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When the desert was green: Grassland expansion during the early Holocene in northwestern Arabia

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ABSTRACT

An early-to-mid Holocene lake in the north of the oasis of Tayma, northwestern Saudi Arabia, proved to be an excellent palynological archive. A shallow, probably brackish water body formed at about 9200 cal BP, with the dominance of goosefoot throughout the sequence indicating the persistence of desert vegetation. However, distinct vegetation changes are recorded during the early Holocene. Grasslands spread soon after 9000 cal BP and reached their maximal expansion ca 8600–8000 cal BP. At about 8000 cal BP these grasslands retreated abruptly and were replaced by more drought-resistant dwarf-shrublands, similar to the present-day ecosystems. The recorded early Holocene grassland expansion furnishes for the first time evidence of an additional and more favourable grazing resource, and thereby improved conditions for herders/hunters, during the Early Holocene in northwestern Arabia, which retreated abruptly due to aridification at about 8000 cal BP.

1. Introduction

Green landscapes were postulated by archaeologists for (northern) Arabia during the early Holocene, enabling the expansion of a Neolithic mobile herding economy (Drechsler, 2009; Crassard et al., 2013). Until now, the assumptions of greener landscapes in north Arabia are mainly based on supra-regional palaeoenvironmental archives including speleothems, lake level fluctuations, and the occurrence of lacustrine sediments. $\delta^{18}O$ values of speleothems in southern Arabia record the northward shift of the monsoon during 10,500–9500 BP, providing more humid conditions until at least 7800 BP, when the monsoonal system began to migrate southward again (e.g. Fleitmann et al., 2007, 2009).

In the eastern Mediterranean, dominated by mid-latitude climate systems, $\delta^{18}O$ records of speleothems show maximum wetness during early-to-mid Holocene (e.g. Bar-Matthews et al., 1999; Verheyden et al., 2008; Develle et al., 2010). Lake level fluctuations of the Dead Sea document an early Holocene wet phase (e.g. Migowski et al., 2006).

Palaeolakes in northwestern Arabia provide further evidence for increased moisture during that time. Shallow lakes in interdune depressions of the Nafud date to about 9500–5800 cal BP (Whitney et al., 1983; Schulz and Whitney, 1986). In the Jubbah region, lake formation started between 12,200 and 10,000 cal BP (Crassard et al., 2013; Hilbert et al., 2014) while a ^{14}C dated palaeosol/swamp near Jubbah yielded an age of about 7500 cal BP (Garrard et al., 1981).

A recently palaeolake north of Tayma in northwestern Arabia corroborates these findings (see Fig. 1). Previous sedimentological, mineralogical, palaeontological (Engel et al., 2012; Ginau et al., 2012), and hydrological (Wellbrock et al., 2011) investigations have the following palaeoclimatic implications: About 10,000–9000/8500 cal BP a palaeoshoreline together with the basal sediments in the depression indicate the highest lake level. Micropalaeontological proxies point to increasing salinity due to aridisation during this wettest period. Long term aridification started about 8500 cal BP, interrupted by at least one probably mid-Holocene short period of increased humidity. Annual precipitation rates were modelled for the Holocene lake period. Annual precipitation amounted to 150 ± 25 mm, an increase of about 300% compared to the present annual average of 45 mm.

How the increased moisture during early-to-mid Holocene impacted the vegetation is unknown, because continuous

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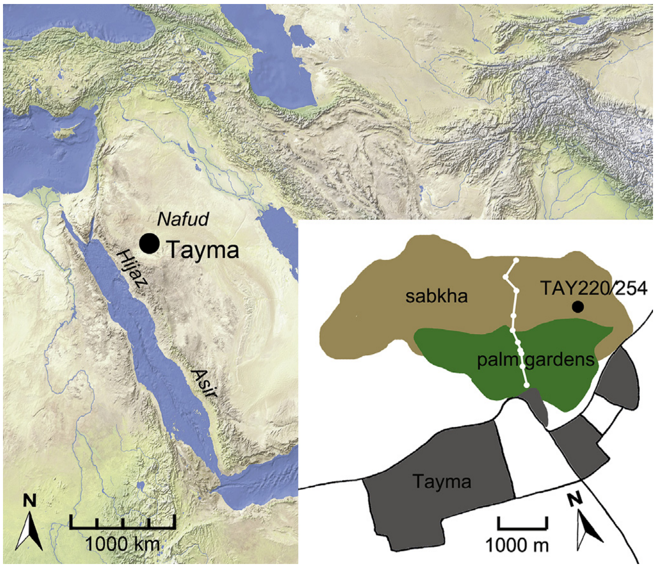

Fig. 1. Location of the study region Tayma and the palaeolake near Tayma, the coring site Tay 220 and Tay 254 and – in white – the coring transect through the sabkha of Engel et al., 2012.

palynological records are missing for northern Arabia. Changing precipitation amounts may not necessarily effectuate vegetation changes due to the resilience of ecosystems. However, if a threshold value is crossed, ecosystems are reorganised, including changes in vegetation (e.g. Campos et al., 2013).

For human populations in prehistory, vegetation and water availability are the key commodities for subsistence. Changing vegetation implies changing pastures, while the abundance and composition of vegetation/pastures impact the size of wild animal populations, which may retreat or migrate when natural vegetation cover retreats or changes. A decrease of natural vegetation cover thus affects the subsistence of hunter-gatherers. Herders may be affected similarly. During the hot season, goats and sheep need water and food everyday or every other day (Smith 1978, cited by Drechsler, 2009, p 88–89). Denser vegetation cover and/or the presence of favoured foraging resources such as grasslands thus are environmental conditions that facilitate a herding economy. Sparse vegetation cover and/or the spread of less palatable plants may impede a herding economy.

To date, ten pollen spectra from four different interdune depressions in the Nafud and adjacent areas were investigated for northwestern Arabia. They record (slightly) denser vegetation cover during early-to-mid Holocene but the same vegetation formation as today (Schulz and Whitney, 1986). Increased early-to-mid Holocene humidity in northwestern Arabia would not have affected terrestrial ecosystems distinctly.

The sediments of the palaeolake near Tayma proved to be an excellent palynological archive with good pollen preservation. Palynological investigations were conducted to get detailed and more precisely dated information on the early Holocene vegetation history of this region.

2. Study site

The oasis of Tayma is situated in northwest Saudi Arabia (27°38′ N, 38°33′ E, ~830 asl). In the west, the Hijaz Mountains run from north to south, and in the east the western fringes of the sand desert Nafud border on the Tayma region (see Fig. 1). Ongoing archaeological excavations have yielded evidence of human occupation since the 7th millennium BP at the oasis Tayma (Hausleiter, 2011).

The region is part of the hyper arid interior of Saudi Arabia. Long-term climate data are available from Tabuk and Al-Ula (north and south of Tayma, respectively). Mean annual rainfall at Tabuk and Al-Ula is 29.3 mm and 61 mm, respectively, with rainfall mostly during November–April, with extreme inter-annual fluctuations of rainfall amounts (Tabuk 2.8–55.1 mm, Al-Ula 2.0–188.9 mm). The mean annual temperatures are 21.4 °C for Tabuk and 24.6 °C for Al-Ula. Frosts are rare and of short duration (Alex, 1985; Almazroui et al., 2012). Thus, the low amount of plant-available water is the main restriction for plant life in the region.

Desert vegetation dominates the Tayma region. Typical for the vast rock (hammada) and gravel deserts (reg) is vegetation dominated by various *Fagonia* species. It is replaced on the extended sandy desert plains by “rimth” shrubland with *Haloxylon salicornicum* (Chenopodiaceae), mixed with the “arfaj” shrubland, dominated by *Rhanterium epapposum* (Asteraceae). These two desert shrubland types are most common in northern Saudi Arabia. On sand dunes, the “adhir” shrubland with *Artemisia jordanica* and *Calligonum* (mainly *C. comosum*) is widespread. A chorotype analysis of the plant communities documents the strong Saharo-Arabian character of the vegetation in the Tayma region (Kürschner and Neef, 2011; Pandalayil, 2011).

3. Material and methods

3.1. Fieldwork and stratigraphy

Closed, overlapping cores of 1 m length were drilled in the eastern part of the sabkha, an ancient lake (see Fig. 1). The overlapping cores Tay 220 and Tay 254 were in direct vicinity (about 25 cm apart), and thus correlation of the cores is possible by stratigraphy. The 1 m long cores have a diameter of 6 cm. Vibracoring was performed with H. Brückner and M. Engel (Universität Köln). Further technical details concerning the drilling equipment are provided in Engel et al. (2012). At 6 m below the surface, bedrock was reached.

The early Holocene sediments discussed in this article are lake sediments. The good pollen preservation supports the assumption of a perennial lake. In Table 1, the main sedimentological characteristics are summarized.

Table 1
Simplified stratigraphy of the basal, early Holocene part of the sequence.

cm below surface	
420–330	Grey-brownish silty marl with clay layers and gypsum crystals (1 mm–1.5 cm)
550–425	Marl, continuously fine laminated, organic-rich
565–550	Silty marl with interrupted lamination
603–565	Grey, silty marl with gypsum concretions up to 4 cm

3.2. Radiometric dating and age depth model

A radiometric chronology based on pollen concentrations was produced for the following reasons: 1. The coring material contains no seeds of terrestrial plants. 2. Dating extracted pollen directly ages the material on which the vegetation development is reconstructed. 3. Molluscs and shell fragments occur, but their dating may be influenced by (sub)fossil carbon (hard water effect).

A combination of different protocols was applied to extract pollen for dating, including the treatment of the samples with

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hydrochloric acid, sodium hydroxide, heavy liquids (sodium polytungstate, caesium chloride), acid sulfur, sodium peroxide and sieving with different mesh sizes (6, 20, 40, 70 μm) (e.g. Brown et al., 1989; Brown et al. 1992; Regnéll and Everitt, 1996; Nakagawa et al., 1998). A detailed protocol will be published elsewhere.

A first series of pollen concentrations were extracted from 3 to 5 cm sediment of core Tay 220. The depths to date were chosen with respect to sedimentological and vegetation changes. Because of the low pollen concentration of the sediment, characteristic for sediments of arid regions, the pollen concentrations partially consisted of numerous micro remains other than pollen, and the amount of datable C partially was very small (see Table 2).

Table 2
Radiocarbon age determinations of pollen concentrations, charred fragments, *Ruppia* seeds and a gastropod shell out of the basal sequence of the palaeolake near Tayma. Dates integrated in the age–depth model are marked by asterisks.

Laboratory code	Depth (cm)	Material	mg C	^{14}C age (bp)	cal years BP (2σ, rounded)	Reason why omitted
*Poz-55863	364–369	Pollen 80%, tissues 15%, charred particles 5%	0.4	6880 ± 40	*7750–7600	
*Poz-55864	378–382	Pollen 50%, tissues 45%, charred particles5%	0.4	7080 ± 50	*7900–7750	
*Poz-62561	405–418	Pollen 70%, tissues 25%, charred particles 5%	0.8	6950 ± 50	*7950–7800	
*Poz-54259	416–420	Pollen 50%, ‘limnic NPP’ 40%, tissues 5%, charred particles 5%	0.4	7100 ± 50	*8000–7900	
Poz-62348	458–459	Gastropod shell	0.3	8910 ± 70	10200–9800	Hard water effect
*Poz-55868	496–499	Pollen 50%, tissues 20%, ‘limnic NPP’ 15%,charred particles 15%		7590 ± 40	*8400–8350	
*Poz-55869	517–522	Pollen 80%, charred particles 15%, tissues 5%	0.5	7660 ± 40	*8500–8400	
Poz-55870	517–527	Pollen 40%, charred particles 60%	0.2	7390 ± 60	8350–8050	Low pollen ratio, contamination by charred particles
*Poz-62563	523–534	Pollen 80%, tissues 10%, charred particles 10%, <5% 'limnic NPP'	0.4	7670 ± 70	*8600–8450	
*Poz-62564	538–552	Pollen 50%, ‘limnic NPP’ 35%, tissues 10%. charred particles 5%	0.5	7670 ± 70	*9000–8750	
Poz-62566	538–552	Charred particles 90%, tissues and pollen 10%	0.3	8330 ± 80	9500–9100	Low pollen ratio, contamination by charred particles
Poz-55871	547–551	Pollen 25%, ‘limnic NPP’ 75%	0.2	8440 ± 80	9550–9300	Low pollen ratio, hard water effect of limnic NPP?
Poz-55872	547–551	6 *Ruppia* seeds	0.7	8280 ± 50	9450–9150	Hard water effect
*Poz-55874	547–551	Pollen 80%, ‘limnic NPP’ 15%, tissues 5%	0.2	7880 ± 70	*8850–8550	
Poz-55875	565–573	Pollen 35%, tissues 35%, charred particles 25%, ‘limnic NPP’ 5%	0.3	7410 ± 60	8350–8050	Low pollen ratio

The first series of dating revealed some inconsistencies, but showed that during the early Holocene the sedimentation rates were relatively high: 10 cm sediment should not comprise more than about 100 years. Therefore, a second series was prepared, investigating up to 13 cm of sediment of Tay 254, to extract pollen concentrations with higher pollen ratios (>50%) and a larger amount of datable C (see Table 2). The samples were dated by accelerator mass spectrometry (AMS) ^{14}C dating at the Poznan Radiocarbon Laboratory.

The ^{14}C dates were calibrated using BCal (Buck et al., 1999; BCal, 2014). The dates incorporated in the age depth model were calibrated considering their stratigraphic position. The open source program psimpoll was used to calculate the best fitting age depth model (wtave, polynominal curve fitted by singular value decomposition (Bennett, 1997–2007), see Fig. 2).

3.3. Pollen analysis

3.3.1. Sampling and sample preparation

The closed cores of TAY 220 were opened in the archaebotanical laboratory of the DAI Berlin. Samples were prepared from every 6–26 cm, which corresponds to a time resolution of ca. 30–200 years. Samples were prepared following the standard techniques (Faegri and Iversen, 1989; Eisele et al., 1994; Moore et al., 1999) and marker spores were added (Stockmarr, 1971).

3.3.2. Pollen analysis: determination, pollen sum and restrictions

Pollen was identified using atlases of pollen morphology (e.g. Bonnefille and Riollet, 1980; El Ghazali, 1991; Reille, 1992), the reference slide collection of the DAI Berlin, and pollen images from the African Pollen Database. Pollen sums show high variability (86–2000 terrestrial pollen grains). As the frequencies of dominant pollen types, such as Poaceae and Chenopodiaceae/Amaranthaceae, are statistically robust even at low pollen sums we focus here on the major vegetational changes documented by these dominating types.

The whole lacustrine sequence from about 9200 to 5000 cal BP, including further under represented pollen types such as cultivated plants, will be published upon completion.

3.4. Geochemical analysis: TOC and TN content

For elemental analysis about 1 cm^3 for every cm has been sampled from Tay 220, freeze dried, and powdered to <63 μm. Total organic carbon (TOC), as well as total nitrogen (TN) were determined using an elemental analyzer (NC2500 Carlo Erba) at the Deutsches GeoForschungsZentrum in Potsdam, Germany. For TN determination, around 25 mg of sample material were loaded in tin capsules and burned in the elemental analyzer. The TOC contents were determined on in-situ decalcified samples. Around 3 mg of sample material was weighed into Ag-capsules, dropped with 20% HCl, heated for 3 h at 75 °C, and finally wrapped and measured as described above. The calibration was performed using elemental standards (Acetanilide, Urea) and proofed with an internal soil reference sample (Boden3). The reproducibility for replicate analyses is 0.2%. For the C/N ratio we used the proportion between TOC relative to TN.

4. Results

4.1. ^{14}C dates and age depth model

Previously, dating of the early Holocene lake sediments of Tayma was performed mainly on gastropods, ostracods and *Ruppia* seeds, remains that are susceptible to hard water effects (Engel et al., 2012). We present here an age depth model based on the dating of pollen concentrations, i.e. dating on organic material from terrestrial plants. The composition of the pollen concentrations and the radiocarbon dates are compiled in Table 2. The dating of pollen concentrations with low pollen ratios (less than 50% pollen grains), *Ruppia* seeds and a gastropod shell yielded results which we consider to be less reliable.

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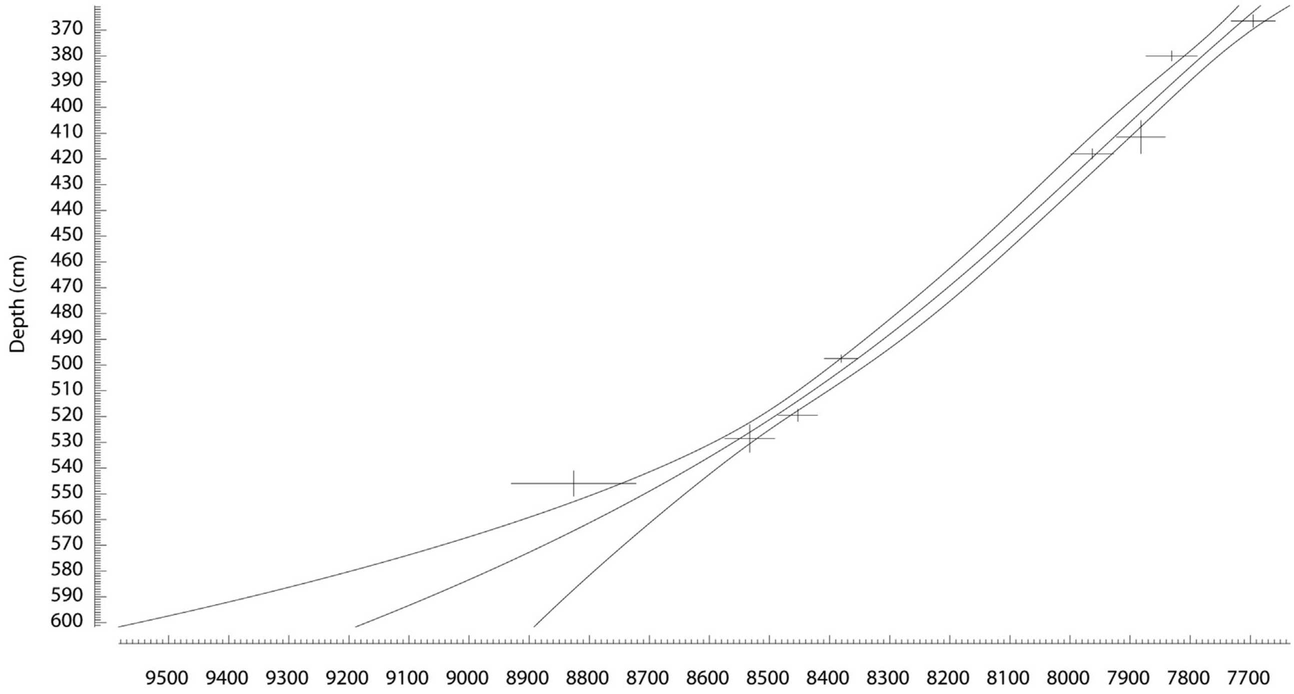

Fig. 2. Age depth model based on radiometric determinations of pollen concentrations with ≥50% pollen. A polynominal curve was fitted, using the open source program psimpoll (Bennett, 1997–2007).

The origin of micro-particles other than pollen may be diverse. We thus agree with Vandergoes and Prior (2003) that pollen concentrations "with high pollen ratios provide age estimates closer to the true age of the sample" and omitted pollen concentrations with low pollen ratios (<50% pollen). Dating *Ruppia* seeds and a pollen concentration with about 80% pollen from the same depth reveals a hard water effect of about 400 radiocarbon years for the *Ruppia* seeds (8280 ± 50 versus 7880 ± 70 BP). The date of the gastropod shell suggests an even more pronounced hard water effect. Assuming that the dated snail was not reworked, the date of the gastropod shell reveals a hard water effect of about 1500 radiocarbon years by comparing the date with the adjacent dates of pollen concentrations (7345 BP versus 8910 BP). We therefore decided to develop the chronology solely on pollen concentrations with pollen ratios greater than 50% pollen and without dates probably affected by hard water effect, such as *Ruppia* seeds or gastropod shells.

The AMS dates included in the age depth model are marked by asterisks. For the two basal dates from the same depth (Poz-62564, 7940 ± 60 BP and Poz-55874, 7880 ± 80 BP) a pooled mean was calculated for the age depth model. Fig. 2 shows the age depth model.

4.2. *Results of the palynological analyses*

Selected pollen types are shown in the diagram (Fig. 3): pollen types represented by high frequencies, showing the major vegetation changes and selected under-represented pollen types that have important ecological or climatic implications. The Chenopodiaceae/Amaranthaceae dominates continuously throughout the sequence.

PAZ-1, ca 9200–8700 cal BP: The basal zone is characterized by very high frequencies of Chenopodiaceae/Amaranthaceae, low frequencies of Poaceae and the near absence of arboreal pollen. The frequencies of *Ruppia* and *Sparganium* type fluctuate and are (very) high at points.

PAZ-2, ca 8700–8600 cal BP: The frequencies of Poaceae and *Ephedra fragilis* type increase, *E. fragilis* type reaches maximum frequencies of 9%. The frequencies of the water and lake-shore vegetation (mainly *Ruppia* and *Sparganium* type) are rather low and fluctuate.

PAZ-3, ca 8600–8000 cal BP: Poaceae increase up to maximum frequencies of 34% (20–34%). These are the highest Poaceae values recorded for the whole of the Tayma sequence. Measurements of the Poaceae pollen grains show a great variance in size (18–60 μm in diameter). There are no distinct peaks of particular sizes. An expansion of typical reed grasses including *Phalaris* (33 μm, 39 μm) or *Phragmites* (31 μm) thus may be excluded. The Poaceae peak represents the expansion of upland grass vegetation.

PAZ-4, after 8000 cal BP: At about 8000 cal BP an abrupt vegetation change is recorded. The Poaceae frequencies decrease sharply, while the frequencies of *Artemisia* and *Haloxylon* type increase.

4.3. *Geochemistry: TOC and C/N*

The source of the organic material embedded in the limnic sediments may originate from production in the lake, terrestrial production or of course a combination of both. No algae are recorded, but numerous unidentified (most probably) eggs of a small aquatic animal (or at least partially aquatic animal) as well as microbial mats and diatoms are present.

At the beginning of the lake development, the TOC values are below 1%. They increase steadily and reach their maximum with up to 5% TOC at about 8600–8000 cal BP. At about 8000 cal BP, the TOC values decrease abruptly to 1% (Fig. 3). The C/N ratios show a similar progression: The basal part is characterized by fluctuating ratios mainly <10 reflecting a preferred internal aquatic production. Around 8700 cal BP, the C/N ratios exceed 10 and to increase to 24. We thus assume that the increasing TOC and C/N values above 10 mainly reflect the input of detrital terrestrial material, indicating the density and stability of the vegetation cover during this time. At

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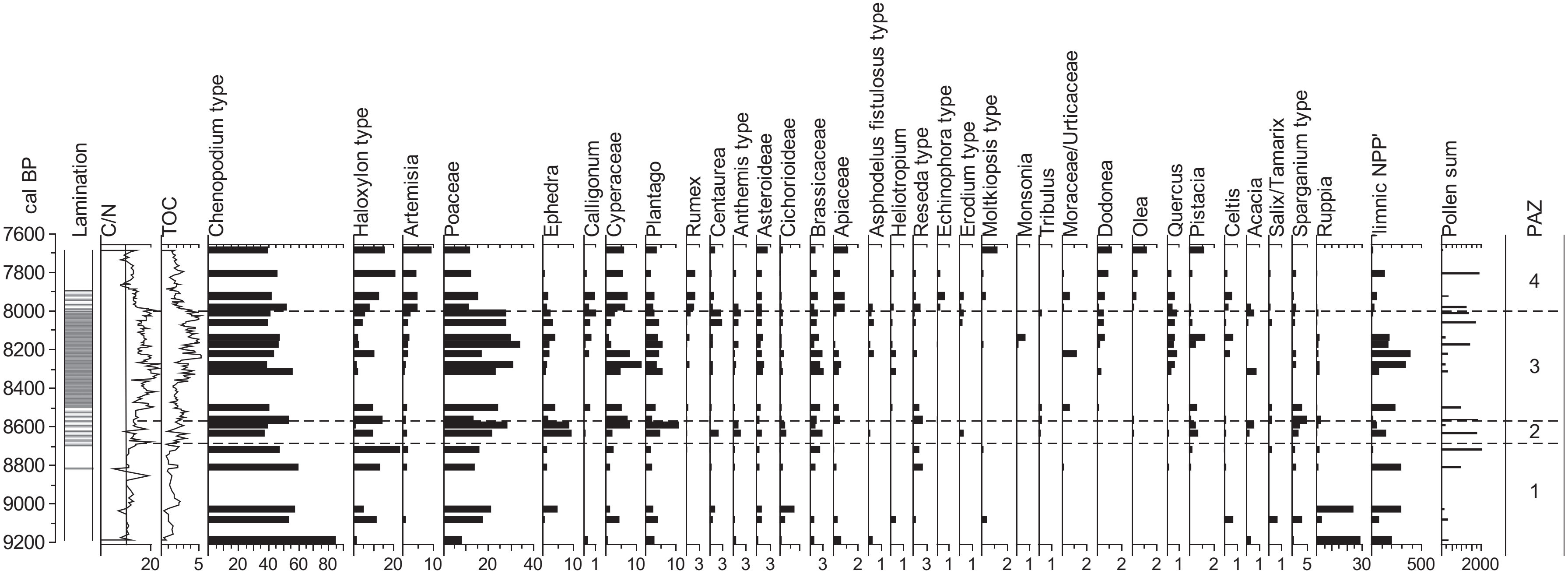

Fig. 3. Diagram showing selected pollen types (percentages calculated against the sum of terrestrial pollen types), TOC and C/N. The suffix type indicates that this pollen type includes more taxa than the mentioned genus. On the left the laminated section is indicated by a line pattern. Data are plotted versus cal BP.

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about 8000 cal BP, the C/N ratio decreases sharply and fluctuates around 10. This may reflect sparser vegetation cover.

5. Interpretation and discussion

5.1. Vegetation development of the Tayma region: Early Holocene expansion of grasslands and their retreat at about 8000 cal BP — a short "humid period" in NW Arabia

5.1.1. Continuous dominance of goosefoots shows the prevalence of desert vegetation

Throughout the sequence, goosefoot family taxa dominate with high frequencies. Chenopodiaceae/Amaranthaceae may reflect marsh plants common on saline shores, such as *Chenopodium rubrum* (e.g. Wasylikowa et al., 2006) or representatives of desert vegetation (e.g. Zohary, 1973, p 386). The Chenopodiaceae/Amaranthaceae pollen grains were divided into two types: *Chenopodium* type with numerous pores (>20 pores) and *Haloxylon* type (<20 pores). The *Chenopodium* type includes numerous *Chenopodium*, *Atriplex* and *Amaranthus* species. By contrast, *Aerva*, *Suaeda* and *Haloxylon* species e.g. belong to the *Haloxylon* type. Both types thus include goosefoot, common in shoreline or desert vegetation formations. A pollen-morphological differentiation of goosefoot of these ecologically different environments is not possible.

Chenopodiaceae/Amaranthaceae clearly dominates the pollen surface samples of desert areas of Jordan and northern Arabia. Today no large lakes, and thus no shore vegetation, occur in the region (Schulz and Whitney, 1986; El-Moslimany, 1990; Lézine et al., 1998; Davies and Fall, 2001). In the Tayma pollen diagram, probable lake level changes are not consistently accompanied by changes in Chenopodiaceae/Amaranthaceae values. We thus assume that the majority of the Chenopodiaceae/Amaranthaceae represents desert vegetation. The continuously high frequencies of Chenopodiaceae/Amaranthaceae, on average about 60%, thus show the prevalence of the desert vegetation in the Tayma region during the early-to-mid Holocene. Similar, continuously high Chenopodiaceae/Amaranthaceae frequencies, about 40%, characterize the pollen spectra of the En Gedi pollen diagram (Litt et al., 2012).

The desert vegetation most probably occurred on edaphically less favourable sites in the Tayma region such as the vast reg formations. For sites with increased plant-available water, such as slight depressions, in and along wadis, runnels or beneath rock outcrops, the pollen diagram of Tayma shows a distinctly different vegetation cover during the early Holocene.

5.1.2. Ca 9200–8700 cal BP: A shallow, fluctuating lake established under arid conditions

The very high frequencies of goosefoot, the low frequencies of grasses and the very low and intermittent frequencies of arboreal pollen indicate arid conditions during lake formation. A similar pattern is recorded in southern Arabia: Very high frequencies of Chenopodiaceae/Amaranthaceae occur at the base of the limnic sequence of al-Hawa in Yemen (Lézine et al., 2007).

Ruppia is well adapted to water-level fluctuations and may even survive desiccation. It occurs usually in brackish to saline habitats (Verhoeven and van Vierssen, 1978; van Vierssen et al., 1984). *Sparganium* type includes several *Sparganium* species and *Typha angustifolia* and *T. domingensis*, plants typically growing on lake and river shores. The at points high and fluctuating frequencies of *Ruppia* and *Sparganium* type indicate a rather shallow, brackish water body with fluctuating lake levels during the first centuries of lake formation.

5.1.3. Ca 8700–8600 cal BP: Lake level fluctuations and the spread of Ephedra steppes and grasslands

The frequencies of Poaceae and *Ephedra* rise. *Ephedra* proportions increase up to maximum frequencies of 9%. *Ephedra* pollen are recorded frequently in surface samples of deserts and steppes of southwestern Asia (Wright et al., 1967; Schulz and Whitney, 1986; Lézine et al., 1998; Davis and Fall, 2011). The *Ephedra* frequencies of these surface samples are rather low. Even where *Ephedra* plants are common, the frequencies do not exceed 5% (Wright et al., 1967). At about 8700–8600 cal BP, therefore, *Ephedra* shrubs must have been a rather important part of the vegetation cover.

Whether this short spread of *Ephedra* steppes indicates slightly more humid conditions, together with the expanding grasslands, or following the 'traditional' interpretation of increasing *Ephedra* frequencies a dry spell, is difficult to decide. The increase of organic content in the sediment may indicate denser vegetation cover. The continually rather low but fluctuating frequencies of the water and lake-shore vegetation (mainly *Ruppia* and *Sparganium* type) may indicate (minor) changes in lake levels.

5.1.4. Ca 8600–8000 cal BP: maximum grassland expansion indicating wettest conditions of the sequence

Between ca 8500 and 8000 cal BP, Poaceae increase, to maximum frequencies of 34% (20–34%). In the younger, mid-Holocene part of the sequence the Poaceae frequencies never exceed 15% (3–15%). Poaceae frequencies in the surface samples of the southern and coastal regions of Arabia range between 20% and 40%, while in the interior of the Arabian Peninsula, Poaceae frequencies are low. Higher grass frequencies in surface samples thus are normally restricted to southern and coastal, less arid regions of Arabia under southwest monsoon influence. Even in the steppes of the Middle East, mean pollen percentages of Poaceae do not exceed 20% (Schulz and Whitney, 1986; El-Moslimany, 1990; Lézine et al., 1998, 2010; Davis and Fall, 2001).

Most grasses have rather shallow, dense root systems. In addition, many perennial grasses (C4 type) are metabolically active during the whole vegetation period. Grasses thus are sensitive to long dry periods. Many of the perennial chenopods and sagebrush taxa have a deeper root system and reduced leaves or leaf dimorphism (summer-/winter leaves). These dwarf shrubs are therefore more drought-resistant. In (semi)arid regions, increasing grass frequencies at the expense of goosefoot and/or sagebrush indicate increased moisture, supplied in the growing season (e. g. Allen, 1982; El Moslimany, 1990). The assumption of increased moisture, based on ecological and physiological features of dominating plant types, is supported by combined pollen- $\delta^{18}O$ investigations of the lakes Eski Acigöl, Van, Zeribar and Mirabad (van Zeist and Bottema, 1977; Roberts et al., 2001; Stevens et al., 2001, 2006, 2008; Wick et al., 2003; Woldring and Bottema, 2003; van Zeist, 2008).

In the modern vegetation of the Tayma region, *Artemisia* (*Artemisia jordanica*) mainly grows on sand dunes, together with *Calligonum* (Kürschner and Neef, 2011). In the north of the Tayma region, *Artemisia sieberi* (misidentified as *Artemisia herba-alba* in older literature) dominates the Irano-Turanian steppe vegetation over large areas in the Middle East (e.g. Zohary, 1973: 391–393). The rise of sagebrush proportions thus may be due to an expansion of the Irano-Turanian steppes from the north into the region, or signals the presence of sand dunes near Tayma.

Rising or high *Calligonum* pollen frequencies are linked with dune activity or occurrence of sand dunes in the pollen-source area (Singh et al., 1990; Lézine et al., 1998, 2010). Frequencies of *Calligonum* remain continuously low in the pollen diagram of Tayma. The rise of *Artemisia* around 8000 cal BP thus shows the southward expansion of the Irano-Turanian sagebrush-steppes rather than the presence of sand dunes.

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The maximal grass frequencies during early Holocene thus indicate the wettest conditions with respect to the whole Holocene sequence. The dominance of chenopods at the beginning of the lake phase and after 8000 cal BP, together with sagebrush, reflects more arid conditions.

The highest values of TOC and the highest C/N ratio may indicate the densest vegetation cover throughout the Holocene. The recorded highest production during early Holocene corroborates the assumption that this section documents the relative wettest conditions of the Holocene.

Neither fresh-water algae nor higher fresh-water plants are recorded. The lower frequencies of *Ruppia* after 9000 cal BP thus may indicate a rise of the lake level rather than the establishment of a fresh-water lake. The onset of continuous lamination seems to corroborate the assumption of a rising lake level and internal aquatic production.

5.1.5. *After 8000 cal BP: retreat of grasslands and expansion of more drought resistant dwarf shrublands indicating aridification*

At about 8000 an abrupt vegetation change is recorded. The Poaceae frequencies decrease sharply, while the frequencies of *Artemisia* and *Haloxylon* type increase. The *Haloxylon* type includes *Aerva*, *Cornulaca* and *Haloxylon*. The rimth shrublands with *Haloxylon salicornicum* cover huge areas in northern Arabia. The increasing frequencies of *Haloxylon* type at about 8000 cal BP thus may reflect the spread of the (nowadays common) drought resistant steppes. Another possible explanation for the expansion of chenopods is the spread of *Suada* on the lake shore. Whether the increase of *Haloxylon* type reflects a local or regional expansion of chenopods, it points in each case to more arid conditions (c.f. van Zeist, 1967, p 310).

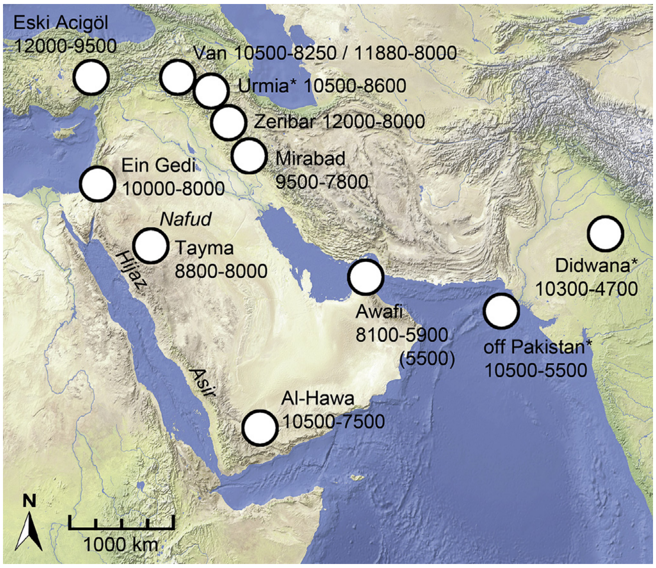

Fig. 4. Pollen diagrams showing an early (to-mid) Holocene grassland expansion. The duration is indicated in cal BP. Sites without published continuous age–depth model are marked by asterisks. The age–depth model of these sites was calculated by linear interpolation between calibrated ^{14}C dates. Eski Acigöl: Roberts et al., 2001, 2011, combined age model according Figs. 7 and 5. Van: Wick et al., 2003, age model according Fig. 4/Litt et al., 2009, age model according Fig. 8. Urmia*: Bottema 1986, linear interpolation between 2 ^{14}C dates after calibration. Zeribar: Wasylikowa et al., 2008, age model according Fig. 15.1; van Zeist 2008; van Zeist and Bottema 1977. Mirabad: Stevens et al., 2006, age model according Fig. 3; van Zeist and Bottema 1977. En Gedi: Litt et al., 2012, age model according Fig. 3. Tayma: this study. Al-Hawa: Lézine et al., 2007, age model according Fig. 4. Awafi: Parker et al., 2006, age model according Fig. 2; Parker et al., 2004. off Pakistan*: Ansari and Vink 2007, linear interpolation between 4 calibrated ^{14}C dates, after Fig. 4. Didwana*: Singh et al., 1990, linear interpolation between 5 ^{14}C dates after calibration.

The increase of drought-resistant dwarf-shrublands and decline of grasslands goes along with a sharp decrease of the TOC values and the C/N ratio. This decrease in total organic material may indicate sparser vegetation cover of drought-resistant dwarf shrubs as compared to the prior dominating grasslands.

Shortly after the marked vegetation changes and decrease of organic component, continuous lamination ends. This is probably due to a lowering in the lake level. The sedimentary record, therefore, also indicates a shift to more arid conditions.

5.2. *Supra-regional comparison of the Early Holocene vegetation development of Tayma, northwestern Arabia*

The Holocene vegetation of northern Arabia has been unknown to now, because continuous pollen diagrams are missing. Comparing the vegetation development on a regional scale is thus not possible. Therefore, the early Holocene vegetation complexes of Tayma are compared with the vegetation history of adjacent areas. Similar supra-regional vegetation development patterns, perhaps controlled by supra-regional or similar climate conditions, and/or differing vegetation patterns can be revealed.

5.2.1. *Spread of Ephedra steppes in south eastern Asia*

The short *E. fragilis* type peak during the grassland expansion is a striking feature in the Tayma pollen diagram. Prominent *Ephedra* peaks are recorded in Lake Van, southeastern Turkey, shortly before the onset of the Holocene (van Zeist and Woldring, 1978; Wick et al., 2003) and in Lake Urmia shortly before the onset of the last interglacial, but less pronounced, during the last glacial (Djamali et al., 2008).

The ecological interpretation and the climatic implications are difficult. Frequently, the expansion of *Ephedra*-dominated vegetation formations is interpreted as indicating arid to very arid conditions (e.g. van Zeist and Woldring, 1978; Wick et al., 2003), but it may in addition be connected with slightly increased plant available moisture (Djamali et al., 2008). The ability to rapidly colonize newly available habitats and the subsequent repression by increasing competition may be another explanation for the spread of *Ephedra* during transitional periods. Further research is required to decipher the climatic and environmental triggers of these short *Ephedra* expansions.

5.2.2. *Early Holocene grassland expansion in south western Asia: climate and/or human agency*

It is probable that the most significant feature in the Tayma pollen diagram is the early Holocene Poaceae maximum. An early Holocene grassland expansion at the expense of chenopods-*Artemisia* dominated vegetation formations is also recorded in pollen diagrams in adjacent regions. The sites vary greatly concerning elevation, basin size and at least mid-Holocene to recent vegetation and climate.

In Fig. 4, the approximate duration of the ‘early Holocene Poaceae phase’ at the different sites is indicated in cal BP. The respective chronology is preferably based on published age–depth models. Where no continuous age–depth model is published, available ^{14}C dates were calibrated and the duration of the grassland expansion was determined by linear extrapolation. These sites are marked by asterisks.

5.2.2.1. Start of the early Holocene grassland expansion. The increase of Poaceae is concordantly interpreted as the onset of the Holocene, characterized by increased plant-available moisture. Dating of the beginning of these grassland expansions vary between about 12,000 and 10,000 cal BP (except for Awafi, southeastern Arabia, Parker et al., 2004, 2006).

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5.2.2.2. Why early Holocene grasslands in the Irano-Turanian region? The reason for the early Holocene persistence of grasslands for at least 2000 years in the Irano-Anatolian region is an ongoing controversy. In this continental, eastern Mediterranean region, oaks spread slowly and reached maximal values only during mid Holocene. Grasslands persisted during the early Holocene, although independent climate proxies such as $\delta^{18}O$ values indicate a relatively rapid increase in moisture during this period. To account for this vegetation–climate paradox, different scenarios are proposed. Possible climatic causes discussed are colder and wetter summers (e.g. Rossignol-Strick, 1995, 1999), increased seasonality (e.g. Stevens et al., 2001, 2006; Djamali et al., 2010; vs. El Moslimany, 1986, 1987) or climatically induced increased natural fire frequencies (Turner et al., 2010). Human impacts including fire management, wood exploitation, and woodland management on the other hand is claimed to encourage the growth of grasses at the expense of trees and shrubs (compare Roberts, 2002; Roberts et al., 2011 with Asouti and Kabukcu, 2014).

5.2.2.3. End of the early Holocene grasslands. The 'early Holocene Poaceae phase' terminates in most of the records at about 8000 cal BP. Climate changes and human agencies, or a combination of both, are suggested for this vegetation change. Grasslands in the eastern regions (Didwana India, Singh et al., 1990; Awafi UAE; Parker et al., 2004, 2006; continental margin sediments from Pakistan, Ansari and Vink, 2007) lasted until mid Holocene.

In the southern Dead Sea region, the retreat of grasslands recorded in the En Gedi pollen diagram is attributed to increasing aridity, supported by the sedimentological record. Higher stands of the Dead Sea level are reconstructed for the period between about 10,000/10,300–8200 cal BP. Around 8200 cal BP, the deposition of gypsum and sand indicate lower lake levels triggered by aridification (Frumkin et al., 2001; Migowski et al., 2006). Human impact is not rejected completely, although no increase in human activity is recorded (Litt et al., 2012).

Also at al-Hawa in southern Arabia, the grassland retreat is probably linked to aridification. A palaeolake is documented between 12,000 and 7500 cal BP. Poaceae frequencies increase around 11,500 cal BP with maximum values between 9000 and 7500 cal BP. $\delta^{18}O$ values decrease distinctly between 9100 and 8000 cal BP, indicating the maximum of monsoon rainfall. About 7500 cal BP the lake dried out (Lézine et al., 1998, 2007). Grass pollen frequencies in pollen spectra are distinctly lower than during early Holocene (Lézine et al., 1998, 2010). Even if a decline of grasses is not recorded, the desiccation of the lake about 7500 cal BP documents aridification.

5.2.2.4. Persisting grasslands: early-to-mid Holocene grasslands. At the easternmost sites of Awafi, off Pakistan, and Didwana grasslands persisted until mid-Holocene. Climatic reasons are suggested for the persistence and the end of the dominance of grasses. For Awafi in southeastern Arabia, penetration of westerly depressions during the mid-Holocene is postulated, compensating for the now missing monsoonal moisture source. The lake desiccated around 4100 cal BP (Parker et al., 2004, 2006). Increased and prolonged monsoonal summer precipitation followed by a gradual reduction of humidity since the mid Holocene correlates with the grassland expansion and reduction in the Pakistan record (Ansari and Vink, 2007). Enhanced summer and winter precipitation is postulated for the Didwana record during the early-to-mid Holocene. The lake dried out about 4700 cal BP (Singh et al., 1990). This brief compilation of pollen diagrams, which reveal a large-scale coincidence of grassland expansion during the early Holocene, pointing to a common climatic trigger at the beginning of the Holocene.

Around 8000 cal BP, the 'early Holocene grassland' period ended. The vegetation development after c. 8000 cal BP indicates distinct, regional differences: (1) Aridification in southern Arabia, illustrating the weakening of monsoon intensity (Lézine et al., 2007); (2) Persisting grasslands in the southeastern sites due to lasting monsoonal precipitation (Singh et al., 1990; Ansari and Vink, 2007) or substitute moisture from the Mediterranean region (Parker et al., 2004, 2006); (3) Changing precipitation patterns resulting in increased plant available water or changed human agencies resulting in a spread of woodlands in the northern, Irano-Turanian region; and (4) Arid conditions for c. 1500 years in northwestern Arabia and the southern Levant (Tayma; Litt et al., 2012).

In view of the above mentioned reasons assigned for the persistence and end of the early Holocene grasslands, the retreat of grasslands at Tayma may in part be due in part to human agency including herding.

Other proxies including the sedimentological change point to aridification at about 8000 cal BP. We therefore assume that aridification triggered the distinct and rapid vegetation change at Tayma. However, similar to the Dead Sea record, human agency can not completely be ruled out (Litt et al., 2012).

6. Summary and conclusions: the Early Holocene vegetation history of the Tayma region (northwestern Arabia) and its environmental, climatic and cultural implications

6.1. Lake development

A shallow but permanent, brackish to saline lake was established around 9200 cal BP under arid conditions. Highly fluctuating proportions of water and marsh plants until about 9000/8700 cal BP indicate fluctuating lake levels. The lower frequencies of water and marsh plants after 8700 cal BP point to reduced shorelines and shallow water zones, suggesting a rise of the lake level. This coincides with the onset of continuous lamination. Shortly after the decrease of Poaceae frequencies, the lamination ends, probably indicating a lowering of the lake-level.

Our refined chronology of the lake sediments, based on AMS dates of terrestrial material (pollen concentrations) reveal a modified lake development as compared to Engel et al. (2012). Lake formation probably started about one thousand years later, at ca. 9200 cal BP. At the beginning, a shallow water body persisted. If the assumptions regarding the hard water effect of about 1500 radiocarbon years for dates of gastropod shells is correct, the clastic shoreline deposits indicating high levels may be correlated with the younger part of the Poaceae 'humid' period (about 8300–7600 cal BP). High lake levels thus would have been achieved only during the 'short humid period' between about 8700–8000 cal BP when grassland expanded at Tayma.

6.2. Vegetation development

After a short period of nearly complete goosefoot-dominance representing desert vegetation, *Ephedra* steppes and grasslands began to spread. *Ephedra* steppes were common between ca 8700–8600 cal BP. The grassland expansion reached its maximum between ca 8600–8000 cal BP. During the mid-Holocene, Poaceae frequencies are distinctly lower. The highest grass proportions between ca 8600–8000 cal BP indicate the wettest conditions during the lake phase in Tayma and correlate with early Holocene grassland expansions in continental southwest Asia.

The humidity increase, documented by early-to-mid Holocene lacustrine sediments, affected terrestrial (vegetation) ecosystems in northwestern Arabia. The Tayma pollen diagram shows not only denser vegetation as postulated (Schulz and Whitney, 1986), but the expansion of other vegetation types (grasslands) and the

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migration of tree taxa into the Tayma region that are at present absent (e. g. *Quercus*, *Pistacia* and *Dodonaea).* Around 8000 cal BP, an abrupt vegetation change is recorded: grasslands retreated and more drought resistant dwarf-shrublands (and perhaps marsh vegetation) expanded.

6.3. A more diverse Early Holocene environment may have facilitated the first phase of Neolithisation in northwestern Arabia

Increased early-to-mid Holocene humidity in northwestern Arabia affected terrestrial ecosystems in the Tayma region during a short period. About 8700–8000 cal BP, a more diverse environment, and thus supplementary natural resources, established in the Tayma region. Grasslands expanded and provided an additional, favoured grazing resource. At the same time, different tree taxa, no longer occurring in the Tayma region today, provided fruits, timber, fodder and fuel. Grasslands were not only present in the Tayma region, but in large areas of southwestern Asia as well.

These 'greener landscapes' in the Tayma region potentially provided more favourable environmental conditions during early the Holocene for a spread of Neolithic herders. Whether the herders exploited this documented short 'greener period' or not has to be resolved by ongoing and further archaeological research (e. g. Crassard and Drechsler, 2013).

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