
ELSEVIER
QUATERNARY
SCIENCE REVIEWS
The International Multidisciplinary Research and Review Journal

Quaternary Science Reviews 59 (2013) 18–29

Contents lists available at SciVerse ScienceDirect

Quaternary Science Reviews

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

Holocene changes in fire frequency in the Daihai Lake region (north-central China): indications and implications for an important role of human activity

Xu Wang*, Jule Xiao, Linlin Cui, Zhongli Ding

Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, China

ARTICLE INFO

Article history:
Received 21 March 2012
Received in revised form
23 October 2012
Accepted 29 October 2012
Available online

Keywords:
Fire history
Climate change
Black carbon
Vegetation
Human activity
Holocene

ABSTRACT

Black carbon (BC) content in a sediment core from Daihai Lake, Inner Mongolia, was analyzed to reconstruct a high-resolution history of fires occurring in northern China during the Holocene and to examine the impacts of natural changes and human activities on the fire regime. The black carbon mass sedimentation rate (BCMSR) was disintegrated into two components: the background BCMSR and the BCMSR peak, with the BCMSR peak representing the frequency of fire episodes. Both the background BCMSR and the magnitude of the BCMSR peak display a close relation with the percentage of tree pollen from the same sediment core, suggesting that regional vegetation type would be a factor controlling the intensity of fires. The inferred fire-episode frequency for the Holocene exhibits two phases of obvious increases, i.e., the first increase from <5 to ~10 episodes/1000 yrs occurring at 8200 cal. yrs BP when the vegetation of the lake basin shifted from grasses to forests and the climate changed from warm/dry to warm/humid condition, and the further increase to a maximum frequency of 13 episodes/1000 yrs occurring at 2800 cal. yrs BP when herbs and shrubs replaced the forests in the lake basin and the climate became cool/dry. Both increases in the fire frequency contradict the previous interpretation that fires occurred frequently in the monsoon region of northern China when steppe developed under the cold/dry climate. We thus suggest that human activities would be responsible for the increased frequencies of fires in the Daihai Lake region in terms that the appearance of early agriculture and the expansion of human land use were considered to take place in northern China at ca 8000 and 3000 cal. yrs BP, respectively.

1. Introduction

Fire is one of the most important components of the Earth's ecological system that is tightly coupled with climate, vegetation and human activities (Harrison et al., 2010). Fire plays a significant role in maintaining the ecosystem and regulating climate change. For example, fires can affect the vegetation succession (Bond et al., 2003, 2005; Franklin et al., 2005) and surface albedo to a large extent (Jin and Roy, 2005; Lyons et al., 2008; Bowman et al., 2009), which could ultimately influence climate change. However, climate changes may also modulate vegetation succession and fire frequency and/or intensity (Clark, 1988a; Kitzberger et al., 1997). Recently, fires of high intensity have occurred frequently in some regions and have been linked to anthropogenic climate change (Westerling et al., 2006). The natural fire regime is being increasingly influenced by human activities (Harrison et al., 2010). In some parts of the world, people who use fire extensively for land clearance and the maintenance of pasture and agricultural lands are estimated to cause over 80% of all fires (FAO, 2007). Human-caused ignitions can increase fire frequency beyond the range of natural variability, thereby altering the species composition and decreasing the soil fertility (Tilman and Lehman, 2001; Syphard et al., 2009).

Although changing climate and human activities have both contributed to the observed changes in fires in some regions, the role of humans as a driving force of fires is still not well understood. Thus, it deserves further study in a diversity of environments, particularly in the Asian monsoonal region of China, where ancient civilization has a long recorded history (at least 5000 yrs). This will provide a more complete understanding of human impact on the fire regimes among different regions over time (Syphard et al., 2009). To date, several studies have linked a shift in fire regimes at individual sites and generalized regions to human activities (Syphard et al., 2007; Marlon et al., 2008; Vannière et al., 2008; Pechony and Shindell, 2010). Nevertheless, the lack of empirical data on the long-term linkage between climate changes, human activities and fire history, particularly in northern China, limits our

* Corresponding author. Tel.: +86 10 8299 8379; fax: +86 10 6201 0846.
E-mail addresses: xuking@mail.iggcas.ac.cn, xukingw@163.com (X. Wang).

0277-3791/$ – see front matter
http://dx.doi.org/10.1016/j.quascirev.2012.10.033

ability to obtain integrated information regarding climate–human–fire relationships in the past and how this information might be useful for projecting future fire activity.

Fire history can be reconstructed by compiling historical records, such as fire atlases (Rollins et al., 2001), the analysis of dendrochronological data, such as fire-scarred trees and stand-ages (Grissino-Mayer and Swetnam, 2000), and the analysis of charcoal particles in lake-sediment cores (Carcaillet et al., 2001; Whitlock and Larsen, 2001). However, the first two methods are limited by both source availability and a short time span (Brunelle and Whitlock, 2003). Conversely, the charcoal and pollen records from lake-sediment cores provide information on the long-term variations in fire and vegetation composition and reveal the changes in fire frequency that might be linked to past shifts in climate and vegetation, as well as to human activities, if applicable. Nevertheless, there are some methodological challenges that need comprehensive study in multi-disciplinary fields to distinguish natural from anthropogenic fires. Bowman et al. (2011) proposed three important sets of information in distinguishing human burning reliably in the palaeoecological record: (1) the temporal or spatial changes in fire activity and vegetation apparent from palaeoecological proxies, (2) a demonstration that these changes are not predicted by climate–fuels–fire relationships and palaeoclimate reconstructions for the period of fire regime change, and (3) a demonstration that the fire regime changes coincide in space and time with changes in human history known from archaeology, anthropology and historical sources. According to these criteria, northern China may be an ideal region to study human biomass burning.

Recent studies of the fire history in northern China have mostly focused on the linkages between fires and climate changes on the orbital to millennial timescales (Yang et al., 2001; Wang et al., 2005, 2012; Zhou et al., 2007). By contrast, there are very few Holocene fire history reconstructions from this area, especially high-resolution multidisciplinary studies (Huang et al., 2006; Jiang et al., 2008; Li et al., 2009). Furthermore, little is known about the relationship between human activities and fire regimes in the region. For example, the potential influence of the establishment of agriculture in northern China during the Holocene (Kong et al., 2003), and how this may have influenced fire has not been considered. Such a study would provide a better context for examining the potential joint impacts of climate and human activities on the long-term fire regime changes.

Here, we present a detailed record of the fire history for the last 11.76 ka from lake sediment cores in the Daihai Lake region in north-central China. The sediment core in the Daihai Lake region was chosen because of the following: the climate and vegetation changes during the Holocene have been extensively studied in the Daihai Lake region (Xiao et al., 2004, 2006; Peng et al., 2005), and they can be used as a comparison for our reconstruction of biomass burning and fire activity; and human activities in the Daihai Lake region can be traced back to Neolithic times based on archaeological sites (Tian, 2000; Lian and Fang, 2001), which allow us to examine the impacts of human activities on the fire regimes through time.

In this study, we measured the black carbon content of the lake sediment to reconstruct the fire history using chemical oxidation pretreatment (Lim and Cachier, 1996). The term black carbon (BC) is used to describe a relatively inert and ubiquitous form of carbon, comprising a range of materials from char and charcoal to elemental or graphitic carbon produced by the incomplete combustion of fossil fuels and biomass (Goldberg, 1985; Schmidt and Noack, 2000). Due to its inertness, the BC signatures in geological deposits can be used as evidence of natural fires (Goldberg, 1985; Lim and Cachier, 1996; Schmidt and Noack, 2000). Although there is some evidence that BC degrades rapidly in soils (Bird et al., 1999; Hockaday et al., 2006), BC degradation in this lake should be far slower than in superficial mineral soils due to the anaerobic conditions at the bottom of this lake. The black carbon sedimentation rate (BCMSR) was employed as an indicator of paleofire occurrence for the following reasons: (1) to better understanding the relationships among fire, vegetation and climate on Holocene timescales; and (2) evaluating how the fire regime changed in the context of long-term human activities.

2. Settings, sampling and chronology

2.1. Site description

Daihai Lake (40°29′–40°37′N, 112°33′–112°46′E) lies 10 km east of Liangcheng County in the Inner Mongolia Autonomous Region in north-central China (Fig. 1). It has an area of 133.5 km^2, a maximum water depth of 16.1 m, a mean water depth of 7.4 m and an elevation of 1221 m a.s.l. (measurements in July 1986 by Wang et al. (1990b)).

Daihai Lake is located at the transition from semi-humid to semi-arid areas in the middle temperate zone of China (Fig. 1). The mean annual temperature is 5.1 °C, with a July average of 20.5 °C and a January average of −13.0 °C (Xiao et al., 2004). The mean annual precipitation is 423 mm, of which approximately 80% falls in June–September, with a peak mean rainfall of 122 mm in August. The mean annual evaporation reaches 1162 mm, which is 2.8 times the annual precipitation value. The lake is covered with approximately 60 cm of ice from November to March. In the lake region, the winter climate is controlled by the dry, cold northwesterly winter monsoon that brings cold winds and generates dust storms from late autumn to spring, whereas the summer climate is dominated by the warm, moist southeasterly summer monsoon that is responsible for most of the annual precipitation and rainstorms (Gao, 1962; Chinese Academy of Sciences, 1984; Zhang and Lin, 1992). At the present time, natural fires in the region mainly occur in the winter and spring seasons (from October to April) (Liu et al., 1999). The dry weather during this time causes more combustible fuel to buildup, and strong winds facilitate the desiccation of fuels and also aid the spread of fires over the landscape (Liu et al., 1999; Seying, 2002).

2.2. Coring and sampling of Daihai Lake sediments

Sediment core DH99a was extracted in the central part of Daihai Lake (Fig. 1) using a TOHO drilling system (Model D1-B) in the summer of 1999. DH99a was recovered at a water depth of 13.1 m to a sediment depth of 11.96 m, with a sediment recovery that approached 98.5%. The core sections were split, photographed and described on site. DH99a core sediments are composed of homogeneous silt and silty clay and can be divided into two parts: a greenish-gray to grayish-black upper part with burrows and a light to dark gray, laminated lower part.

The upper 11 m of the DH99a core was used for the present study. DH99a was sampled at 4-cm intervals to determine the black carbon contents. Eight bulk samples were collected for AMS radiocarbon dating from the organic-rich horizons of the DH99a core sediments.

2.3. Chronology of the Daihai Lake sediment core

Radiocarbon samples from DH99a core were dated using a HVEE Tandetron AMS-II system at the Center for Chronological Research, Nagoya University, Japan. The detailed methods for sample preparation and measurement are described in Xiao et al. (2004).

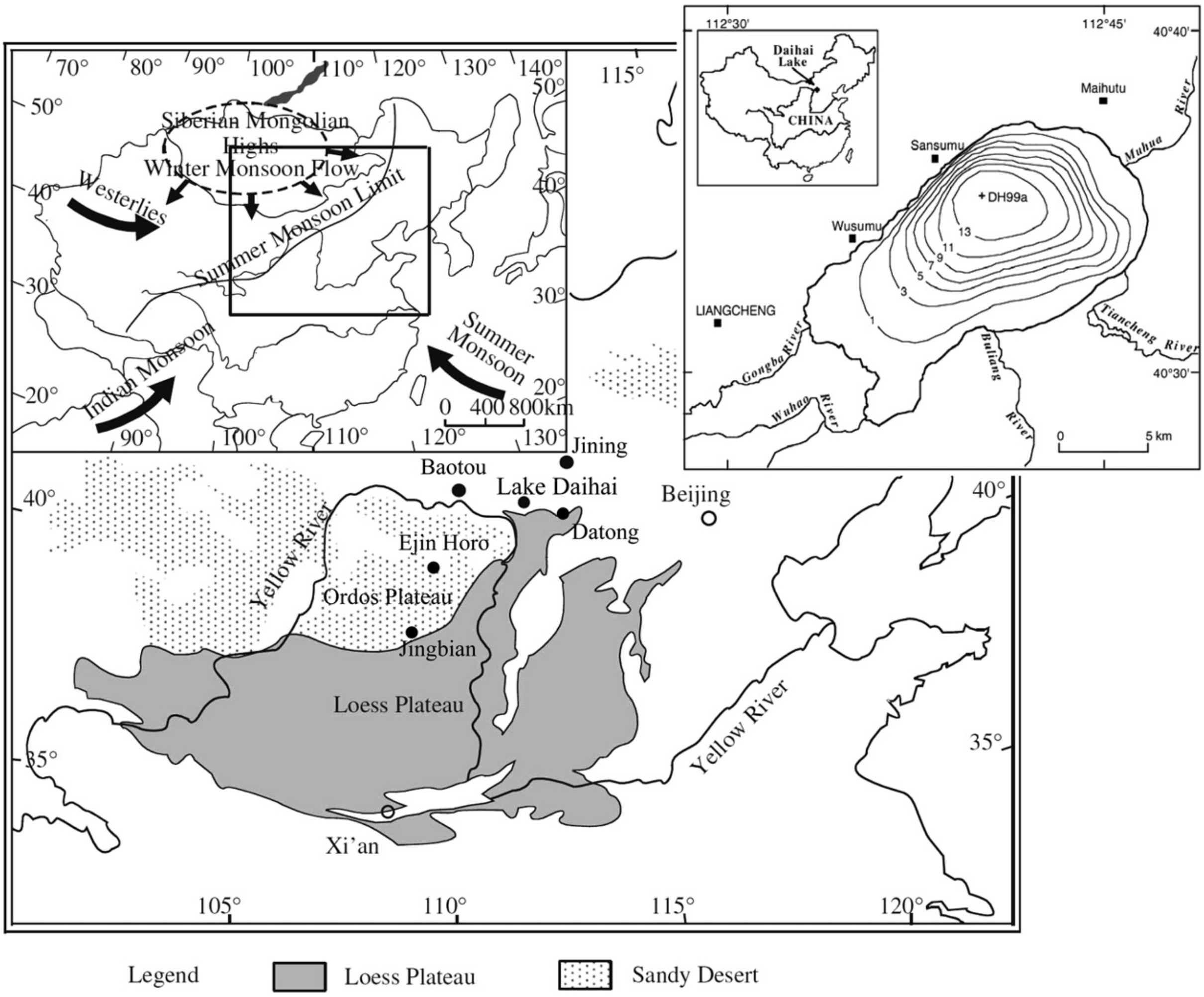

Fig. 1. The map of the study area, showing the monsoon/arid climate system of northern China, the location of Daihai Lake, the lake bathymetry and the sediment core site (modified after Gao, 1962; Chinese Academy of Sciences, 1984; Zhang and Lin, 1992; Xiao et al., 2004; Sun et al., 2009).

The ^{14}C ages of eight bulk samples from DH99a core were determined with a half-life of 5568 yrs (Fig. 2; Table 1). The conventional ages were converted to calibrated ages using CALIB 4 of the INTCAL98 radiocarbon age calibration program (Stuiver et al., 1998) (Fig. 2). The ages of the sampled horizons of the DH99a core were derived using linear interpolation between the radiocarbon-dated horizons.

AMS ^{14}C dates indicate that the Daihai Lake sediments reach a thickness of ca 11 m for the Holocene Epoch (Fig. 2; Table 1). As shown in Fig. 2, the age–depth curve of the upper 11 m of the DH99a sediment core displays a prominent inflection at ca 7500 cal. yrs BP, yielding an average sedimentation rate of ca 132 cm/ka for the segment since ca 7500 cal. yrs BP and ca 26 cm/ka for the period before that. The average sedimentation rates and a sampling interval of 4 cm provide potential temporal resolutions of ca 30 yrs for the last ca 7500 yrs and ca 154 yrs for the period before ca 7500 cal. yrs BP.

3. Materials and methods

In this study, we used the dichromate oxidation method developed by Lim and Cachier (1996) to extract the BC in the lake sediment samples. In brief, the carbonates and part of the silicates in the samples were removed by an acid treatment with HCl (3 mol/L) and HF (10 mol/L)/HCl (1 mol/L) in sequence. The treated samples were then oxidized using a solution of 0.1 mol/L $K_2Cr_2O_7$/2 mol/L H_2SO_4 at 55 °C for 60 h to remove the soluble organic matter and kerogen (Wang et al., 2001). After the treatment, the remaining refractory carbon in the residue was operationally defined as BC, including charcoal and atmospheric BC particles (Lim and Cachier, 1996). Recently, Knicker et al. (2007) argued that chemical oxidation methods are not unequivocal and may leave non-BC derived paraffinic structures and may also attack some types of charcoal. However, the oxidation time they used (4–6 h) is substantially shorter than ours, and the results are not comparable with the common approach we adopted in this study. In contrast, Song et al. (2002) have shown that paraffinic carbon only accounts for a much smaller fraction in the BC samples using the same dichromate oxidation process as ours. Conversely, our method may also attack certain types of charcoal due to the relatively long oxidation time. Therefore, the remaining refractory carbon in the residue only represents the oxidation-resistant part of BC, resulting in underestimations of BC contents in soils or sediments. However, this underestimation should not affect the usefulness of BC as a proxy for fires due to the high reproducibility of the BC contents in our chemical treatment procedure.

The content of BC in the residues was determined using a continuous-flow isotope ratio mass spectrometer (CF-IRMS). The CF-IRMS system consists of an EA (Flash 1112 series) coupled to a Finnigan MAT 253 mass spectrometer. The combustion

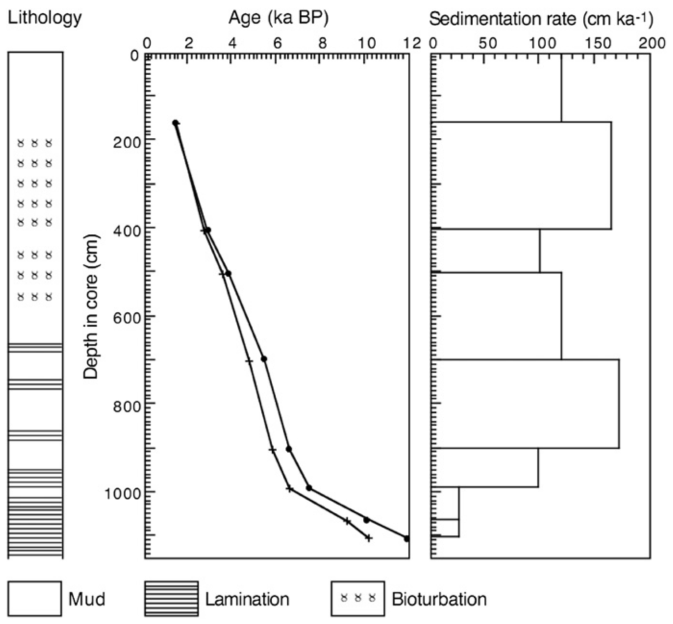

Fig. 2. The lithology, age–depth curve and sedimentation-rate histogram of the upper 11 m of the DH99a sediment core recovered in the central part of Daihai Lake. Crosses represent AMS radiocarbon datings, and solid circles represent calibrated radiocarbon ages. Sedimentation rates (cm ka^{-1}) were calculated between calibrated radiocarbon ages.

temperature was set at 960 °C, and the temperature of reduction tube was set at 680 °C. Standard samples with known carbon contents (glycine: $C_{wt}\% = 32\%$) were used to calibrate the measurement and to monitor the working conditions. The BC content was expressed as mg/g dry sediment. Sextuplicate determinations on one sample using the above chemical treatment procedure showed that the relative error was within 5.44% for the BC content.

4. Data and mathematical analysis

The original BC record was analyzed using the decomposition technique of Long et al. (1998). The BCMSR was calculated by multiplying the BC content (mg C/g dry sediment) by the dry bulk density (g/cm^3) and sedimentation rate (cm/yr). This BCMSR time series was then interpolated to pseudo-annual accumulation rates and binned in 30-yr time intervals. The 30-yr interval was selected because it generally represents the shortest deposition time in the Daihai Lake record at our sampling interval. This approach preserves the total amount of BC accumulated over time and allows for the presentation of the data at equally spaced time intervals (Long et al., 1998; Mohr et al., 2000). The BCMSR time series were logarithmically transformed for variance stabilization (log(BCMSR + 1)) before being decomposed into background and peak components (Charster software, D.G. Gavin, unpublished data, 2006). A locally weighted mean was used to estimate the background component of the BCMSR data. The peak components (or fire episode series) were derived as the positive deviations from a local mean that exceeded a certain threshold value. The background component is often ascribed to changes in regional fire incidence (Clark and Royall, 1995) and fuel abundance (Long et al., 1998; Whitlock et al., 2003), as well as to non-fire-related processes, such as masswasting and redeposition (e.g., from lake-level fluctuations; Lynch et al., 2004), sedimentation rates and bioturbation (Millspaugh and Whitlock, 1995; Carcaillet et al., 2002). By contrast, the peak components represent local fire events or episodes (i.e., more than one fire occurring during a given time interval). This interpretation is based on the assumption that fire events produce a large number of charcoal particles which exceed the delivery of charcoal from other processes (Clark, 1988b; Whitlock and Millspaugh, 1996; Ohlson and Tryterud, 2000). It is also assumed that the fires consumed enough biomass to produce enough charcoal to register a peak in the lake sediments. Small fires that produce only a little amount of charcoal are hard to detect (Whitlock et al., 2004). Here, all of the positive peaks were considered as signals reflecting discrete fire episodes. The peak data were smoothed to produce a summary of fire episodes over time (expressed as the number of episodes/1000 yrs). The peak magnitudes represent the total accumulation of BC for all samples of a peak exceeding the threshold value and may be related to the fire size, fire intensity, and/or charcoal delivery (Whitlock et al., 2006; Higuera et al., 2007).

To help decide the appropriate width of the temporal window for calculating the locally weighted mean (and, hence, the smoothness of the background component), different window widths were examined by visually comparing the resulting background component with the BCMSR time series. Window widths <300 yrs produced a background component which mimicked the peak component, while window widths >900 yrs generalized the background component and may have obscured some meaningful indication of regional fire activities or fire intensity at narrow/shorter timescales. Window widths between 300 and 900 yrs showed similar variations in the resulting background component, and an intermediate window width of 600 yrs was selected as optimal (Fig. 3a). A range of threshold ratios from 1.00 to 1.20 was evaluated concurrently to determine an appropriate value for identifying peaks with a 600-yr background window (Fig. 3b). The results show that the threshold ratios between 1.05 and 1.20 allow us to recognize the peak components with a roughly similar distribution over time (Fig. 3b). However, the threshold ratios of 1.10 and 1.20 identified fewer peak components and produced a long fire-free interval between ca 2000 and 3500 yrs BP (see arrow in Fig. 3b). It is difficult to determine the appropriate threshold ratio for identifying peaks because there are no independently known fire events in historical documents, nor is there

Table 1
AMS radiocarbon dates of samples from the upper 11 m of DH99a sediment core recovered in the central part of the Daihai Lake.

Laboratory number	Depth in core (cm)	Dating material	$\delta^{13}C$ (%)	AMS ^{14}C age (yr BP)	Calibrated ^{14}C ago (2σ) (cal. yr BP)
NUTA2-2954	160	Organic matter	−25.1	1434 ± 28	1385–1290
NUTA2-2864	402	Organic matter	−26.8	2688 ± 27	2845–2750
NUTA2-2868	501	Organic matter	−25.2	3531 ± 28	3885–3700
NUTA2-2719	701	Organic matter	−24.8	4729 ± 32	5585–5325
NUTA2-2721	901	Organic matter	−24.3	5809 ± 33	6720–6500
NUTA2-2724	989	Organic matter	−25.1	6593 ± 34	7565–7430
NUTA2-2877	1063	Organic matter	−25.5	9175 ± 34	10,470–10,235
NUTA2-2725	1103	Organic matter	−24.7	10,171 ± 39	12,300–11,570

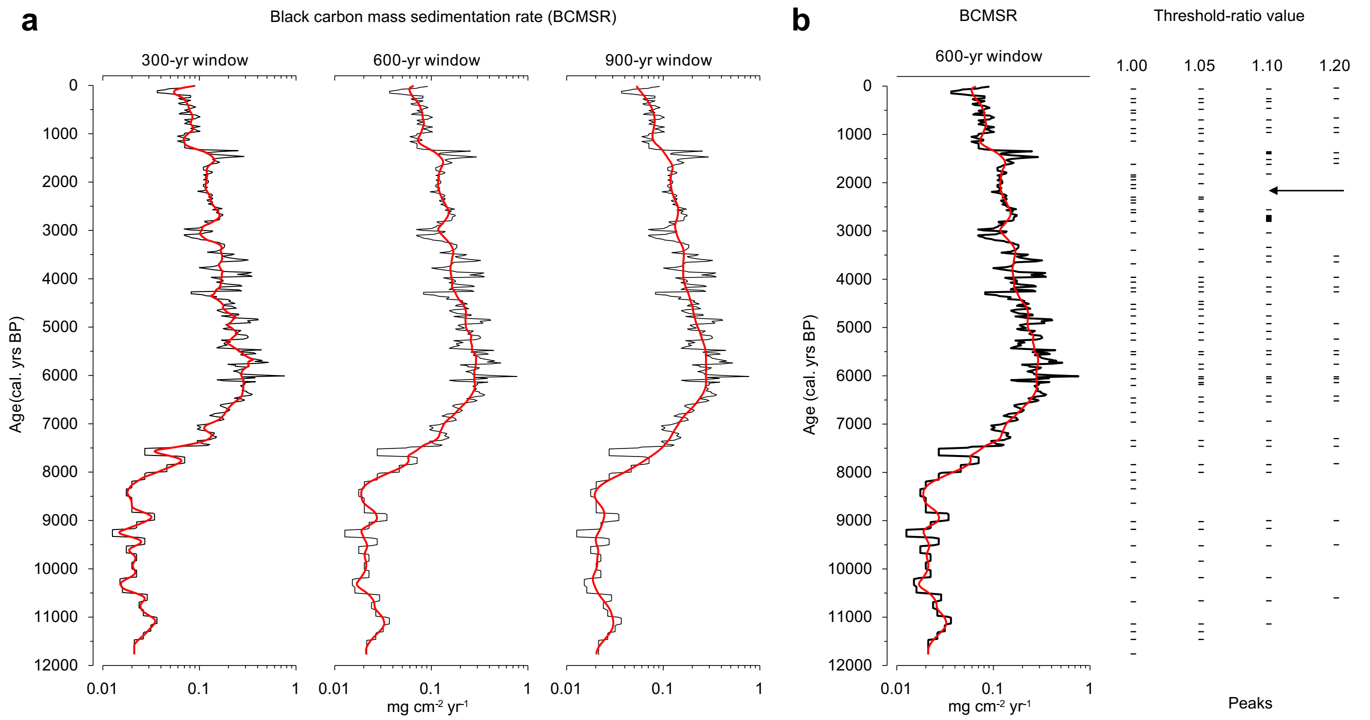

Fig. 3. (a) A comparison of different window widths (300, 600, and 900 yrs) in defining the background levels of log-transformed BCMSR. The values were interpolated to reflect a constant time step. The intermediate width of 600 yrs was used for fire-history reconstruction; (b) a comparison of the threshold-ratio values of 1.00, 1.05, 1.10, and 1.20 in detecting the peaks in log-transformed BCMSR using a background window width of 600 yrs. Peaks (–) indicate a fire episode. Threshold-ratio values higher than 1.06 were selected for the fire history reconstruction.

any information on occurrences of fire in the vegetation type at the study location. By taking the relative analytical error of 5.44% for the BC contents into consideration, we decided to select threshold ratios higher than 1.06 to infer fire episodes to see if the multiple lines of fire episode frequencies converged to produce a consistent fire history. The fire episode frequency was determined using a 2000-yr locally weighted mean on the fire episode binary series. Because there is a sampling resolution of only ~30–150 yrs, the peaks in our BC record may reflect centuries of high fire activity, not individual fire events, as inferred from the charcoal records of some higher-resolution lake sediments. Therefore, the inferred fire frequency should be called the apparent fire frequency, which is a reconstruction of the general trend for the fire regime over time for the Daihai Lake region.

5. Results

The changes in the black carbon content for sediment core DH99a are shown in Fig. 4a. The BC contents ranged from 0.7 to 16.1 mg C/g of dry sediment. The most striking feature is that the BC contents vary frequently and have significantly high values during the middle Holocene. By contrast, the BC contents during the early and late Holocene are relatively low and less variable.

The background BCMSR levels were initially low, with a mean value of 0.023 mg C cm^{-2} yr^{-1} (ranging from 0.017 to 0.033 mg C cm^{-2} yr^{-1}), between 11,760 and 8200 cal. yrs BP. They then increased from 0.023 to 0.30 mg C cm^{-2} yr^{-1} between 8200 and 6000 cal. yrs BP and remained high from 0.21 to 0.30 mg C cm^{-2} yr^{-1} until ca 4500 cal. yrs BP before gradually declining to the present-day values of approximately 0.064 mg C cm^{-2} yr^{-1} (Fig. 4b). Generally, the background BCMSR shows a clear correlation with the tree percentage (Fig. 4e) (data from previous palynological work of Xiao et al., 2004). The low background BCMSR corresponded to low tree percentages during both the early and late Holocene, whereas the high background BCMSR was associated with high tree percentages during the middle Holocene and a short warm/humid spell (ca 1700–1350 cal. yrs BP) in the late Holocene.

The inferred fire episode frequencies and peak magnitudes are displayed in Fig. 4c and d. Three lines of fire episode frequencies, inferred from threshold ratios of 1.06, 1.10 and 1.20, display a generally consistent changing pattern, indicating two phases of fire episode increases initiated at ~8200 and at ~2800 cal. yrs BP. By comprehensive comparisons among the inferred apparent fire episode frequencies, peak magnitudes and pollen data, we divided them into three distinct zones: an early Holocene interval featuring relatively low fire episode frequencies (4–5, 3–4 and 1–3 episodes/1000 yrs for threshold ratios of 1.06, 1.10 and 1.20, respectively) and peak magnitudes (0.00022–0.0062, 0.000055–0.0051 and 0.00062–0.0030 mg C/cm^2/yr $peak^{-1}$ for threshold ratios of 1.06, 1.10 and 1.20, respectively) (ca 11,760–8200 cal. yrs BP; zone 3); a middle Holocene interval containing intermediate fire episode frequencies (5–10, 4–9 and 3–8 episodes/1000 yrs for threshold ratios of 1.06, 1.10 and 1.20, respectively) and intermediate to high peak magnitudes (0.00015–0.33, 0.000033–0.32 and 0.00019–0.29 mg C/cm^2/yr $peak^{-1}$ for threshold ratios of 1.06, 1.10 and 1.20, respectively) (ca 8200–2800 cal. yrs BP; zone 2); and a late Holocene interval characterized by intermediate to high fire episode frequencies (9–12, 8–13 and 2–9 episodes/1000 yrs for threshold ratios of 1.06, 1.10 and 1.20, respectively) and intermediate peak magnitudes (0.0015–0.11, 0.00035–0.11 and 0.0022–0.095 mg C/cm^2/yr $peak^{-1}$ for threshold ratios of 1.06, 1.10 and 1.20, respectively) (ca 2800 cal. yrs BP–present; zone 1) (Fig. 4).

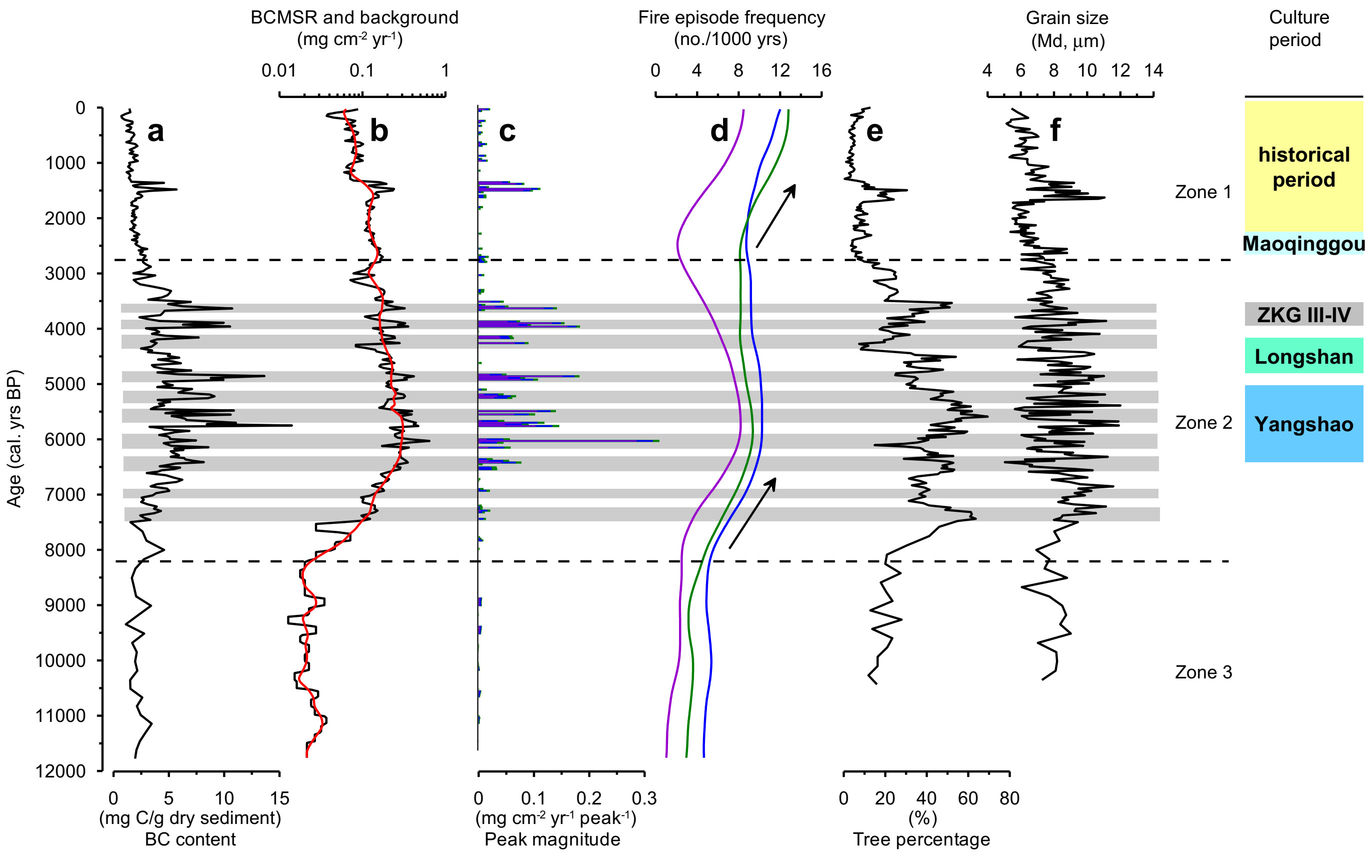

Fig. 4. A plot showing (a) the black carbon content, (b) log-transformed BCMSR and background BCMSR (red), (c) peak magnitudes and (d) inferred fire episode frequencies for the DH99a core using a background window width of 600 yrs and threshold-ratio values of 1.06 (blue), 1.10 (green) and 1.20 (purple); (e) tree percentage of pollen sum and (f) median grain size for lake sediments for the same sediment core (cited from Xiao et al., 2004 and Peng et al., 2005) are shown for comparison. Horizontal lines denote boundaries between pollen zones. These data are compared with the archaeological record for the Daihai Lake region. ZKG III–IV are Zhukaigou III and IV periods (ca 4000–3600 cal. yrs BP); Maoqinggou culture belongs to Ordos Bronze period (ca 2600–2300 cal. yrs BP). The colored boxes indicate the approximate chronological occurrence and duration of these periods (Tian, 2000). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

6. Discussion

6.1. Holocene climate and vegetation dynamics in the Daihai Lake region

Changes in the Holocene climate have been systematically studied in the Daihai Lake region over the last two decades. Previous studies have suggested that the early Holocene (ca 10–7 ^{14}C ka BP) was warm and humid or a ‘Climate Optimum’ (Wang et al., 1990a; Liu and Li, 1992). However, many recent studies in the Daihai region have recognized that the climate was warm and dry during the early Holocene (before ca 8000 cal. yrs BP), warm and humid during the middle Holocene (ca 8000–3000 cal. yrs BP), and cool and dry during the late Holocene (ca 3000–0 cal. yrs BP) (Xu et al., 2003, 2004a; Xiao et al., 2004, 2006; Peng et al., 2005; Sun et al., 2009, 2010). A similar variation in the Holocene climate was also reported at other study sites in eastern Inner Mongolia (Wang and Sun, 1997; Shi and Song, 2003; Xiao et al., 2008; Yang et al., 2008, 2011; Zhai et al., 2011) and the northwestern Chinese Loess Plateau (An et al., 2003; Sun et al., 2008) in North China although uncertainties in chronology and in the interpretation of palaeoclimatic proxies do need to be considered (Yang and Scuderi, 2010). The dry early Holocene could be attributed to the stagnant northward retreat of the polar front in the North Pacific Ocean due to remnant Northern Hemisphere ice sheets, which would hamper the northward shift of the summer monsoonal front, thereby suppressing monsoonal precipitation over eastern Asia (Xiao et al., 2008).

During the early Holocene, arid herbs and shrubs dominated the lake basin in concert with patches of mixed pine and broadleaved forests (Xiao et al., 2004). For example, *Artemisia* was detected at up to 60–75% of the total pollen sum, whereas arboreal tree pollen, mainly derived from *Pinus*, *Quercus*, *Betula* and *Ulmus*, accounted for 13–28% of the pollen sum and displayed a trend of gradual increase (Fig. 4e). During the middle Holocene, a large-scale cover of mixed coniferous and broadleaved forests occupied the Daihai Lake region. The tree pollen percentage was characterized by an obvious increase, reaching a maximum of 70% of the pollen sum (Fig. 4e). *Pinus* is the predominant contributor, accompanied by *Quercus* and *Ostryopsis*. By contrast, herbs, especially *Artemisia*, decline remarkably during this period (Xiao et al., 2004). During the late Holocene, the forests disappeared and the vegetation density decreased, with a scrub-steppe covering the Daihai Lake area. The herbaceous plants, composed mainly of *Artemisia* and *Gramineae*, grew on the mountain slopes, and herbs dominated by *Chenopodiaceae* grew in the valleys and depressions (Xiao et al., 2004). Noticeably, a short interval between ca 1700 and 1350 cal. yrs BP is characterized by an increase in tree pollen to 9–30% of the total pollen (Fig. 4e), reflecting a comparatively warm and humid episode intervening between the cool and dry periods of the late Holocene.

6.2. Linkages of fire, vegetation and climate during the Holocene in the Daihai Lake region

In recent studies, the background charcoal trends have been interpreted as a record of regional fire activity (Clark and Royall, 1995; Clark and Patterson, 1997; Whitlock and Bartlein, 2004; Higuera et al., 2007). Meanwhile, background charcoal has also been considered to represent the relative amount of biomass burned (Marlon et al., 2006, 2009). If the background BCMSR in our record reflected regional fire activity, the high background BCMSR during the middle Holocene indicates that high regional fire activity (i.e., high fire frequency) occurred under warm and humid conditions whereas the low background BCMSR values during the early and late Holocene represent low regional fire activity under cold and dry conditions. This conclusion, although being in accordance with global fire activity patterns, is inconsistent with the recent findings that cold and dry climates favor high fire activity on the orbital to millennial timescales in North China (Yang et al., 2001; Wang et al., 2005, 2012).

Paleofire studies at global scales (Power et al., 2008; Daniau et al., 2010) and those in some individual regions such as Australia and Africa (Daniau et al., 2007; Mooney et al., 2011) reveal that less fires occurred during cold stadial or glacial stages, and an increase in fires occurred during warmer interstadials and interglacials. These studies emphasized that fuel availability is an overwhelming controlling factor (i.e., cold and dry conditions have severe influences on plant productivity, thereby limiting fuels for fire). Some modern studies of fire and climate at annual-to-decadal scales illustrate that fuel availability and climate conditions conducive to combustion jointly determine regional and global fire patterns (Le Page et al., 2008; Archibald et al., 2009; Krawchuk et al., 2009). In contrast, we consider that dry climate (i.e., high rainfall seasonality) is the most important factor determining fire occurrence (or fire frequency) in the monsoonal region of China unless the fuel is too limited (or inadequately continuous) to support fires, as is, the case in deserts. Since dry conditions are usually coupled with a cold climate in the Asia monsoon region (Liu and Ding, 1998; Yang and Ding, 2008; Wang et al., 2012), cold/dry conditions during stadial or glacial stages are conducive to frequent fires in the region. This is noted in paleofire studies at glacial/interglacial cycles in a variety of regions in China from south to north (e.g., Jia et al., 2000; Sun et al., 2000; Luo et al., 2001; Yang et al., 2001; Huang, 2002; Wang et al., 2005, 2012). The increased fire activity occurring during cold stadial or glacial stages may be explained by the following three aspects. (1) Relatively dry climates persisted during stadial or glacial periods and favored the expansion of grassland and fostered a continuous fuel buildup that promoted fire. (2) The dry climate could lengthen the fire season by reducing the number of rainy days in summer, thus increasing the probability of fire occurrences. (3) A strengthened dry winter monsoon wind during these cold periods facilitating an increase in fuel desiccation and promoting the propagation of fires over the landscape once they were ignited. The different fire regimes in China from other locations in the world may reveal regional differences in climate conditions determining vegetation type, amount of fuel and fire weather (Wang et al., 2012).

Based on the above discussion, the background BCMSR could not be interpreted as a record of regional fire activity in Daihai Lake region. Conversely, the close correlation of background BCMSR with the tree percentage (Fig. 4b and e) may indicate a relationship between the vegetation dynamics and the intensity of the fires. Herb-dominated vegetation generates low fuel loads and highly flammable fuels, which tends to produce less BC than woody vegetation when burned (Stocks and Kauffman, 1997). Moreover, fires in xeric grasslands are fast-moving, low-energy fires with poorly developed convection plumes, and thus, the BC deposition is fairly local (Stocks and Kauffman, 1997). Conversely, a high fuel load and a large fuel continuity in woodlands and forests may have promoted high-intensity fires and more convectional uplift that carried BC particles aloft and increased their deposition into lakes (Clark, 1988b; Whitlock and Larsen, 2001). Thus, the herb-dominated vegetation in the Daihai Lake region during the early and late Holocene would result in low BC production, accounting for the low background BCMSR. In comparison, more woody fuels (i.e., coniferous and broadleaved forests) during the middle Holocene and the short interval between ca 1700 and 1350 cal. yrs BP would increase the BC production, explaining the high background BCMSR during these periods. Additionally, the enhanced BC sedimentation rates during the above-mentioned humid periods might also be a product of increased overland flow and higher soil erosion rates (Whitlock and Millspaugh, 1996). This process may not largely increase the BC contents in lake sediments if no fires occurred during the same periods. However, the high BC contents during the middle Holocene and the short interval of ca 1700–1350 cal. yrs BP (Fig. 4a) may rule out this possibility, suggesting that the increased background BCMSR mostly originates from the concurrent biomass burning. In summary, the changes in the background BCMSR in the Daihai Lake region may reflect the changing intensity of the fires associated with vegetation dynamics.

The magnitude of a charcoal peak is related solely to the amount of fuel consumed, i.e., a larger peak indicates either more fuel per unit area was consumed or that a greater area was burned (Gardner and Whitlock, 2001). Previous studies have interpreted peak magnitude as a proxy for fire size, fuel consumption (Higuera et al., 2009) and fire proximity or intensity (Whitlock et al., 2006; Hély et al., 2010; Higuera et al., 2011). Therefore, the peak magnitude of BCMSR in this study may represent fire intensity or fire size. The inferred apparent fire episode frequencies and peak magnitudes suggest that fires were relatively infrequent (e.g., 1–5 episodes/1000 yrs, depending on threshold ratios) and less intensive or relatively small in size in the Daihai Lake region during the early Holocene (ca 11,760–8200 cal. yrs BP) (Fig. 4c and d). During this time the climate was warm and dry and arid herbs and shrubs (e.g., *Artemisia*, Chenopodiaceae and *Ephedra*) dominated the lake basin (Xiao et al., 2004, 2006; Peng et al., 2005). During the middle Holocene (ca 8200–2800 cal. yrs BP), fires became comparatively more frequent (e.g., 3–10 episodes/1000 yrs, depending on threshold ratios) and very intense or large in size when the climate was warm and humid and more woody vegetation covered the Daihai Lake region. The apparent fire episode frequencies during the late Holocene (ca 2800–0 cal. yrs BP) displayed a further increase and reached the current frequency, which is the highest level of the analyzed record (e.g., 9–13 episodes/1000 yrs, depending on threshold ratios), and the fire intensity or fire size dropped to an intermediate level (Fig. 4c and d). Meanwhile, the climate was cool and dry during this period, with herb-dominated vegetation over the lake basin. The two phases of gradual increases in fire episode frequencies during the Holocene could not be readily explained by the changes in vegetation and climate. In northern China, a cold/dry climate and the development of steppes are conducive to frequent fires during stadial and glacial stages (Yang et al., 2001; Wang et al., 2005, 2012). Furthermore, the charcoal records from several sites in the adjacent Chinese Loess Plateau revealed that wildfires occurred frequently during the early and late Holocene when the climate was dry and steppe vegetation expanded over the region whereas natural wildfires were largely reduced during the Holocene climatic optimum between 8500 and 3100 yrs BP (Huang et al., 2006; Tan et al., 2011). A recent observation shows that vegetation structure (tree versus grass cover) can also have large impact on fire occurrence, i.e., when tree cover exceeds 40%, fire activity declines rapidly in Africa's savanna and grassland due to a tendency of canopy closure (Archibald et al., 2009). If this observation is applicable to our study site, the tree percentage was higher than 40% during most of the middle Holocene and would have largely reduced fire activity in Daihai Lake region. In this case, if no other driving factors, such as human activity, occurred, the expected fire regimes in the Daihai Lake region should be the same as that on the Chinese Loess Plateau. However, the two records are not similar. Therefore, the two phases of gradual increases in fire episode frequencies during the Holocene might have been related to human fire use. This hypothesis will be discussed in the next section.

It is also possible that the observed low fire episode frequencies during the early Holocene may be associated with the low sedimentation rate during this period, which can probably obscure some fire peaks. The mean fire return interval was estimated to be approximately 220 yrs with a time resolution of 154 yrs before ca 7500 cal. yrs BP (Fig. 2). Conversely, the mean fire return interval was approximately 150 yrs when the time resolution was 30 yrs during the late Holocene period. Thus, the reduction in time resolution did not significantly increase the mean fire return interval during the early Holocene period. Therefore, the inferred low fire frequency during this period probably reflects the true characteristics of fire activities. At the same time, the more frequent rainfall, as indicated by the increase in median grain size during the middle Holocene (Peng et al., 2005), would induce a highly variable surface runoff, which could have carried secondary BC into the lake sediments and contributed to the peak components of the BCMSR record, resulting in elevated BCMSR values during non-fire periods. Such a process should have also affected other terrestrial clastic materials as well, leading to an increase in the grain size of the sediment. However, at our study site, the BCMSR peaks corresponded well to the significant decreases in the median grain sizes of clastic particles at the intervals of ca 7500–7300, 7000–6800, 6600–6300, 6100–5900, 5000–4800, 4400–4100, 4000–3800, and 3600–3500 cal. yrs BP (see gray bars in Fig. 4f), indicating that the surface runoff has a limited influence on the peak components of our BCMSR record.

6.3. Human impacts on fire regimes since the middle Holocene in the Daihai Lake region

Prehistoric human settlements in the Daihai Lake region can be traced back to ca 7000 cal. yrs BP (Tian, 2000), coinciding with the onset of the Holocene climate optimum. Since then, the early Yangshao culture (archaeological site: Shihushan, starting from ca 6500 cal. yrs BP), middle Yangshao culture (archaeological site: Lower Wangmushan, starting from ca 6000 cal. yrs BP), late Yangshao culture (archaeological site: upper Wangmushan, ca 5800–5000 cal. yrs BP), and the Longshan Culture (archaeological site: Laohushan, ca 4800–4300 cal. yrs BP) occurred in this area in sequence (Fig. 4) (Tian, 1991a, 1991b; Fang and Sun, 1998). To date, a total of 12 archaeological sites have been discovered, which are distributed on the mountain slopes around the Daihai Lake (Fig. 5). The cultural remains found in the Daihai Lake region indicate that humans inhabiting the lake area were primarily engaged in agricultural production (Inner Mongolia Culture and Archaeology Institute, 1991). Primitive agricultural cultures were developed and flourished in the Daihai region during the Holocene climate optimum period (Lian and Fang, 2001). For example, the Laohushan culture relics were widely distributed in the Daihai Lake region and Ordos Plateau, ranging from Jining in the north to Ejin Horo Banner in the south and from Datong in the east to Baotou in the west (Fig. 1). At the archaeological sites in these regions, many different types of polished stone implements such as machetes, axes, hoes, lower millstones and grinding rods were unearthed, indicating a highly developed agriculture (Tian, 2000).

Fire was often used by early people to accelerate the process of establishing areas for agriculture. Since Neolithic times, slash-and-burn techniques have been widely used for converting forests into crop fields and pasture (Awe, 2006). Archaeological studies indicate that people in Yangshao culture region along the central Yellow River in China cultivated millet using slash-and-burn techniques from around 5000 B.C. to 3000 B.C. (Chang, 1987). A recent study has shown that the slash-and-burn cultivation can be at least dated back to ca 7700 cal. yrs BP in north China (e.g., Li et al., 2009). In

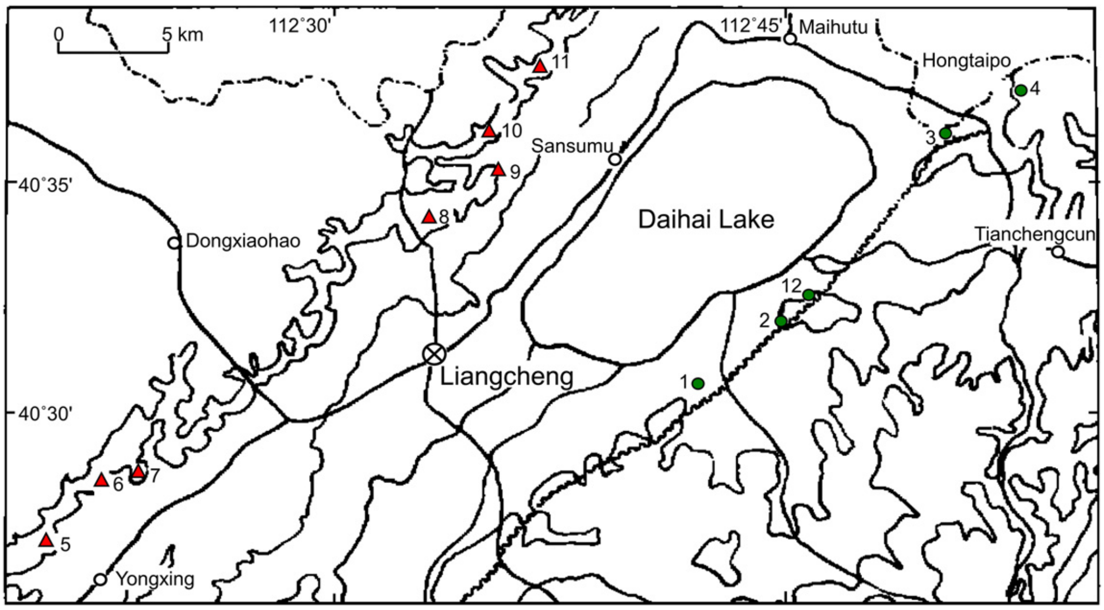

Fig. 5. The map showing the distribution of the archaeological sites in the Daihai Lake region (modified from Lian and Fang, 2001), including Huzishan (1), Wangmushan (2), Dongtan (3), Hongtaipo (4), Xibaiyu (5), Laohushan (6), Bancheng (7), Qianchougou (8), Yuzigou (9), Hetongyao (10), Damiaopo (11) and Shihushan (12). The archaeological sites of (1), (2), (3), (4) and (12) belong to the Yangshao culture (ca 6500–5000 cal. yrs BP), whereas the archaeological sites of (5), (6), (7), (8), (9), (10) and (11) belong to the Longshan culture (ca 5000–4000 cal. yrs BP).

slash-and-burn agriculture, forest will typically be cut months before a dry season. The 'slash' is permitted to dry, and then burned in the following dry season. The resulting ash fertilizes the soil, and the burned field is then planted at the beginning of the next rainy season with crops. Most of this work is typically done by hand, using machetes, axes, hoes, and other such basic tools (see http://en.wikipedia.org/wiki/Slash-and-burn). The finding of stone machetes, axes and hoes at the archaeological sites in Daihai Lake region may suggest that local settlers had suitable tools and ability to carry out slash-and-burn agricultural activity during the middle Holocene. Therefore, human fire use in forest clearance and land cultivation in the Daihai Lake region might have largely contributed to the high fire episode frequencies during the middle Holocene period (Fig. 4d).

The Laohushan Culture ended ca 4300 cal. yrs ago as a result of climate deterioration in the lake area (Fang and Sun, 1998; Tian, 2000). Because the drainage basin became unsuitable for farming as the climate became cold and dry, humans stop cultivating in the lake basin and left, leading to a cultural hiatus from ca 4300 to 4000 cal. yrs BP in the Daihai Lake region (Tian, 2000). However, a decrease in the inferred fire episode frequency was not observed for this period. This observation may reflect that our BC record possibly registered the human biomass burning outside the Daihai Lake region. For example, during ca 4200–3500 cal. yrs BP, another primitive agricultural culture (called the Zhukaigou culture, with a typical archaeological site at Ejin Horo Banner (Fig. 1)) appeared in the neighboring Ordos Plateau and was well developed (Tian, 1997; Lian and Fang, 2001), which presumably contributed to the inferred high fire episode frequency during this time. After ca 4000 cal. yrs BP, Zhukaigou III–IV culture appeared in Daihai Lake region (Fig. 4).

During the late Holocene (ca 2800–0 cal. yrs BP), the inferred fire episode frequencies continued to increase and reached a maximum level of 13 episodes/1000 yrs (Fig. 4d), which may be attributed to an increase in human activity in the study area since ca 2300 cal. yrs BP. Historical accounts indicate that there were three main Han occupation phases in Ordos Plateau and the neighboring regions, including in Daihai during the last 2300 yrs: the West Han Period (206 B.C.–A.D. 8), the Tang Dynasty (A.D. 618–907), and the period from A.D. 1697 to 1949 (Wang, 1985; Sun, 2000). The earliest large-scale migration and cultivation occurred during the West Han Period. Historical accounts state that up to one million people migrated from central China to the Ordos Plateau between 127 and 111 B.C., where they cultivated lands for agriculture (Wang, 1985). The second phase of cultivation occurred in the Tang Dynasty, when more than 130 thousand people cultivated land in the Ordos Plateau. The most extensive cultivation occurred during the latest phase of cultivation (A.D. 1697–1949) (Wang, 1985). Additionally, other studies have also revealed intensified human activities in the Daihai Lake region during the late Holocene. For instance, the increase in the magnetic frequency-dependent susceptibility and decrease of *Artemisia* and Chenopodiaceae pollen percentages in the Daihai Lake sediments since ca 300 cal. yrs BP have been thought to reflect intensified land cultivation (Zhang and Wu, 2001). Meanwhile, a clear increase in *Humulus* and *Urticaceae* pollen percentages of the Daihai Lake sediments after ca 980 cal. yrs BP also indicates the intensification in human activities (Xu et al., 2004b). A similar pattern of frequent fire occurrence during late Holocene has been revealed by charcoal and BC records on Chinese Loess Plateau, which was attributed to widespread agriculture activity in the region (Huang et al., 2006; Wang et al., 2012).

In summary, the two phases of gradual increases in the inferred fire episode frequencies from the early to the late Holocene show that human-induced fires became more important for fire regimes than natural fires in the Daihai Lake region. A sedimentary charcoal record in Guanzhong basin (i.e., southern Loess Plateau) has shown that human fire use in agriculture was initiated at ca 7700 cal. yrs BP and gradually intensified during the late Holocene (Li et al., 2009). These findings imply the ever increasing role of mankind in affecting the fire regime in north China during the Holocene period.

7. Conclusions

In this study, we have linked the Holocene fire regime to the vegetation, climate changes and past human activity in north-central China by comparing a high-resolution BC record in the Daihai Lake region with the associated pollen data, median grain size and archaeological studies. The BCMSR was employed as a palaeofire record proxy and was decomposed into two components: the background BCMSR and the BCMSR peaks representing fire episode frequencies. The results show that the background BCMSR and peak magnitude display a close correlation with the tree percentage, indicating the relationship between vegetation dynamics and fire intensity or fire size. The inferred apparent fire episode frequency showed two phases of gradual increases starting at ca 8200 and ca 2800 cal. yrs BP, which cannot be explained simply by vegetation dynamics and climate change. Based on archaeological studies in the region, we propose that the two phases of gradual increases in the inferred fire episode frequencies are attributed to an increase in human activity starting at the middle Holocene. This reinforces the evidence for the ever increasing role of mankind in affecting the fire regime in northern China during the Holocene period.

Acknowledgments

We are greatly indebted to Dr S.D. Mooney and the other two anonymous reviewers for their constructive comments on the early version of the manuscript. Support for this research was provided by the National Basic Research Program of China (973 Program) (No: 2010CB950204 and 2012CB821905), the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA05120103) and National Science Foundation of China (grant 40502019). We thank Dr P.D. White, S.L. Yang and D.Y. Zhai for discussions.

References

An, C.B., Feng, Z.D., Chen, F.H., 2003. Evidence of a humid mid-Holocene in the western part of Chinese Loess Plateau. Chinese Science Bulletin 48, 2472–2479.
Archibald, S., Roy, D.P., van Wilgen, B.W., Scholes, R.J., 2009. What limits fire? an examination of drivers of burnt area in Southern Africa. Global Change Biology 15, 613–630.
Awe, J., 2006. Maya Cities and Sacred Caves (A Guide to the Maya Sites of Belize). Cubola Publication, 104 pp.
Bird, M.I., Moyo, C., Veenendaal, E.M., Lloyd, J., Frost, P., 1999. Stability of elemental carbon in a savanna soil. Global Biogeochemical Cycles 13, 923–932.
Bond, W.J., Midgley, G.F., Woodward, F.I., 2003. The importance of lower atmospheric CO_2 and fire in promoting the spread of grasslands and savannas. Global Change Biology 9, 973–982.
Bond, W.J., Woodward, F.I., Midgley, G.F., 2005. The global distribution of ecosystems in a world without fire. New Phytologist 165, 525–538.
Bowman, D.M.J.S., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M.A., D'Antonio, C.M., DeFries, R.S., Doyle, J.C., Harrison, S.P., Johnston, F.H., Keeley, J.E., Krawchuk, M.A., Kull, C.A., Marston, J.B., Moritz, M.A., Prentice, I.C., Roos, C.I., Scott, A.C., Swetnam, T.W., van der Werf, G.R., Pyne, S.J., 2009. Fire in the Earth System. Science 324, 481–484.
Bowman, D.M.J.S., Balch, J., Artaxo, P., Bond, W.J., Cochrane, M.A., D'Antonio, C.M., DeFries, R., Johnston, F.H., Keeley, J.E., Krawchuk, M.A., Kull, C.A., Mack, M., Moritz, M.A., Pyne, S.J., Roos, C.I., Scott, A.C., Sodhi, N.S., Swetnam, T.W., 2011. The human dimension of fire regimes on Earth. Journal of Biogeography 38, 2223–2236.
Brunelle, A., Whitlock, C., 2003. Postglacial fire, vegetation, and climate history in the Clearwater Range, Northern Idaho, USA. Quaternary Research 60, 307–318.

Carcaillet, C., Almquist, H., Asnong, H., Bradshaw, R.H.W., Carrion, J.S., Gaillard, M.-J., Gajewski, K., Haas, J.N., Haberle, S.G., Hadorn, P., Muller, S.D., Richard, P.J.H., Richoz, I., Rosch, M., Sanchez Goni, M.F., von Stedingk, H., Stevenson, A.C., Talon, B., Tardy, C., Tinner, W., Tryterud, E., Wick, L., Willis, K.J., 2002. Holocene biomass burning and global dynamics of the carbon cycle. Chemosphere 49, 845–863.

Carcaillet, C., Bergeron, Y.S., Richard, P.J.H., Fréchette, B., Gauthier, S., Prairie, Y.T., 2001. Change of fire frequency in the eastern Canadian boreal forests during the Holocene: does vegetation composition or climate trigger the fire regime? Journal of Ecology 89, 930–946.

Chang, K.C., 1987. The Archaeology of Ancient China, fourth ed. Yale University Press, New Haven, 483 pp.

Chinese Academy of Sciences (Compilatory Commission of Physical Geography of China), 1984. Physical Geography of China: Climate. Science Press, Beijing, pp. 1–30 (in Chinese).

Clark, J.S., 1988a. Effect of climate change on fire regimes in northwestern Minnesota. Nature 334, 233–235.

Clark, J.S., 1988b. Particle motion and the theory of stratigraphic charcoal analysis: source area, transport, deposition and sampling. Quaternary Research 30, 67–80.

Clark, J.S., Royall, P.D., 1995. Particle-size evidence for source areas of charcoal accumulation in late Holocene sediments of Eastern North American Lakes. Quaternary Research 43, 80–89.

Clark, J.S., Patterson III, W.A., 1997. Background and local charcoal in sediments: scales of fire evidence in the paleorecord. In: Clark, J.S., Cachier, H., Goldammer, J.G., Stocks, B. (Eds.), Sediment Records of Biomass Burning and Global Change. NATO ASI Series. Series I, Global Environmental Change, No. 51. Springer-Verlag, Berlin, pp. 23–48.

Daniau, A.-L., Sánchez-Goñi, M.F., Beaufort, L., Laggoun-Défarge, F., Loutre, M.-F., Duprat, J., 2007. Dansgaard–Oeschger climatic variability revealed by fire emissions in southwestern Iberia. Quaternary Science Reviews 26, 1369–1383.

Daniau, A.-L., Harrison, S.P., Bartlein, P.J., 2010. Fire regimes during the last glacial. Quaternary Science Reviews 29, 2918–2930.

Fang, X.Q., Sun, N., 1998. Cold event: possible cause for the suspension of the Laohushan Culture in the Lake Daihai region at 4.3 ka BP. Human Geography 13, 71–76 (in Chinese with English abstract).

FAO, 2007. Fire Management: Global Assessment 2006. FAO Forestry Paper 0258-6150. Food and Agriculture Organization of the United Nations, 151 pp.

Franklin, J., Syphard, A.D., He, H.S., Mladenoff, D.J., 2005. Altered fire regimes affect landscape patterns of plant succession in the foothills and mountains of Southern California. Ecosystems 8, 885–898.

Gao, Y.X., 1962. On some problems of Asian monsoon. In: Gao, Y.X. (Ed.), Some Questions About the East Asian Monsoon. Science Press, Beijing, pp. 1–49 (in Chinese).

Gardner, J.J., Whitlock, C., 2001. Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies. The Holocene 11, 541–549.

Gavin, D.G., unpublished data, 2006. Charster Software. For detail to see http://geography.uoregon.edu/gavin/charster/Introduction.html.

Goldberg, E.D., 1985. Black Carbon in the Environment. John Wiley& Sons, New York, 198 pp.

Grissino-Mayer, H.D., Swetnam, T.W., 2000. Century-scale climate forcing of fire regimes in the American Southwest. The Holocene 10, 213–220.

Harrison, S.P., Marlon, J.R., Bartlein, P.J., 2010. Fire in the earth system. In: Dodson, J. (Ed.), Changing Climates, Earth Systems and Society. Springer, Dordrecht, The Netherlands, pp. 21–47.

Hély, C., Girardin, M.P., Ali, A.A., Carcaillet, C., Brewer, S., Bergeron, Y., 2010. Eastern boreal North American wildfire risk of the past 7000 years: a model-data comparison. Geophysical Research Letters 37. http://dx.doi.org/10.1029/2010GL043706.

Higuera, P.E., Peters, M.E., Brubaker, L.B., Gavin, D.G., 2007. Understanding the origin and analysis of sediment charcoal records with a simulation model. Quaternary Science Reviews 26, 1790–1809.

Higuera, P.E., Brubaker, L.B., Anderson, P.M., Hu, F.S., Brown, T.A., 2009. Vegetation mediated the impacts of postglacial climate change on fire regimes in the southcentral Brooks Range, Alaska. Ecological Monographs 79, 201–219.

Higuera, P.E., Whitlock, C., Gage, J.A., 2011. Linking tree-ring and sediment-charcoal records to reconstruct fire occurrence and area burned in subalpine forests of Yellowstone National Park, USA. The Holocene 21, 327–341.

Hockaday, W.C., Grannas, A.M., Kim, S., Hatcher, P.G., 2006. Direct molecular evidence for the degradation and mobility of black carbon in soils from ultrahigh-resolution mass spectral analysis of dissolved organic matter from a fire-impacted forest soil. Organic Geochemistry 37, 501–510.

Huang, C.C., Pang, J.L., Chen, S.E., Su, H.X., Han, J., Cao, Y.F., Zhao, W.Y., Tan, Z.H., 2006. Charcoal records of fire history in the Holocene loess-soil sequences over the southern Loess Plateau of China. Palaeogeography, Palaeoclimatology, Palaeoecology 239, 28–44.

Huang, F., 2002. Charcoal record and natural fire history during 0.36–1.02 Ma in Northern South China Sea. Acta Micropalaeontologica Sinica 19, 76–82 (in Chinese with English abstract).

Inner Mongolia Culture and Archaeology Institute, 1991. Proceedings of Researches on the Primitive Culture in Central-Southern Inner Mongolia. China Ocean Press, Beijing, 216 pp. (in Chinese).

Jia, G.D., Peng, P.A., Sheng, G.Y., Fu, J.M., 2000. Sedimentary records of black carbon in the sea area of the Nansha Islands since the last glaciation. Chinese Science Bulletin 45, 1594–1597.

Jiang, W.Y., Leroy, S.A.G., Ogle, N., Chu, G.Q., Wang, L., Liu, J.Q., 2008. Natural and anthropogenic forest fires recorded in the Holocene pollen record from a Jinchuan peat bog, northeastern China. Palaeogeography, Palaeoclimatology, Palaeoecology 261, 47–57.

Jin, Y., Roy, D.P., 2005. Fire-induced albedo change and its radiative forcing at the surface in northern Australia. Geophysical Research Letters 32. http://dx.doi.org/10.1029/2005GL 022822.

Kitzberger, T., Veblen, T.T., Villalba, R., 1997. Climate influences on fire regimes along a rainforest-to-xeric woodland gradient in northern Patagonia, Argentina. Journal of Biogeography 24, 35–47.

Knicker, H., Müller, P., Hilscher, A., 2007. How useful is chemical oxidation with dichromate for the determination of “Black Carbon” in fire-affected soils. Geoderma 142, 178–196.

Kong, Z.C., Liu, C.J., Zhang, J.Z., Jin, G.Y., 2003. The plant relic and original agriculture in the archaeological sites in China. Cultural Central China 4, 4–13 (in Chinese with English abstract).

Krawchuk, M.A., Moritz, M.A., Parisien, M.A., Dorn, J.V., Hayhoe, K., 2009. Global pyrogeography: the current and future distribution of wildfire. PLoS ONE 4 (4), e5102.

Le Page, Y., Pereira, J.M.C., Trigo, R., da Camara, C., Oom, D., Mota, B., 2008. Global fire activity patterns (1996–2006) and climatic influence: an analysis using the World Fire Atlas. Atmospheric Chemistry and Physics 8, 1911–1924.

Li, X.Q., Shang, X., Dodson, J., Zhou, X.Y., 2009. Holocene agriculture in the Guanzhong Basin in NW China indicated by pollen and charcoal evidence. The Holocene 19, 1213–1220.

Lian, P.L., Fang, X.Q., 2001. On the relationship between the development of prehistorical cultures and environmental change in the Daihai Lake Region, Inner Mongolia. Geographical Research 20, 623–628 (in Chinese with English abstract).

Lim, B., Cachier, H., 1996. Determination of black carbon by oxidation and thermal treatment in recent marine and lake sediments and Cretaceous-Tertiary clays. Chemical Geology 131, 143–154.

Liu, G.X., Su, H., Li, S.L., 1999. The summarization on the fire accident of grassland in Inner Mongolia. Grassland of China 4, 76–78 (in Chinese with English abstract).

Liu, Q.S., Li, H.Z., 1992. The Holocene environmental evolution of the mixed zone of agriculture and animal-husbandry (Daihai and Huangqihai area) in Northern China. In: Zhou, T.R., Zhang, L.S. (Eds.), The Holocene Environmental Evolution and Its Prediction of the Mixed Zone of Agriculture and Animal-husbandry in Northern China. Geological Publishing House, Beijing, pp. 16–50 (in Chinese).

Liu, T.S., Ding, Z.L., 1998. Chinese loess and the paleomonsoon. Annual Review of Earth and Planetary Sciences 26, 111–145.

Long, C.J., Whitlock, C., Bartlein, P.J., Millspaugh, S.H., 1998. A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. Canadian Journal of Forest Research 28, 774–787.

Luo, Y.L., Chen, H.C., Wu, G.X., Sun, X.J., 2001. Records of natural fire and climate history during the last three glacial–interglacial cycles around the South China Sea – Charcoal record from the ODP 1144. Science in China (Series D) 44, 897–904.

Lynch, J.A., Hollis, J.L., Hu, F.S., 2004. Climatic and landscape controls of the boreal forest fire regime: Holocene records from Alaska. Journal of Ecology 92, 477–489.

Lyons, E.A., Jin, Y.F., Randerson, J.T., 2008. Changes in surface albedo after fire in boreal forest ecosystems of interior Alaska assessed using MODIS satellite observations. Journal of Geophysical Research 113. http://dx.doi.org/10.1029/2007 JG000606.

Marlon, J.R., Bartlein, P.J., Whitlock, C., 2006. Fire–fuel–climate linkages in the northwestern USA during the Holocene. The Holocene 16, 1059–1071.

Marlon, J., Bartlein, P.J., Carcaillet, C., Gavin, D.G., Harrison, S.P., Higuera, P.E., Joos, F., Power, M.J., Prentice, I.C., 2008. Climate and human influences on global biomass burning over the past two millennia. Nature Geoscience 1, 697–702.

Marlon, J.R., Bartlein, P.J., Walsh, M.K., Harrison, S.P., Brown, K.J., Edwards, M.E., Higuera, P.E., Power, M.J., Anderson, R.S., Briles, C., Brunelle, A., Carcaillet, C., Daniels, M., Hu, F.S., Lavoie, M., Long, C., Minckley, T., Richard, P.J.H., Scott, A.C., Shafer, D.S., Tinner, W., Umbanhowar Jr., C.E., Whitlock, C., 2009. Wildfire responses to abrupt climate change in North America. Proceedings of the National Academy of Sciences of the United States of America 106, 2519–2524.

Millspaugh, S.H., Whitlock, C., 1995. A 750-year fire history based on lake sediment record in central Yellowstone National Park, USA. The Holocene 5, 283–292.

Mohr, J.A., Whitlock, C., Skinner, C.N., 2000. Postglacial vegetation and fire history: Eastern Klamath Mountains, California, USA. The Holocene 10, 587–601.

Mooney, S.D., Harrison, S.P., Bartlein, P.J., Daniau, A.-L., Stevenson, J., Brownlie, K.C., Buckman, S., Cupper, M., Luly, J., Black, M., Colhoun, E., D'Costa, D., Dodson, J., Haberle, S., Hope, G.S., Kershaw, P., Kenyon, C., McKenzie, M., Williams, N., 2011. Late Quaternary fire regimes of Australasia. Quaternary Science Reviews 30, 28–46.

Ohlson, M., Tryterud, E., 2000. Interpretation of the charcoal record in forest soils: forest fires and their production and deposition of macroscopic charcoal. The Holocene 10, 519–525.

Pechony, O., Shindell, D.T., 2010. Driving forces of global wildfires over the past millennium and the forthcoming century. Proceedings of the National Academy of Sciences of the United States of America 107, 19167–19170.

Peng, Y.J., Xiao, J.L., Nakamura, T., Liu, B.L., Inouchi, Y., 2005. Holocene East Asian monsoonal precipitation pattern revealed by grain-size distribution of core sediments of Daihai Lake in Inner Mongolia of north-central China. Earth and Planetary Science Letters 233, 467–479.

Power, M.J., Marlon, J., Ortiz, N., Bartlein, P.J., Harrison, S.P., Mayle, F.E., Ballouche, A., Bradshaw, R.H.W., Carcaillet, C., Cordova, C., Mooney, S., Moreno, P.I., Prentice, I.C., Thonicke, K., Tinner, W., Whitlock, C., Zhang, Y., Zhao, Y., Ali, A.A., Anderson, R.S., Beer, R., Behling, H., Briles, C., Brown, K.J., Brunelle, A., Bush, M., Camill, P., Chu, G.Q., Clark, J., Colombaroli, D., Connor, S., Daniau, A.L., Daniels, M., Dodson, J., Doughty, E., Edwards, M.E., Finsinger, W., Foster, D., Frechette, J., Gaillard, M.J., Gavin, D.G., Gobet, E., Haberle, S., Hallett, D.J., Higuera, P., Hope, G., Horn, S., Inoue, J., Kaltenrieder, P., Kennedy, L., Kong, Z.C., Larsen, C., Long, C.J., Lynch, J., Lynch, E.A., McGlone, M., Meeks, S., Mensing, S., Meyer, G., Minckley, T., Mohr, J., Nelson, D.M., New, J., Newnham, R., Noti, R., Oswald, W., Pierce, J., Richard, P.J.H., Rowe, C., Goni, M.F.S., Shuman, B.N., Takahara, H., Toney, J., Turney, C., Urrego-Sanchez, D.H., Umbanhowar, C., Vandergoes, M., Vanniere, B., Vescovi, E., Walsh, M., Wang, X., Williams, N., Wilmshurst, J., Zhang, J.H., 2008. Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. Climate Dynamics 30, 887–907.

Rollins, M.G., Swetnam, T.W., Morgan, P., 2001. Evaluating a century of fire patterns in two Rocky Mountain wilderness areas using digital fire atlases. Canadian Journal of Forest Research 31, 2107–2123.

Schmidt, M.W.I., Noack, A.G., 2000. Black carbon in soils and sediments: analysis, distribution, implications, and current challenges. Global Biogeochemical Cycles 14, 777–793.

Seying, B., 2002. Dynamics of combustible materials on grassland. Grassland of China 5, 48–52 (in Chinese with English abstract).

Shi, P.J., Song, C.Q., 2003. Palynological records of environmental changes in the middle part of Inner Mongolia, China. Chinese Science Bulletin 48, 1433–1438.

Song, J.Z., Peng, P.A., Huang, W.L., 2002. Black carbon and kerogen in soils and sediments. 1. Quantification and characterization. Environmental Science & Technology 36, 3960–3967.

Stocks, B.J., Kauffman, J.B., 1997. Biomass consumption and behavior of wildland fires in boreal, temperate, and tropical ecosystems: parameters necessary to interpret historic fire regimes and future fire scenarios. In: Clark, J.S., Cachier, H., Goldammer, J.G., Stocks, B. (Eds.), Sediment Records of Biomass Burning and Global Change. NATO ASI Series. Series I: Global Environmental Change. Springer, Berlin, pp. 169–188.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., v.d. Plicht, J., Spurk, M., 1998. INTCAL98 radiocarbon age calibration, 24,000–0 cal. BP. Radiocarbon 40, 1041–1083.

Sun, A.Z., Feng, Z.D., Tang, L.Y., Ma, Y.Z., 2008. Vegetation and climate changes in the western part of the Loess Plateau since 13 ka BP. Acta Geographica Sinica 63, 280–291 (in Chinese with English abstract).

Sun, Q.L., Wang, S.M., Zhou, J., Shen, J., Cheng, P., Xie, X.P., Wu, F., 2009. Lake surface fluctuations since the late glaciation at Lake Daihai, north central China: a direct indicator of hydrological processes responded to East Asian monsoon climate. Quaternary International 194, 45–54.

Sun, Q.L., Wang, S.M., Zhou, J., Chen, Z.Y., Shen, J., Xie, X.P., Wu, F., Chen, P., 2010. Sediment geochemistry of Lake Daihai, north-central China: implications for catchment weathering and climate change during the Holocene. Journal of Paleolimnology 43, 75–87.

Sun, J.M., 2000. Origin of eolian sand mobilization during the past 2300 years in the Mu Us desert, China. Quaternary Research 53, 78–88.

Sun, X.J., Li, X., Chen, H.C., 2000. Evidence for natural fire and climate history since 37 ka BP in the northern part of the South China Sea. Science in China (Series D) 43, 487–493.

Syphard, A.D., Radeloff, V.C., Keeley, J.E., Hawbaker, T.J., Clayton, M.K., Stewart, S.I., Hammer, R.B., 2007. Human influence on California fire regimes. Ecological Applications 17, 1388–1402.

Syphard, A.D., Radeloff, V.C., Hawbaker, T.J., Stewart, S.I., 2009. Conservation threats due to human-caused increases in fire frequency in Mediterranean-climate ecosystems. Conservation Biology 23, 758–769.

Tan, Z.H., Huang, C.C., Pang, J.L., Zhou, Q.Y., 2011. Holocene wildfires related to climate and land-use change over the Weihe River Basin, China. Quaternary International 234, 167–173.

Tian, G.J., 1991a. Studies on Cultural Remains of the Yangshao Age in Central-Southern Inner Mongolia. In: Inner Mongolia Culture and Archaeology Institute, Proceedings of Researches on the Primitive Culture in Central-Southern Inner Mongolia. China Ocean Press, Beijing, pp. 55–85 (in Chinese).

Tian, G.J., 1991b. Studies on Cultural Remains of the Longshan Age in Central-Southern Inner Mongolia. Inner Mongolia Culture and Archaeology Institute. In: Proceedings of Researches on the Primitive Culture in Central-Southern Inner Mongolia. China Ocean Press, Beijing, pp. 140–160 (in Chinese).

Tian, G.J., 1997. On prehistoric archaeology of south middle Inner Mongolia. Acta Archaeologica Sinica 2, 121–145 (in Chinese).

Tian, G.J., 2000. The relationships between archaeological culture and ecological environment, Daihai Lake area. In: Zhou, K.S., Song, Y.Q. (Eds.), Researches of Environmental Archaeology, vol. 2. Science Press, Beijing, pp. 72–80 (in Chinese).

Tilman, D., Lehman, C., 2001. Human-caused environmental change: Impacts on plant diversity and evolution. Proceedings of the National Academy of Sciences of the United States of America 98, 5433–5440.

Vannière, B., Colombaroli, D., Chapron, E., Leroux, A., Tinner, W., Magny, M., 2008. Climate versus human-driven fire regimes in Mediterranean landscapes: the Holocene record of Lago dell'Accesa (Tuscany, Italy). Quaternary Science Reviews 27, 1181–1196.

Wang, B.Y., Sun, X.J., 1997. Preliminary study of Holocene environmental change in Chasuqi. Chinese Science Bulletin 42, 514–518.

Wang, S.Y., 1985. Historical changes of pastoral and farming economy in Ordos Plateau and its impacts on natural environment. Historical Geography 5, 11–24 (in Chinese).

Wang, S.M., Wu, R.J., Jiang, X.H., 1990a. Environment evolution and paleoclimate of Daihai Lake, Inner Mongolia since the last glaciation. Quaternary Sciences 3, 223–232 (in Chinese with English abstract).

Wang, S.M., Yu, Y.S., Wu, R.J., Feng, M., 1990b. The Daihai Lake: Environment Evolution and Climate Change. University of Science and Technology of China Press, Hefei, 191 pp. (in Chinese).

Wang, X., Yu, C.L., Peng, P.A., Ding, Z.L., 2001. Extraction and determination of black carbon in sediments: error analysis and recovery ratio experiment. Geochimica 30, 439–444 (in Chinese with English abstract).

Wang, X., Peng, P.A., Ding, Z.L., 2005. Black carbon records in Chinese Loess Plateau over the last two glacial cycles and the implications for paleofires. Palaeogeography, Palaeoclimatology, Palaeoecology 223, 9–19.

Wang, X., Ding, Z.L., Peng, P.A., 2012. Changes in fire regimes on the Chinese Loess Plateau since the last glacial maximum and implications for linkages to paleoclimate and past human activity. Palaeogeography, Palaeoclimatology, Palaeoecology 315–316, 61–74.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313, 940–943.

Whitlock, C., Bartlein, P., Marlon, J., Brunelle, A., Long, C., 2003. Holocene fire reconstructions from the northwestern U.S.: an examination at multiple time scales. In: 5th Symposium on Fire and Forest Meteorology, and 2nd International Wildland Fire Ecology and Fire Management Congress, American Meteorological Society, 16–20 November 2003, Orlando.

Whitlock, C., Bartlein, P.J., 2004. Holocene fire activity as a record of past environmental change. In: Gillespie, A., Porter, S.C., Atwater, B. (Eds.), The Quaternary Period in the United States. 2003 INQUA Volume. Elsevier, pp. 479–489.

Whitlock, C., Bianchi, M.M., Bartlein, P.J., Markgraf, V., Walsh, M., Marlon, J.M., McCoy, N., 2006. Postglacial vegetation, climate, and fire history along the east side of the Andes (lat 41–42.5 S), Argentina. Quaternary Research 66, 187–201.

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. Biological Techniques and Indicators, vol. 2. Kluwer Academic Publishers, Dordrecht, pp. 85–97.

Whitlock, C., Millspaugh, S.H., 1996. Testing the assumptions of fire history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA. The Holocene 6, 7–15.

Whitlock, C., Skinner, C.N., Bartlein, P.J., Minckley, T., Mohr, J.A., 2004. Comparison of charcoal and tree-ring records of recent fires in the eastern Klamath Mountains, California, USA. Canadian Journal of Forest Research 34, 2110–2121.

Xiao, J.L., Xu, Q.H., Nakamura, T., Yang, X.L., Liang, W.D., Inouchi, Y., 2004. Holocene vegetation variation in the Daihai Lake region of north-central China: a direct indication of the Asian monsoon climatic history. Quaternary Science Reviews 23, 1669–1679.

Xiao, J.L., Wu, J.T., Si, B., Liang, W.D., Nakamura, T., Liu, B.L., Inouchi, Y., 2006. Holocene climate changes in the monsoon/arid transition reflected by carbon concentration in Daihai Lake of Inner Mongolia. The Holocene 16, 551–560.

Xiao, J.L., Si, B., Zhai, D.Y., Itoh, S., Lomtatidze, Z., 2008. Hydrology of Dali Lake in central-eastern Inner Mongolia and Holocene East Asian monsoon variability. Journal of Paleolimnology 40, 519–528.

Xu, Q.H., Xiao, J.L., Nakamura, T., Yang, X.L., Yang, Z.J., Liang, W.D., Inouchi, Y., Yang, S.Y., 2003. Quantitative reconstructed climatic changes of Daihai basin by pollen data. Marine Geology and Quaternary Geology 23, 99–108 (in Chinese with English abstract).

Xu, Q.H., Xiao, J.L., Nakamura, T., Yang, X.L., Zheng, Z.H., Liang, W.D., Li, Y.C., Inouchi, Y., 2004a. Pollen evidence of vegetation and climate changes in Daihai Lake area during the Holocene. Journal of Glaciology and Geocryology 26, 73–80 (in Chinese with English abstract).

Xu, Q.H., Xiao, J.L., Nakamura, T., Yang, X.L., Yang, Z.J., Liang, W.D., Inouchi, Y., 2004b. Climate changes of Daihai Basin during the past 1500 from a pollen record. Quaternary Sciences 24, 341–347 (in Chinese with English abstract).

Yang, S.L., Ding, Z.L., 2008. Advance-retreat history of the East-Asian summer monsoon rainfall belt over northern China during the last two glacial–interglacial cycles. Earth and Planetary Science Letters 274, 499–510.

Yang, X.P., Zhu, B., Wang, X., Li, C., Zhou, Z., Chen, J., Yin, J., Lu, Y., 2008. Late Quaternary environmental changes and organic carbon density in the Hunshandake sandy land, eastern Inner Mongolia, China. Global and Planetary Change 61, 70–78.

Yang, X.P., Scuderi, L., 2010. Hydrological and climatic changes in deserts of China since the late Pleistocene. Quaternary Research 73, 1–9.

Yang, X.P., Scuderi, L., Paillou, P., Liu, Z., Li, H., Ren, X., 2011. Quaternary environmental changes in the drylands of China – a critical review. Quaternary Science Reviews 30, 3219–3233.

Yang, Y., Shen, C.D., Yi, W.X., Sun, Y.M., Liu, T.S., 2001. The elemental carbon record in Weinan loess section since last 21 ka. Chinese Science Bulletin 46, 1541–1544.

Zhai, D.Y., Xiao, J.L., Zhou, L., Wen, R.L., Chang, Z.G., Wang, X., Jin, X.D., Pang, Q.Q., Itoh, S., 2011. Holocene East Asian monsoon variation inferred from species assemblage and shell chemistry of the ostracodes from Hulun Lake, Inner Mongolia. Quaternary Research 75, 512–522.

Zhang, J.C., Lin, Z.G., 1992. Climate of China. John Wiley& Sons, New York, 376 pp.
Zhang, Z.K., Wu, R.J., 2001. Climatic variation and human activities recorded by lake sediment in the catchment of Daihai Lake during the past 300 years. Journal of Capital Normal University (Natural Science Edition) 22, 70–76 (in Chinese with English abstract).
Zhou, B., Shen, C.D., Sun, W.D., Zheng, H.B., Yang, Y., Sun, Y.B., An, Z.S., 2007. Elemental carbon record of paleofire history on the Chinese Loess Plateau during the last 420 ka and its response to environmental and climate changes. Palaeogeography, Palaeoclimatology, Palaeoecology 252, 617–625.