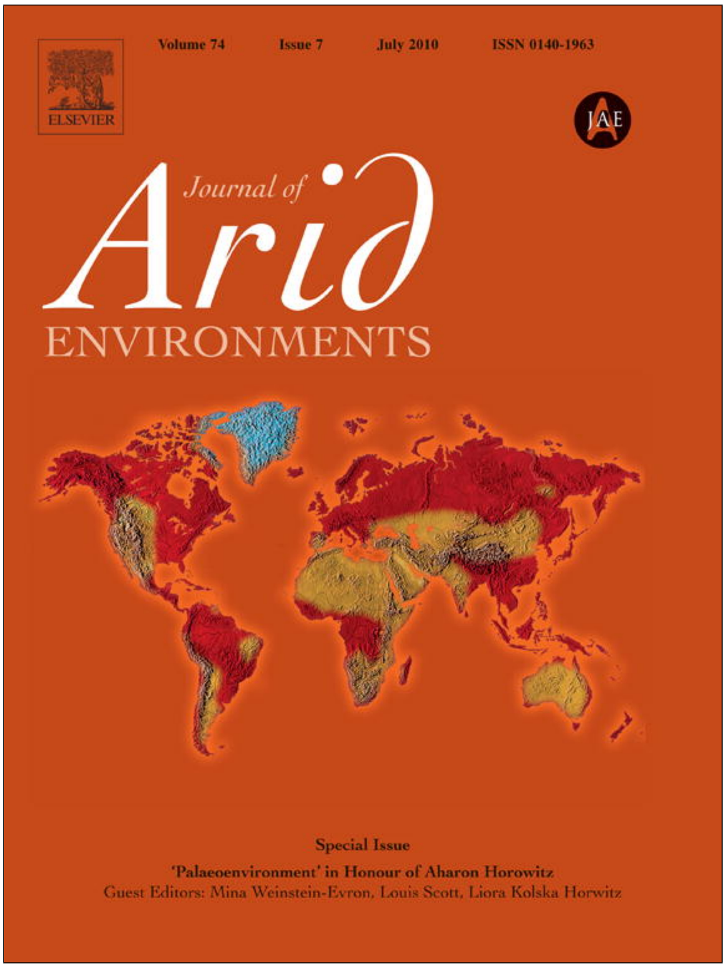
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Vegetation history and climate fluctuations on a transect along the Dead Sea west shore and their impact on past societies over the last 3500 years

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ABSTRACT

This study represents the vegetation history of the last 3500 years and conducts an analysis of the climatic fluctuations on a 75 km long transect on the western Dead Sea shore. Palynological and sedimentological data are available from six cores near Mount Sedom, Ein Boqeq, and Ein Gedi and from outcrops near Ze'elim and Ein Feshkha. The comparison of the pollen data with the lake levels shows synchronous trends. During the Middle Bronze Age, Iron Age and Hellenistic to Byzantine Period the high lake level of the Dead Sea signals an increase in precipitation. Contemporaneously, values of cultivated plants indicate an increase in agriculture. Lake level is low during the Late Bronze Age, within the Iron Age and at the end of the Byzantine period, indicating dry periods when all pds show a decrease of cultivated plants. Forest regeneration led by drought-resistant pines is observed in all pollen diagrams (pds) following the agricultural decline in the Byzantine period and, in the pds near Ein Boqeq, Ze'elim and Ein Feshkha, during the late Iron Age. The modern vegetation gradient is reflected in the palaeorecords: a stronger expansion of Mediterranean vegetation and cultivated plants in the northern sites is recognisable.

1. Introduction

The rise and fall of Near-Eastern civilisations are often discussed within the archaeological community in terms of socio-economic determinism. High-resolution palaeoclimatic data, however, give evidence of climatic fluctuations correlating with historical or archaeological data (Weiss and Bradley, 2001). The Dead Sea region is suitable for the exploration of links between climate, vegetation and settlement history because it is characterised by climatic contrasts, is close to centres of settlement and agriculture (e.g. Judean Hills) and has itself been an economic resource for ~10 000 years (Nissenbaum, 1993). Crucial for the discussion of climate change are reconstructions of the Holocene Dead Sea lake levels (Bookman et al., 2006; Bookman (Ken-Tor) et al., 2004; Enzel et al., 2003; Frumkin, 1997; Frumkin and Elitzur, 2002; Frumkin et al., 1991; Klein and Flohn, 1987; Klinger et al., 2003; Migowski et al., 2006; Neev and Emery, 1967). Several cores from the western shore of the Dead Sea were used for palynological investigations during the 1990s, but pollen records span maximally 3000 years and few radiocarbon ages were available (Baruch, 1990, 1993; Heim et al., 1997). High-resolution palynological and sedimentological investigations from two erosional gullies at the western shore of the Dead Sea (Ze'elim and Ein Feshkha) revealed a relationship between vegetation dynamics, climate and human impact based on comparison with fluctuations of the Dead Sea (Neumann et al., 2007). Therefore pollen data from six sites spanning a north–south transect of 75 km along the shore of the Dead Sea with a temperature and rainfall gradient provide the possibility of highlighting synchronous changes in vegetation in different eco-regions.

2. Morphology and geology of the Dead Sea area

The Dead Sea water level, 418 m bsl (meters below sea level) in 2006, has dropped by 1 m/year since the 1980s (Gavrieli et al., 2006). Approximately 90% of the flow that would reach the lake from the Jordan River is diverted by surrounding countries (Dayan

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and Morin, 2006). The lake is located in a pull-apart basin along the Dead Sea Transform fault (DST, Freund et al., 1970; Garfunkel and Ben-Avraham, 1996). Since the Neogene the depressions along the DST were filled by lakes (Stein, 2001) and in the Holocene the Dead Sea itself developed. The sediments (fluvial, fan deltas, shores, and lacustrine) comprise the Ze'elim Formation, which is exposed in erosion gullies at the shores and accessible in drillholes (Bookman (Ken-Tor) et al., 2004; Yechieli et al., 1993). The channel incision is a response to base level lowering due to lake level drops (Ben Moshe et al., 2008).

3. Climate, water and vegetation around the Dead Sea

Israel and western Jordan are in the winter rain climate zone. In winter, cyclones bring rain while the summer is dry and hot (Walter and Breckle, 1999). Rainfall and temperature are influenced by topography. The rift valley is a rain shadow desert. The rainfall declines from 600 to 700 mm/year near Jerusalem to <400 mm/year in the Negev and around 100 mm/year at the shore of the Dead Sea and in the Arava valley to the S (Fig. 1B). Fluctuations of the Dead Sea lake level are induced by rainfall changes (Dayan and Morin, 2006). In winter rain climates, evaporation varies little annually, but rainfall fluctuations are high, so that the variability of evaporation plays only a minor role (Klein and Flohn, 1987). The main watercourse is the Jordan River. Most of the wadis draining the Judean Hills and the highlands of Moab and Edom are dry with the exception of winter floods from October through May. Few perennial streams such as Wadi el Mujib in Jordan discharge into the lake (El-Naqa, 1993). Springs like Ein Feshkha, fed by aquifers from the Judean Hills, emerge along the flanks of the Dead Sea (Ben-Itzhak and Gvirtzman, 2005). Winds, a consequence of depressions during winter and spring, are mostly westerlies (Hecht et al., 1997). Topography can change the general wind direction to the north or northwest (Bitan, 1974). Dust deposition rates peak during spring blossoming period and autumn. A grain size distribution curve for atmospheric dust deposition shows that the dust

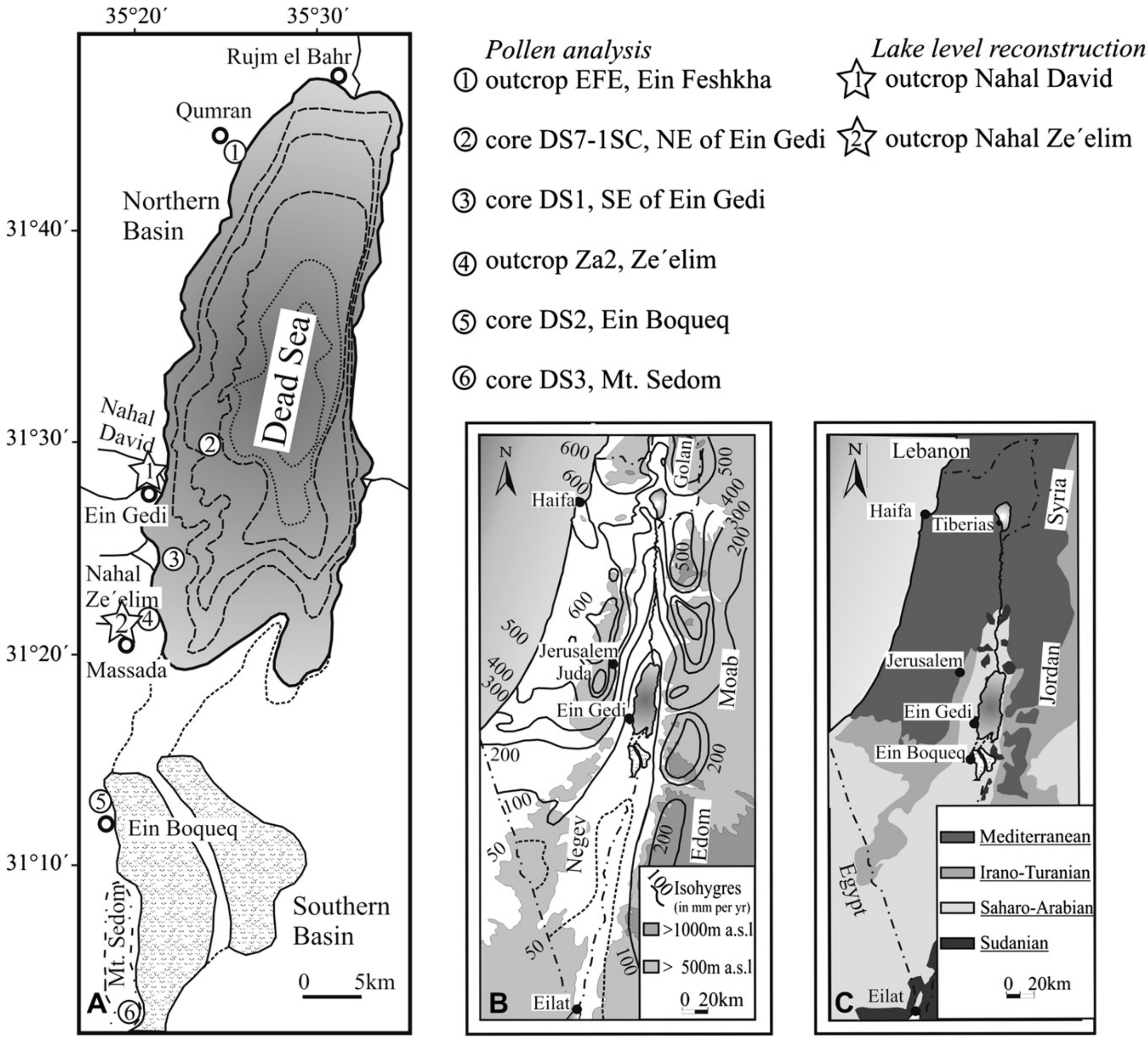

Fig. 1. A: Map of the Dead Sea showing the location of the cores and outcrops used for palynological and sedimentological research and discussed in this paper (after Baruch, 1990, 1993; Bookman (Ken-Tor) et al., 2004; Heim et al., 1997; Neumann et al., 2007), B: Topographical map of Israel and adjacent areas, black lines: annual rainfall contour lines in mm/year (after Jaffe, 1988),C: Plant geographical territories of Israel and adjacent areas (after Danin, 1988).

(including pollen) is primarily of long and mid-range transported origin (Singer et al., 2003). The vegetation geography of Israel and western Jordan depends on precipitation gradient. Four plant geographical territories are defined by statistical methods for the Israeli territory: the Mediterranean, the Irano-Turanian, the Saharo-Arabian, and the Sudano-Deccanian territories which meet at the Dead Sea (Fig. 1B) (Danin and Orshan, 1999; Danin and Plittmann, 1987). Mediterranean trees are *Olea europea*, *Quercus calliprinos*, summergreen oaks (e.g. *Quercus boisseri* at >400 m asl; Feinbrun-Dothan and Danin, 1991), *Ceratonia siliqua* and *Pinus halepensis*. In the mountains of southern Jordan *Juniperus phoenicia* grows (Al-Eisawi, 1996). At the transition towards the steppe *Sarcopoterium spinosum* is abundant (Baruch, 1993; Danin, 1988). Irano-Turanian steppe elements (precipitation < 300 mm/year) are *Artemisia* sp. and *Retama raetam* (Danin, 1995). The Saharo-Arabian territory is characterised by a desert climate (<100 mm/year) with salt-tolerant Chenopodiaceae and *Tamarix* (Al-Eisawi, 1996; Zohary, 1983). This vegetation is abundant at the Dead Sea level. The Sudano-Deccanian territory includes the oases at the coasts of the Dead Sea where *Acacia* sp., *Moringa peregrina*, *Ziziphus spina-christi*, *Salvadora persica* and *Phoenix dactylifera* grow (Al-Eisawi, 1996; Zohary, 1995). Human pressure has resulted in the degradation of vegetation and alien species were introduced as crops or as weeds (Danin, 1995).

4. Palynological records at the Dead Sea

We present vegetation developments from six pollen diagrams (pds) near Ein Gedi (2pds), Ein Feshkha, Ze'elim, Ein Boqeq, and Mount Sedom (Baruch, 1993; Heim et al., 1997; Neumann et al., 2007). Pollen records span the period between the Late Bronze Age and the 20th century. Since limited information about the Middle Bronze Age and the transition between the Neolithic and Chalcolithic are only available from Ze'elim (Neumann et al., 2007) we will concentrate on the vegetation development since the Late Bronze Age. The sites will be discussed from south to north. Appendices 1–6, containing selected pollen curves of the individual pollen diagrams with lithology and chronology, are only published in the electronic version of this paper. Uncalibrated radiocarbon dates from cores DS2 and DS7-1SC were calibrated in this study using CALIB 5.0.2 in conjunction with Stuiver and Reimer (1993). Discussions of the chronologies of each diagram have been previously published. Here we correlate the pollen zones directly to archaeological and historical periods.

4.1. Core DS3 (Mount Sedom)

An 11 m-long core from the Sedom saltpan was prepared and analysed by B. Lanjouw in 1978 (at the Biological–Archaeological Institute of Groningen University), but never published in a journal. A concise version of the diagram is presented and discussed in Baruch (1990, 1993) (Appendix 1). The DS3 pd, like the pds of cores DS1 near Ein Gedi and DS2 near Ein Boqeq (Fig. 1), is tentatively dated by correlation with the radiocarbon dated pd of Lake Kinneret on the basis of fluctuations of major pollen curves, e.g. *Olea* and *Pinus* (Baruch, 1993). Due to low *Q. calliprinos* values characterising the pds of DS3 and Lake Kinneret, the profile probably starts at ~1000 yr BC.

Zone X – ca. 1000–350 yr BC (Middle to Late Iron Age): The low values of *Q. calliprinos* might be a result of anthropogenic activities in the lower forest belt (Baruch, 1990). Since *Q. boisseri* might have been restricted to the northern part of the Judean hills percentages are low. Anthropogenic indicators, e.g. *Plantago lanceolata* and *Sarcopoterium*, are rare. Tree pollen values vary ~10%. *Olea* reaches ~8% at the end of the zone indicating limited cultivation.

Zone Y – 350 yr BC–AD 550 (Hellenistic–Roman–Byzantine period): An increase of *Olea* (15%) indicates major human activity. The *Olea* expansion culminates during the first quarter of the past millennium, i.e. the Roman–Byzantine period, reflecting wide expansion of olive cultivation during this period. C^{13} values from wood in the Roman Masada ramp point to humid conditions (Yakir et al., 1994). The *Olea* curve declines at the transition to the Early Arab period, probably as a result of contraction of olive cultivation, attributed to geo-political changes. At the end of this period, pollen grains of *S. spinosum*, a distinctive anthropogenic indicator, become prominent.

Zones Z1, Z2, Z3 AD 550–present (Arab–Modern period): *Pinus* values are increasing to ~14% in sub-zone Z1. This episode of pine expansion can be explained by its peculiar ecology (Baruch, 1990; see chapter 6 for details). In Z2 the curve of *Q. calliprinos* reaches its climax and a southward migration of the maquis is assumed. The culmination of the evergreen oaks in the 16–17th century AD may be explained as a result of the decrease of anthropogenic pressure on the Mediterranean maquis due to population decrease. However, as this period also correlates with the Little Ice Age a climatic factor cannot be ruled out (Lamb, 1982). The subsequent drop of evergreen oaks may be explained by a combination of a decrease in precipitation at the end of the Little Ice Age and renewed anthropogenic pressure on the vegetation, resulting from the onset of the Industrial Revolution.

4.2. Core DS2 (Ein Boqeq)

A 5.20 m-long core from the southern basin of the Dead Sea near Ein Boqeq was retrieved by U. Baruch in 1987 with the help of the late Professor S. Bottema of the Biological–Archaeological Institute of Groningen University. The palynological analysis of this core is from Baruch's Ph.D. dissertation (Baruch, 1993), but the pollen diagram has never been fully published (Appendix 2).

Zone X – ca. 1000–350 yr BC (Middle to Late Iron Age): The low *Quercus* values in this zone may reflect forest decimation as a result of anthropogenic activities. The rather high *Olea* values (~8%) in the middle of sub-zone X1, accompanied by marked *Vitis* values, which remain high throughout this and the following zone (Y), points to cultivation. The local vegetation was dominated by chenopods, which fluctuate markedly. This may point to shifts of the local coastline, resulting from slight modifications in lake level since the lake in this area is very shallow. Forest regeneration, which may have resulted from temporary ease of anthropogenic pressure on the vegetation, is reflected by high *Pinus* values (~14%) at the end of sub-zone X1. *Artemisia*, a steppe element, reaches >40% at the end of the zone.

Zone Y – 350 yr BC–AD 550 (Hellenistic–Roman–Byzantine period): Zone Y is marked by a prominent rise of the *Olea* curve, which reaches nearly 30%. This reflects extensive olive cultivation in the Judean Hills. *Olea* was accompanied by other fruit trees such as *Juglans* and *Ceratonia*, which make their first appearance in this zone. *Vitis* and *Phoenix* were already noted in the previous zone. The marked oscillations of the *Olea* curve throughout zone Y cannot be explained satisfactorily, but short-term climatic fluctuations cannot be entirely ruled out. The appearance of anthropogenic indicators, such as *S. spinosum* and *Plantago*, the curves of which become continuous in the course of this zone, corroborates the anthropogenic interpretation for the rise of olive and the other fruit trees. The radiocarbon date at the top of Zone Y seems to be too old, perhaps caused by redeposition of older carbon.

Zone Z – AD 550–after 1800 (Arab–Modern period): After the olive decline *Pinus* shows a peak ~15% in sub-zone Z1 reflecting the onset of forest regeneration. This most probably reflects a decline of anthropogenic pressure on the regional vegetation. Sub-zone Z2 is marked by the highest rise of the evergreen oak pollen curve throughout the entire diagram here reaching nearly 20%. The drop of the oaks in Z3 might be caused by a drier climate at the end of the Little Ice Age or by human disturbances or by a combination of both. The anthropogenic indicators *S. spinosum* and *Plantago* reach their highest values.

4.3. Outcrop ZA2 (Ze'elim)

The pd of Ze'elim is derived from a 10.75 m section from an erosion gully in a hyperarid environment where vegetation is almost absent (<100 mm/year, Neumann et al., 2007; Appendix 3). The profile, with lacustrine and fluvial sediments, was used for palaeo-lake reconstructions (Bookman (Ken-Tor) et al., 2004) which were compared to vegetation history (Neumann et al., 2007). The Middle Bronze Age (2000–1550 yr BC) shows high *Olea* percentages reflecting agriculture when Canaanitic city states were prospering (Neev and Emery, 1995). At the transition to the Late Bronze Age a decrease of oak and olive values and an expansion of Chenopodiaceae might indicate aridity.

Late Bronze Age (1550–1200 yr BC): A pollen sample shows low tree and high herb percentages, e.g. Chenopodiaceae, which might together with the sedimentation of a 110 cm thick beach ridge point to rather arid conditions.

Iron Age – Persian Period (1200–332 yr BC): Pastoral Judea close to Ze'elim was sparsely settled (Finkelstein, 1995). Peaks of *Q. calliprinos*, *Q. boisseri*, *Pinus* and *Pistacia* are followed by at least two phases with low tree and high chenopod values. The chenopods mainly inhabit the lake shores, which are probably more exposed when the lake level is low as evidenced by several sand layers. At the end of the Iron Age pollen indicators, e.g. *Olea* (>10%), show may be slightly moister conditions and a settlement period. Reforestation with slightly higher values of *Quercus*, *Pistacia* and *Pinus* is observed at the transition to the Hellenistic period whereas Chenopodiaceae values are declining.

Hellenistic Period (332–63 yr BC): An increase of cultivated plants shows the growing importance of agriculture. *Olea* values increase to ~12%, *Vitis* and the first pollen grains of *Juglans* are detected. The strong influence of cultivated plants is in agreement with lacustrine sediments, which indicate a rise of the Dead Sea lake level.

Roman Period (63 yr BC–AD 324) and Byzantine Period (AD 324–638): *Juglans*, *Vitis* and *Phoenix* reach maximal percentages. *Olea* values increase to 22%. *Xanthium*, a weed, and *Plantago lanceolata*, an indicator for grazing and openland (Behre, 1990), signal human disturbances. Around ~AD 240–430 *Olea* values dropped to ~2%. Other cultivated plants are missing. Ze'elim is close to ecological border regions (Negev) and might be affected by minor climatic fluctuations. In the Byzantine Period values of cultivated plants, like *Olea*, rise. Farms and towns prospered in the northern Negev, wheat, olives and grapes were cultivated (Rosen and Finkelstein, 1992; Rubin, 1996). The Dead Sea region was densely settled (Beit-Arieh, 1997). In the 6th century AD *Olea* decreased.

Early Arab Period (AD 638–1099), Crusaders – Mamelukes (AD 1099–1516): A *Pinus* peak follows the *Olea* decrease. The *Artemisia* curve runs in parallel to *Pinus*, perhaps pointing to a strong impact of steppe vegetation. A pine decrease is followed by an increase of *Q. calliprinos* and *Sarcopoterium*. May be the environment was too dry for a full recovery of the oak forest. *Q. boisseri* remains low.

4.4. Core DS1 (SE of Ein Gedi)

Core DS1 was retrieved by M. Stiller in 1979 as a part of joint project of the Department of Geophysics of the Weizman Institute, Israel and the Department of Geophysics of the University of Edinburgh (Stiller et al., 1988). Together with core DS2 the pollen analysis of this core formed part of Baruch's Ph D. dissertation (Baruch, 1993), and is here published in full for the first time (Appendix 4).

Zone X – ca. 1000–350 yr BC (Middle to Late Iron Age): Low *Q. calliprinos* percentages (<5%) and relatively high *Q. boisseri* values (>10%) characterise this zone. Anthropogenic interpretation is suggested for the generally low arboreal pollen values with the relatively high deciduous oak values pointing to a lower human pressure in the higher forest belt, than in the lower, evergreen-oak-dominated lower belt. A comparison between the ratio of both oak types in the samples of zone X and upper zone Z clearly shows that in the past deciduous oaks were far more common in the Judean Hills than today. Probably the site was close to stands of deciduous oaks in the northern Judean Hills during the Iron Age. *Vitis* pollen grains are more prominent in this zone than anywhere else throughout the diagram. This demonstrates that, besides olive, grape culture was also thriving in the area at this period. The local vegetation was dominated by chenopods.

Zone Y – (350 yr BC–550) Hellenistic–Roman–Byzantine period: This zone is marked by the prominent rise of the *Olea* curve. However, the fact that *Q. boisseri* values remain high indicates that olive cultivation must have been confined mainly to the lower forest zone, which is the natural habitat of the evergreen oak. *Olea* cannot tolerate temperatures below −4 °C. Seemingly climate was more favourable for agriculture during the Roman–Byzantine period.

Zone Z – AD 550–after 1800 (Arab–Modern period): The olive decrease is followed by a *Q. boisseri* decline. This sharp decline of the deciduous oaks reflects forest decimation, probably induced by anthropogenic factors, sometime during the concluding centuries of the first millennium AD. The following rise of *Pinus* reflects a short-termed expansion of this species, made possible by the rather abrupt disappearance of the deciduous oaks and the slow regeneration of evergreen oaks. Horowitz (1992) mentions the oak-pine ratio as an indicator for aridity. If this is correct a predominance of pine over oaks might point to aridity. Subsequently the evergreen oaks rise to their highest values throughout the core, which is explained by a possible combination of climatic amelioration and decrease of anthropogenic pressure. The recent decrease of evergreen oaks was caused by human activity. The marked rise of *Plantago* and *Sarcopoterium* curves, especially as from sub-zone Z2, points to the basically anthropogenic origin of the phenomena.

4.5. Core DS7-1SC (NE of Ein Gedi)

The 3.65 m-long core was recovered at 203 m water depth in the deep northern basin close to the western border fault of the Dead Sea graben and comprises a sequence of three massive salt layers interrupted by two annually laminated marl units (Appendix 5). AMS ^{14}C dates point to an age of ~749–50 BC at 60 cm from the base of the section. Post-modern AMS ^{14}C dates were obtained for the top of the profile. The pollen analysis confirms that the white and gray layers were formed during summer (low pollen concentration) whereas dark layers were deposited in autumn, winter and spring (high pollen concentration; Leroy in Heim et al., 1997; S. Leroy, unpublished data). The following descriptions of the pollen zones are given in Heim et al. (1997) and in S. Leroy, unpublished data.

Zones 1, 2: 332–63 yr BC Hellenistic–Roman–Byzantine period: *Olea* and *Vitis* values are high. With the exception of the lowermost part of zone 1, sediments are laminated and point to a humid environment. The lowermost part of zone 1 might belong to the late Iron Age. The halite layer from 3.65 to 3.20 m depth (with only one pollen spectrum dominated by chenopods) suggests arid conditions.

Zone 3a: Early Arab Period (638–1099 AD): This zone might have started already in the late Byzantine period. An abandonment of cultivated land is indicated by the drop of the olive values and the absence of *Vitis*. In contrast steppe vegetation and open dry woodlands become more abundant, e.g. *Q. calliprinos*, *Pistacia* and *Sarcopoterium*, and evidence like the halite layers in zones 3a and 3b show more arid conditions. The decline of cultivated plants is accompanied by a brief bell-shaped curve of Pine (zone 3a) and by forest regeneration during zone 3b.

Zone 3b: Mamelukes–Ottomans (1099–1918 AD): *Q. calliprinos* replaces *Olea* in the Judean Hills. Aridity is shown by a halite unit.

Zones 3c, 3d: WWI-modern period (1918-Post 1983 AD): Poaceae and other indicators of human activities show a clear increase. The decrease of evergreen oaks might be the consequence of wood cutting in WWI. In zone 3c a laminated sequence shows more humid conditions. In zone 3d, southern Hemisphere Neophytes illustrate human impact during the last 100 years (*Casuarina* and *Eucalyptus*). Salt forms again, as a result of water withdrawal from the Jordan River.

4.6. Outcrop EFE (Ein Feshkha)

The palynology, sedimentology and chronology of the erosion gully at the Ein Feshkha oasis, where *Tamarix* taxa and *P. dactylifera* are abundant, were described in Neumann et al. (2007) (Appendix 6). The 5.85 m-long section is predominantly lacustrine and was compared with and correlated to the section of Ze'elim.

Zone 1, Late Bronze Age (1550–1200 yr BC): A beach ridge at a depth of 5.8 m indicates aridity. Settlements and cultivated land were abandoned (Finkelstein, 1988). The pd of Ein Feshkha shows low tree pollen values up to a depth of 5.4 m. *Olea* and oak percentages reach 5%.

Zones 2 – 1st half of zone 4, Iron Age–Persian Period (1200–332 yr BC): The pd shows an *Olea* peak at the beginning of the Iron Age, values of *Phoenix* are high. This might be a signal for agriculture perhaps supported by higher rainfall. High Chenopodiaceae values point to a large influence of desert vegetation. The population during Iron Age I was concentrated north of Jerusalem and in the Jordan valley near Ein Feshkha (Finkelstein, 1995). At a depth of 495 cm, the Chenopodiaceae values increase, and low *Olea* values perhaps indicate a drop in rainfall. Abandonment of settlements during the 10th century BC or Assyrian destructions during the 8th century BC (Dever, 1995; Náaman, 1992) might be linked to this period of droughts. It cannot be excluded that a peak of *Pinus*, *Quercus* and *Pistacia* might be the consequence of higher precipitation. At the end of the period a settlement phase is visible by an increase of *Olea*. Oak values decline, probably due to wood cutting.

End of zone 4 to 1st half of 5, Hellenistic Period (332–63 yr BC): *Olea* increases, *Juglans* appears and Chenopodiaceae are decreasing. This might indicate humid conditions, which allow some agriculture. *Plantago lanceolata* occurs more regularly. Oaks decrease perhaps as a result of deforestation.

2nd half of zone 5–6, Roman–Byzantine Period (63 yr BC–638 yr AD): Ein Feshkha is close to agricultural centres in the Judean Hills and in oases. *Olea* reaches ~32%. Pollen grains of *Vitis*, *Phoenix* and *Juglans* are detected regularly. *Ceratonia* might grow near Ein Feshkha. *Plantago* indicates grazing. Higher values of *Pistacia*, *Q. calliprinos* and *Sarcopoterium* might point to an expansion of the maquis in the Byzantine period. Values of *Q. boisseri* remain low, apparently indicating that under conditions of strong human disturbances evergreen oaks are more competitive. *Vitis*, *Phoenix* and *Ceratonia* are absent at the end of the Byzantine period, which might point to a degradation of agriculture, although *Olea* values are still high.

Zones 7, 8, Early Arab Period (AD 638–1099), Crusaders – Mamelukes (AD 1099–1516): At the transition to the Early Arab period *Olea* declines. *Pinus* values are rising to ~15%. A 2nd step in forest regeneration is shown by the increase of *Q. calliprinos* following the decline of pines. The top of the Ein Feshkha profile, dated to AD 1240–1400, is characterised by higher values of *Olea* and *Vitis*. This weakly pronounced settlement phase might be within the Crusader or Mameluke Period when the lake level was higher and rainfall was increasing (Issar and Zohar, 2004).

5. Reconstruction of the Dead Sea lake level

The curve of the lake levels reconstructed at the erosion gullies of Ze'elim and Nahal David (Bookman (Ken-Tor) et al., 2004) (Fig. 2) was chosen for a comparison with the pollen records because it covers the same time span represented in the pds. Bookman (Ken-Tor) et al. (2004) have worked in the erosion gully in the Ze'elim wadi from where Neumann et al. (2007) have taken their pollen samples. It allows a direct comparison between the vegetation development and the fluctuations of the Dead Sea lake level. The curve is based on shoreline identification and radiocarbon ages. The lake level oscillations are associated with average annual precipitation in the southern Levant (Enzel et al., 2003). Highstands occurred during the 2nd and 1st century BC and during the 4th century AD. Additional wet periods were recorded in the 11th and 12th century AD and at the end of the 19th century. We correlate the Ze'elim pd including the lake level reconstruction to the pds at Ein Gedi, Ein Feshkha and Mount Sedom. Alternation between salts and laminated units in DS7-1SC core are also useful lake level indicators.

6. Vegetation history and past societies

Palynological investigations of Holocene vegetation history are available from six sites. ^{14}C dates are available for four sites (EFE, ZA2, DS7-1SC, DS2) (Baruch, 1993; Heim et al., 1997; Neumann et al., 2007) (Fig. 2). Cores DS1 and DS3 are not radiometrically dated (Baruch, 1993; Heim et al., 1997; Neumann et al., 2007) (Fig. 2). A comparison between pds starts in the Late Bronze Age (Fig. 2). This must however be taken with caution since radiocarbon dates are often missing or insufficient, resolution is often low and the correlation of the diagrams is predominantly based on pollen. All pds show a remarkably similar succession of pollen zones.

In the *Late Bronze Age*, represented in the pds of Ein Feshkha and Ze'elim, herb values reach a maximum (Appendices 3 and 6). The values of cultivated plants like *Olea* and Mediterranean trees (Fig. 2: *Q. calliprinos*, *Pinus*) are low. The lake level drops to −417 m. So lake level reconstruction and pollen data jointly point to relatively arid conditions (Miller Rosen, 2007). The beach ridge, indicator for a low level around 1510–1400 yr BC, and higher Chenopodiaceae values in Ze'elim might be an indicator for aridity in the South of the Dead Sea region. The southern basin of the Dead Sea was dry (Frumkin et al., 1991). Enzel et al. (2003) emphasize that a drop of the lake level below the sill (−402 m) means that annual rainfall must have been below the modern mean rainfall and prolonged droughts must have prevailed in the Levant. It is possible that the bottom part of the Sedom diagram, showing very low tree and high chenopod values, belongs to the Late Bronze Age (Fig. 2, Appendix 1). The Late Bronze Age is, in agreement with the possibly unfavourable climate, a period of cultural decline in the region when many sites were abandoned and few rural settlements existed in the highlands (Finkelstein, 1988).

The *Iron Age* is well documented in the six pds, but sharp differentiation with the Hellenistic period and the Late Bronze Age is often not possible. Vegetation in all locations shows similar developments. A slow increase of *Olea* can be observed until ~10%

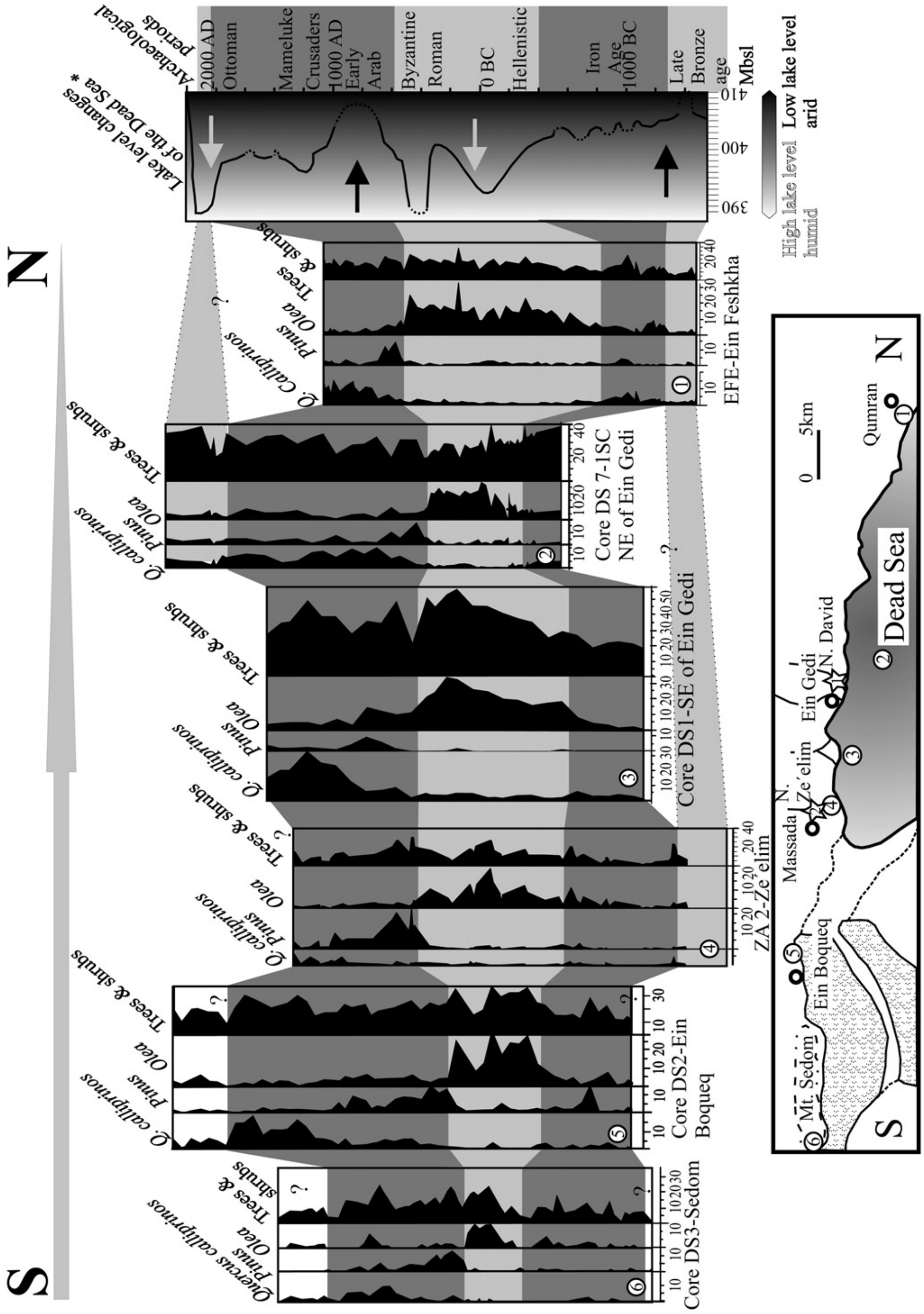

Fig. 2. Comparison of pds from the Dead Sea area (references in Fig. 1) to Dead Sea lake level changes since the Late Bronze Age (after Bookman (Ken-Tor) et al., 2004; Migowski et al., 2006). Four main pollen curves are given (*Q. calliprinos*, *Pinus* – members of the Mediterranean forests and maquis, *Olea* – the most important cultivated plant and the curve of trees & shrubs). Further pollen information for the sites is available from Appendices 1–6 (electronic version only). The illustration at the bottom shows the location of each of the sites along the western shore of the Dead Sea from S to N (details see Fig. 1). *Bookman (Ken-Tor) et al., 2004. The curve of trees & shrubs sums all arboreal pollen.

are reached in all pds (Fig. 2). In the same period a decrease of herbs, e.g. Chenopodiaceae, is observed. The olive rise reflects expansion of olive cultivation. Additionally the rise of the lake level from ~405 to ~401 mbsl points to more humid conditions at the end of the Iron Age, although several sand layers in the pd of Ze'elim indicate aridity during certain periods of the Iron Age. The pd of DS7-1SC might start in the late Iron Age although an allocation to this period is uncertain. Low tree values at the beginning of the diagram and the deposition of a salt layer might signal a lake level drop during the end of the Iron Age. An *Olea* peak followed by forest regeneration is observed in the pds of DS2, ZA2 and EFE. *Pinus* is increasing in DS2 whereas the rise of the pine curve is accompanied by *Q. calliprinos* and *Q. boisseri* increases in ZA2 and EFE. Apparently a short-term settlement period is a common signal throughout the region. It is uncertain if the expansion of cultivation is triggered by a more favourable climate. The steady rise of the lake level towards the end of this period, points to climatic amelioration at the end of the Iron Age and the onset of the Hellenistic Period.

The diagram of Ze'elim (ZA2) shows increasing values of *Olea* at the end of the Iron Age but also a short-term drop of tree pollen which might be correlated to a lake level decrease ~500 yr BC.

During the *Hellenistic, Roman and Byzantine period*, *Quercus* and *Pinus* values show a decrease due to forest clearings (more pronounced in Ein Feshkha and Ein Gedi) and olive values strongly rise. This is in good agreement with evidence showing an increase of settlements and agriculture along with a climatic amelioration (Issar and Zohar, 2004). *Q. boisseri* values in the pds of EFE and, more pronounced, DS1 remain relatively high. This indicates that the lower forest belt was more disturbed than the higher regions. The Roman and Byzantine periods were relatively humid as reflected by higher lake levels (Fig. 2). Roman–Byzantine olive cultivation is mostly distinguished in the pds near Ein Gedi (>30%), whereas *Olea* values in Sedom and Ze'elim are ~15%. Minor fluctuations of the Dead Sea level, e.g. the drop during the 3rd–5th century AD, where aridity is reported by archaeological investigations (Bruins, 1994), might be correlated with decreases in the *Olea* values that can be observed in the pds of ZA2, DS2 and DS1 at the end of this period. *Olea* values are higher in the pds of DS1 (maximally ~35%), DS7-1SC and Ein Feshkha (maximally 32%), a consequence of intensified agriculture in the Judean Hills (Neumann et al., 2007). Probably the wind regime at the NW corner of the lake, where EFE is located, is more dominated by winds coming from N and NW (Bitan, 1974). The influence of the desert vegetation in the Jordan valley might be stronger in Ein Feshkha than in Ein Gedi. The pd of core DS2 near Ein Boqeq shows similar *Olea* values to that of Ein Feshkha (maximally 32%). Olives were probably cultivated to the West of the site in the Negev, where settlements and farms prospered (Rubin, 1996). It is possible, although unlikely, that olive trees were cultivated near Ein Boqeq for the local perfume production – olive oil was the base of the perfume – as was the case in the arid Arava site of Moyat ´Avad during the late 2nd and early 3rd century AD. However, archaeological or historical evidence is missing (Brun, 2000; personal communication F. Erickson-Gini). *Olea* values in the south are, with the exception of DS2, lower than in the north, pointing to more arid environments and a longer distance between regions where olives are growing in the Mediterranean Judean Hills and the southern sites. At the end of the Byzantine period *Olea* values abruptly decrease at all sites. This might be the result of the Arab occupation of Palestine in AD 638 (Baruch, 1986, 1990; Baruch and Bottema, 1999), or an arid climate resulting in the drop of the Dead Sea lake level starting in the late 5th century AD (S. Leroy, unpublished data) (Fig. 2).

The *Early Arab until Ottoman period* is characterized by low *O. europea* values. The period is characterised by a decrease of agriculture and population and possibly drier climate if compared to the Byzantine period (Issar and Zohar, 2004). *Pinus* shows a strong peak in the pds of the Dead Sea region. This signal is characteristic for pollen records in the Dead Sea region and reflects a regional effect. *P. halepensis*, fast growing, specialized to unfavourable soils and a common pioneer, might have invaded abandoned orchards (Néeman et al., 2004). Arid periods might cause prevalence of *Pinus* over *Quercus,* because pines are adapted to droughts. The *Pinus* abundance can be seen as a sign for aridity also shown by the decrease of the Dead Sea level (Bookman (Ken-Tor) et al., 2004). The seedlings are sensitive to overshadowing and are suppressed by deciduous trees (Rabinowitch-Vin, 1982). The forest regeneration, led by pines and followed by evergreen oaks, might be the consequence of the abandonment of cultivated fields and settlements and the decrease of wood cutting at the transition from the Byzantine to the Early Arab period. According to Horowitz (1992), arid periods cause a high pine/oak ratio which is observed in all six pds in the Dead Sea region following the collapse of the *Olea* values. A pronounced peak of *Q. calliprinos* can be observed in the pds DS1, DS2, DS3, EFE and DS7-1SC. There is a possibility that those peaks might be a result of a wetter climate in the medieval period. The most recent decline of *Q. calliprinos* might be explained by human impact or by an arid period at the end of the Little Ice Age (Baruch, 1990). Between AD 1400 and 1600 the lake level of the Dead Sea drops (Fig. 2). In the profile of Ze'elim a sand layer was formed AD 1210–1420. The values for the Mediterranean *Q. calliprinos* are much higher in the northern pds, which might be a result of the shorter distance to the mostly Mediterranean Judean Hills. The values of *Q. calliprinos* are less pronounced in the pds of Ze'elim and Ein Feshkha, but are highest at the top of the profiles. This might be a consequence of erosion, which led to the destruction of the uppermost sequences at both sites. Pollen data from the *Modern period* showing Neophyte pollen (*Casuarina*, *Carya*, *Eucalyptus*) are available from core DS7-1SC. The retreat of the evergreen oaks is may be a consequence of wood cutting in WW I. Slightly higher values of oaks and olives might be a consequence of climate amelioration and plantation during the first half of the 20th century (high lake level of the Dead Sea; Fig. 2).

7. Conclusion

1. The study of surface samples clearly demonstrates that the origin of pollen influx into the Dead Sea is primarily in the region west of the lake, i.e. the Judean Hills. This is extrapolated to the interpretation of six sedimentary sequences at the west shores of the Dead Sea along a 75 km long transect. The changes in the Mediterranean vegetation, broadly similar and synchronous in all pds, are interpreted as changes mostly in the vegetation of the Judean Hills.
2. There is a broad synchronism between the fluctuations of cultivation, vegetation, lithology and climate change in the Dead Sea region during the last ~3500 years as derived from pollen data, sediments and lake level reconstructions along the western shore of the Dead Sea. In the Iron Age and Hellenistic to Byzantine Period the lake level reconstruction of the Dead Sea, as well as laminated sediments in the profiles of ZA2, EFE and DS7-1SC, point to a more humid climate. In the same periods values of cultivated plants are high in the pds and indicate an increase of agriculture. These were periods of more intensive agriculture activity due to socio-economic activity in the area west of the Dead Sea. The possible contribution of favourable climatic conditions to the expansion of agriculture and horticulture in these times cannot be ruled out. Low lake levels during the Late Bronze Age, the Iron Age and at the end of the Byzantine period point to climatic deterioration, which may contribute to the decrease of cultivated plants. This suggestion is strengthened by the deposition of sand layers in ZA2 and EFE and halite layers in DS7-1SC during those arid periods. In general cultural factors should be considered to be of least equal, if not higher, importance in affecting the intensity and extent of agriculture.
3. It is clear from all pds that Mediterranean trees, e.g. *Q. calliprinos*, *Q. boisseri*, *Pistacia* and *Pinus*, are largely replaced by cultivated plants during settlement periods. Cultivation developed mainly in the Mediterranean territory which was more favourable for settlers. Judging from relatively high *Q. boisseri* values in comparison to low *Q. calliprinos* values during the Roman–Byzantine period in the pds of EFE and DS1 settlements were concentrated, at least in the vicinity of those sites, in the lower *Q. calliprinos* forest belt whereas the higher regions were less affected.

4. Forest regeneration is clearly pronounced in all pds after the agricultural decline at the end of the Byzantine period. Drought-resistant and fast-growing pines are soon overshadowed by oaks especially evergreen oak and its regular companions *Pistacia* and *Sarcopoterium*. We conclude that the collapse of the settlement system near the transition to the Early Arab period affected the whole study area. Forest regeneration can be detected during the end of the Iron Age in the pds of Ein Boqueq, Ze'elim and Ein Feshkha after a short-lived and limited period of olive cultivation. The forest regeneration is soon interrupted at the transition to the Hellenistic period, probably by wood cutting at the beginning of a new settlement period.
5. The relatively higher frequencies of anthropogenic indicators, e.g. *Sarcopoterium*, in the pollen record from the Hellenistic period on, seem to indicate that from now on the Mediterranean vegetation was never free of anthropogenic pressure. This may imply that the Mediterranean maquis, as we know it today in the Judean Mountains, started to take shape some 1300–1400 years ago.
6. Although similarities of pollen fluctuations dominate in all pds, regional variations in pollen distribution are observed along the transect. Mediterranean vegetation elements and cultivated plants are less pronounced in the pds to the South (Ze'elim, Sedom) and stronger in the diagrams in the north (Ein Gedi, Ein Feshkha). This can be explained by a shorter distance from the sites near Ein Feshkha and Ein Gedi to settlement centres and to the Mediterranean plant geographical territory in the Judean Hills. Oases, centres of agriculture, exist near Ein Feshkha and at Ein Gedi and might be a source for some pollen of locally cultivated plants (*Phoenix*).
7. The pollen results might point to regions to the west of the sites where agriculture and settlement activities are concentrated. The pds of DS1 and DS7-1SC, showing the highest *Olea* values of all pds, reflect Roman–Byzantine centres of agriculture in the Judean Hills. The high *Olea*, *Vitis*, *Phoenix* and *Juglans* percentages in the pd of DS2 near Ein Boqueq during the Roman–Byzantine period might be a consequence of enhanced agriculture in the Negev.
8. Some Mediterranean elements and crops, e.g. *Q. boisseri*, *Pistacia*, and *Olea*, in EFE show lower values than in the pd of DS7-1SC near Ein Gedi to the South. This might be connected to a predominance of winds from the N and NW leading to a higher influence of the desert and oasis vegetation (e.g. Chenopodiaceae, *Phoenix*) because the lower Jordan valley and the region around Jericho are dominated by Saharo-Arabian and, to a lesser degree, Sudano-Deccanian vegetation

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Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.jaridenv.2009.04.015

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