ovens/tannurs versus fireplaces/hearths. Our proxy method detects the earliest indications for dung fuel use in a few contexts dated at around 7000 BC, e.g., from Bouqras and Cafer Höyük in Northern Mesopotamia (Fig. 4). This matches with evidence that this practice was already in use as early as the 11th millennium BC there (Smith et al. 2022). The most substantial peak in overgrazing indicators, and likely the practice of dung use, appears to have been in areas that received annual rainfall below 300 mm (Fig. 4, Fig. 11), starting around the end of the 3rd millennium BC and continuing until ca. 700 BC. The start of this peak is of interest as it is shortly after increased specialization in the pastoral sector was visible (Zeder 1995), that may have caused a greater need for dung management. It also coincides with the later part of the second urban wave in Northern Mesopotamia that was associated with population growth (Lawrence et al. 2021a) (Fig. 6) and a substantial expansion of settlement into the Zone of Uncertainty (Burke 2020; Lawrence et al. 2021b,a; Wilkinson et al. 2014). This expansion into marginal zones was possible because urban economies had become sufficiently large-scale to buffer against the high risk of losses in harvests, and also supported herds associated with opportunistic agropastoral activities typically suited to that zone (Smith et al. 2014; Wilkinson et al. 2014). The marginal zone became especially important for wool production, which increasingly became in demand by urban institutions as population and trade networks expanded (Smith et al. 2014; Wilkinson et al. 2014; Burke 2020; McCorriston 1997). Texts indicate the management of huge flocks, e.g., up to 670,000 sheep related to Ebla, a major center near the Zone of Uncertainty (Milano 1995). In this area, using dung as fuel was likely a practical response to the availability of dung near the settlement, while wood fuel was becoming scarce (Fig. 11). Although using dung as fuel is somewhat more labor intensive and often considered lower quality, it was likely a practical choice given the ecological and socio-economic circumstances and may also have been preferred for certain activities. It is of note, though, that increased dung use was also attested in cases of de-urbanization, as was the case of Malyan ca. 1250 BC (Fig. 4), where the urban decline was joined by increased pastoral nomadism (Zeder 1988). Hence, deciding on dung use relates strongly to the intensity of pastoralism and not (only) urbanization.

While pastoral activities were also incorporated into the economy of settlements in zones that received more than 300 mm of rainfall, the agropastoral system was more stable and the focus was more on a variety of species there (Gaastra et al. 2021, 2024; Wilkinson et al. 2014). Dung was used as manure from the beginning of agriculture, as indicated by high δ^{15}N values on seeds (Araus et al. 2014; Styring et al. 2017). However, decreasing δ^{15}N values indicate a decreased intensity of manuring with fresh dung in the 3rd millennium BC in northern Mesopotamia (Styring et al. 2017) while at the same time, dung appears to have been increasingly used as (additional) fuel (Figs. 6 and 11), as reflected by the overgrazing proxy. Fuel ashes were likely still utilized as manure in the fields, as indicated by the sherd scatters surrounding the settlements, which are assumed to derive from ash manure enriched with other household waste (Wilkinson 1989; 1994). While such ash manure would be less visible in the δ^{15}N values, it would still have increased soil fertility and nutrient availability somewhat (Deckers et al. 2024a).

We only have very few indications of overgrazing and dung used in the southern part of the Northern Levant and the Southern Levant (Fig. 4). It seems that in the Southern Levant, extensification was not focused on agropastoral activities but on an expansion of olive cultivation between 4000–2000 BC and grape from 3600 BC onwards, away from their natural distributions (Burke 2020; Deckers et al. 2024b), with olive mainly not expanding into the Zone of Uncertainty though (Burke 2020; Deckers et al. 2024b). Of interest is an oven context from Qatna (2000–1500 BC) (Appendix Table 3a, sample QATN_7_3059), within the Zone of Uncertainty, that likely was fueled with jift/pomace, indicative of a focus on arboricultural activities there (Fig. 5). Other possible pomace/jift finds are located within the less arid parts of the Levant, as expected (Fig. 5). They start to occur after 4000 BC (Fig. 6), hence after cultivation of olive started; also, olive pruning remains are increasingly used as fuel after the earliest indications for olive cultivation, dated to ca. 5000 BC (Deckers et al. 2024b) (Fig. 8). We currently lack oven/hearth data for the period between 5000 and 4000 BC.

The earliest indications for using jift/pomace are substantially later than those for dung as fuel. However, both alternatives to wood fuel seem to have had their peak use when population density increased between 3400 BC and 1000 BC (Fig. 6). Both can be related to wider land use changes, with dung relating to extensification at a site level, and at a regional level with the expansion of agropastoral activities into the Zone of Uncertainty in Northern Mesopotamia and the Northern Levant. Jift/pomace use in the Southern Levant relates to extensification processes associated with olive arboriculture that also intensified fuel needs for storage pottery production (Badreshany et al. 2020). While increasing roughly simultaneously, it is possible that jift/pomace fuel use increased slightly earlier than dung fuel use, which also matches the timing of the observed sociocultural changes related to increased social complexity in both regions (Lawrence et al. 2021a). It is of interest that jift/pomace seems to be associated with ovens/tannurs, while absent in hearths in our dataset, which may amongst others perhaps relate to the high moisture content of pomace, causing smoke, though further data is needed to confirm this possible pattern.

4.2. *Wood/charcoal fuel use*

4.2.1. *Regional trends in wood fuel use*

Regional differences are visible in wood fuel use (Fig. 7) and can be related to local vegetation availability. This supports the hypothesis of the so-called 'principle of least effort', which assumes that wood was preferentially collected in the direct surroundings of the site and in proportion to the available species (Asouti and Austin 2005; Chabal 1992; Scholtz 1986; Smart and Hoffman 1988; Tusenius 1986), notwithstanding selection within the local environment is possible (e.g., Delhon 2021 and discussion further below). For example, fuel contents from the Euphrates region correlate with riverine vegetation, while those from the Levant correlate with typical Mediterranean taxa. The samples near the mountains of the Northern Levant include an abundance of conifers typically occurring in these mountains. In contrast, the samples from extremely arid zones of the Southern Levant show an association with xerophytic vegetation. Hence, the location strongly influences the sample composition (compared with, e.g., Zohary 1973). Olive pruning remains only seem to have played a significant role in the fuel provisioning of the Levant from 3000 BC onwards (Fig. 8). In Mesopotamia, olive pruning remains never seem to have played an important role in fuel provisioning (Fig. 8) as olive cultivation in this region was small-scale (Deckers et al. 2024b). Hence, the contribution of olive wood to fuel seems to relate strongly with local cultivation. On the other hand, although grape cultivation is also thought to have played an important role in the economy of the Levant since the 4th millennium BC (Deckers et al. 2024b), evidence for the use of vine pruning remains as fuel only starts to become visible from ca. 1200 BC (Fig. 8) and remains at a much smaller scale than use of olive wood pruning remains, notwithstanding grape and olive pruning today result in a similar mass of waste per hectare (Özkan 2006). Grape pruning remains are hardly represented in Mesopotamian samples, though grape seems to have played a larger role there than olive (Deckers et al. 2024b). The underrepresentation of grape pruning remains in fuel contexts may relate to management practices, such as a lesser emphasis on grape pruning compared to olive, and potentially due to wedded grapes (Deckers et al. 2024b). Differences in the preservation of olive and grape wood through charring may also have played a role in the underrepresentation of grape (Deckers et al. 2024b), such as vine shoots having a smaller diameter, lower wood density (Nasser et al. 2014 versus Govorčin et al. 2010), less compact structure, making them more prone to complete combustion (Hietaniemi 2005) and susceptible to post-combustion degradation.

Our data also indicates that in regions with more rainfall, the wood fuel collected tended to burn hotter (Fig. 12a and b). Since oak, that has a high caloric value seems to have played a significant role in this pattern also occurs more in regions with more rainfall, it is difficult to disentangle whether this pattern is the reflection of its increased natural occurrence in regions with more rainfall or positive selection towards oak, or a combination of both. Overall, though, a higher diversity of wood was used in regions with more rainfall, reflecting the broader range of wood resources (Fig. 12c). We could not detect differences in selection towards different wood caloric properties between ovens/tannurs and fireplaces/hearths for the region as a whole.

4.2.2. *Case studies demonstrating diachronic trends*

4.2.2.1. Fuel use through time along the Euphrates river system (10000–0 BC). In the region along the Euphrates River, riverine woody vegetation dominates fuel remains across our study period. However, there is a strong gradient in fuel use from north to south, which can be related to rainfall changes (Fig. 11). Detailed work on *Populus/Salix* indicates that *Populus* was used more regularly, and typically small diameter pieces were used as fuel, alongside some larger diameter wood (Fig. 13). The diameter and ring width measurement results suggest the possibility of poplar management, including coppicing or pollarding in the Early Bronze Age (Fig. 14), though we lack modern local reference material to gain a better understanding. The existence of centralized forest management along the Euphrates seems plausible. Administrative texts from southern Mesopotamia dating to the end of the 3rd millennium BC describe centrally managed procurement of wood through specialized 'foresters' under the control of the central authority (Steinkeller 1987). The central authority at the city of Umma, for example, controlled over 30 forests and employed 30 work groups of foresters, who received barley rations and land allotments in exchange for their work. Wood was harvested in forests, in plantations for timber and fuel, and from the edges of fields for various purposes and sizes, with an emphasis on poplar and two unidentified tree species (Steinkeller 1987), possibly willow and tamarisk. The wood harvests were stored in a central storehouse (Steinkeller 1987). The scale of the forestry works is visible from texts that refer to two deliveries of respectively 4,134 and 2,700 poplar trunks from the warehouse for constructing a temple (Steinkeller 2013). Foresters not only harvested trunks but also delivered branches and twigs bundled into bales. One text, for example, documents that a forester delivered 120 bundles of poplar branches and 12 bundles of foliage (Steinkeller 1987: 107). Poplar twigs were sometimes delivered as fuel in the 'cattle slaughterhouse' at Umma, alongside more consistent reed deliveries (Steinkeller 2008). Poplar is dominant in the texts (Steinkeller 1987), as it is in the wood charcoal data for Mesopotamia (zone NMW), and in observations of 20th century vegetation (cf. Steinkeller 1987 and reference therein).

To the north of the Middle Euphrates, in the zone receiving more than 300 mm rainfall (Fig. 11), the oak-pistachio woodland (steppe) that occurred away from the river (cf. Deckers 2016a; Deckers et al. 2024a; Deckers and Pessin 2010) was also used as fuel. It is thought that this woodland (steppe) vegetation was relatively open (de Gruchy et al. 2016, Moore et al. 2000), and that the riverine zone had the densest vegetation (Deckers 2016). Considering sites in the Northern Middle Euphrates had a similar setting as in the Southern Middle Euphrates regarding access to riverine woodland, people did not solely use riverine taxa as fuel in the north, whereas they had no other local wood alternatives away from the riverine gallery in the south. The inclusion of oak in the Northern Middle Euphrates fuel could indicate they did not prefer riverine taxa, and by inference that oak was likely preferred above riverine taxa, in part due to its good burning properties, particularly its high caloric values (Appendix Table 1). Such a selection towards higher caloric values appears to have been especially marked for fireplaces/hearths as opposed to ovens/tannurs, suggestive of possible selection towards a cleaner burn and longer-lasting heat, whereas this is not visible further south (cf. Cañas et al. 2023 regarding efficiency). This difference between the Northern Middle Euphrates and Southern Middle Euphrates region matches the conceptual model regarding the applicability of the 'principle of least effort' to anthracology, that selection is highest when resources are abundant (Shackleton and Prins 1992). However, there may also have been a scarcity of wood resources, with available oak a welcome additional fuel supply in the north. So far, no evidence exists for systematic oak woodland management (Deckers et al. 2024a). On the contrary, in the 4th-2nd millennium BC, oak grew extremely slowly and had a shrub-like appearance, possibly through animal browsing in some of the densely inhabited regions of northern Syria. Better growth was observed further north, at Horum Höyük (3500–2900 BC) (37.100°N, 37.867°E) and Tille Höyük (1300–1050 BC) (37.733° N, 38.883°E) (Deckers et al. 2024a). Below the 300 mm rainfall, taxa belonging to the oak-pistachio woodland (steppe) were hardly used as fuel (Fig. 11), most likely because this vegetation was unavailable due to unsuitable climatic conditions.

Between 3000 BC and 50 AD (likely), pruning remains (Fig. 11) were found amongst the fuel of the Northern Middle Euphrates, mainly from olive and in relatively small proportions compared to the Levant. At that time, an incursion of olive cultivation into northern Mesopotamia took place, but it does not seem to have been at a large scale as the seed and wood charcoal contents from all (not just fuel) contexts suggest (Deckers et al. 2024b). The results from the fire installation contexts agree with those from the entire dataset and show a persistent presence at much lower proportions when compared to the Levant (Fig. 8) and with no evidence for jift/pomace use (Fig. 11). In the Southern Middle Euphrates, the burning of imported and reused conifers becomes visible from the 2nd millennium BC onwards. Conifers in this region are often associated with elite buildings, reflecting the high value of such imported wood (e.g., Deckers 2010; Feisel 2000; Neef 1992; van Zeist and Bakker-Heeres 1985), and their use as fuel is possibly related to reuse after discard or use of remnants. However, they may have been directly imported from the closest wood source with the required scale, likely in southern Türkiye, and floated down the Euphrates system. The inclusion of imported (and reused/remnant) wood was possibly a response to the reduced availability of local wood fuel, as already from the later 3rd millennium BC onwards we see an increase in overgrazing indicators (Fig. 11), and dung fuel.

4.2.2.2. Case study Kinet at the foot of the lush Amanus Mountains in the Northern Levant, 1700 to 400 BC. The high proportion of conifer wood in the fuel used at Kinet, at the foot of the Amanus Mountains, is not surprising considering its widespread occurrence in this region, including pine in modern times (Aytaç and Semenderoğlu 2011). Pine has somewhat inferior combustion characteristics and lower calorific value compared to wood fuels such as oak, which was also available in the surroundings (Appendix Table 1). It also produces more smoke than oak, causes creosol accumulation when not dried properly, has a short burning duration and sparks, and does not produce nice coals (cf. some of these characteristics are listed in Wright 2016). Pine also does not regenerate after cutting, unlike oak. Pine is, however, useful for kindling fires, providing a bright flame, though in all periods, larger logs were represented amongst the pine fuel, suggesting it was not only used to kindle fires (Appendix Table 7). While this region likely had plentiful wood resources throughout its occupation history, it does not show strong preferential use of what is often considered the most desirable fuel (compared with the conceptual model by Shackleton and Prins 1992). Perhaps the factor elevation played a limiting role in this.

While only conifers were used in the fireplace dated to 1650 BC (center point of phase), in samples of the later periods there was a tendency to include wood with higher caloric values and better-burning properties (e.g., oak and olive) (Fig. 9). Agricultural production likely also played a role in wood selection. For example, fireplaces around 1300 BC had a large proportion of olive wood, likely related to olive cultivation and pruning. After the tumultuous time around 1200 BC (Cline 2021) and destructions at Kinet around 1150/1130 BC (Gates 2013), the oven contexts from the beginning of the middle Iron Age (900 BC) contain fewer olive wood charcoal proportions besides the pine and, instead, more oak. The decrease in olive wood likely reflects changes in land use. Around 775 BC, wood fuel use appears to have been very variable, with some contexts exclusively consisting of conifer wood while others hardly have conifers. Site-based, the differences in conifer fuel wood do not seem to be related to the type of feature. The tendency of increased grape vine wood remains in the fireplaces around 775 BC is most marked, likely reflecting an intensive focus on grape cultivation in the site's surroundings, especially since grape wood generally seems to be underrepresented at many sites in Southwest Asia (Deckers et al. 2024b). There is evidence for some large-diameter grape wood in the fuel contexts from this period, which may relate to cutting away old and unproductive vines or dead growth. At ca. 475 BC, olive wood became increasingly incorporated amongst the fuel wood besides conifers, while oak decreased. Large-diameter olive logs were used as fuel, which may relate to the management, such as cutting away dead parts, but may also relate to clearance.

In summary, at Kinet there is a strong baseline of pine wood fuel use that was likely most abundant and readily available despite being an inferior fuel to other taxa. In some periods the landscape was reorganized around olive or grape production with pruning and maintenance waste material contributing to the fuel (cf. also Deckers et al. 2024b). At other times, such as in the Early Iron Age, pine fuel could be supplemented by oak, leading to higher caloric values.

4.2.2.3. Fuel use in metallurgical production in the hyperarid zone of the Southern Levant between 2700 and 450 BC. The wood charcoal remains from slag heaps, which represent fuel for metallurgical production, from the hyperarid Faynan region of the southern Levant, show marked diachronic changes between 2700 and 450 BC. While *Juniperus* and some olive wood dominate the 3rd millennium BC charcoal remains, these taxa are hardly present from 1050 BC onwards. Instead, from this period, *Tamarix*, *Retama*, and *Phoenix* are represented, which likely occurred in different parts of the landscape, as suggested by the fact that *Tamarix* and *Phoenix* are often found close to water sources. This change in wood taxa is associated with an overall decrease in the caloric heating value of the charcoal. It may suggest vegetation changes and depletion through human impact, considering metallurgical processing needs lots of fuel and is intensive in this region (Löffler 2013). Based on 5,000 tons of slag heaps found, it has been estimated that ca. 45,000 tons of wood was needed in the Bronze Age to support metallurgical activities (Hauptmann 2000). In the Iron Age, the production scale increased, and the finding of 100,000 to 130,000 tons of slag implies an approximate need for 800,000 tons of wood (Hauptmann 2000). Whether *Juniperus* was present in the direct surroundings of the Early Bronze Age smelting site of Fenan has been debated since it currently only has its distribution in the adjacent Edomite Highlands (e.g. Baierle et al. 1989; Engel 1993; Engel and Frey 1996; Cavanagh et al. 2022; Hauptmann 2000), but has been noted to occur today even in areas receiving only 80–100 mm of rainfall (Albert et al. 2004). Some have argued for it to have had a more widespread distribution in the past in the hyperarid zone of the southern Levant (cf. summary in Vardi et al. 2023). Rainfall reconstructions for the site locations suggest values below 80 mm of rainfall per year, with decreasing rainfall averages from the Early Bronze Age to the Iron Age (Fig. 10). If we consider a 15 km radius as a local exploitation zone (cf. Wood et al. 1980), then this includes the hillslopes, where even today a few *Juniperus* finds have been identified (Mithen et al. 2007). The sharp decrease in *Juniperus* from the Early Bronze Age to the Iron Age may indicate that its occurrence on the hillslopes was strongly reduced, possibly because of the exploitation of parts of the landscape for the enormous amount of wood needed for metallurgical production, combined with somewhat more arid conditions (cf. also Engel 1993; Cavanagh et al. 2022). Notably also in other parts of Southwest Asia, like in Türkiye a decline in juniper is visible in Iron Age assemblages, e.g., at Kaman Kalehöyük (Wright et al. 2017), Kınık Höyük (Castellano 2021), and Gordion (Marston 2009), likely related with its slow growth compared to other taxa in the region.

Hence, the observed changes in wood exploitation in the Faynan region indicate a shift from selecting preferable wood resources in more favorable conditions to a reduced possibility of selection when resources became limited (Shackleton and Prinz 1992), suggesting the 'principle of least effort' model applies best to the latter situation.

5. Conclusion

Wood charcoal identification from oven contexts from ancient Southwest Asia indicates regional differences in wood use related to the availability. Northern Mesopotamian sites along major water bodies are strongly associated with fuel from riverine taxa, like *Populus/Salix*, *Ulmus*, *Alnus* and *Phragmites*, while fuel use in the hyperarid southern Levant was especially associated with saline and irrigated taxa typical for the Jordanian region. Fuel from the Northern Levant showed the strongest association with pine wood, which is an important vegetation component in this region. Within the Levant people exploited also typical Mediterranean taxa as fuel, like evergreen *Quercus*, *Pistacia*, *Rhamnus/Phillyrea*, *Olea*. People also tended to use more wood taxa as fuel in regions with more rainfall, which is parallelled by the vegetation diversity. This generally supports the 'principle of least effort' paradigm as it is often applied in anthracological research to reconstruct vegetation, that fuel wood was collected in the settlement neighborhood to minimize transportation and labor costs. This 'principle of least effort' overrides the properties of particular fuels, with the significant use of low-quality pine fuel in all kinds of fire installations at Kinet Höyük being a good example. The regional differences indicate that the 'principle of least effort' is a useful heuristic for reconstructing past vegetation, but there are some limitations and considerations that become noticeable through investigating diachronic changes and smaller regions.

In some regions where fuel options were available, people tended to select wood with higher caloric values and better fuel qualities. For example, in the Northern Middle Euphrates region oak may have been preferred above riverine species, especially for their hearths. However, its inclusion may also relate to using the full range of available resources. Additionally, in the Faynan metal production, where the originally more abundant juniper was preferentially selected above tamarisk, date palm, or white broom with lower caloric values and other aspects that make them less preferable, indicating a selection for more efficient fuels. In these cases, selection appears to have been stronger when resources were more abundant.

There are also indications for branch size selection in wood fuel exploitation for the Middle Euphrates, possibly through woodland management practices consisting of coppicing poplar and willow, allowing efficient wood production without the necessity for logging, in line with the 'principle of least effort'. Similarly, the inclusion of olive and grape wood pruning and maintenance where available in local agriculture matches the 'principle of least effort'. Olive pruning and olive tree management contributed strongly to the fuel of the Levant after widespread olive cultivation started around 5000 BC. Olive was much less important in other regions, e.g., Mesopotamia, as reflected in its proportionally smaller representation. Grape cultivation also started to play an essential role in the Levant sometime after the 4th millennium BC. However, grape pruning appears to have contributed somewhat less to the fuel of the Levant, except for Kinet Höyük. While increased fruit tree cultivation, mainly olive cultivation, is reflected in the wood fuel dataset, it occurred alongside critical societal changes and coincident with population increase and an increased scale of pottery production. All of these factors would have increased fuel scarcity, and evidence for this is visible in increased jift/pomace use in the Levant between the late 4th millennium BC and 500 BC which is an opportunistic, 'least effort' behavior. However, it seems to have been strategically used more typically in ovens. In other regions, people moved from the 3rd millennium BC into the steppe for agro-pastoral reasons, where trees for fuel were scarce and saw a continual decrease. They had an abundantly available byproduct of livestock rearing, dung, that we found can be detected through the presence of overgrazing indicator taxa, like *Adonis*, *Anthemis*, *Centaurea*, and *Verbascum.* However, dung use as fuel was more labor-intensive and less efficient than other sources, suggesting that it was an opportunistic adaptation to the environmental constraints. Dung has been used since the 11th millennium BC, both in ovens/tannurs and fireplaces/hearths. The two processes of using increasingly alternatives to wood fuel are similar and seem to correspond with socio-economic changes, population increase, and depletion of wood resources.

There were, however, exceptions to the use of local fuel. For example, in the Southern Middle Euphrates region, imported coniferous wood that derived from a further distance started becoming increasingly popular from the 2nd millennium BC onwards, which indicates opportunistic behavior. While this may seem to violate the 'principle of least effort', it is possible that this decision was driven by local wood shortages leading to the exploitation of the nearest remote wood stands, with floating conifers down the river being the least effort compared to overland transport. The imported wood may also have been derived from resource recycling or remnants of wood sourced remotely for specific purposes.

Studying fuel use from archaeobotanical data gives us valuable insights into how societies interact with their environment, and we have documented examples of more or less successful models of exploitation and adaptation. Although the data has some limitations, overall, we do not observe much evidence for controlled management or sustainability, except for the inclusion of arboricultural waste into the fuel products and possibly some coppicing and pollarding in the Middle Euphrates during the Early Bronze Age. State-controlled woodland management in southern Mesopotamia is attested contemporaneously, as indicated by the texts and supported by the anthracological evidence. More anthracological measurement data from oven/hearth contexts and reference material from the region are needed to investigate this issue further. The use of dung as fuel, on the other hand, appears to have been less sustainable, as it was no longer available as fresh manure in agriculture, impacting soil fertility. Over the long term, woodland management appears not to have been sufficient to maintain the resource. We observe an increased use of alternative fuels where available under population pressure and evidence for the exhaustion of local wood resources over time.

CRediT authorship contribution statement

Katleen Deckers: Writing – original draft, Writing – review & editing, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Simone Riehl:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **Doğa Karakaya:** Writing – review & editing, Data curation. **Tabea Müller:** Writing – review & editing, Investigation, Data curation. **Kamal Badreshany:** Writing – review & editing. **Valentina Tumolo:** Writing – review & editing, Data curation. **Dan Lawrence:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.104999.

Data availability

All raw data is in the Supplementary Information

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