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Vegetation history of the Maharlou Lake basin (SW Iran) with special reference to the Achaemenid period (550–330 BC)

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Abstract

This study presents the results of a palynological investigation on a sediment core from the seasonal and saline Lake Maharlou in the Zagros Mountains in southwest Iran. We emphasised studying the role of man in modifying the vegetation of the area and the dominant agricultural practices during the Imperial Persia period (2,500–1,299 cal BP; 550 BC-AD 651), particularly the Achaemenid Empire (2,500–2,280 cal BP; 550–330 BC). Scattered pistachio-almond scrub combined with *Quercus brantii* was the main vegetation type of the basin during the period studied. The present study depicts a significant increase in agriculture, suggesting urban development during the Late Antiquity and early Islamic Iranian dynasties. The inferred chronology of arboricultural activities is compatible with historical evidence showing that Fars Province witnessed economic and agricultural flourishing during these periods. The presence of the 'Persian gardens' is supported by the co-increase of cypress tree pollen frequencies with pollen of other cultivated trees, especially *Platanus*; both trees were cultivated for their shade and symbolic values. This study also provides pollen evidence of *Punica granatum* during the Achaemenid period and *Phoenix dactylifera* cultivation during the early post-Sasanian era. The variations in indicator pollen ratios among Poaceae, *Artemisia*, and Amaranthaceae appear compatible with the palaeohydrology of the basin and show periods of aridity followed by higher moisture availability. We suggest that anthropogenic activities played the leading role in vegetation change in the Maharlou Lake basin enhanced by climatic changes during the last ~4,000 years.

Keywords Persian Empire · Human impact · Arboricultural activities · *Punica granatum* · *Platanus* · *Cupressus*

Introduction

As the progenitor sanctuary for early civilisations, the Zagros Mountains have been the centre of attention for many palaeoenvironmental studies investigating human–environment interactions in the past (e.g. Djamali et al. 2009a; Jones et al. 2015; Kimiaei 2006; Miller 1985; Miller et al 2003; Riehl et al. 2015; Sumner 1972; Sumner and Whitcomb 1999;

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Shumilovskikh et al. 2017). Through their particular geological and geographical features, the foothills and valleys of the Zagros Mountains have provided appropriate resources of water and arable land for human settlement in the past (Petrie et al. 2018). The abundance of karstic springs supports human settlements with numerous freshwater resources (Djamali et al. 2018), while the variety of microclimates with different precipitation and altitudinal ranges provided the early settlements with diversified raw materials and natural supplies (flora and fauna). The central and southern Zagros are considered among the very first locations for plant and animal domestication attempts and, therefore, the best setting for studying the interactions between human and environment (Sumner 1972; Zeder and Hesse 2000; Kimiaei 2006; Miller 2011, 2013, 2014; Riehl et al. 2013). For instance, the rich archaeobotanical remains from the aceramic Neolithic site of Chogha Golan west of the Zagros Mountains shifted the starting point of agriculture practices into the Epipaleolithic period (Riehl et al. 2013). Livestock management history in the highlands of the western Zagros dates back to 10,000 years ago (Verdugo et al. 2019; Zeder and Hesse 2000).

Beside the Khuzestan plains (Khuzestan province – SW Iran), the more extensive basin of the Kur River at the eastern end of the Zagros in the Fars province has experienced the presence of human settlements for millennia (Sumner 1972). The Kur River basin (KRB) has witnessed profound changes in human lifestyle from local and scattered populations with a nomadic way of living to settled farmers and the developed urban communities started by the Elamite dynasties (2700–540 BC). The Elamites were amongst the civilisations that increased the social complexity in the Near East by dominating different landscapes and centralising the populations in the plains during the fourth millennium BC. The city of Anshan, the eastern capital of Elam, constructed in the highlands of the KRB (Tal-e Malyan), had several phases of occupation and abandonment from the fourth to the late second millennia BC (Miller 2014). The Kur River basin (*Pārsa*) roughly covers the area where Persians started their domination during the Achaemenid period (550–330 BC) to establish their 'universal empire' (Wiesehöfer 1996). They chose this area to establish their new capitals of Pasargadae and Persepolis. After the conquest of the Muslims (AD 651), the governors of the Early and Middle Islamic periods, such as the Buyids (AD 935–1062), continued development in the area and expanded irrigation works and agriculture in the lower Kur River basin (Sumner and Whitcomb 1999).

Although anthropogenic impacts on the landscape and even permanent changes in plant species composition and distribution pattern in the KRB existed since the Elamites period (Miller 2014), the Persepolis Basin and surrounding basins has witnessed unprecedented urbanism and human influences since the beginning of the Achaemenid period. The changes in livelihood, demographic increase as well as the development of urban centres and innovation of associated infrastructure such as hydraulic works resulted in agricultural development (Gondet 2011; Wiesehöfer 1996). This prosperity combined with the appreciation for gardens in Persian culture led to the expansion of agriculture and extensive tree cultivation during the Achaemenid and Sasanian periods (Djamali et al. 2010, 2015; Shumilovskikh et al. 2017). According to available pollen data from Lake Maharlou (Djamali et al. 2009a) and Lake Parishan (Jones et al 2015), the main cultivated trees in the southern Zagros were *Juglans* (walnut), *Platanus* (plane tree), and *Vitis* (grapevine). These species have a long history of domestication and cultivation in the area dating back to the first to second millennia BC, but their continuous presence as cultivated woody species began after the Late Elamite period (~1200 BC) (Djamali et al. 2011; Miller 1985; Potts 2018; Shumilovskikh et al. 2017). *Olea* (olive) appeared as an important arboricultural element during the Achaemenid and Seleucid periods around Lake Parishan (Djamali et al. 2015; Jones et al. 2015). In addition, pollen and archaeological wood fragments of the cypress tree family (Cupressaceae) reveal different purposes for arboricultural practices (providing timber and shade) from the Achaemenid to the post-Sasanian periods (Djamali et al. 2017). Maharlou Lake has excellent pollen preservation conditions that, combined with its large basin, provide a great opportunity to study agro-pastoral and arboriculture activities on a regional scale through a palynological investigation. However, despite several palynology surveys (Djamali et al. 2009a, 2011; Jones et al. 2015), detailed data about the vegetation history in the southern Zagros Mountains during Imperial Persia (2,500–1,299 cal BC; 550 BC-AD 651) remains obscure. In addition, in the former study by Djamali et al. (2009a), the material dating by radiocarbon is affected by a variable reservoir effect – estimated between several centuries and one millennium depending the periods. Thus the correspondence of the vegetation changes discussed to historical periods is uncertain. Therefore, by studying a new sediment core from Maharlou Lake with an improved chronology (Brisset et al. 2019), we aimed to reconstruct the regional vegetation dynamics and agricultural practices during the last four millennia with a special focus on the Classical and Late Antiquity periods.

Study site

Physical setting

Lake Maharlou (1,455 m a.s.l.) is a large shallow hypersaline lake (average depth of 1.5 m), located in Fars Province, 20 km from Shiraz and about 60 km southeast of Persepolis at the south-eastern tail of the Zagros Mountains. This lake (Fig. 1), which is assumed to have existed since the early Pleistocene, has an area of 24,910 km^2 and is fed by precipitation, surface runoff and karstic springs

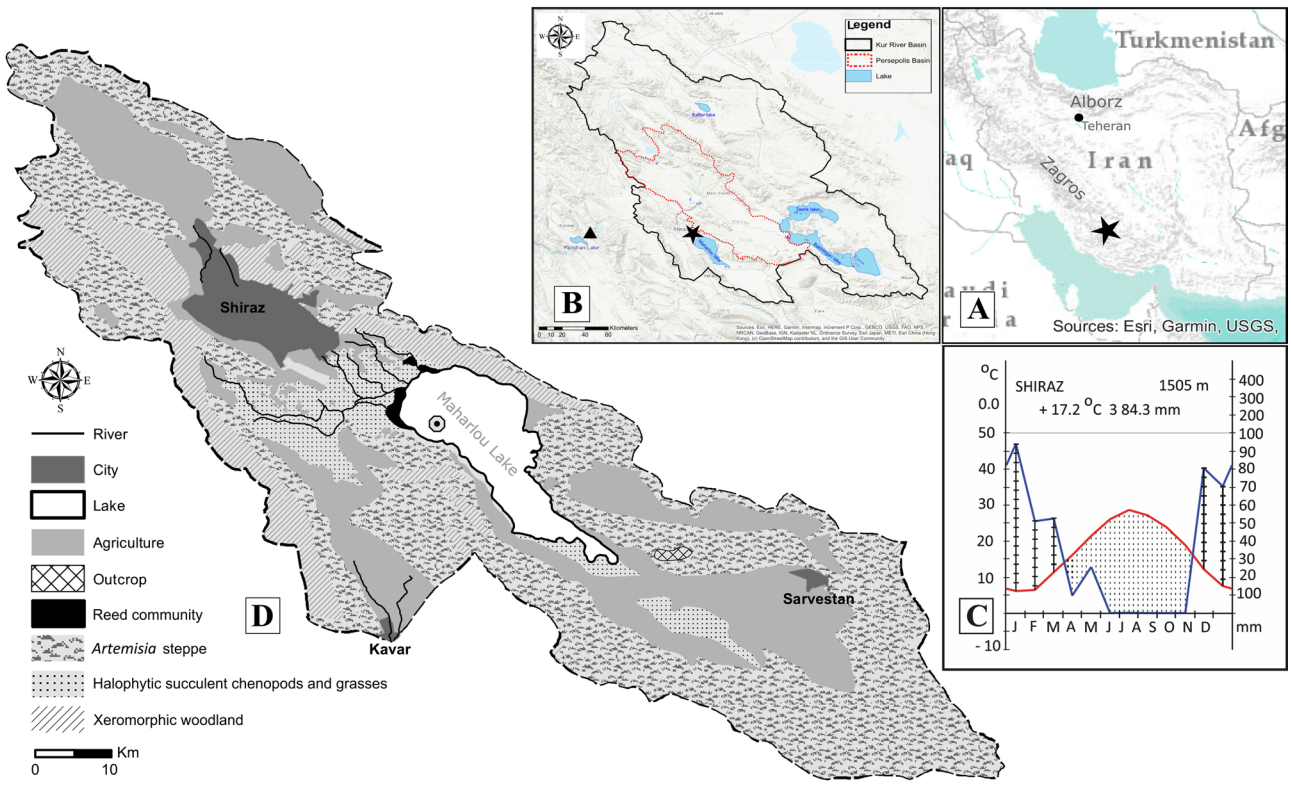


Fig. 1 **a** Location of the study site in the southwest of Iran (black star). **b** Map of the Kur River basin (black line) and Persepolis basin (dotted red line). Black star: Lake Maharlou; black triangle: Lake Parishan. **c** Bioclimatic diagram of Shiraz (from Worldwide Bioclimatic Classification System 1996–2019). **d** Lake Maharlou watershed including the general land use and main vegetation communities. The location of the MAH-B core is shown with a black-and-white circle

around the lakeshore. From a geological point of view, the Maharlou catchment is dominated by sedimentary rocks mainly composed of limestone, sandstone, shale and dolomite (Safe et al. 2016).

According to the Koppen climatic classification system (Critchfield 1974; Rahimzadeh et al. 2009), the study area is a mid-latitude steppe: semi-arid; cool or cold climate type and, in the Worldwide Bioclimatic classification (Rivas-Martìnez and Rivas-Sáenz 1996–2019), having a Mediterranean xeric-continental type bioclimate (Djamali et al. 2011). Based on recorded meteorological data from the World Meteorological Organisation (WMO 2017) at the Shiraz synoptic station (the nearest station 20 km east of the lake), recorded mean annual precipitation and temperature are 384.3 mm and 17.2 °C, respectively. The maximum precipitation falls in January (89.8 mm) and the dry season lasts about six months, from April to October.

Vegetation

According to Zohary (1973), Lake Maharlou is situated in the Irano-Turanian phytogeographical region with the steppic vegetation of pistachio and almond (*Pistacia-Amygdalus* synonym: *Prunus*) xeromorphic forest. In the Lake Maharlou basin today, this vegetation type consists of scattered high-growing wild pistachio (*Pistacia khinjuk, P. atlantica*) and almond trees and shrubs (mainly *Prunus scoparia*), associated with shrubs such as *Prunus microcarpa*, *Rhamnus persica*, and *Ficus carica*. They associate gradually with *Quercus brantii* (Brant's oak) at higher altitudes (ca. 1,000–2,000 m) (Carle and Frey 1977; Frey 1982; Frey and Probst 1974; Zohary 1973). However, due to the long-term history of anthropogenic activities, *Pistacia-Amygdalus* vegetation has been delimited and substituted with cushion-shaped mountainous tragacanthic species at higher altitudes and *Artemisia* steppes in the lowlands (Djamali et al. 2011). In addition, the saline flat plains surrounding the lake are mostly dominated by succulent chenopods such as *Salicornia* spp. and *Halopeplis pygmaea,* and halophytic grass and sedge species like *Aeluropus littoralis*, and *Juncus rigidus* (Akhani 2004). Moreover, small and large wetland systems with dense aquatic vegetation dominated by a reed community (*Phragmites australis, Typha* spp.) cover the north and northwest of the lake as well as round the emergence of karstic springs (Carle and Frey 1977).

Materials and methods

Coring. The first palynological study was conducted on a 150-cm core of Lake Maharlou taken in 2009 (Djamali et al. 2009a). In autumn 2012, four short and continuous sediment cores (each 1 m in length) were recovered by a Russian corer in the northwestern part of Lake Maharlou (29°27′40.5"N; 52°43′45.6"E). At the Institut Méditerranéen de Biodiversité et d'Ecologie (IMBE-France), the disturbed overlapping parts between each drive were excluded and the resulting master core (MAH-B) had a total length of 355 cm (Brisset et al. 2019). It was then subsampled and studied for pollen analysis.

Chronology. One major challenge in arid to semi-arid environments, such as the Maharlou basin, is to find organic materials of terrestrial origin well-suited for radiocarbon dating. Bulk sediments from most of the sites investigated over the last decades were dated by ^{14}C (e.g. Lake Zeribar, Wasylikowa and Witkowski 2008; Lake Maharlou, Djamali et al. 2009a). Unfortunately, carbonated geological formations are abundant in the Zagros mountain chain including the Maharlou catchment, likely resulting in ageing the ^{14}C values determined on bulk sediments, as demonstrated for Lake Mirabad (bias estimated between 2,000 and 5,000 years by Stevens et al. 2006), and Lake Parishan (bias estimated at 300–400 years by Jones et al. 2015).

To avoid contamination by fossil organic carbon and the 'hard water effect', the core MAH-B was sliced every 2 cm, wet-sieved through a 100 µm mesh, and materials of exclusively terrestrial origin (i.e. millimetre-size fragments of plant, charcoal, Coleoptera and seeds) were picked out one by one under a stereo microscope (Brisset et al. 2019). Fragments of an approximate size < 500 µm were needed to reach a sufficient carbon weight for ^{14}C measurements. Sometimes, several sediment slices were analysed together, as detailed in Table 1. In all, seven samples contained enough material to allow for analysis and were radiocarbon dated at the Poznan Radiocarbon Laboratory. In establishing the age-depth model, the Poz-83775 (0.03 mg C) dating was rejected due to insufficient weight of carbon. The remaining samples were stratigraphically in order except the samples Poz-83773 and Poz-81500, which presented ages that appeared to be too old. The main cause of age inversion on the material of terrestrial origin (excluding plant roots) is long-term storage in the lake catchment, so it is more likely that Poz-83773 was reworked while Poz-81500 was rejuvenated. The age-depth model was been calculated using a smooth spline (type 4 argument) in the Clam R package (Blaauw 2010), based on probability distributions of the accepted ^{14}C ages (Table 1), and the IntCal13 calibration curve (Reimer et al. 2013). As the 2σ calibration range of Poz-83775 fitted within the model's uncertainty, this age has been accepted a posteriori. The final age-depth model (Fig. 2) indicates that MAH-B spans the last 3,800 ± 370 years, with an average 2σ uncertainty of 250 years. Comparison with previous work on Lake Maharlou (Djamali et al. 2009a) shows that ^{14}C dating on bulk sediments has shifted age-dating between 800 and 2,500 years, depending on the sedimentological facies. Thus, if the precision of the present model is not as good as in other environments, the study of MAH-B provides a greatly improved dating accuracy than previous work, emphasising the necessary efforts that need to be made in sampling terrestrial materials, even though those materials are rare in an arid context. This problem can be tackled by sampling more sediments, doing core replicates, during the initial coring campaigns, together with implementing other relevant dating methods such as U/Th (Jones et al. 2015).

Palynology. The total length of the core was subsampled at 10 cm intervals. In addition, for the higher resolution palynological analysis during the Achaemenid period (2,500–2,280 cal BP), subsamples were taken every 2 cm from 185 to 230 cm. This sections corresponds to the time interval between 1,700 and 2,800 cal BP. Samples were

Table 1 Radiocarbon ages obtained on core MAH-B

Core section/ depth (cm)	Master core depth (cm)	Material	Lab. code Poz-	^{14}C age BP	Age cal BP (±2σ)	Weight (mg C)
D1/43	43	Charcoal, Coleoptera, seed	81502	390 ± 30	320–509	0.2
D1/88	88	Plant fragment	81501	655 ± 35	556–673	0.15
D2/62–70	*159*	*Charcoal, Coleoptera, seed*	*83773*	*2,450 ± 50*	*2,359–2,707*	*0.12*
D3/14	193	Charcoal	81500	1,950 ± 50	1,741–2,002	0.1
D3/58–66	237	Charcoal, Coleoptera	83774	2,820 ± 90	2,762–3,162	0.07
D3/90–96	269	Charcoal, Coleoptera, seed	83775	3,800 ± 180	3,717–4,803	0.03
D4/66–74	321	Charcoal, Coleoptera, seed	83776	3,370 ± 35	3,496–3,697	0.16

Adapted from Brisset et al. (2019)

The rejected age is in italics

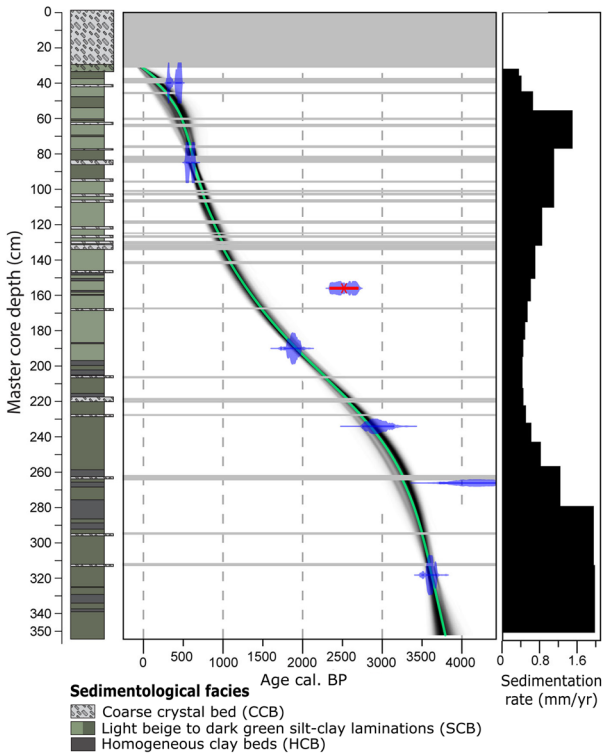


Fig. 2 Age-depth model for core MAH-B and lithostratigraphy and sedimentation rate. The AMS ^{14}C ages are represented by their probability density functions. The age rejected before modelling is marked in red. The calculated model is given in greyscale (higher probability is darker), and the best model is shown as a green line. The grey horizontal band illustrates a layer interpreted as non-continuous sedimentation (coarse crystal beds), which were 'removed' before age modelling (Adapted from Brisset et al. 2019). Details of the model are discussed in Brisset et al. (2019)

treated according to Moore et al. (1991), and *Lycopodium* markers (Batch no. 1031, 3862) were used to assess the pollen concentrations (Stockmarr 1971). The general palynological process of Moore et al. (1991) was modified by multiple warm HCl treatments to eliminate the residual fluorosilicate complexes of HF reaction. Pollen samples were studied with ZEISS light microscopes at IMBE and the Institute of Ecology and Conservation Biology, University of Regensburg. Terrestrial pollen taxa were identified to the lowest possible taxonomic group using the reference collections of the IMBE as well as Beug (2004), Moore and Webb (1978), and Reille (1992). At least 300 pollen grains were counted in each sample as well as non-pollen palynomorphs (NPPs) that provided useful information. Micro charcoal concentrations were determined, according to Wang et al. (1999), as an indicator of regional fire events. TILIA (ver. 2.0.4, Grimm 2011) and C2 (ver. 1.7.7, Juggins 2010) software were used to calculate the pollen percentages and to create the pollen diagram. The variations in the pollen spectra and CONISS cluster analysis (included in TILIA, Grimm 1987) were applied to define the local pollen assemblage zones (LPAZ).

Results

In the 57 spectra, 121 pollen types were identified, including 41 arboreal and 80 non-arboreal taxa, in addition to a selection of NPPs providing useful information. A list of identified pollen types and the reference ecological groups with their indicator types is available in the ESM (Tables 1 and 2). Figure 3 depicts the variation of pollen percentages and cluster analysis based on variation in the relative frequencies of different pollen types. The main characteristics of each pollen zone and the interpretation of their inferred dominant vegetation types are summarized in Table 2. Based on the age-depth model (Fig. 2), the best-calculated ages of the top and the base of the diagram were around 13 and 3,739 cal BP, respectively, which correspond to the present time and the Middle Elamites period. Based on variations in pollen spectra and CONISS cluster analysis, the diagram was divided into three zones (A, B and C) and four subzones (B1, B2, C1 and C2) (Table 2).

LPAZ A is dated between 3,348 and 3,731 cal BP. A glance at the pollen percentages shows an evident decrease in *Artemisia* pollen percentages (from around 55% to 15%) at the beginning of the zone. Grass-type pollen (Poaceae > 30 µm) shows its highest values (up to 10%) during this period. Among the natural forest vegetation indicators, *Quercus* values vary between 30–10% and show a general decrease towards the end of zone A, while *Pistacia* pollen increases up to 15% in the same zone. The decline of the *Quercus* pollen percentage is associated with a remarkable growth in the amount of Cerealia-type pollen towards the end of zone A. Ruderal plant communities (Behre 1981) such as *Rumex* and *Plantago lanceolata* pollen types show relatively high values. Meanwhile, *Sporormiella* (coprophilous fungi) spores, as an indication of pastoral activities (van Geel and Aptroot 2006), show relatively high values in the middle of the zone.

LPAZ B (ca. 3,348–1,612 cal BP) is divided into two subzones of B1 (ca. 3,348–2,812 cal BP) and B2 (ca. 2,812–1,612 cal BP). Zone B is characterised by a significant rise in *Artemisia* (up to 55%), and the simultaneous decline of arboreal pollen with the lowest value (< 20%) at the end of subzone B2. This general reduction in arboreal pollen is clearly due to a decline in natural trees and shrub pollen including *Quercus*, *Pistacia* and *Amygdalus*. Some tree taxa, including *Fraxinus*, Cupressaceae, *Pinus* and *Salix*, naturally grow in the modern flora of the study area beside their use as cultivated trees for shade and timber. Therefore, in the present study, they are discussed under a separate group of cultivated and/or natural trees. In zone B, *Fraxinus* decreases

Table 2 Summarised description and interpretation of local pollen assemblage zones (LPAZ) shown in Fig. 3

LPAZ	Historical period	Zone description	Interpretation
C 177–30 cm 1,612–13 cal BP 1,599 years 19 samples subzone C1, C2	Early Sasanian to present time	Significant increase in arboreal pollen, striking high values of *Platanus* with highest values of other cultivated trees. Lowest values of *Pistacia* (< 5%) and *Acer* (< 1%), increase in desert shrubs values, significant peak of microcharcoal	Increase in arboriculture, urbanisation and evolution of new urban centres, possible destruction in pistachio-almond vegetation in lower altitudes in the lake basin, possible increase in aridity
B 264–177 cm 3,348–1,612 cal BP 1,736 years 26 samples subzone B1, B2	Late Elamites to early Sasanian	Increase in *Artemisia* (> 50%) concurrent with grassland and natural arboreal pollen decline (< 20%), high diversity of cultivated trees, presence of *Punica granatum* pollen type – appearance of *Riella* spores, constant presence of *Tribulus* and *Prosopis farcta*, increase in Amaranthaceae pollen type	Arboriculture development and higher diversity of cultivated species, possibility of water management practices, decline in grassland and possible deforestation as well as increase in pastoral activities, presence of disturbed lands
A 352–264 cm 3,731–3,348 cal BP 383 years 12 samples	Early to Middle Elamites	40% decrease in *Artemisia*, high values of Ephedraceae (up to 5%), highest values of Poaceae > 30%, generally high value of P/A ratio and very low values of C + A/P ratios, 20% decrease in *Quercus* at the end of the zone—increase in agriculture indicator types and coprophilous fungi spores—presence of *Rumex* and *Plantago lanceolata*	Dominance of grasslands and open vegetation (*Pistacia-Amygdalus* (syn: *Prunus*) scrubs); steady status of natural forest vegetation, cereal cultivation and pastoral activities, higher moisture availability

along the same trend as natural trees, while *Pinus* and *Salix* show slight increases during the Imperial Persia period. In this zone, cultivated trees show higher diversity than in zone A, and *Platanus* and *Olea* show slightly higher values than the previous zone. This pattern continues over zone B and approximately until the end of subzone C1. Meanwhile, the amount of pollen from desert indicator shrubs, particularly Ephedraceae, starts declining. An important point in zone B is the appearance of the underrepresented (van Zeist et al. 2001) pollen of *Punica granatum* in B2, which is centred around 2,300 cal BP.

Moreover, grass pollen-type (Poaceae > 30 μm) shows a gradual decrease during zone B, coinciding with the constant presence of *Tribulus*, *Prosopis farcta*, Euphorbiaceae and *Cousinia* as disturbance indicators, as well as with the highest percentages of *Sporormiella* spores (up to 4%) indicating pastoral activities. Simultaneously, relatively high values (30%) of Amaranthaceae pollen occur in this zone, suggesting the dominance of Amaranthaceae in saline habitats around the lake. These plants may also increase due to overgrazing.

LPAZ C (ca. 1,612 cal BP to present) comprises subzone C1 (ca. 1,612–815 cal BP) and C2 (ca. 815 cal BP to present). The most characteristic feature in the lower part of LPAZ C (subzone C1) is the remarkable increase in arboreal pollen. This growth is mainly due to strikingly high values of *Platanus* pollen (more than 5%) that is unique throughout the record. This pollen shows nearly the same values towards the end of the diagram. In addition to *Platanus*, other cultivated trees like *Juglans*, *Olea* and *Vitis* demonstrate their highest values. In this zone, Cerealia-type pollen depicts a continuous curve along with ruderal taxa like *Centaurea solstitialis*, *Plantago lanceolata*, Euphorbiaceae and *Rumex*. However, together with increasing amounts of cultivated trees, the frequencies of *Sporormiella* and cereal-type pollen suggest an increase in agro-pastoral activities in peri-urban and ruderal areas. Regional forest vegetation does not change significantly in subzone C1, while in C2, *Pistacia* and *Acer* pollen drop to their lowest values (less than 5% and 1%, respectively) and *Platanus* decreases significantly, although the *Quercus* curve grows slightly. Additionally in zone C, desert shrubs (e.g. Ephedraceae and *Tamarix*) show increasing amounts towards the end of the zone.

Discussion

Changes in the vegetation of the Maharlou Lake basin

The new palynology diagram of the Maharlou Lake basin (Fig. 3) shows the status and the distinctive phases of change in the vegetation during the last ~3,800 years. *Grasslands*.

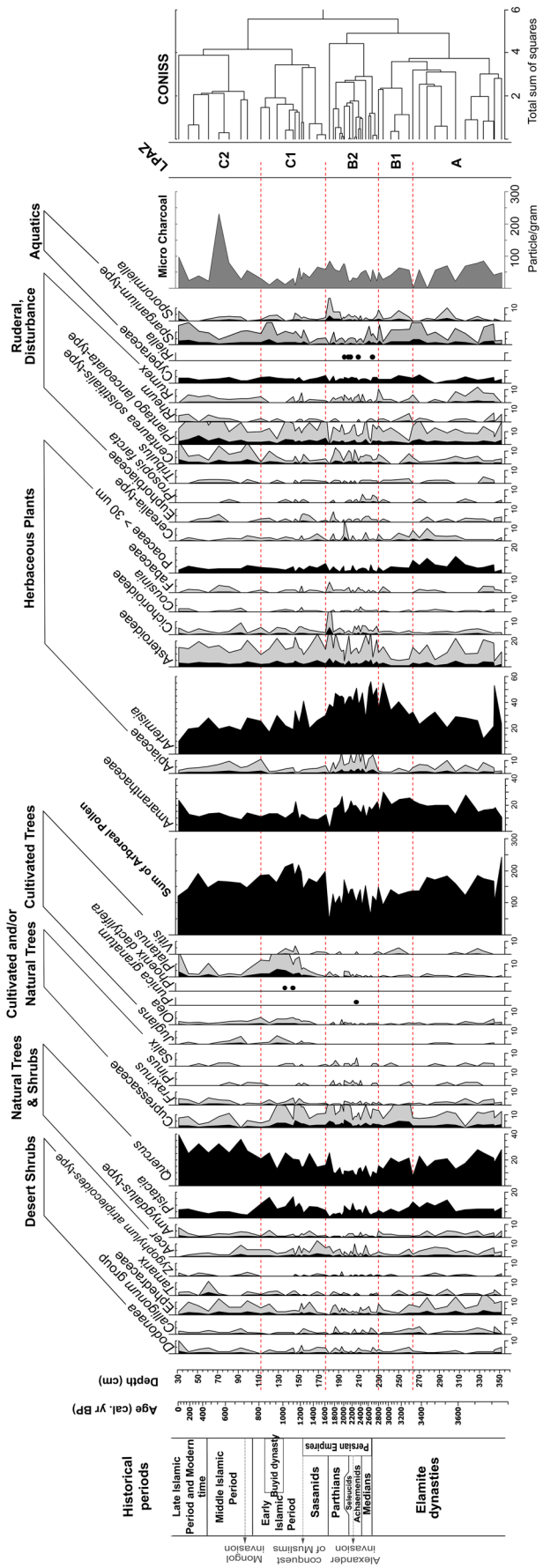


Fig. 3 Pollen percentage diagram for Lake Maharlou for a selection of taxa; exaggeration curves (×5) are coloured in light grey; rare species with percentages <0.5% are marked with filled circle. Horizontal dashed lines separate the local pollen assemblage zones (LPAZ)

A period of increase in grassland and/or grass steppe coverage can be inferred from the highest values of grass-type pollen (Poaceae > 30 µm) at the beginning of the record, during the LAPZ A. Figure 4 shows the highest values of the Poaceae/*Artemisia* (P/A) ratio as a moisture indicator (Dehghani et al. 2017), and the highest values of *Sparganium*-type pollen in zone A. Additionally, the aridity index (*Artemisia* + Chenopodiaceae [Amaranthaceae])/Poaceae ((A + C)/P) presents its lowest values. The interpretation of higher moisture availability for the Maharlou basin based on pollen analysis agrees with sedimentological and geochemical evidence of a period of frequent flood events associated with a high sediment discharge to the lake (dated from 3,800 to 2,000 cal BP, Brisset et al. 2019). These results are consistent with interpretations of moisture increase in Southwest Asia during the mid- to late Elamite period. This increase has been shown in speleothems in Yemen and Oman (Fleitmann et al. 2003, 2007; Flohr et al. 2017), as well as by the higher level of the Caspian Sea (Rychagov 1997). Moisture availability, and therefore the presence of marshland vegetation around the lake and denser grasslands in higher elevations, could have provided more fodder and better conditions for livestock husbandry. The first peak of *Sporormiella*, centred around 3,500 cal BP, supports this fact. LPAZ A corresponds to the mid- to late Elamite period dynasties; hence, growth in grass-type pollen and coprophilous fungi spores can be indirect evidence for population increase and development of the first urban centres during the late Kaftari phase (ca. 2200–1600 BP; 4,150–3,550 BP) in the Kur River basin (Miller 2014). The high values of *Artemisia* pollen represented in the middle of the diagram (Fig. 3) can be correlated with the transportation of fluvial material from distant areas with *Artemisia*-dominated vegetation. Stevenson (1981) discussed a similar phenomenon in the fossil pollen record of the Turan biosphere reserve in Iran.

Historically, the second part of the diagram (Zone B) coincides with the late Elamite period in subzone B1 and covers most of Imperial Persia (including the Median, Achaemenid, Seleucid, Parthian and the early Sasanid period) in B2. In this part, a period of decline in marshlands and grassland vegetation, and lower available moisture (ca. 3,350–1,610 cal BP), can be inferred from the P/A and ((A + C)/P) indices together with *Sparganium*-type pollen. This period coincides with the constant presence of disturbance indicators and *Cousinia* (Fig. 3). These taxa have poor representation in modern and fossil pollen records; they represent disturbed and overgrazed habitats in semi-arid areas (Dehghani et al. 2017; Djamali et al. 2012; Stevenson 1981).

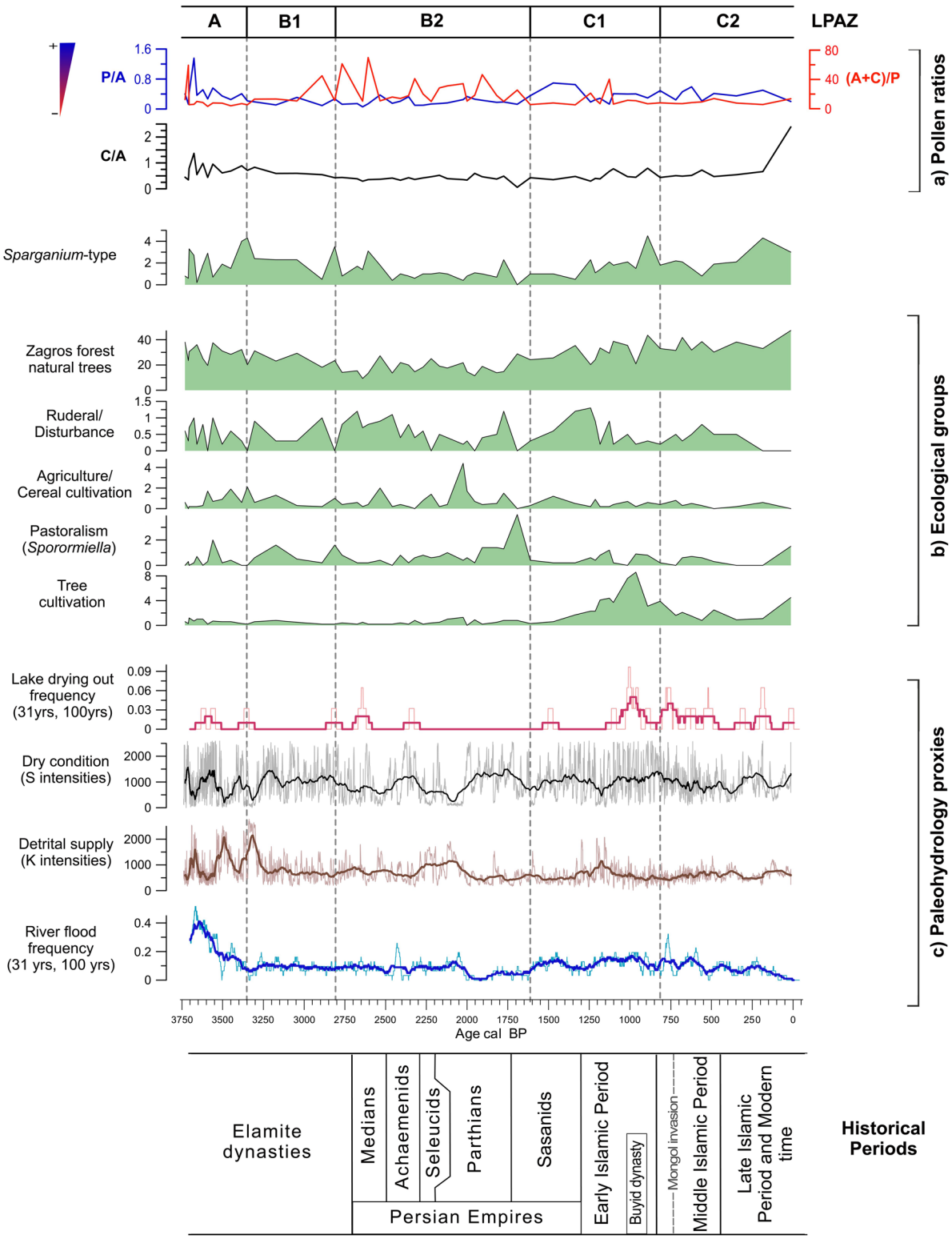


Fig. 4 Synthesis diagram of main pollen ratios (a), selected ecological groups and taxa (b) and reconstructed palaeohydrology (c) in Lake Maharlou. Gradient-coloured arrow indicates moisture correlation with the respective index; vertical dashed lines show the LPAZ

The spiny shoots of these plants are unpalatable for livestock and demonstrate the low-quality and least-favoured fodder for grazing. The presence of disturbed areas is also reflected in simultaneous high values of Amaranthaceae. According to floristic studies and vegetation maps of Maharlou Lake (Carle and Frey 1977; Frey and Probst 1974), the xerophytic-halophytic habitats around the lake are dominated by species of the Amaranth family. Considering the relatively low values of Chenopodiaceae (Amaranthaceae)/*Artemisia* (C/A) ratio (Fig. 4), the variation in Amaranthaceae percentages were at least partly related to the presence of ruderal taxa rather than the exclusively halophytic groups of this family. Similarly, Stevenson (1981) described the same pattern in the modern and fossil pollen records of the Turan Biosphere in northeast Iran. Altogether, the decline in grasslands, expansion of ruderal and thorny taxa, as well as the highest percentages of *Sporormiella* spores suggest intensified pastoral activities and overgrazing during this period.

In addition to pastoral activities, agriculture and tree cultivation played important roles in defining the vegetation dynamics of the study area. This fact is inferred from the continuous curve of cereal-type pollen (Fig. 3) and pollen from several cultivated trees (Fig. 4). However, an increase in arboriculture coincides with a slight decrease in cereal cultivation and pastoralism indicators in zone C (C1 and C2), from around 1,600 cal BP to the present time. Historically, subzone C1 coincides with the early period of the Sasanian Empire to almost the end of the Early Islamic period (ca. 1,150–800 BP), following the chronology of Sumner and Whitcomb (1999). Subzone C2 covers the Middle Islamic period (ca. 800–450 BP) and the Late Islamic period (Safavid to modern times). The changes in cereal cultivation and pastoralism indicators, as well as the high concentration of microcharcoal particles in this zone are compatible with archaeological and historical evidence (Sumner and Whitcomb 1999) and may indicate urbanisation and development of new urban areas, respectively.

Natural Forests. Looking at the main pollen spectra of the natural forest vegetation (oak, wild pistachio and almond) suggests several phases of change in the natural landscape during the last four millennia. Relatively high values of oak and pistachio in zone A and subzone B1 are mainly centred around the period of frequent flood events with peaks in terrigenous sediment influx in ca. 3,700–3,200 cal BP in Maharlou Lake (Brisset et al. 2019). Hence, despite the increasing values of these pollen types, a rather stable status in the natural forest vegetation can be postulated for this period in the Maharlou catchment basin. In contrast, the lowest values of *Quercus*, *Pistacia* and *Amygdalus* (*Prunus*) occur around 2,800–1,600 cal BP in subzone B2. This event is centred around the cool and wet climatic event of ~ 2,600 BP correlated with the high stands of the Caspian Sea region and in north-western Iran (Djamali et al. 2009b; Kroonenberg et al. 2007). Moreover, Brisset et al. (2019) documented an overall hydrological balance in Lake Maharlou corresponding to more water inflow and less evaporation during 3,800–2,000 cal BP. They correlated this period with the wet climatic condition and a regional moisture increase in Southwest Asia inferred from geomorphic records (interdune formation in the United Arabic Emirates, Parker et al. 2006; and river incision in Saudi Arabia, Matter et al. 2016) and moisture-sensitive proxies (e.g. Soreq Cave in Socotra, van Rampelbergh et al. 2013). Theoretically, the regional ecological conditions could have been in favour of preserving or even expanding natural forests in the study area. In this regard, the anthropogenic factor should be considered in explanation of the oak and pistachio forest decline. Historically, the lowest values of the curves for natural trees are represented during the Imperial Persia, including the Achaemenid period. The Achaemenids started to build the first superpower centre of the Late Antiquity period with a comprehensive and well-organised management system centred in Persepolis (50 km north of Maharlou Lake) and other intermountain basins of Fars. The rise of such a geopolitical power, and the later Sasanian Empire, required the intensive exploitation of natural resources and left impacts on the ecosystems. In this regard, the decline in values for natural trees may reflect deforestation activities to provide timber and intensive grazing.

Lake Maharlou underwent several periods of dry/wet climate conditions after 2,000 cal BP (Brisset et al. 2019 and Fig. 4). In the post-Achaemenid period, the pollen graph (Fig. 3) represents signs of a local aridification phase corresponding to lower lake levels (after 2,000 cal BP). This evidence is combined with variation in the amounts of pollen from *Zygophyllum*, *Ephedra* and *Tamarix* shrubs, which mainly grow in desertic habitats, and with anthropogenic pollen indicators (e.g. ruderals). It is conceivable that they illustrate overexploited vegetation that also suffered from a drying climate. Furthermore, the shrinkage of the wet areas around Lake Maharlou is revealed by the absence of *Riella* spores during the Late Antiquity period. In saline lake systems with vast flat littoral zones, *Riella* is suggested to be an indicator of higher lake levels (Djamali et al. 2008). Therefore, its absence could show the decrease in river inflow to the lake, possibly related to lower precipitation.

By the early Sasanian Empire (~1,600 cal BP), the natural forest started to recover. Oak pollen values increase slightly towards modern times, while in the last 800 years, *Pistacia* and *Acer* pollen drop significantly. Miller (2014) explained similar differences between *Quercus* and *Pistacia* values in the Kur River basin, during the Kaftari phase (ca. 2,200–1,600 BC). Such differences suggest that compared to oak, in lower altitudes pistachio-almond vegetation

was further destroyed because of an increasing number and area of settlements. In more detail, pistachio grows in lower altitudes with warmer microclimates (Taheri Abkenar et al. 2016), and it is more accessible to people as a source of firewood, edible nuts or fodder. Pourreza et al. (2008) showed that overgrazing, the absence of a desirable seedbed and lack of seeds (due to low seed production rate or the collection of seeds and young shoots for human and animal consumption) have the main impacts on *Pistacia* vegetation in the Zagros Mountains. In addition, El-Moslemany (1986) noted the sensitivity of pistachio seedlings to high temperatures and their negative impact on regeneration potential.

In the last part of the diagram, the most recent cooling interval in Maharlou Lake (700 cal BP to present), expressed with few desiccation events, approximately corresponds to the Little Ice Age (LIA) (600–150 cal BP). This event affected agriculture in Europe in different ways with both negative (Central Europe) as well as positive (England) impacts (Pfister and Brázdil 2006; Poschlod 2017; Tello et al. 2017). This period has been documented in several pollen records from Iran (Djamali et al. 2009b; Leroy et al. 2011; Ramezani et al. 2008). In Lake Almalou in northwest Iran, lower values of Cerealia-type and cultivated tree pollen have been reported (Djamali et al. 2009b). Agriculture indicators in Maharlou Lake show almost the lowest values in this interval as do natural forest trees, particularly *Pistacia*, *Amygdalus* and *Acer*, in addition to the remarkable peak in microcharcoal and high values of *Plantago lanceolata*-type pollen. This evidence supports increasing anthropogenic pressure (e.g. deforestation, intentional fire and disturbance). In conclusion, the climatic variations after 2,000 cal BP, combined with intense human impacts during the Classical and Late Antiquity periods, and later in the middle-to-late Islamic periods, were presumably affecting the natural pistachio vegetation.

Finally, in the most recent 200 years, increasing values of desert shrubs (e.g. Ephedraceae and *Tamarix*) with a slight increase in Amaranthaceae and C/A values at the end of the diagram are probably related to the expanding halophytic vegetation belt around the lake due to drier climatic conditions with enhanced evaporation. In addition, regional groundwater levels are dropping due to overexploitation for intensive agriculture (Motagh et al. 2008; Tourian et al. 2015).

A note on the cultivated trees in the Maharlou Lake basin

In contrast to the early history of the domestication of cereals and other crops (12,000–10,000 BP; Allard 1999), humans started to plant trees, in particular fruit trees, during the last 5,000 years (Chandra et al. 2010). Some pollen studies (e.g. Jones et al. 2015) in the Zagros Mountains have provided vegetation records for long periods (e.g. the Holocene epoch) with no special focus on agricultural events during Imperial Persia (550 BC-AD 651) and the Achaemenid period. The long history of tree cultivation and introduction of new arboreal elements in southwest Iran is documented in a few publications (Djamali et al. 2009a, 2011, 2015, 2017; Jones et al. 2015; Miller 1985; Shumilovskikh et al. 2017). In this study, pollen types of *Platanus*, *Punica granatum*, *Vitis*, *Olea*, *Juglans* and *Phoenix dactylifera* are used to define arboricultural activities. By the beginning of the Imperial Persia period, the sum of pollen from cultivated trees demonstrates increasing numbers with the first peak centred around the Achaemenid period (Fig. 3). The presence of the pollen of *Vitis* and *Punica granatum*, considering the under-represented nature of these species in pollen rain (Turner and Brown 2004; van Zeist et al. 2001), supports the idea of arboriculture development as orchards and vineyards close to the lake.

A modern pollen rain and vegetation study in the Irano-Turanian region showed evidence of covariation between indigenous trees with the cultivated trees, related to their use as ornamental trees (Dehghani et al. 2017). Considering that *Fraxinus*, *Salix*, *Pinus* and Cupressaceae have naturally grown stands in the Maharlou Lake basin, particular attention is paid to the pollen curves of these taxa, which show visible changes when compared to the cultivated trees (Fig. 3). Cupressaceae represent a continuous pollen curve with distinct phases of increasing values from around the late Elamite period to the Achaemenid, and up to the early Islamic period (Fig. 3). Regarding the near-complete absence of juniper trees from the region today, we hypothesised that the pollen of this family is mostly produced by the cypress tree. The values of cypress pollen, varying in the same fashion with cultivated trees, support the hypothesis according to which cypress was an important constituent of ancient 'Persian gardens' and was favoured by the Achaemenids and Sasanians (Djamali et al. 2017). Indeed, *Cupressus sempervirens* timber was used in the construction of monuments by the Sasanian and early Muslim dynasties (Djamali et al. 2017). However, the starting date for cypress plantation may go back to the late Elamite period.

Among cultivated trees, *Platanus* shows the most significant changes throughout the new Maharlou record and is present in almost all periods. Miller (1985) suggested the early cultivation of *Platanus* by Elamites, based on charcoal records from 2200 to 1800 BC. The constant presence of plane tree pollen in southwest Iran is also well described in previous investigations (Djamali et al. 2009a, 2011, 2017; Shumilovskikh et al. 2017). The present diagram shows the increase in *Platanus* pollen values centred around the Achaemenid period and reaching to the highest percentages during the Sasanian Empire to the Early Islamic period and the Buyid dynasty in particular. *Platanus* and *Juglans* both show

an increasing trend from the late Sasanian period. According to Potts (2018) and following the "Radde dictum", both *Platanus* and *Juglans* trees are introduced to the Iranian flora with the exception of a very few wild trees in the Hyrcanian region. Based on available palynological records, archaeological data and written sources, plane trees were cultivated in Iran since the early second millennium BC, while walnut planting had begun by the middle of the third millennium BC. In contrast to the results of Djamali et al. (2009a, 2011, 2017), the prominent peak of tree cultivation in the current pollen diagram from Lake Maharlou closely coincides with the late Sasanian and the Early Islamic period. However, it is not possible to directly compare the current pollen record with the former study (Djamali et al. 2009a) because of the different age-depth model of the former record, which was obtained from radiocarbon dating on different materials (Djamali et al. 2010). In Parishan Lake, pollen records documented the peak of plane tree and walnut cultivation concurrent with the rise of the Achaemenids (Jones et al. 2015) (Fig. 5). The Lake Parishan basin (~100 km West of Maharlou Lake) is closely located, and displays similar geology to Maharlou Lake, although they have relatively different elevations and bioclimatic conditions.

The maximum values of plane tree and walnut pollen correlate with the significant presence of *Vitis*, a very under-represented tree in modern pollen rain (Turner and Brown 2004). It can suggest different crop type cultivation in the Maharlou Lake basin compared to the adjacent basin of Lake Parishan. Based on the condition of natural habitats and ecological preferences of *Vitis*, the open valleys in the Maharlou Lake basin could provide more suitable conditions for developing vineyards. Also, the hydrological condition of the basin during 3,800–2,000 cal BP provided more water on slopes and a higher river flow (Brisset et al. 2019), which could support viticulture without advanced irrigation requirements. Therefore, the appearance of *Vitis* values from the Elamite to the mid-Parthian period in the Maharlou record can be correlated to fluvial input of pollen grains, possibly from river valleys (Turner and Brown 2004). Later, that fluvial input may have been through the advanced irrigation techniques of the Sasanian, then reached its maximum in the Early Islamic period. The influence of Sasanian management on tree cultivation is similarly documented in the Almalou record (Fig. 5) (Djamali et al. 2009b). This hypothesis needs to be verified by historical and archaeological evidence.

In accordance with other cultivated trees, *Olea* pollen-type depicts a constant presence throughout the MAH-B record. It shows relatively low values during the Elamite and Median periods and starts to increase after the Achaemenid. The frequent changes in *Olea* pollen values and peak percentages during the Persian Empires, specifically the late Sasanian period, have been interpreted as olive cultivation in many pollen records from Iran (Djamali et al. 2009a, b, 2011, 2015; Jones et al. 2015). The historical evidence of seedling inventories obtained from the Persepolis Fortification Archive (PFa 33) also supports olive cultivation in southern Iran and the Achaemenid heartland (Henkelman 2013).

Figure 3 shows that the distinctive values of *Olea* occurred almost after the Sasanian period and clearly declined by the Mongol invasion. This observation provides comparable evidence for olive cultivation in the northern Zagros (Djamali et al. 2009b; van Zeist 1967; van Zeist and Bottema 1977); however it is not concurrent with similar evidence from the Lake Parishan (Djamali et al. 2011, 2015). In this context, we suggest that the olive cultivation was first practised by the Achaemenids in the lower plains around Lake Parishan and was most probably extended later to the Maharlou basin by the Sasanians and Buyids.

In the Maharlou Lake basin, arboriculture most probably started with *Olea*, *Punica* and *Platanus* cultivation by the Achaemenids, and *Juglans* by the Sassanians. Then, it continued to the summit of arboriculture with *Phoenix dactylifera* and *Platanus* approximately during the Buyid dynasty (Fig. 3). A similar trend of arboriculture maximum during the post-Achaemenid period has been documented in Lake Almalou, in northwest Iran (Djamali et al. 2009b) (Fig. 5). Agriculture development under the semi-arid climate of southern Iran relies on the availability of water. Geoarchaeological studies show intensive and sophisticated water resource and hydraulic network management during the Achaemenid period in the Kur River basin (De Schacht et al. 2012). Subsequently, the Sasanians and early post-Sasanian Iranian governors such as Adud al-Dawla (Ajod al-Dawla, of the Buyid dynasty) invested much effort in renovating, as well as developing, the irrigation systems for intensive agriculture in the lower Kur River basin with the impressive example of the construction of the Band-e Amir dam (Sumner and Whitcomb 1999). The productive agriculture continued for a few centuries but was ended by the Mongol invasion of the Iranian plateau (AD 1220; 730 BP). During the Ilkhan period (677–700 BP), the province of Fars suffered from severe destruction and abandonment of irrigation channels, followed by the abandonment of arable fields and orchards. Cultivated trees like *Olea*, *Juglans* and especially *Platanus* show similar declining trends during this period (Fig. 3). A similar decrease in agriculture has also been shown in NE Iran in the Gorgan plain by pollen studies (Shumilovskikh et al. 2017) and by archaeological charcoal analysis (Qal'eh Kharabeh; Poole and Gale 2013).

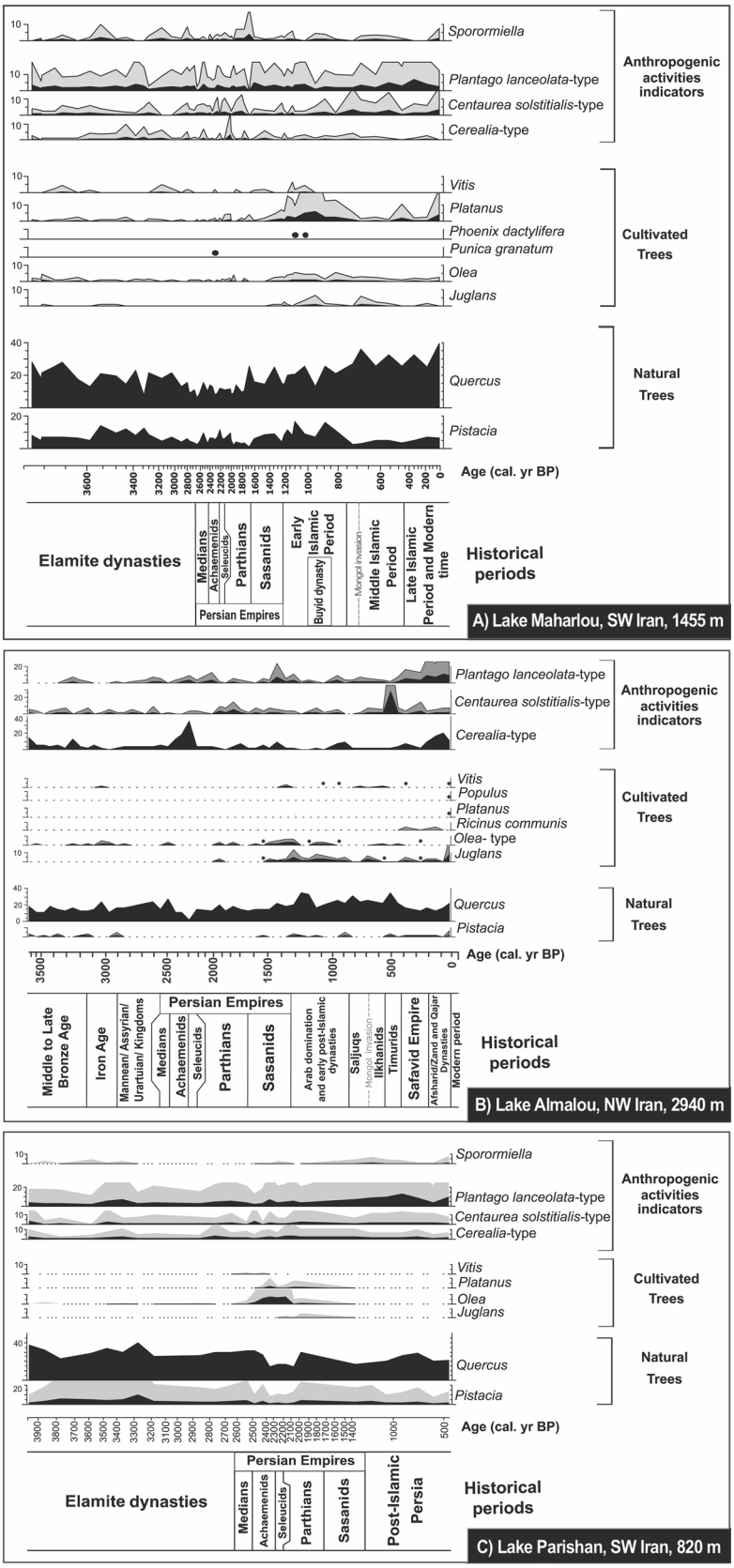


Fig. 5 Summarised pollen diagram of A: Lake Maharlou, B: Lake Almalou, and C: Lake Parishan to compare the anthropogenic activities, tree cultivation and changes in natural forest based on a selection of main taxa; exaggeration curves (×5) are coloured in light grey; rare species with percentages <0.5% are marked with filled circle

New arboricultural element for the Southern Zagros mountains

Punica granatum has a vast natural distribution from the Balkans to north western India, but is mostly restricted to the Irano-Turanian and Mediterranean floristic regions (Levin 2006; Zohary 1973). Despite the difficulties in detecting the indigenous species, Rechinger (1966) reported natural pomegranate populations from northern Iran (Gorgan, Mazandaran and Gilan provinces) as well as the northern part of Azerbaijan, Kurdestan, Qazvin and Baluchestan. The documented *P. granatum*-type in the Maharlou pollen record (Fig. 3) is the first report for southern Iran and the south-western Zagros. This region is geographically far from the proposed locations of wild pomegranate populations in Iran. Pomegranate is extremely under-represented in modern pollen rain due to insect- and self-pollination, suggesting that the few counted pollen grains may indicate pomegranate plantations (Morton 1987). The documented pomegranate pollen grains were extracted from sediments approximately corresponding to the Achaemenid period (subzone B2). In 1986, Bottema documented rare pomegranate pollen in the Urmia Lake record in north-western Iran. However, due to the age uncertainty of the Lake Urmia chronology, no solid conclusion could be made about the exact age and possible cultivation of the tree. It has been discussed that pomegranate domestication took place independently in different regions of the world (Mars 2000). For instance, Xhuveli (2012) suggested separated pomegranate domestication practices in Albania during the Bronze Age (third-second millennia BC). The first pomegranate domestication practices presumably started around the late Neolithic period in the Transcaucasia-Caspian region and Northern Turkey (Chandra et al. 2010; Levin 2006). Pomegranate use can be traced back to the fourth millennium BC in the ancient Middle East and Mediterranean region (Zeynalova and Novruzov 2017). Besides having dietary and medicinal properties, the pomegranate fruits were widely being used as a symbol of fertility to decorate clothes and jewellery of noble people, for instance, the royal Assyrian women (State Archives of Assyria 2019: letters SAA 7, 72 and 81). Moreover, the fruit appeared in several Assyrian rituals and royal gardens, as shown by their rock relief representations (SAA 20). Outside the Eastern Mediterranean, pomegranate pollen and seeds have been recovered and reported from Carthaginian ancient harbours in Tunisia, both with extremely low values (van Zeist et al. 2001). In addition, the pomegranate name appears in PFa 33 from the Persepolis Fortification Archive (PFA). The Elamite administrative texts mention the inventories of tree seedlings that were produced to be planted in five 'paradises' in the Achaemenid heartland (Henkelman 2013). In PFa 33, pomegranate ('ka-ru-kur') is listed together with other fruits including pear, quince, mulberry, olive, date and apple.

In conclusion, the special pollen dispersal of *P. granatum*, along with the historical records, supports cultivation of fruit trees, including pomegranates, in the Maharlou Lake basin. These facts also strengthen the hypothesis that states the flowers offered by the Achaemenid kings in Persepolis reliefs are most probably pomegranate rather than lotus flowers (Keshavarzi 2014; Tilia and Tilia 1972–1978; Ward 2003).

Conclusions

The present palynological study on the MAH-B core provides an updated reconstruction for the vegetation dynamics of the Lake Maharlou basin over the last four millennia. The results demonstrated the role of anthropogenic activities, modulated by hydroclimatic changes, in modifying the landscape of the basin during the last ~4,000 years. Several periods of change in the natural vegetation of the basin can be inferred from the present pollen record, in accordance with the reconstructed periods of dry/wet climatic conditions of Lake Maharlou. In general, the oak forest in the study area experienced a relatively stable situation until around 2,800 cal BP, correlated with the period of positive hydrological balance in the lake as well as wetter climatic conditions over the Iranian Plateau. A subsequent decline in natural forest vegetation is inferred and correlated to a drying climate and an increase in anthropogenic activities, mainly after 2,000 cal BP. Pollen indicator groups and ratios show that pastoral activities, agriculture and tree cultivation played important roles in defining the vegetation dynamics of the study area. The Little Ice Age is clearly recorded in the present Maharlou pollen record. Low values of agriculture pollen indicators during this period, in addition to the significant peak in microcharcoal particles and ruderal species, support a sedentary to nomado-pastoral change in lifestyle. The highest diversity of cultivated trees documented during the Imperial Persia (550 BC-AD 651) period includes the plane tree, grapevine, walnut, date palm and pomegranate, which is a new arboricultural pollen record for southern ancient Persia. The orchards and garden development ('Persian garden') most probably started during the Achaemenid Empire period (550–330 BC) with quasi-permanent symbolic cultivation of cypress and plane trees. Agricultural development was likely promoted by advanced irrigation systems that were mainly developed by the Achaemenids and Sasanians and maintained and renovated by later Iranian dynasties. In contrast to the nearby basin of Lake Parishan, our results suggest that arboriculture in the Lake Maharlou basin may have reached its most advanced level during the late Sasanian and Early Islamic Iranian dynasties.

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References

Akhani H (2004) Halophytic vegetation of Iran: towards a syntaxonomical classification. Ann Bot 4:65–82

Allard RW (1999) Principles of plant breeding. Wiley, New York

Behre K-E (1981) The interpretation of anthropogenic indicators in pollen diagrams. Pollen Spores 23:225–245

Beug HJ (2004) Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Pfeil, München

Blaauw M (2010) Methods and code for "classical" age-modelling of radiocarbon sequences. Quat Geochronol 5:512–518. https://doi.org/10.1594/PANGAEA.873023

Bottema S (1986) A late quaternary pollen diagram from Lake Urmia (NW Iran). Rev Palaeobot Palynol 47:241–261

Brisset E, Djamali M, Bard E et al (2019) Late Holocene hydrology of Lake Maharlou, southwest Iran, inferred from high-resolution sedimentological and geochemical analyses. J Paleolimnol 61:111–128. https://doi.org/10.1007/s10933-018-0048-6

Carle R, Frey W (1977) Die Vegetation des Mahārlū-Beckens bei Šīrās (Iran): unter besonderer Berücksichtigung der Vegetation im Bereich der Süß- und Salzwasserquellen am Seeufer. Reichert, Wiesbaden

Chandra R, Babu KD, Jadhav VT, Teixeira da Silva JA (2010) Origin, history and domestication of pomegranate. In: Chandra R (ed) Pomegranate. Fruit, vegetable and cereal science and biotechnology, vol 4 (Special Issue 2). Ikenobe, Global Science Books, pp 1–6

Critchfield HJ (1974) General climatology, 3rd edn. Prentice-Hall, Upper Saddle River

De Schacht T, De Dapper M, Asadi A et al (2012) Geoarchaeological study of the Achaemenid dam of Sad-i Didegan (Fars, Iran). Geomorphologie: Relief, Processus, Environnement 1:91–108

Dehghani M, Djamali M, Gandouin E, Akhani H (2017) A pollen rain-vegetation study along a 3600 m mountain-desert transect in the Irano-Turanian region: implications for the reliability of some pollen ratios as moisture indicators. Rev Palaeobot Palynol 247:133–148. https://doi.org/10.1016/j.revpalbo.2017.08.004

Djamali M, Kürschner H, Akhani H et al (2008) Palaeoecological significance of the spores of the liverwort *Riella* (Riellaceae) in a late Pleistocene long pollen record from the hypersaline Lake Urmia, NW Iran. Rev Palaeobot Palynol 152:66–73. https://doi.org/10.1016/j.revpalbo.2008.04.004

Djamali M, de Beaulieu J-L, Miller NF et al (2009a) Vegetation history of the SE section of the Zagros mountains during the last five millennia; a pollen record from the Maharlou Lake, Fars Province, Iran. Veget Hist Archaeobot 18:123–136. https://doi.org/10.1007/s00334-008-0178-2

Djamali M, de Beaulieu J-L, Andrieu-Ponel V et al (2009b) A late Holocene pollen record from Lake Almalou in NW Iran: evidence for changing land-use in relation to some historical events during the last 3700 years. J Archaeol Sci 36:1364–1375. https://doi.org/10.1016/j.jas.2009.01.022

Djamali M, Miller NF, Ramezani E, Andrieu-Ponel V, de Beaulieu JL, Berberian M (2010) Notes on arboricultural and agricultural practices in ancient Iran based on new pollen evidence. Paleorient 36:175–188

Djamali M, Akhani H, Khoshravesh R et al (2011) Application of the global bioclimatic classification to Iran: implications for understanding the modern vegetation and biogeography. Ecol Mediterr 37:91–114

Djamali M, Baumel A, Brewer S et al (2012) Ecological implications of *Cousinia* Cass. (Asteraceae) persistence through the last two glacial–interglacial cycles in the continental Middle East for the Irano-Turanian flora. Rev Palaeobot Palynol 172:10–20. https://doi.org/10.1016/j.revpalbo.2012.01.005

Djamali M, Jones MD, Migliore J et al (2015) Olive cultivation in the heart of the Persian Achaemenid empire: new insights into agricultural practices and environmental changes reflected in a late Holocene pollen record from Lake Parishan, SW Iran. Veget Hist Archaeobot 25:255–269. https://doi.org/10.1007/s00334-015-0545-8

Djamali M, Chaverdi A, Balati S, Guibal F, Santelli C (2017) On the chronology and use of timber in the palaces and palace-like structures of the Sasanian Empire in "Persis" (SW Iran). J Archaeol Sci: Rep 12:134–141. https://doi.org/10.1016/j.jasrep.2017.01.030

Djamali M, Gondet S, Ashjari J et al (2018) Karstic spring wetlands of the Persepolis Basin, southwest Iran: unique sediment archives of Holocene environmental change and human impacts. Can J Earth Sci 55:1158–1172. https://doi.org/10.1139/cjes-2018-0065

El-Moslimany AP (1986) Ecology and late-Quaternary history of the Kurdo-Zagrosian oak forest near Lake Zeribar, western Iran. Vegetatio 68:55–63

Fleitmann D, Burns SJ, Mudelsee M, Neff U, Kramers J, Mangini A, Matter A (2003) Holocene forcing of the Indian Monsoon recorded in a stalagmite from Southern Oman. Science 300:1737–1739

Fleitmann D, Burns SJ, Mangini A et al (2007) Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra). Quat Sci Rev 26:170–188

Flohr P, Fleitmann D, Zorita E et al (2017) Late Holocene droughts in the Fertile Crescent recorded in a speleothem from northern Iraq. Geophys Res Lett 44:1528–1536

Frey W (1982) Mahārlū -Becken bei Shiraz/Šīrās (Iran), Mittlerer Teil, Vegetation. Tübinger Atlas des Vorderen Orients A,6 10,2. Reichert, Wiesbaden

Frey W, Probst W (1974) Vegetationszonierung an Süsswasserquellen des Maharlu-Salzsees bei Shiraz (Iran). Vegetatio 29:109–114

Gondet S (2011) Occupation of the Persepolis Plain in the first millennium B.C. J.-C. (Central Fars, Iran). Dissertation, University Lumière Lyon 2, Lyon
Grimm EC (1987) CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Comput Geosci 13:13–35. https://doi.org/10.1016/0098-3004(87)90022-7
Grimm EC (2011) Tilia, version 2.0.41. Illinoise State Museum, Springfield
Henkelman WFM (2013) Administrative realities: The Persepolis archives and the archaeology of the Achaemenid heartland. In: Potts DT (ed) The Oxford handbook of Ancient Iran. Oxford University Press, Oxford, pp 528–546
Jones MD, Djamali M, Holmes J et al (2015) Human impact on the hydro environment of Lake Parishan, SW Iran, through the late Holocene. Holocene 25:1651–1661. https://doi.org/10.1177/0959683615594242
Juggins S (2010) C2 (Version 1.7.7). https://www.staff.ncl.ac.uk/stephen.juggins/software/C2Home.htm
Keshavarzi KH (2014) A new approach to Persepolis based on Avesta and religious-ritual ceremonies. Behjat Publication, Tehran
Kimiaei M (2006) (In Farsi) Archeobotanical investigations in Tole Bashi: reconstruction of the preferred environment and life style of a Neolithic rural society in Kur River basin. Iranian J Archeol Hist 20:8–21
Kroonenberg SB, Abdurakhmanov GM, Badyukova EV et al (2007) Solar-forced 2600BP and Little Ice Age highstands of the Caspian Sea. Quat Int 173:137–143
Leroy S, Lahijani H, Djamali M et al (2011) Late Little Ice Age palaeoenvironmental records from the Anzali and Amirkola Lagoons (south Caspian Sea): vegetation and sea level changes. Palaeogeogr Palaeoclimatol Palaeoecol 302:415–434
Levin GM (2006) Pomegranate. Third Millennium Publishing, Tempe
Mars M (2000) Pomegranate plant material: genetic resources and breeding, a review. Options Mediterr Ser A 42:55–62
Matter A, Mahjoub A, Neubert E, Preusser F, Schwalb A, Szidat S, Wulf G (2016) Reactivation of the Pleistocene trans-Arabian Wadi ad Dawasir fluvial system (Saudi Arabia) during the Holocene humid phase. Geomorphology 270:88–101
Miller NF (1985) Paleoethnobotanical evidence for deforestation in ancient Iran: a case study of urban Malyan. J Ethnobiol 5:1–21
Miller NF (2011) An archaeobotanical perspective on environment, plant use, agriculture, and interregional contact in South and Western Iran. Iranian J Archaeol Stud 1:1–8
Miller NF (2013) Agropastoralism and archaeobiology: connecting plants, animals and people in west and central Asia. Environ Archaeol 18:247–256. https://doi.org/10.1179/1749631413Y.0000000003
Miller NF (2014) Vegetation proxy data and climate reconstruction. In: Madella M, Lanceolotti C, Savard M (eds) Ancient plants and people. University of Arizona Press, Tucson, Contemporary trends in archaeobotany, pp 120–134
Miller NF, Abdi K, Sumner WM (2003) Yeki bud, yeki nabud: essays on the archaeology of Iran in honor of William M. Sumner. Monograph, vol 48. Cotsen Institute of Archaeology Press, Los Angeles
Moore PD, Webb JA (1978) An illustrated guide to pollen analysis. Wiley, New York
Moore PD, Webb JA, Collinson ME (1991) Pollen analysis, 2nd edn. Blackwell, Oxford
Morton J (1987) Pomegranate. In: Morton JF (ed) Fruits of warm climates. Creative Resource Systems, Winterville, pp 352–355
Motagh M, Walter TR, Sharifi MA, Fielding E, Schenk A, Anderssohn J, Zschau J (2008) Land subsidence in Iran caused by widespread water reservoir overexploitation. Geophys Res Lett 35:L16403
Parker AG, Goudie AS, Stokes S, White K, Hodson MJ, Manning M, Kennet D (2006) A record of Holocene climate change from lake geochemical analyses in southeastern Arabia. Quat Res 66:465–476
Petrie CA, Djamali M, Jones MD (2018) Physical geography and environment of Elam. In: Álvarez-Mon J, Basello GP, Wicks Y (eds) The Elamite World, 1st edn. Routledge, London, pp 99–118
Pfister C, Brázdil R (2006) Social vulnerability to climate in the "Little Ice Age": an example from Central Europe in the early 1770s. Clim Past 2:115–129. https://doi.org/10.5194/cpd-2-123-2006
Poole I, Gale R (2013) Charcoal. In: Sauer E, Wilkinson TJ, Omrani Rekavandi H, Nokandeh J (eds) Persia's imperial power in late antiquity: the Great Wall of Gorgan and frontier landscapes of Sasanian Iran. Oxbow Books, Oxford, pp 581–590
Poschlod P (2017) Geschichte der Kulturlandschaft, 2nd edn. Ulmer, Stuttgart
Potts DT (2018) Arboriculture in ancient Iran: Walnut (*Juglans regia*), plane (*Platanus orientalis*) and the "Radde dictum." DABIR 6:101–109
Pourreza M, Shaw JD, Zangeneh H (2008) Sustainability of wild pistachio (*Pistacia atlantica* Desf.) in Zagros forests, Iran. For Ecol Manage 255:3667–3671. https://doi.org/10.1016/j.foreco.2008.01.057
Rahimzadeh F, Asgari A, Fattahi E (2009) Variability of extreme temperature and precipitation in Iran during recent decades. Int J Climatol 29:329–343. https://doi.org/10.1002/joc.1739
Ramezani E, Marvie Mohadjer R et al (2008) The late-Holocene vegetation history of the Central Caspian (Hyrcanian) forests of northern Iran. The Holocene 18:305–319
Rechinger KH (1966) Punicaceae. In: Rechinger K-H (ed) Flora Iranica 22. Naturhistorisches Museum Wien, Wien, pp 3–4
Reille M (1992) Pollen et spores d'Europe et d'Afrique du Nord. Laboratoire de botanique historique et palynologie, Marseille
Riehl S, Zeidi M, Conard NJ (2013) Emergence of agriculture in the foothills of the Zagros mountains of Iran. Science 341(6141):65–67. https://doi.org/10.1126/science.1236743
Riehl S, Asouti E, Karakaya D, Starkovich BM, Zeidi M, Conard NJ (2015) Resilience at the transition to agriculture. The long-term landscape and resource development at the Aceramic Neolithic Tell Site of Chogha Golan (Iran). BioMed Res Int 2015:532481. https://doi.org/10.1155/2015/532481
Reimer PJ, Bard E, Bayliss A et al (2013) IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP radiocarbon 55:1869–1887. https://doi.org/10.2458/azu_js_rc.55.16947
Rivas-Martìnez S, Rivas-Sáenz S (1996–2019) Worldwide bioclimatic classification system. Shiraz-Iran. Phytosociological Research Center, Spain. https://www.globalbioclimatics.org
Rychagov GI (1997) Holocene oscillations of the Caspian Sea, and forecasts based on palaeogeographical reconstructions. Quat Int 41:167–172
Safe A, Sabokkhiz F, Ramesht MH, Djamali M, Naderi Beni A (2016) Study clastic sediments and evaporite deposits' changes in the sedimentary core Lake Maharlou. Iran Modern Appl Sci 10:1–11. https://doi.org/10.5539/mas.v10n4p1
Shumilovskikh LS, Djamali M, Andrieu-Ponel V et al (2017) Palaeoecological insights into agri-horti-cultural and pastoral practices before, during and after the Sasanian Empire. In: Sauer E (ed) Sasanian Persia: between Rome and the Steppes of Eurasia, 2nd edn. Edinburgh University Press, Edinburgh, pp 51–73
State Archives of Assyria Online (2019) The SAAo project. https://oracc.org/saao/
Stevens LR, Ito E, Schwalb A, Wright HE Jr (2006) Timing of atmospheric precipitation in the Zagros mountains inferred from a multi-proxy record from Lake Mirabad. Iran Quat Res 66:494–500
Stevenson AC (1981) Pollen studies in semi-arid environments: North East Iran and South West Spain. Unpublished PhD Thesis, King's College, London

Stockmarr J (1971) Tablets with spores used in absolute pollen analysis. Pollen Spores 13:615–621
Sumner WM (1972) Cultural development in the Kur River basin, Iran. An archaeological analysis of settlement patterns. PhD dissertation, University of Pennsylvania, Pennsylvania
Sumner WM, Whitcomb D (1999) Islamic settlement and chronology in Fars: an archaeological perspective. Iranica Antiqua 34:309–324
Taheri Abkenar K, Salehi A, Bagheri J, Ravanbakhsh H (2016) Some ecological properties of *Pistacia atlantica* Desf. in Khojir National Park of Iran. Chin J Appl Environ Biol 19:415–420. https://doi.org/10.3724/SP.J.1145.2013.00415
Tello E, Martínez JL, Jover-Avellà G, Olarieta JR (2017) The onset of the English agricultural revolution: climate factors and soil nutrients. J Interdiscip Hist 47:445–474
Tilia G, Tilia AB (1972–1978) Studies and Restoration at Persepolis and Other Sites of Fārs. IsMEO, Rome
Tourian MJ, Elmi O, Chen Q, Devaraju B, Roohi S, Sneeuw N (2015) A spaceborne multisensor approach to monitor the desiccation of Lake Urmia in Iran. Remote Sens Environ 156:349–360
Turner SD, Brown AG (2004) *Vitis* pollen dispersal in and from organic vineyards. Rev Palaeobot Palynol 129:117–132. https://doi.org/10.1016/j.revpalbo.2003.12.002
van Geel and Aptroot, 2006 van Geel B, Aptroot A (2006) Fossil ascomycetes in quarternary deposites. Nova Hedwigia 82:313–329. 10.1127/0029-5035/2006/0082-0313
van Rampelbergh M, Fleitmann D, Verheyden S et al (2013) Mid- to late Holocene Indian Ocean Monsoon variability recorded in four speleothems from Socotra Island. Yemen Quat Sci Rev 65:129–142
van Zeist W (1967) Late quaternary vegetation history of western Iran. Rev Paleobot Palynol 2:301–311
van Zeist W, Bottema S (1977) Palynological investigations in western Iran. Palaeohistoria 19:19–85
van Zeist W, Bottema S, van der Veen M (2001) Diet and vegetation at ancient Carthage: the archaeobotanical evidence. Groningen Institute of Archaeology, Groningen
Verdugo MP, Mullin VE, Scheu A et al (2019) Ancient cattle genomics, origins, and rapid turnover in the Fertile Crescent. Science 365:173–176
Wang X, van der Kaars S, Kershawa P et al (1999) A record of fire, vegetation and climate through the last three glacial cycles from Lombok Ridge core G6–4, eastern Indian Ocean, Indonesia. Palaeogeogr Palaeoclimatol Palaeoecol 147:241–256
Ward C (2003) Pomegranates in eastern Mediterranean contexts during the Late Bronze Age. World Archaeol 34:529–541. https://doi.org/10.1080/0043824021000026495
Waylikowa K, Witkowski A (2008) The palaeoecology of Lake Zeribar and surrounding areas, Western Iran, during the last 48,000 years. Diatom Monographs, vol 8. Gantner, Ruggell
Wiesehöfer J (1996) Ancient Persia. From 550 BC to 650 AD. With assistance of Azizeh Azodi. Tauris, London
WMO (2017) World Weather Information Service. https://worldweather.wmo.int/en/city.html?cityId=936. Updated on 30 Oct 2017, checked on 22 Nov 2017
Xhuveli L (2012) Albania, the domestication country for pomegranate (*Punica granatum*). Genet Resour Crop Evol 59:1605–1610
Zeder MA, Hesse B (2000) The initial domestication of goats (*Capra hircus*) in the Zagros mountains 10,000 years ago. Science 287(5461):2254–2257. https://doi.org/10.1126/science.287.5461.2254
Zohary M (1973) Geobotanical foundations of the Middle East, vol 2. Fischer, Stuttgart
Zeynalova AM, Novruzov EN (2017) Origin, taxonomy and systematics of pomegranate. Proceedings of the Institute of Botany 37:20–25

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