Quaternary Research 80 (2013) 396–405

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Climatic and human controls on the late Holocene fire history of northern Israel

Nadine B. Quintana Krupinski [a,*], Jennifer R. Marlon [b], Ami Nishri [c], Joseph H. Street [d], Adina Paytan [d]

[a] Department of Earth and Planetary Sciences, University of California Santa Cruz, Santa Cruz, CA 95064, USA
[b] Yale School of Forestry & Environmental Studies, New Haven, CT 06511, USA
[c] Yigal Allon Kinneret Limnological Laboratory, Israel Oceanographic and Limnological Research, P.O. Box 345, Tiberias N/A 14102, Israel
[d] Institute of Marine Sciences, University of California Santa Cruz, Santa Cruz, CA 95064, USA

ARTICLE INFO

Article history:
Received 5 April 2013
Available online 27 August 2013

Keywords:
Fire
Israel
Holocene
Climate
Kinneret
Galilee
Charcoal
Black carbon

ABSTRACT

Long-term fire histories provide insight into the effects of climate, ecology and humans on fire activity; they can be generated using accumulation rates of charcoal and soot black carbon in lacustrine sediments. This study uses both charcoal and black carbon, and other paleoclimate indicators from Lake Kinneret (Sea of Galilee), Israel, to reconstruct late Holocene variations in biomass burning and aridity. We compare the fire history data with a regional biomass-burning reconstruction from 18 different charcoal records and with pollen, climate, and population data to decipher the relative impacts of regional climate, vegetation changes, and human activity on fire. We show a long-term decline in fire activity over the past 3070 years, from high biomass burning ~3070–1750 cal yr BP to significantly lower levels after ~1750 cal yr BP. Human modification of the landscape (e.g., forest clearing, agriculture, settlement expansion and early industry) in periods of low to moderate precipitation appears to have been the greatest cause of high biomass burning during the late Holocene in southern Levant, while wetter climate apparently reduced fire activity during periods of both low and high human activity.

Introduction

Fire is an integral component of Mediterranean ecosystems, and is sensitive to both human activities and climate changes (Vanniere et al., 2011; Pausas and Fernandez-Muñoz, 2012). Given the potential for rapid changes in both factors over coming decades, improving our ability to disentangle their relative influences on fire is an important objective. Lake sediment records that span millennia are a unique source of information about fire because they provide a long-term context for current changes; they can also yield insights into the response of fire to environmental changes that are much larger than modern observations, and perhaps more analogous (in terms of rates) to future changes (Whitlock and Larsen, 2001; Conedera et al., 2009).

The eastern Mediterranean has a long history of extensive and varying human population, agriculture and early industry; the region also experienced significant climate fluctuations over past millennia (Roberts et al., 2011). As a result, paleofire data from the Levant provide a rare opportunity to examine the combined impacts of humans and climate on fire activity in a part of the world that is central to human history. A recent synthesis of fire history from other parts of the Mediterranean found an increasing human influence on fire activity after 3–4 ka before present (Vanniere et al., 2011), but temporal coverage of the eastern Mediterranean in the late Holocene is too limited to investigate the role of human influence. The only published record of Holocene fire history in Israel (Lake Hula) is limited by uncertain chronology, low resolution, and discontinuous sampling (Turner et al., 2010). Low resolution and discontinuous sampling also limit the utility of a charcoal record from northwest Syria (Yasuda et al., 2000), and both studies contain only a handful of data points in the late Holocene. Several more detailed studies exist in more distant areas of the eastern Mediterranean, (Wick et al., 2003; Turner et al., 2008, 2010) but it is unclear whether these are relevant for understanding the controls on fire in the southern Levant.

Records of fire history may be particularly relevant for areas such as Israel, as climate models project that Israel and the eastern Mediterranean will experience significantly higher mean annual temperatures and reduced annual precipitation (IPCC, 2007) over the next century. Recent work (Daniau et al., 2012) shows that over the past 21 ka, fire increased monotonically with temperature and peaks at intermediate moisture levels, with temperature showing quantitatively the greatest correlation with variations in biomass burning. This leaves open the question of whether the southern Levant will be at increasing or decreasing risk for wildfire (Moriondo et al., 2006; Vanniere et al., 2011) as temperature rises and moisture decreases. This highlights the need for fire history records to help constrain future fire trends in a region where the fire regime could be near a tipping point.

---

* Corresponding author.
E-mail address: nadine@pmc.ucsc.edu (N.B. Quintana Krupinski).

0033-5894/$ – see front matter © 2013 University of Washington. Published by Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.yqres.2013.06.012

Charcoal deposited in sediments of small lakes (e.g., <0.1 km^2; Whitlock and Anderson, 2003) has been used widely for fire history reconstruction because pollen analyses (e.g., Sugita, 1993) show that such sites provide information on a local scale. Although large lakes have occasionally been used in fire history reconstructions (e.g., Singh and Geissler, 1985; Yasuda et al., 2000; Lozano-García et al., 2005; Thevenon and Anselmetti, 2007), their use has been limited partly due to concerns that river and stream flux can bias charcoal variability through remobilization of older charcoal, particularly during high river-flux periods (Whitlock and Anderson, 2003). However, paleofire reconstructions from large lakes could potentially reduce inter-site variability compared to reconstructions based on multiple small lakes, thus enabling more robust regional fire history reconstructions. Lake Kinneret (the Sea of Galilee) is the largest freshwater lake in Israel, and comparing its charcoal record with records reflecting hydro-climatic parameters such as river flux and precipitation and with other regional charcoal records allows an assessment of the utility of charcoal records in a large lake.

Another emerging topic of interest in the fire history community is whether sedimentary deposits of soot (black carbon) are comparable to regional syntheses of charcoal records. Black carbon is an aerosol product from a continuum of combustion products ranging from lightly charred biomass to graphite (Masiello, 2004). Black carbon can be transported over much longer distances (hundreds or thousands of kilometers) than charcoal (typically less than tens of kilometers), is generated at higher temperatures, and is much smaller (Masiello, 2004). As a result, black carbon may be combined with charcoal to more thoroughly characterize the fire history of a region (Han et al., 2012). Comparisons between the two proxies at regional scales provide an opportunity to improve our understanding of the different signals they preserve (Thevenon et al., 2010). In this study, we quantify both black carbon (BC) and charcoal in the same sediment core to compare the two fire proxies. While we expect they will differ because BC aerosols are transported further than charcoal particles (and thus reflect a larger area), we nonetheless anticipate broad similarities between the two proxies if large lakes in fact reflect landscape-scale or broader environmental changes.

Methods

Site description

Lake Kinneret has a surface area of 162 km^2 (maximum depth 43 m), is fed and drained primarily by the Jordan River, and is located in a tectonic depression of the Dead Sea transform fault (Fig. 1). The lake has a relatively large watershed (~2700 km^2; Singer et al., 1972) and is located in northern Israel's semi-arid and fire-prone Mediterranean environment in an area of large topographic and precipitation gradients. Modern vegetation in this area is primarily a mix of trees, shrubs and grasses of the Mediterranean and Irano–Turanian biomes (Zohary, 1973), and fire proxies have not been studied in this lake.

A 280-cm gravity core (core AA3) was collected in 2005 from the center of Lake Kinneret at approximately 40 m water depth (32.81°N,

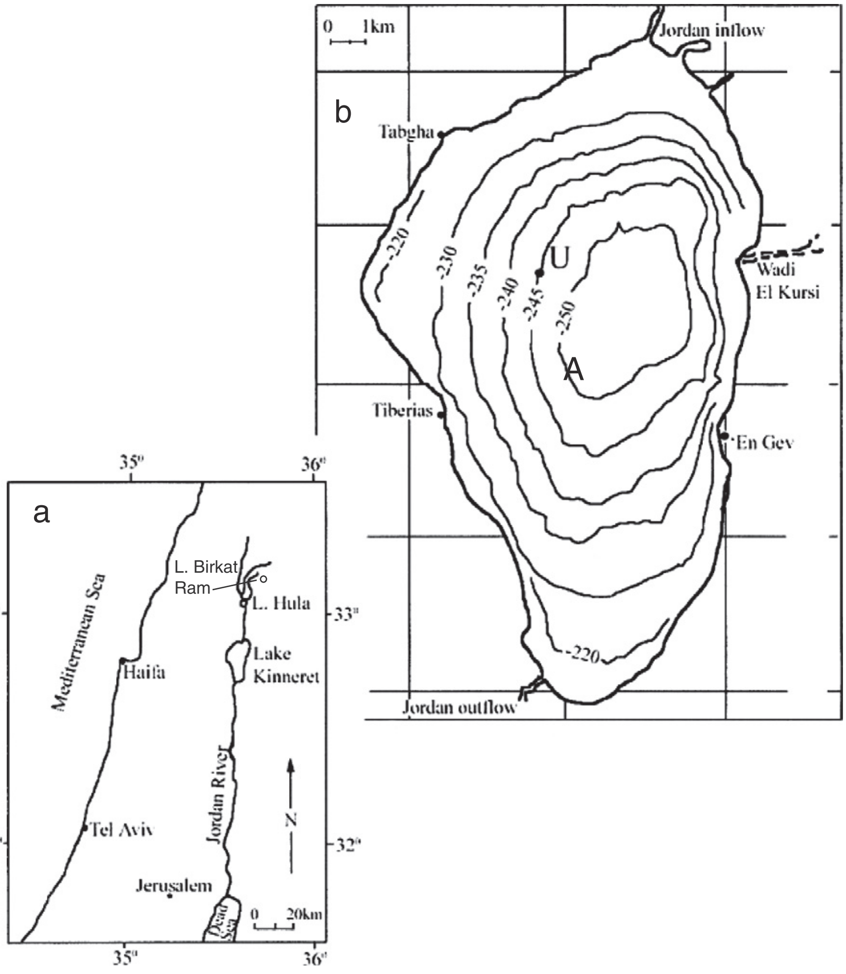

Figure 1. a) Map of study region, showing Lake Kinneret, Jordan River, Dead Sea, Lake Birkat Ram, and Lake Hula; and b) Map of Lake Kinneret and coring site, showing lake depth in meters below sea level. The core (AA3) was collected from site A (32.81°N, 35.58°E). The location of a core from Dubowski et al. (2003) is also shown in panel b (site U). Modified from Dubowski et al. (2003).

35.58°E). The core was split longitudinally into two halves, stored at 4°C, and later sectioned into 5-cm intervals. All analyses were conducted on contiguous/adjoining intervals of 5-cm length, which represent 23 yr (oldest interval) to 104 yr (youngest interval) of sedimentation. The core is composed of fine-grained carbonates and siliciclastics of buff color with short gradations to more brown-red color at ~10–20 cm, ~25–35 cm and ~165–180 cm, and contains very few macrofossils due to its shore-distal location.

Chronology

The chronology of core AA3 is based on five accelerator mass spectrometry (AMS) radiocarbon dates analyzed at Lawrence Livermore National Laboratory. Calibrated ages from these samples show that the 280-cm core represents the past 3070 yr of sedimentation (Table 1, Fig. 2); the core top is assumed to be modern. Material for radiocarbon samples was prepared similarly to a pollen preparation procedure (Faegri and Iversen, 1989) with the goal of separating cellulose (due to a lack of macrofossils), as Kitagawa et al. (2007) showed that lake sediment cellulose can be used to accurately date lake sediments. To concentrate organic matter from bulk sediment, we used chemical treatment and physical separation (hot solutions of potassium hydroxide, sodium pyrophosphate, hydrochloric acid, sieving to remove fine sediment, hydrofluoric acid, and final hydrochloric acid). The material remaining for radiocarbon analysis was dominantly composed of cellulose, with small amounts of charcoal and pollen (confirmed by microscopy). Because the organic matter isolated by this procedure was nearly all terrestrial in origin, no reservoir age correction was applied to the ^{14}C ages. Radiocarbon dates were converted to calendar ages using Calib 6.0 software (Stuiver and Reimer, 1993) and the IntCal04 Calibration curve (Reimer et al., 2004). All subsequent ages discussed refer to calibrated ages in years before AD 1950 (cal yr BP). A core chronology (Fig. 2) was generated using a linear interpolation between dated intervals with Analyseries software (Paillard et al., 1996).

Fire proxies

We apply two complementary fire proxies, charcoal accumulation rates (CHAR; pieces cm^{-2} yr^{-1}), and soot black carbon accumulation rates (µg BC cm^{-2} yr^{-1}) to reconstruct fire history. Charcoal primarily reflects fire events within the basin's watershed, as the larger particles are transported both aerially and via slopewash during fires or are remobilized from soils and sediments after fires (this semi-continuous input of remobilized charcoal particles is referred to as *background CHAR*; Millspaugh and Whitlock, 1995; Whitlock and Anderson, 2003). Lake Kinneret's watershed is large (~2700 km^2); accordingly, charcoal accumulation represents fires in the northern Jordan River Valley (essentially a regional signal), and BC includes this area and potentially a larger region, so we assume both proxies here represent regional burning.

Table 1
AMS radiocarbon ages from Kinneret core AA3.

Laboratory ID (CAMS #)	Core	Depth (cm)	^{14}C yr BP	Error ($\pm 2\sigma$)	calibrated yr BP	2σ range [cal yr BP]
140519	AA3	30–35	715	30	676	641–705
140520	AA3	90–95	1900	35	1847	1754–1918
140521	AA3	130–135	2170	90	2170	1954–2345
140522	AA3	190–195	2550	80	2610	2369–2774
140523	AA3	240–245	2220[a]	30	2232[a]	2152–2325
140524	AA3	270–275	2840	90	2970	2768–3213

Dated material for all samples is predominantly cellulose (see methods for further description). Dates with error >50 yr have been rounded to the nearest 10 yr.

[a] Omitted from age model due to age reversal.

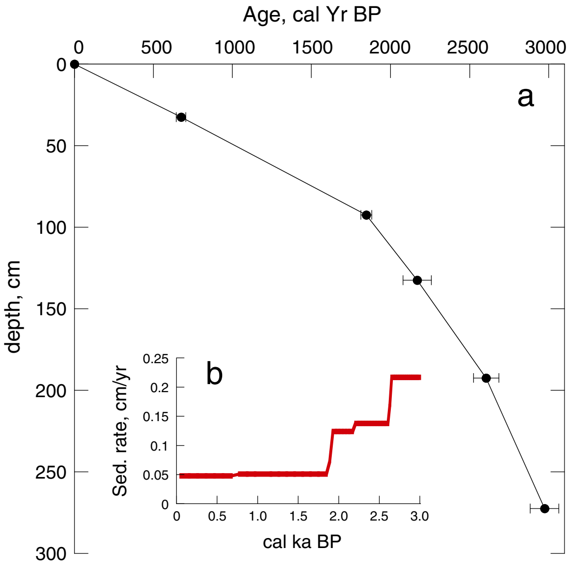

Figure 2. a) Age-versus-depth relationship for core AA3; 2σ age error bars. b) Sedimentation rate versus calibrated age.

Charcoal

Charcoal particle abundance was determined following Whitlock and Anderson (2003). Sediment samples (~5 cc) were dried, weighed, soaked in 5% sodium hexametaphosphate (1–5 days), and gently wet-sieved through 63, 125 and 250 µm sieves. The number of charcoal pieces present were counted in the 125–250 µm and >250 µm size fractions under a stereomicroscope at 8–40 times magnification. Counts from both size fractions were summed during data analysis for consistency with previous studies. Each sample's charcoal counts were normalized to volume (# particles cm^{-3}). Charcoal concentration was converted to charcoal accumulation rates (CHAR; number of >125 µm pieces cm^{-2} yr^{-1}) using sedimentation rate (cm yr^{-1}). The program CharAnalysis 0.9 (Higuera, 2009) was used to calculate background CHAR (parameters: 200-yr smoothing interval with Lowess smoother; CHAR data re-sampled to 23-yr interval). A composite of 18 regional CHAR records was constructed from Version 2 of the Global Charcoal Database (Daniau et al., 2012) using all published records (0–3 ka) within the area 30 to 45°N, 20 to 45°E. For the regional CHAR composite curve, all records were rescaled with a minimax transformation (transforming and homogenizing the variance using the Box-Cox transformation), and were rescaled again by calculating Z-scores. A base period of 2000 to 200 cal yr BP (present = AD 1950) was used for the transformation. Finally, the values were binned into 20-yr intervals and smoothed using a Lowess curve with a 100-yr moving half-window. The standardization methods follow the protocol detailed in Power et al. (2010).

Black carbon

BC concentration measurement followed the chemothermal oxidation method (CTO-375; Gustafsson et al., 1997, 2001; Masiello, 2004; Nguyen, 2004; Hammes et al., 2007). Sample preparation consisted of 1) sediment homogenization and weighing into silver capsules (~50 mg), 2) ashing in a muffle furnace at 375°C for 18 h with additional air inflow, 3) vapor acidification of wetted samples with concentrated hydrochloric acid (~12 h) to remove carbonate, and 4) sample drying and packing into a second silver capsule. The samples were analyzed at the University of California Santa Cruz (UCSC) for weight percent carbon and carbon isotopes using a Carlo Erba elemental analyzer connected to an Isotope Ratio Mass

Spectrometer (EA-IRMS; Iso-Prime). Weight % BC was converted to mass accumulation rate (μg cm^{-2} yr^{-1}) using dry bulk density and sedimentation rate. Reproducibility was evaluated by analyzing in-house and international reference standards and a core-specific standard composed of a small amount of homogenized sediment from all depth intervals of core AA3. Reproducibility of the core-specific standard is ±0.04 wt.% BC (2σ).

Carbonate and organic matter analyses

Concentration and isotopic composition of inorganic carbon, organic carbon and total nitrogen in lake sediments were measured and used as proxies for climatic conditions. Weight percent $CaCO_3$, $\delta^{13}C_{CaCO3}$ and $\delta^{18}O_{CaCO3}$ were measured on homogenized bulk sediment samples. Samples were weighed into pre-cleaned stainless steel boats and analyzed at UCSC using an IRMS (Prism model) with a dual inlet carbonate device. Reproducibility of in-house carbonate standards is ±0.1‰ for $\delta^{18}O_{CaCO3}$ and ±0.04‰ for $\delta^{13}C_{CaCO3}$ (2σ).

Weight percent organic carbon (OC) and total nitrogen (N) and $\delta^{13}C_{org}$ and $\delta^{15}N$ were measured on homogenized bulk sediment samples. Sample preparation and analysis for OC samples was identical to the procedure described above for black carbon samples except without ashing (steps 1, 3 and 4). Samples for N were analyzed un-acidified in a single tin capsule using the same instrument. Organic carbon and total nitrogen reproducibility on the core-specific standard is ±0.13 wt.% OC, ±0.001 wt.% N, ±0.8‰ for $\delta^{13}C_{org}$ and ±0.65‰ for $\delta^{15}N$ (2σ).

Correlation analysis

To differentiate the major factors controlling fire occurrence through the record, we evaluated the relationship between proxies of fire and climate via the Pearson correlation coefficient of $\delta^{18}O_{CaCO3}$ with CHAR and BC, and of CHAR and BC, and a student's *T*-test. We use $\delta^{18}O_{CaCO3}$ as the indicator of climate because it integrates several climate-related signals, as discussed in the *Interpretive framework* below. A direct correlation of human activity with fire proxies is not possible due to the limited population data available (local population records are of low resolution, and regional records span an area much larger than our climate proxies represent); accordingly, this relationship is discussed qualitatively.

Comparison to other records

We assessed the relative influence of climate and human activity on fire frequency in the Galilee region by comparing our fire records to records to 1) a regional biomass burning composite for the area 30°N to 45°N and 20°E to 45°E (Daniau et al., 2012; following methods of Power et al., 2010); 2) our Lake Kinneret core AA3 sediment geochemistry to infer local climate (Fig. 3); 3) other local and regional climate records to infer changes in precipitation and temperature (Bar-Matthews et al., 1997, 2003; Dubowski et al., 2003; Migowski et al., 2006; Bartov et al., 2007; Orland et al., 2009); 4) variations in arboreal and olive (*Olea*) pollen in Lake Kinneret (Baruch, 1986, 1990), Lake Birkat Ram (a small hydrologically isolated maar lake in the Golan Heights about 45 km north of Lake Kinneret within the Lake Kinneret watershed; Schwab et al., 2004; Neumann et al., 2007), and the Dead Sea (Litt et al., 2012) to infer ecological changes; 5) estimated changes in local population (Broshi and Finkelstein, 1992); and 6) archeological period transitions in the Middle East (as in Litt et al., 2012).

Results

Figure 3 summarizes the variation of fire and climate proxies in core AA3 over time. To facilitate description and discussion of our results, we divide the record into four stages based on variations in climate proxies (primarily wt% $CaCO_3$, $\delta^{18}O_{CaCO3}$, $\delta^{13}C_{CaCO3}$, and also wt% OC and wt % N) with estimated stage boundaries. The selected stage boundaries are not intended to be precise; because of the gradual nature of the environmental changes captured in the proxy records, the stage delineations are by necessity qualitative, and transitions between stages are often gradual. For comparative purposes, mean proxy values and measures of variability are presented in the supplementary data (Supplementary Table 1).

Stage A (3070 to 2620 cal yr BP)

This stage is characterized by the highest accumulation rates of CHAR and BC in the whole record and also by high variability. Wt.% $CaCO_3$, $\delta^{18}O_{CaCO3}$, $\delta^{13}C_{CaCO3}$, wt% OC, wt.% N and C:N are also higher than all other periods (Fig. 3; Supplementary Table 1).

Stage B (2620 to 2300 cal yr BP)

CHAR and BC accumulation in this stage decrease to a brief local minimum around 2460 cal yr BP and subsequently begin to rise again. This decrease to ~2460 cal yr BP and subsequent rise also occurs in all other parameters (wt.% $CaCO_3$, $\delta^{18}O_{CaCO3}$, $\delta^{13}C_{CaCO3}$, wt% OC, wt% N) and also C:N (Supplementary Fig. 1).

Stage C (2300 to 750 cal yr BP)

CHAR accumulation rates during this stage are initially moderate to high and decrease shortly after a decrease in sedimentation rate, while BC accumulation rates are moderate and decrease with sedimentation rate around 1900 cal yr BP. Values of wt% $CaCO_3$ and $\delta^{13}C_{CaCO3}$ are high, while $\delta^{18}O_{CaCO3}$ gradually increases from moderate to high values late in this stage (~1000 cal yr BP), and wt.% OC, and wt.% N are moderate. All climate proxies show values similar to Stage A, and all show the greatest stability in this stage.

Stage D (750 cal yr BP to present)

This stage is characterized by the lowest values of CHAR and BC accumulation in the record. All other proxies show an abrupt decline at the beginning of this stage, and have the lowest mean values of the whole record (Supplementary Table 1) in this stage, but show large-magnitude variability.

Sedimentation rate

Rapid sedimentation during the oldest part of the record (2.1 mm/yr) declined to moderate sedimentation (0.5 mm/yr) in the youngest interval (Figs. 2, 3). The largest change in the sedimentation rate occurred around 1900 cal yr BP, though the exact timing of this change cannot be determined without higher resolution dating.

Discussion

Interpretive framework

Sediments deposited in Lake Kinneret are composed of two primary end-member sources, which can be used to distinguish arid and humid periods: allochthonous Jordan River sediment, and authigenic Lake Kinneret sediment. Previous work (Stiller and Kaufman, 1985; Dubowski et al., 2003) described these sources: authigenic Lake Kinneret sediment is dominated by $CaCO_3$, has higher $\delta^{18}O_{CaCO3}$ and $\delta^{13}C_{CaCO3}$ values (−1.3‰ and −1.7‰, respectively), and higher organic carbon (OC) and nitrogen (N) content, compared to allochthonous Jordan River sediment, which is low in $CaCO_3$ (~25%), OC (~1.5%), N, and has lower $\delta^{18}O_{CaCO3}$ and $\delta^{13}C_{CaCO3}$ values (−4.1‰ and −7.1‰, respectively). Accordingly, arid periods of low river discharge and less allochthonous input are characterized by high

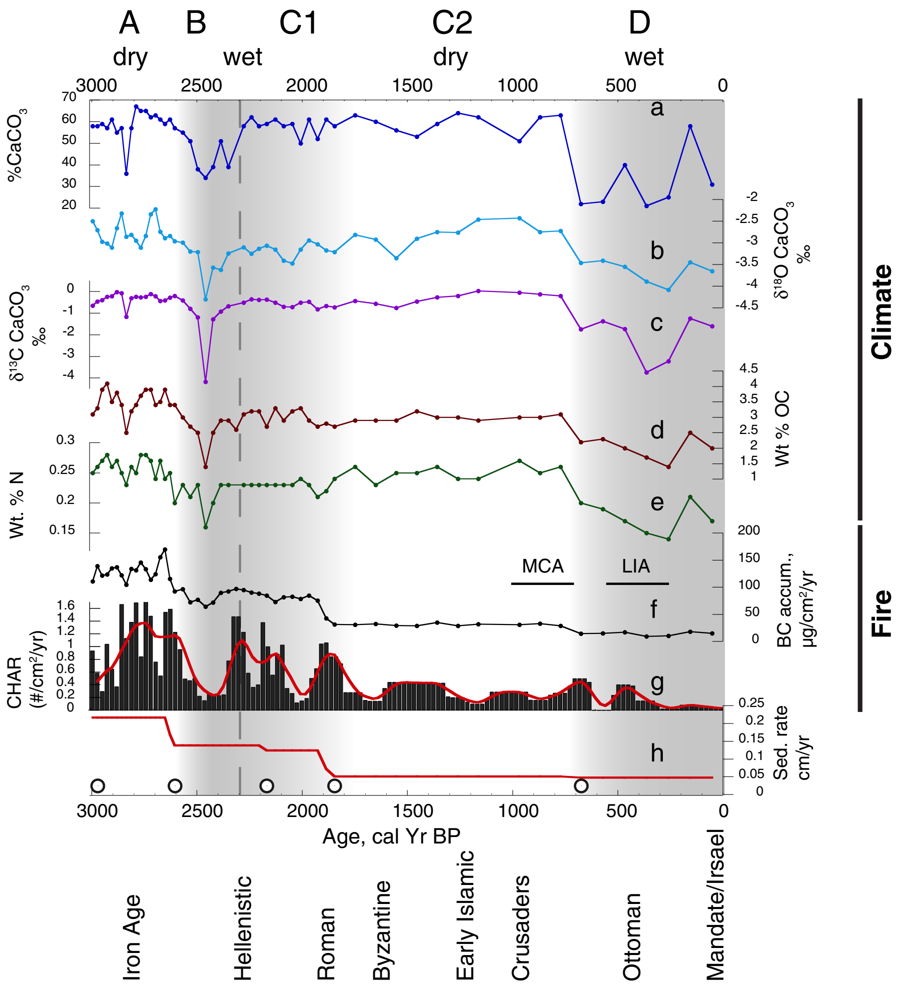

Figure 3. Sedimentary records from core AA3, subdivided into wet and dry stages (A–D; shaded bars); stage boundaries are intended to be approximate (see text for further discussion). Accumulation rates are calculated using a variable sedimentation rate derived from the age model. a) Weight percent calcium carbonate, ($CaCO_3$) b) Oxygen isotopes of $CaCO_3$, c) Carbon isotopes of $CaCO_3$, d) Weight percent Organic Carbon, e) Weight percent Total Nitrogen, f) Black Carbon accumulation rate (µg/cm^2/yr), g) Charcoal accumulation rate (pieces/cm^2/yr; CHAR) and background charcoal (red curve), h) Sedimentation rate (with circles indicating ages of the radiocarbon dates). Archeological periods as in Litt et al. (2012); timing of the Medieval Climate Anomaly (MCA) and Little Ice Age (LIA) (Mann et al., 2009) are also shown for reference.

sediment wt % $CaCO_3$, OC, N, and higher $\delta^{18}O_{CaCO3}$ and $\delta^{13}C_{CaCO3}$ values, while wet periods with high Jordan River sediment influx have low $CaCO_3$, OC, N, $\delta^{18}O_{CaCO3}$ and $\delta^{13}C_{CaCO3}$ values.

Another interpretive approach attributes changes in lake $\delta^{18}O_{CaCO3}$ to variations in precipitation amount and/or temperature (Dansgaard, 1964; Rozanski et al., 1993), where high $\delta^{18}O$ values indicate dry (evaporative) and cold conditions, and low $\delta^{18}O$ values indicate wet (less evaporative) and warm periods (Develle et al., 2010); this interpretation would imply a dampening of our record's $\delta^{18}O_{CaCO3}$ signal as a recorder of sediment source changes. However, local studies characterize the mid-late Holocene eastern Mediterranean as alternating between warm and dry conditions or cool and wet conditions (Bar-Matthews et al., 2003; Litt et al., 2012). This interpretation (hot and dry vs. cool and wet) is in agreement with the two end-member approach described above and would amplify the $\delta^{18}O_{CaCO3}$ signal of our record. Changing air mass trajectories may also result in isotopic variability, but are beyond the scope of this study. $\delta^{18}O_{CaCO3}$ alone cannot distinguish whether the hot/dry and cool/wet interpretation, or the opposite combination, is correct, but we assume the local late-Holocene interpretation (hot and dry vs. cool and wet) of Bar-Matthews et al. (2003) and Litt et al. (2012) is most appropriate.

Periods of high CHAR and high BC accumulation are interpreted as evidence of increased regional fire activity (i.e., increased biomass burning). The CHAR record is not converted to fire frequency (# of fires per unit time) because Lake Kinneret's larger size conflicts with assumptions used to calculate fire frequency, nor are individual fires or discrete events (i.e., one or more fires within a given time period) determined due to the relatively low resolution of the record. Another objective is to assess the degree to which the BC and CHAR curves agree, which may help constrain potential interpretations of BC and its utility in recording signals of regional biomass burning.

Stage A (3070 to 2620 cal yr BP)

This stage represents the driest time interval in our record, as sediment carbonate, organic matter and isotope ratios are the highest, representing low input from the Jordan River, increased evaporation from the lake relative to freshwater input, or increased temperature (Fig. 3). Aridity is also indicated by another record of Lake Kinneret $\delta^{18}O_{CaCO3}$ (Dubowski et al., 2003; Fig. 4) and by lowstands in Lake Kinneret and the Dead Sea during this time (Hazan et al., 2005; Migowski et al., 2006; Bartov et al., 2007). Speleothem-based precipitation and temperature estimates (Bar-Matthews et al., 2003) are

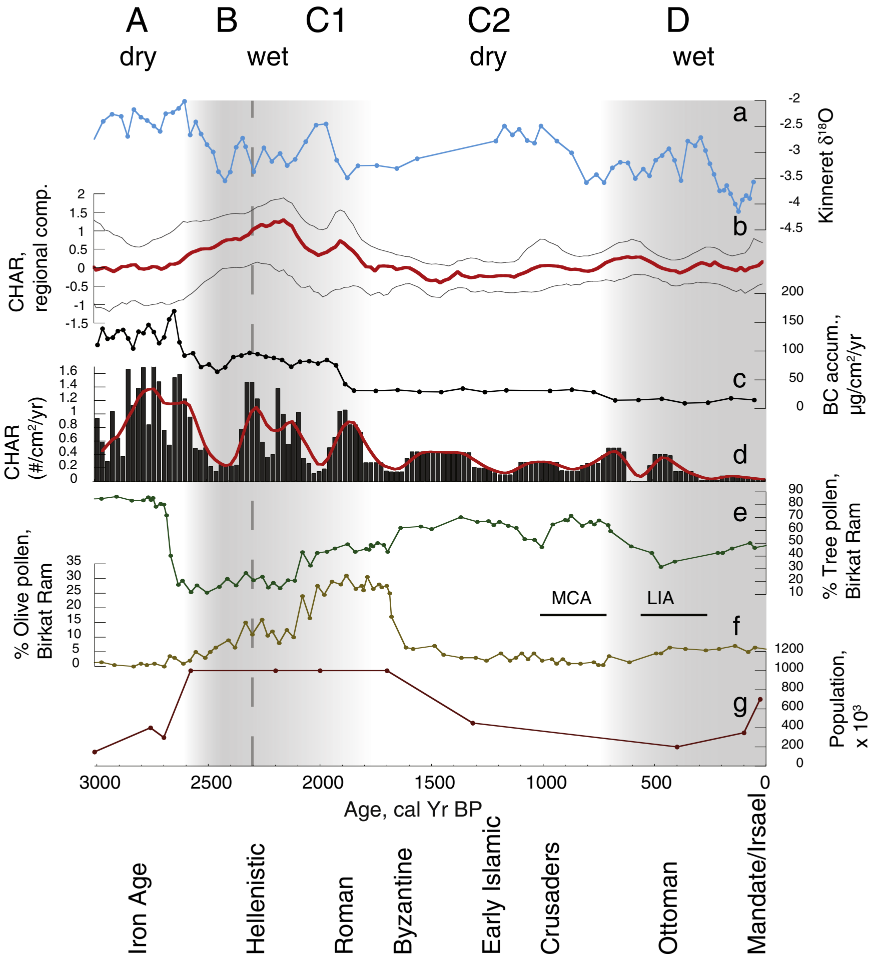

Figure 4. Compilation of records of local and regional climate, pollen, and population with Kinneret climatic stages from Figure 3 superimposed. a) Lake Kinneret core U bulk sediment $\delta^{18}O_{CaCO3}$ (Dubowski et al., 2003; location shown in Fig. 1), b) composite of 18 regional CHAR records from Version 2 of the Global Charcoal Database (Daniau et al., 2012), as further described in our text's methods, c) Lake Kinneret BC accumulation (this study), d) Lake Kinneret CHAR (this study), e) Percent arboreal pollen, and f) percent olive (*Olea*) pollen from Lake Birkat Ram, Golan Heights (Schwab et al., 2004; Neumann et al., 2007), g) Population of ancient Palestine (Broshi and Finkelstein, 1992). Archeological periods, as in Litt et al. (2012), and timing of the Medieval Climate Anomaly (MCA) and Little Ice Age (LIA) (Mann et al., 2009), are also shown for reference.

consistent with a transition to dryer and warmer conditions, and two regional climate compilations characterize this period as arid (Rambeau, 2010; Roberts et al., 2011).

During this stage (the Iron Age), archeological and pollen records show the first major population increase in the Kinneret area (Fig. 4), widespread clearing of often extensively forested land (indicating that a lack of fuel had not previously limited fires), likely by both burning and cutting of native oak (*Quercus*) forest, and a transition from wild to cultivated plant species (Baruch, 1986; Broshi and Finkelstein, 1992). Pollen data from the northern Golan Heights show that deforestation and agriculture were not yet as widespread there as around Lake Kinneret (Schwab et al., 2004; Neumann et al., 2007; Fig. 4); however, this setting is slightly removed from Lake Kinneret (~45 km north). The high C:N and more positive $\delta^{13}C_{org}$ in this stage (Supplementary Fig. 1) are consistent with higher inputs of terrestrial organic matter into the lake, perhaps reflecting forest clearing.

Very high CHAR and BC accumulation in this stage indicate high fire activity, which we interpret as resulting from a combination of arid conditions and the first significant human modification of the local landscape. Turner et al. (2010) also observed high fire activity in nearby Lake Hula (located in the Jordan River watershed north of Lake Kinneret; Fig. 1a) during this stage. Regional CHAR (Fig. 4) is not elevated at that time, suggesting perhaps human impacts were more significant locally than regionally.

Stage B (2620 to 2300 cal yr BP)

Low sediment carbonate, carbonate isotope, and organic matter values during this time indicate a relatively rapid transition into and out of more humid conditions, characterized by increased fluvial sediment input into Lake Kinneret and/or decreased evaporation and reduced temperatures. Dubowski et al. (2003) also described this as a wet period in Lake Kinneret. In contrast, speleothems from Soreq Cave (Bar-Matthews et al., 2003) and Dead Sea lake levels (Migowski et al., 2006; Bartov et al., 2007) characterize the time as dry and warm. However, Litt et al. (2012) propose that the Dead Sea signal of aridity in this time is specific to that location (central Israel, which includes the Soreq area) and find that it does not extend as far north as the Golan Heights (near the Kinneret). Minima for all parameters at 2460 cal yr BP suggest this was the wettest time in this stage with the highest river discharge, and a low $\delta^{18}O_{CaCO3}$ value (−4.3‰) suggests that much of the carbonate at this time may be allochthonously sourced.

Lake Kinneret and Golan Heights pollen records from this time (late Iron age) document a further decline in forest cover resulting from widespread forest clearing for settlements and agriculture, and increases in olive (*Olea*), grape (*Vitis*), walnut (*Juglans*), *Plantago* and *Rumex* pollen indicate expansion of agricultural crops and pasture land (Baruch, 1986, 1990; Schwab et al., 2004; Neumann et al., 2007; Fig. 4). Archeological records show that a large population developed early in this stage and settlements increased in number (Broshi and Finkelstein, 1992).

Low CHAR and BC imply that, despite a large human population and widespread land-clearing, fire activity was low during this stage. Nearby Lake Hula also showed low fire activity during this time (Turner et al., 2010), suggesting that the humid climate exerted the dominant control on the fire activity in the Kinneret area during this stage in spite of extensive human activity. However, high CHAR in the broader region (Fig. 4) may indicate more frequent or extensive burning in more distant regions, coinciding with more arid climate records in other parts of the Mediterranean at that time (Bar-Matthews et al., 2003; Wick et al., 2003; Migowski et al., 2006; Bartov et al., 2007).

Stage C (2300 to 750 cal yr BP)

A gradual increase in $\delta^{18}O_{CaCO3}$ during this stage indicates a gradual transition over a period of up to 1000 yr from early wetter conditions (loosely referred to as Stage C1 hereafter) to later dry conditions (Stage C2). The driest time within stage C occurred around ~1200–900 cal yr BP (high values of wt. % $CaCO_3$, $\delta^{18}O$ and $\delta^{13}C$ at this time are similar to dry Stage A), which overlapped with the Medieval Climate Anomaly (1000–700 cal yr BP). Other climate reconstructions and regional climate summaries also consistently show relatively humid conditions early during this stage and a transition to arid conditions in the later portion (Bar-Matthews et al., 2003; Dubowski et al., 2003; Orland et al., 2009; Rambeau, 2010).

Archeological and historical records document relative political stability during the earlier portion this stage (the Hellenistic and Roman/Byzantine periods), and human population reached a pre-modern maximum in the southern Levant (ca. 1 million; Broshi and Finkelstein, 1992; Fig. 4). Around the Kinneret, the Golan Heights and the Dead Sea, this time is characterized by intensive agricultural activity (high levels of olive, grape and walnut pollen occur), and low levels of oak pollen suggest forest was cut and/or burned (Baruch, 1986, 1990; Schwab et al., 2004; Neumann et al., 2007; Litt et al., 2012). Archeological records document mining and ore processing in the area, which likely involved timber consumption and charcoal production for extraction and processing of metals (Neumann et al., 2007); this could have directly contributed charcoal and BC to Lake Kinneret.

Around 1400 cal yr BP, a widely documented decline in population and agriculture occurred in the southern Levant due to political changes (transition from the Byzantine to the Early Islamic period); these political and ecologic changes are believed to have been related to aridification (Rosen, 2007; Orland et al., 2009; Rambeau, 2010; Litt et al., 2012). Pollen from Lake Kinneret and Lake Birkat Ram in the Golan Heights records a sharp decline in regional agriculture and an increase in native oak forest cover beginning ~1700 cal yr BP, which have been attributed to this political change (Fig. 4; Baruch, 1986, 1990; Schwab et al., 2004; Neumann et al., 2007).

High CHAR and moderate BC in the first portion of this stage (C1) are in agreement with high regional CHAR (Fig. 4), indicating high fire activity locally and regionally. Sharp declines in CHAR, BC and regional CHAR around 1800–1900 cal yr BP indicate reduced fire activity for the remainder of the stage (C2). Declines in agriculture and fire activity around 1700–1900 cal yr BP suggest that perhaps changes in population may have begun before 1400 cal yr BP, as suggested by Neumann et al. (2007).

Stage C documents the impact of changing human activity in this region on fire activity. Early in Stage C (C1), high population, agriculture and industry, reduced forest cover, and moderate precipitation coincided with high fire activity, suggesting that the high fire activity was primarily driven by intensive agriculture and industrial activity and was less impacted by climate (though increased fuel availability is also possible). Later in Stage C (C2), a decrease in human activity (indicated by low population, limited agriculture and industry, and increased forest cover) was likely the cause of the low fire activity, as arid conditions and moderate to high proportions of woody fuel were likely otherwise favorable for fires.

Stage D (750 cal yr BP–present)

This stage, which includes the Little Ice Age (550–250 cal yr BP), was likely the wettest in our record. Low carbonate and organic matter content and low carbonate stable isotope values imply a dilution of authigenic sediment by Jordan River sediment, increased precipitation and runoff in the Kinneret basin, and/or lower temperatures. Speleothem-based calculations of paleoprecipitation for the eastern Mediterranean show that recent centuries represent one of the wettest and coolest period of the past 7.5 ka (Bar-Matthews et al., 2003), and Dead Sea and Lake Kinneret lake levels show highstands in this time (Hazan et al., 2005; Migowski et al., 2006; Bartov et al., 2007). Records of $\delta^{18}O$ from Lake Kinneret (Dubowski et al., 2003) and pollen-based Dead Sea climate reconstructions (Litt et al., 2012) also characterize this time as wet and cool.

During most of Stage D, (the Ottoman and Mandate periods), local population was low (Fig. 4; Broshi and Finkelstein, 1992), and large population losses occurred regionally due to the Black Plague (~600 cal yr BP). Palynological studies (Fig. 4) show that little agricultural activity occurred in the southern Levant during this time, and arboreal pollen was moderate to low (Baruch, 1986, 1990; Schwab et al., 2004; Neumann et al., 2007; Litt et al., 2012). Only in the past ~150 yr have population, agricultural activity and forest clearing increased rapidly, but low age resolution prevents detailed comparison with historical and/or archeological records (e.g., the first sampling interval of 5 cm represents ~100 yr).

Low CHAR and BC accumulation rates in this stage indicate low fire activity, which is also observed in the regional CHAR compilation (Fig. 4). Humid conditions and limited human-induced fire activity likely both contributed to low biomass burning during this stage.

Controls on fire activity

Our record shows that both climate and human activity caused changes in biomass burning. We note that human activity in the Mediterranean region was itself likely related to climate changes (Horowitz, 1979; Roberts et al., 2011), and thus climate may have both directly and indirectly (through climate-related changes in population) affected fire activity, but addressing potential indirect effects of climate is beyond the scope of this study.

We find low positive correlation between $\delta^{18}O_{CaCO3}$ and CHAR ($r^2 = 0.13$; $p < 0.01$) and $\delta^{18}O_{CaCO3}$ and BC accumulation ($r^2 = 0.16$; $p < 0.01$) for the cumulative record (Table 2). To explore

Table 2
Correlation of fire proxies with $\delta^{18}O$ and with each other.

Stage (designation)	r^2, CHAR	p value	r^2, BC accum.	p value	r^2, CHAR & BC	p value	n
All	0.13	($p < 0.01$)	0.16	($p < 0.01$)	0.32	($p < 0.01$)	54
Wet (B, D)	0.43	($p < 0.01$)	0.21	($p = 0.07$)	0.46	($p < 0.01$)	17
Dry (A, C1&C2)	0.01	($p >> 0.05$)	0.02	($p >> 0.05$)	0.22	($p < 0.01$)	37

whether the effect of climate on fire differs between wet and dry stages, we assess the correlation of $\delta^{18}O_{CaCO3}$ with BC and CHAR when our data are separated into wet (B, D) and dry stages (A, C1, C2). Moderate correlation of $\delta^{18}O_{CaCO3}$ with CHAR ($r^2 = 0.43$; $p < 0.01$) and BC ($r^2 = 0.21$; $p = 0.07$) during the two wet stages of our record (Table 2) suggests that during wet climate periods, climate exerted greater control on fire activity, as wet conditions likely suppressed fire during times of both high and low human activity. Conversely, lack of correlation of $\delta^{18}O_{CaCO3}$ with CHAR ($r^2 = 0.01$; $p >> 0.05$) and BC ($r^2 = 0.02$; $p >> 0.05$) during drier stages implies that during stages of low to moderate precipitation, climate was not the primary control on fire activity; instead, the inferred increases in fire activity were likely triggered by increased human activity.

To investigate the relationship between human activity and fire activity, we must rely on qualitative comparison of fire proxies with proxies for human activity (population, pollen and archeological records) because high-resolution records of human activity are not available. We assume that periods during which fire and climate proxies are not correlated (Stages A, C1, C2) have a different primary control on biomass burning, likely human activity. When we assess periods of increasing or high human activity (Stages A, B, C1), we find these were periods of high fire activity except during wet conditions (Stage B). Conversely, periods of low human activity (Stage C2, D) coincided with times of low fire activity during both wet and dry climates. This suggests that human activity imposed greater control than climate on biomass burning in the Kinneret region except during periods of high precipitation, when wet conditions likely suppressed biomass burning.

Other studies of paleo-fire in the Mediterranean similarly observed a change from climate-dominated fire regimes to human-dominated fire regimes occurring in the late Holocene at ~3–4 ka (Wick et al., 2003; Turner et al., 2008, 2010; Roberts et al., 2011; Vanniere et al., 2011). However, it is worth noting that the seasonal timing of increased moisture and its effects on fuel availability cannot be distinguished with our data. For example, while wetter summers would have suppressed fire activity, wetter conditions in winter, spring or fall in conjunction with dry summers could have increased fire activity by increasing biomass and thus fuel availability.

Climate and human activity in our record were apparently reinforcing or antagonistic in their effects on fire activity. The highest fire activity occurred when both climate was arid and human activity increased rapidly (Stage A), while the lowest fire activity occurred during a stage of wet climate and low human activity (Stage D), implying that these two controls reinforce one another when they are synchronized.

Sedimentation rate variations

High sedimentation rates early in the record may have been caused by increased erosion due to the widespread forest clearing, agriculture, and often high fire occurrence, while in the younger period, decreased human activity and fire activity and often greater forest cover may have slowed erosion and sedimentation. Dusar et al. (2011) also describe the highest sedimentation rates in the eastern Mediterranean between ~3100–2300 yr ago due to extensive forest clearing, grazing, agriculture and arboriculture.

Fire proxies in a large lake

This study can shed light on how well-suited this large lake is for studying past fire history, and how CHAR and BC records in this lake compare.

To determine the degree to which variations in the CHAR record are independent of sedimentation rate (e.g., external fluvial input) in this large lake, we assess the CHAR record over periods of steady sedimentation and over times of large sedimentation rate change. Large fluctuations in CHAR during periods of steady sedimentation, such as the time spanning Stages B-C1, and Stages C2-D (Fig. 3), indicate that sedimentation rate was not the primary driver of fluctuations in CHAR during these intervals. For example, low CHAR during Stage B, a period of rapid sedimentation, demonstrates that high sediment accumulation does not necessarily result in high CHAR accumulation. A decrease in CHAR around 1750 cal yr BP is similar to sedimentation rate changes around 1900 cal yr BP, but CHAR from the regional compilation (Fig. 4) shows a similar decrease at approximately the same time, suggesting that a true decrease in fire activity occurred around this time.

A comparison of the Lake Kinneret CHAR record with the regional compilation of CHAR records shows similar trends (higher values occur in both before ~1750 cal yr BP, and lower values occur after ~1750 cal yr BP). Some peaks are offset slightly between the two records, which might be explained both by differences in the age models and in the spatiotemporal distribution of fires. The similarity of these records, however, and the fluctuations in CHAR that are largely consistent with known changes in human activity and climate (and occur during periods of steady sedimentation) suggest that, despite the large size of the lake, Lake Kinneret's CHAR is not significantly affected by variations in river flux, and is a suitable indicator of regional biomass burning.

Comparison of CHAR and BC accumulation data over the entire record shows moderate positive correlation between the two fire proxies ($r^2 = 0.32$; $p < 0.01$; Table 2), consistent with similar comparisons from a large lake in China (Han et al., 2012). Such findings imply that CHAR and BC share some of the same controls (primarily human activity and climate), and that there is some overlap in the spatial scales they represent.

Conclusions

Analysis of charcoal, black carbon and climate proxies from Lake Kinneret provides a 3070-yr record of regional-scale fire activity and its controls, which helps address significant gaps in the fire history of the eastern Mediterranean. Fire activity in the Kinneret region, similar to other Mediterranean landscapes, is particularly sensitive to changes in human impact and moisture: fire activity in the past 3070 yr was highest during periods of large population (and significant agricultural/industrial activity) and low to moderate precipitation. Conversely, the lowest fire activity occurred during periods of reduced human activity and/or increased precipitation. Fire activity showed a decreasing trend during the past 3070 yr, with predominantly high fire activity before ~1750 cal yr BP, and low fire activity during both arid and humid stages since 1750 cal yr BP. This long-term decline in fire frequency over the study period is likely the result of a transition from high human impact on the landscape between 3070 and 1750 cal yr BP to lower population or sometimes wetter climate since 1750 cal yr BP, and is in agreement with similar declines observed at other eastern Mediterranean sites during the late Holocene (Vanniere et al., 2011) and a compilation of regional CHAR records (Daniau et al., 2012). Charcoal accumulation in this lake appears to be not significantly affected by variations in river flux, but primarily by changes in biomass burning. This record, combined with the high population density in the region today and projections of future aridification and warming, implies that future increases in fire activity are a real possibility, and fire prevention precautions will be of increasing importance.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.yqres.2013.06.012.

Acknowledgments

This research was supported by NSF-P2C2 0902218 to A.P., a grant from UCSC's CDELSI, and a University of California Cota Robles fellowship to N.Q.K. We thank Jonathan La Riviere, Kelsey Dyez and Ana Christina Ravelo for constructive discussion and suggestions to improve the article, Dyke Andreasen for assistance in implementing the black carbon method, and Paula Zermeno and Tom Guilderson of Lawrence Livermore National Laboratory for guidance in preparing radiocarbon samples. The final version of the manuscript benefited for constructive comments of two anonymous reviewers and editor A. Gillespie.

References

Bar-Matthews, M., Ayalon, A., Kaufman, A., 1997. Late Quaternary paleoclimate in the Eastern Mediterranean Region from stable isotope analysis of speleothems at Soreq Cave, Israel. Quaternary Research 47, 155–168. http://dx.doi.org/10.1006/qres.1997.1883 (http://linkinghub.elsevier.com/retrieve/pii/S0033589497918834).

Bar-Matthews, M., Ayalon, A., Gilmour, M., Matthews, A., Hawkesworth, C.J., 2003. Sea–land oxygen isotopic relationships from planktonic foraminifera and speleothems in the Eastern Mediterranean region and their implication for paleorainfall during interglacial intervals. Geochimica et Cosmochimica Acta 67, 3181–3199. http://dx.doi.org/10.1016/S0016-7037(02)01031-1 (http://linkinghub.elsevier.com/retrieve/pii/S0016703702010311).

Bartov, Y., Enzel, Y., Porat, N., Stein, M., 2007. Evolution of the Late Pleistocene Holocene Dead Sea Basin from Sequence Statigraphy of Fan Deltas and Lake-Level Reconstruction. Journal of Sedimentary Research 77, 680–692. http://dx.doi.org/10.2110/jsr.2007.070 (http://jsedres.sepmonline.org/cgi/doi/10.2110/jsr.2007.070).

Baruch, U., 1986. The Late Holocene Vegetational History of Lake Kinneret (Sea of Galilee), Israel. Paléorient 12, 37–48.

Baruch, U., 1990. Palynological evidence of human impact on the vegetation as recorded in Late Holocene lake sediments in Israel. In: Bottema, Entjes-Nieborg, Zeist, V. (Eds.), Man's Role in the Shaping of the Eastern Mediterranean Landscape. Balkema, pp. 283–293.

Broshi, M., Finkelstein, I., 1992. The population of Palestine in Iron Age II. Bulletin of the American Schools of Oriental Research 47–60.

Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A.F., Krebs, P., 2009. Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. Quaternary Science Reviews Elsevier Ltd 28, 555–576.

Daniau, A.-L., Bartlein, P.J., Harrison, S.P., Prentice, I.C., Brewer, S., et al., 2012. Predictability of biomass burning in response to climate changes. Global Biogeochemical Cycles 26. http://dx.doi.org/10.1029/2011GB004249 (n/a–n/a, http://doi.wiley.com/10.1029/2011GB004249).

Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus 16, 438–468.

Develle, A.-L., Herreros, J., Vidal, L., Sursock, A., Gasse, F., 2010. Controlling factors on a paleo-lake oxygen isotope record (Yammoûneh, Lebanon) since the Last Glacial Maximum. Quaternary Science Reviews 29, 865–886. http://dx.doi.org/10.1016/j.quascirev.2009.12.005 (http://linkinghub.elsevier.com/retrieve/pii/S0277379109004181).

Dubowski, Y., Geifman, Y., Stiller, M., 2003. Isotopic paleolimnology of Lake Kinneret. Limnology and Oceanography 48, 68–78. http://dx.doi.org/10.4319/lo.2003.48.1.0068 (http://www.aslo.org/lo/toc/vol_48/issue_1/0068.html).

Dusar, B., Verstraeten, G., Notebaert, B., Bakker, J., 2011. Earth-Science Reviews Holocene environmental change and its impact on sediment dynamics in the Eastern Mediterranean. Earth Science Reviews Elsevier B.V. 108, 137–157. http://dx.doi.org/10.1016/j.earscirev.2011.06.006 (http://dx.doi.org/10.1016/j.earscirev.2011.06.006).

Faegri, K., Iversen, J., 1989. Textbook of Pollen Analysis. John Wiley & Sons, New York (328 pp.).

Gustafsson, Ö., Haghseta, F., Chan, C., MacFarlane, J., Gschwend, P.M., 1997. Quantification of the Dilute Sedimentary Soot Phase: Implications for PAH Speciation and Bioavailability. Environmental Science & Technology 31, 203–209. http://dx.doi.org/10.1021/es960317s (http://pubs.acs.org/doi/abs/10.1021/es960317s).

Gustafsson, Ö., Bucheli, T.D., Kukulska, Z., Andersson, M., Largeau, C., Rouzaud, J.-N., Reddy, C.M., Eglinton, T.I., 2001. Evaluation of a protocol for the quantification of black carbon in sediments. Global Biogeochemical Cycles 15, 881–890.

Hammes, K., Schmidt, M.W.I., Smernik, R.J., Currie, L. a, Ball, W.P., Nguyen, T.H., Louchouarn, P., Houel, S., Gustafsson, Ö., Elmquist, M., Cornelissen, G., Skjemstad, J.O., Masiello, C.A., Song, J., Peng, P., Mitra, S., Dunn, J.C., Hatcher, P.G., Hockaday, W.C., Smith, D.M., Hartkopf-Fröder, C., Böhmer, A., Lüer, B., Huebert, B.J., Amelung, W., Brodowski, S., Huang, L., Zhang, W., Gschwend, P.M., Flores-Cervantes, D.X., Largeau, C., Rouzaud, J.-N., Rumpel, C., Guggenberger, G., Kaiser, K., Rodionov, A., Gonzalez-Vila, F.J., Gonzalez-Perez, J. a, De la Rosa, J.M., Manning, D.a.C., López-Capél, E., Ding, L., 2007. Comparison of quantification methods to measure fire-derived (black/elemental) carbon in soils and sediments using reference materials from soil, water, sediment and the atmosphere. Global Biogeochemical Cycles 21. http://dx.doi.org/10.1029/2006GB002914 (http://www.agu.org/pubs/crossref/2007/2006GB002914.shtml).

Han, Y.M., Marlon, J.R., Cao, J.J., Jin, Z.D., An, Z.S., 2012. Holocene linkages between char, soot, biomass burning and climate from Lake Daihai, China. Global Biogeochemical Cycles 26 (4). http://dx.doi.org/10.1029/2011GB004197 (p. n/a–n/a).

Hazan, N., Stein, M., Agnon, A., Marco, S., Nadel, D., Negendank, J., Schwab, M.J., Neev, D., 2005. The late Quaternary limnological history of Lake Kinneret (Sea of Galilee), Israel. Quaternary Research 63, 60–77. http://dx.doi.org/10.1016/j.yqres.2004.09.004 (http://linkinghub.elsevier.com/retrieve/pii/S0033589404001103).

Higuera, P., 2009. CharAnalysis 0. 9: Diagnostic and Analytical Tools for Sediment-Charcoal, Analysis. 1–27.

Horowitz, A., 1979. The Quaternary of Israel. Academic Press, New York, 394 pp.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

Kitagawa, H., Tareq, S., Matsuzaki, H., Inoue, N., Tanoue, E., Yasuda, Y., 2007. Radiocarbon concentration of lake sediment cellulose from Lake Erhai in southwest China. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 259, 526–529. http://dx.doi.org/10.1016/j.nimb.2007.01.195 (http://linkinghub.elsevier.com/retrieve/pii/S0168583X07002947).

Litt, T., Ohlwein, C., Neumann, F.H., Hense, A., Stein, M., 2012. Holocene climate variability in the Levant from the Dead Sea pollen record. Quaternary Science Reviews Elsevier Ltd 49, 95–105. http://dx.doi.org/10.1016/j.quascirev.2012.06.012 (http://linkinghub.elsevier.com/retrieve/pii/S0277379112002430).

Lozano-García, S., Sosa-Nájera, S., Sugiura, Y., Caballero, M., 2005. 23,000 yr of vegetation history of the Upper Lerma, a tropical high-altitude basin in Central Mexico. Quaternary Research 64, 70–82. http://dx.doi.org/10.1016/j.yqres.2005.02.010 (http://linkinghub.elsevier.com/retrieve/pii/S0033589405000360).

Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., Ni, F., 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. Science (New York, N.Y.) 326 (5957), 1256–1260. http://dx.doi.org/10.1126/science.1177303.

Masiello, C.A., 2004. New directions in black carbon organic geochemistry. Marine Chemistry 92, 201–213. http://dx.doi.org/10.1016/j.marchem.2004.06.043 (http://linkinghub.elsevier.com/retrieve/pii/S0304420304002051).

Migowski, C., Stein, M., Prasad, S., Negendank, J., Agnon, a, 2006. Holocene climate variability and cultural evolution in the Near East from the Dead Sea sedimentary record. Quaternary Research 66, 421–431. http://dx.doi.org/10.1016/j.yqres.2006.06.010 (http://linkinghub.elsevier.com/retrieve/pii/S0033589406000925).

Millspaugh, S.H., Whitlock, C., 1995. A 750-year fire history based on lake sediment records in central Yellowstone National Park, USA. The Holocene 5, 283–292. http://dx.doi.org/10.1177/095968369500500303 (http://hol.sagepub.com/cgi/doi/10.1177/095968369500500303).

Moriondo, M., Good, P., Durao, R., Bindi, M., Giannakopoulos, C., Corte-Real, J., 2006. Potential impact of climate change on fire risk in the Mediterranean area. Climate Research 31, 85–95. http://dx.doi.org/10.3354/cr031085 (http://www.int-res.com/abstracts/cr/v31/n1/p85-95/).

Neumann, F.H., Schölzel, C., Litt, T., Hense, A., Stein, M., 2007. Holocene vegetation and climate history of the northern Golan heights (Near East). Vegetation History and Archaeobotany 16, 329–346. http://dx.doi.org/10.1007/s00334-006-0046-x (http://www.springerlink.com/index/10.1007/s00334-006-0046-x).

Nguyen, T.H., 2004. An evaluation of thermal resistance as a measure of black carbon content in diesel soot, wood char, and sediment. Organic Geochemistry 35, 217–234. http://dx.doi.org/10.1016/j.orggeochem.2003.09.005 (http://linkinghub.elsevier.com/retrieve/pii/S0146638003002171).

Orland, I., Bar-Matthews, M., Kita, N., Ayalon, A., Matthews, A., Valley, J., 2009. Climate deterioration in the Eastern Mediterranean as revealed by ion microprobe analysis of a speleothem that grew from 2.2 to 0.9 ka in Soreq Cave, Israel. Quaternary Research University of Washington 71, 27–35. http://dx.doi.org/10.1016/j.yqres.2008.08.005 (http://linkinghub.elsevier.com/retrieve/pii/S0033589408001099).

Paillard, D., Labeyrie, L., Yiou, P., 1996. Macintosh program performs time-series analysis. EOS Transactions of the American Geophysical Union 77, 379.

Pausas, J.G., Fernandez-Muñoz, S., 2012. Fire regime changes in the Western Mediterranean Basin: from Fuel-limited to drought-driven fire regime. Climatic Change 110 (1–2), 215–226.

Power, M.J., Marlon, J.R., Bartlein, P.J., Harrison, S.P., 2010. Fire history and the Global Charcoal Database: a new tool for hypothesis testing and data exploration. Palaeogeography, Palaeoclimatology, Palaeoecology 291 (1–2), 52–59. http://dx.doi.org/10.1016/j.palaeo.2009.09.014.

Rambeau, C.M.C., 2010. Palaeoenvironmental reconstruction in the Southern Levant: synthesis, challenges, recent developments and perspectives. Mathematical, Physical, and Engineering Sciences 368, 5225–5248. http://dx.doi.org/10.1098/rsta.2010.0190 (http://www.ncbi.nlm.nih.gov/pubmed/20956369).

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., Van der Pflicht, J., Weyhenmeyer, C.E., 2004. IntCal04 terrestrial radiocarbon age calibration, 0–26 Cal Kyr BP. Radiocarbon 46, 1029–1058.

Roberts, N., Eastwood, W.J., Kuzucuoglu, C., Fiorentino, G., Caracuta, V., 2011. Climatic, vegetation and cultural change in the eastern Mediterranean during the mid-Holocene environmental transition. The Holocene 21, 147–162. http://dx.doi.org/10.1177/0959683610386819 (http://hol.sagepub.com/cgi/doi/10.1177/0959683610386819).

Rosen, A.M., 2007. Civilizing Climate: Social Responses to Climate Change in the Ancient Near East. AltaMira Press, Lanham, MD.

Rozanski, K., Araguas-Araguas, L., Gonfiantini, R., 1993. Isotopic patterns in modern global precipitation. Climate Change in Continental Isotopic Records. Geophysical Monograph 78. American Geophysical Union, Washington, DC, pp. 1–36.

Schwab, M.J., Neumann, F.H., Litt, T., Negendank, J., Stein, M., 2004. Holocene palaeoecology of the Golan Heights (Near East): investigation of lacustrine sediments from Birkat Ram crater lake. Quaternary Science Reviews 23, 1723–1731. http://dx.doi.org/10.1016/j.quascirev.2004.05.001 (http://linkinghub.elsevier.com/retrieve/pii/S0277379104001258).

Singer, a, Gal, M., Banin, a, 1972. Clay minerals in recent sediments of lake Kinneret (Tiberias), Israel. Sedimentary Geology 8, 289–308. http://dx.doi.org/10.1016/0037-0738(72)90045-0 (http://linkinghub.elsevier.com/retrieve/pii/0037073872900450).

Singh, G., Geissler, E.A., 1985. Lake Cainozoic history of vegetation, fire, lake levels and climate, at Lake George, New South Wales, Australia. Philosophical Transactions of the Royal Society of London 311, 379–447.

Stiller, M., Kaufman, A., 1985. Paleoclimatic trends revealed by the isotopic composition of carbonates in Lake Kinneret. Zeitschrift fuer Gletscherkunde 21, 79–87.

Stuiver, M., Reimer, P., 1993. Extended 14C database and revised CALIB 3.0 14C age calibration program. Radiocarbon 35, 215–230.

Sugita, S., 1993. A model of pollen source area for an entire lake surface. Quaternary Research 39, 239–244.

Thevenon, F., Anselmetti, F.S., 2007. Charcoal and fly-ash particles from Lake Lucerne sediments (Central Switzerland) characterized by image analysis: anthropologic, stratigraphic and environmental implications. Quaternary Science Reviews 26, 2631–2643. http://dx.doi.org/10.1016/j.quascirev.2007.05.007.

Thevenon, F., Williamson, D., Bard, E., Anselmetti, F.S., Beaufort, L., Cachier, H., 2010. Combining charcoal and elemental black carbon analysis in sedimentary archives: Implications for past fire regimes, the pyrogenic carbon cycle, and the human–climate interactions. Global and Planetary Change 72 (4), 381–389. http://dx.doi.org/10.1016/j.gloplacha.2010.01.014.

Turner, R., Roberts, N., Jones, M.D., 2008. Climatic pacing of Mediterranean fire histories from lake sedimentary microcharcoal. Global and Planetary Change 63, 317–324. http://dx.doi.org/10.1016/j.gloplacha.2008.07.002 (http://linkinghub.elsevier.com/retrieve/pii/S0921818108000787).

Turner, R., Roberts, N., Eastwood, W.J., Jenkins, E., Rosen, A., 2010. Fire, climate and the origins of agriculture: micro-charcoal records of biomass burning during the last glacial–interglacial transition in Southwest Asia. Journal of Quaternary Science 25, 371–386. http://dx.doi.org/10.1002/jqs.

Vanniere, B., Power, M.J., Roberts, N., Tinner, W., Carrion, J., Magny, M., Bartlein, P., Colombaroli, D., Daniau, A.-L., Finsinger, W., Gil-Romera, G., Kaltenrieder, P., Pini, R., Sadori, L., Turner, R., Valsecchi, V., Vescovi, E., 2011. Circum-Mediterranean fire activity and climate changes during the mid-Holocene environmental transition (8500–2500 cal. BP). The Holocene 21, 53–73. http://dx.doi.org/10.1177/0959683610384164 (http://hol.sagepub.com/cgi/doi/10.1177/0959683610384164).

Whitlock, C., Anderson, R.S., 2003. Fire history reconstructions based on sediment records from lakes and wetlands. In: Veblen, T.T., Baker, W.L., Montenegro, G., Swetnam, T.W., Whitlock, C., Anderson, R.S. (Eds.), Fire and Climatic Change in Temperate Ecosystems of the Western Americas. Springer, New York, pp. 3–31.

Whitlock, C., Larsen, C., 2001. Charcoal as a fire proxy. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal, and Siliceous Indicators. KluwerAcademic Publishers, pp. 1–23.

Wick, L., Lemcke, G., Sturm, M., 2003. Evidence of Lateglacial and Holocene climatic change and human impact in eastern Anatolia: high-resolution pollen, charcoal, isotopic and geochemical records from the laminated sediments of Lake Van, Turkey. The Holocene 13, 665–675. http://dx.doi.org/10.1191/0959683603hl653rp (http://hol.sagepub.com/cgi/doi/10.1191/0959683603hl653rp).

Yasuda, Y., Kitagawa, H., Nakagawa, T., 2000. The earliest record of major anthropogenic deforestation in the Ghab Valley, northwest Syria: a palynological study. Quaternary International 73-74, 127–136. http://dx.doi.org/10.1016/S1040-6182(00)00069-0 (http://linkinghub.elsevier.com/retrieve/pii/S1040618200000690).

Zohary, M., 1973. Geobotanical Foundations of the Middle East, vol. 2. Gustav Fischer Verlag, Stuttgart.