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Holocene climate change evidence from high-resolution loess/paleosol records and the linkage to fire–climate change–human activities in the Horqin dunefield in northern China

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ABSTRACT

The combination of high-resolution sedimentary paleoclimate proxies of total organic carbon and magnetic susceptibility of a loess/paleosol section with black carbon (BC) records provides us with information about climate change and the linkage of fire–climate change–vegetation–human activities in the Horqin dunefield over the past 11,600 cal yr BP. We found that during 11,600–8000 cal yr BP (the early Holocene), the area was dominated by a dry climate. The vegetation coverage was low, which limited the extent of fire. The Holocene optimum can be placed between 8000 and 3200 cal yr BP, and during this period, anthropogenic fire was a key component of total fire occurrence as the intensity of human activity increased. The development of agricultural activities and the growing population during this period increased the use of fire for cooking food and burning for cultivation and land fertilization purposes. During 2800–2600 cal yr BP, a warm/moister climate prevailed and was associated with a high degree of pedogenesis and vegetation cover density, evident at 2700 cal yr BP. Fires may have contributed to human survival by enabling the cooking of food in the warm and wet climate. In the period since 2000 cal yr BP, fires linked to agriculture may have led to increased biomass burning associated with agricultural activity.

1. Introduction

The Horqin dunefield, situated in a mid-latitude ecotone in northern China, a semi-arid zone, is influenced by both the East Asian monsoon and the Westerlies (Fig. 1). Therefore, the dunefield is sensitive to variations in monsoon intensity. Archaeological records from this region indicate that human occupation has been continuous during the Holocene period (Yang et al., 2012).

In past decades, a great number of paleoclimatic scientists have investigated abundant geological records (including lake sediments and loess/paleosol sediment) near the Horqin dunefield in attempts to construct a detailed history of the East Asian monsoon and climate change variations during the Holocene (An et al., 2000; Dykoski et al., 2005; Janssen et al., 2012; Jiang et al., 2006; Jin et al., 2004; Spiro et al., 2009; Wen et al., 2010a, 2010b; Xiao et al., 2002). These studies have yielded a variety of results. Some studies have indicated that wet climate conditions appeared during the early Holocene (An et al., 2000; Jiang et al., 2006). An et al. (2000) proposed that the East Asian summer monsoon precipitation reached a peak in northeastern China approximately 10,000–8000 yr ago. Jiang et al. (2006) suggested that the summer monsoon influenced northern China most strongly between 10,500 and 6500 cal yr BP. In contrast, according to other records, the early Holocene was characterized by less rainfall, and the summer monsoon reached a peak during the mid-Holocene. For example, Zhao et al. (2007) concluded that dunes in the region stabilized widely between approximately 7.5 and 2.0 ka and that this dune activity was basically consistent with the timetable of Holocene climatic changes in northeastern China. Based on the archeological and geological evidence, analogous processes of climate change during the Holocene period have been reported by Hu et al. (2002) to have occurred in the Horqin region and the region of the West Liaohe River, i.e., changes from a relative cold and dry climate between 10 ka and 7.3 ka to a warm and wet climate during 7.3–2.8 ka and then a cool and dry climate since 2.8 ka. Because of the debate among many Quaternary scientists concerning climate change in this region during different Holocene periods, detailed records from various sources are required to obtain a clearer understanding of the history of climate change in northern China.

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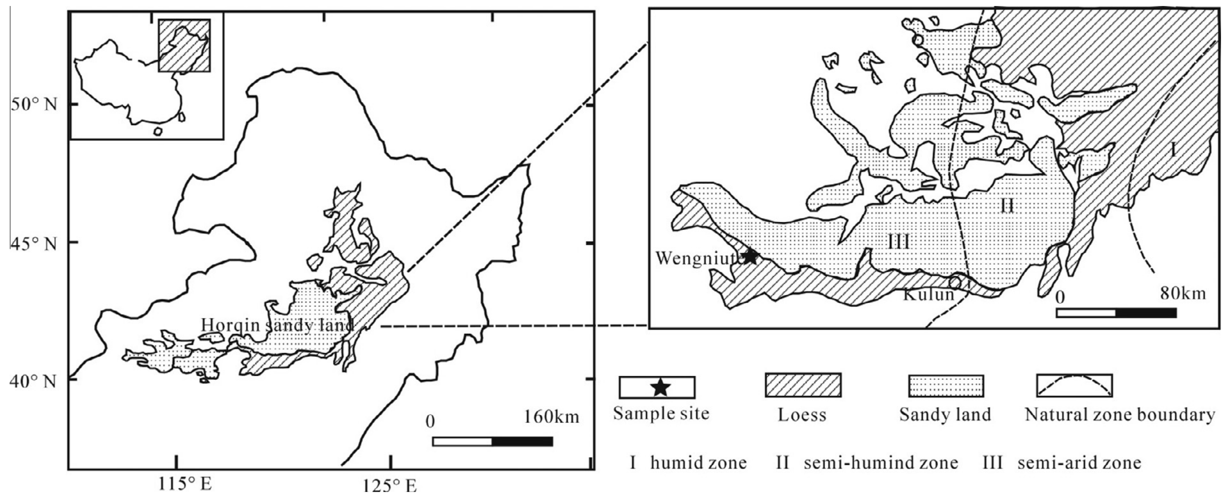

Fig. 1. Location of the Horqin dunefield.

Human activity developed rapidly in this region during the Holocene period, giving rise to the Xiaohexi, Xinglongwa, Zhaobaogou, Hongshan, Xiaoheyan, Lower Xiajiadian, and Upper Xiajiadian cultures (Deng, 1997; Xia et al., 2000; Hu et al., 2002; Mo et al., 2002; Li et al., 2003, 2006). Many studies have been focused on the linkage between Holocene climate change and human activities (Bowman et al., 2011; Carcaillet, 1998; Marlon et al., 2006; Tan et al., 2015; Wang et al., 2013; Whitlock et al., 2007). In the Chinese Loess Plateau in particular, the relationship between fires and climate changes have been discussed on orbital to millennial timescales (Huang et al., 2006; Tan et al., 2015; Wang et al., 2012b; Yang et al., 2001; Zhou et al., 2007). The results of these studies have contributed to our current research on the Horqin dunefield.

Fire occurrence in these mid-arid and arid regions was largely linked to climate change, which also influenced the vegetation types and coverage (Tan et al., 2015; Wang et al., 2012b). Humans are unique in being a fire-making species, so prehistoric human-made fires cannot be negligible. Charcoal, present as combustion residues in sediments (lake and loess), can provide information on past fire history (Ali et al., 2009; Clark, 1988; Huang et al., 2006; Whitlock et al., 2007; Yang et al., 2001). In previous paleoenvironmental work, charcoal and other proxies, e.g., total organic carbon (TOC), magnetic susceptibility, and pollen, have been used to analyze the linkage of fire–climate change–vegetation–human activities in North and South America, Europe, and Australia (Carcaillet, 1998; Huang et al., 2006; Marlon et al., 2006, 2009; Tan et al., 2015). In recent years, many scientists have studied fire charcoal records in East Asia, especially in China (Han et al., 2012; Long et al., 1998; Tan et al., 2015; Wang et al., 2012b, 2013; Zhou et al., 2007). However, more research is required to obtain a clearer understanding of the Asian monsoonal region because of the lack of charcoal data from sedimentary sources.

In this paper, we present detailed climate and anthropogenic records for the last 11,600 cal yr BP derived from loess sediment in Horqin sandy land. Our construction provides a detail history of Holocene climate change in this region. The relationship between climate and human activities is also discussed.

2. Study area

The Horqin dunefield is located in southeastern Inner Mongolia, in the transition zone between the northeastern Chinese plains and the Inner Mongolian Plateau (location: 42°41′–45°45′N, 118°35′–123°30′E) (Fig. 1). This region is approximately 400 km northeast of Beijing, with an area of approximately 50,000 km^2 and an elevation range of 180–650 m above sea level. In the summer, the dominant wind is southeasterly and brings humid air masses from the Pacific Ocean. In the winter, the prevailing wind is northwesterly, and the climate is cold and dry. This region is characterized by a continental monsoon climate. The mean annual temperature varies between 5.8 and 6.4 °C, and the mean annual precipitation varies between 343 and 451 mm.

Horqin Sandy Land sits in the Western Liaohe River Basin in northeastern China, which is fed by the Xar Moron River and its tributaries, the Laoha River and the Jiaolai River. Numerous archeological studies indicate that the Western Liaohe River Basin was one of the cradles of ancient Chinese civilization (An, 1998; Li et al., 2006).

3. Materials and methodology

3.1. Section

The loess and paleosol samples used in this study were taken from the loess/paleosol section (34°34′N, 109°32′E), near Xinwopu Village, Jiefangyingzi Town, Wengniute County, Inner Mongolia. The section is situated in a flat highland located on the edge of the southern Horqin dunefield, where savanna develops. Our profile also sits downwind of the Horqin dunefield, so aeolian deposition can reflect the occurrence of dust storms and climate changes in this sandy terrain.

The thickness of the loess/paleosol sequence is approximately 2.94 m in total. The upper 10 cm is a farmed soil layer, and the rest is a silt layer. A detailed description of the stratigraphy was made through field observations of the color and texture (Fig. 2; Table 1).

The section was sampled at depth intervals of 2 cm, and a total of 148 samples were obtained. The samples were named WNT-2011-3 through WNT-2011-150 (Fig. 2).

3.2. Indices of paleoenvironment and measurement methods

The thermal/optical reflectance method (TOR) has been used in previous studies to quantify black carbon (BC) and OC (organic carbon) content based on the preferential oxidation of OC and BC compounds at different temperatures. The method relies on the fact that organic compounds can be volatilized from sample deposits in a helium (He) atmosphere at low temperatures, while BC is not oxidized and removed. Interagency monitoring of protected visual environments (IMPROVE) is a protocol that is commonly

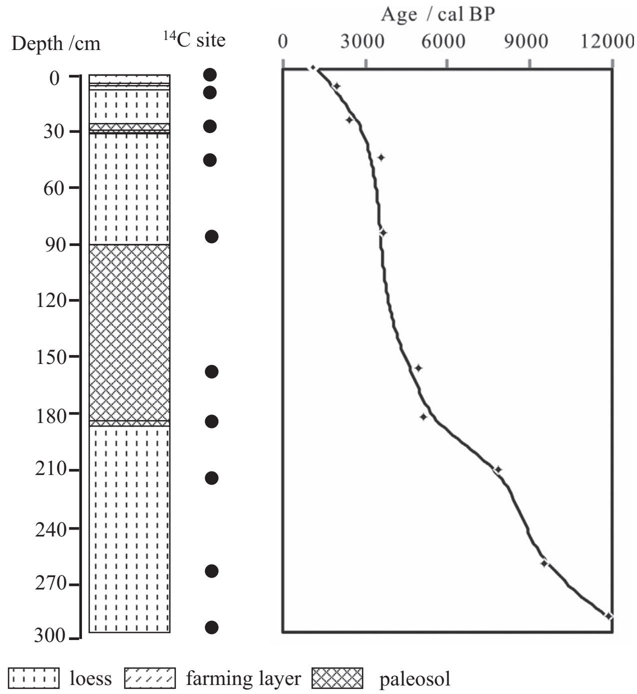

Fig. 2. Loess/paleosol stratigraphic and age–depth model of the section in the study area.

Table 1
A description of the loess/paleosol sequence at the Wengniute site (WNT).

Depth (cm)	Stratigraphic subdivision	Pedological description
0–10	Farming layer	Silt, porous, dull yellow,
10–28	Loess	Silt, pale yellow
28–30	Paleosol	Dark brown, silt
30–90	Loess	Pale yellow, silt, some black carbon
90–190	Paleosol	Red brown, silt,
190–294	Loess	Silt, pale yellow, some $CaCO_3$ concretion

used in black carbon analysis (Chow et al., 2004; Han et al., 2007a, 2009a, 2009b, 2008, 2007b; Wang et al., 2012a).

The instrument used in this study was a DRI Model 2001 Thermal/Optical Carbon Analyzer. Carbonate and silicate were extracted by adding hydrochloric acid (HCl) and hydrofluoric acid (HF). The pretreatment procedures used are those described by (Mu et al., 2014).

After pretreatment, the residue was filtered on a quartz filter. A 0.526-cm^2 punch from the sample filter was placed in a quartz boat and placed in the sample oven. The carbon compounds were converted to carbon dioxide (CO_2) by passing the volatilized compounds through an oxidizer (heated manganese dioxide, MnO_2). The CO_2 was reduced to methane (CH_4) by the flow being passed through a methanator (a hydrogen-enriched nickel catalyst), and the quantification of CH_4 equivalents was determined using a flame ionization detector (FID).

First, with the oven temperature progressively raised to 120 °C, 250 °C, 450 °C, and 550 °C in a pure helium (He) atmosphere, carbon was evolved from the filter punch, and four OC fractions were produced: OC_1, OC_2, OC_3, and OC_4. Carbon was then evolved from the filter punch in a He/oxygen (O_2) atmosphere (98% He/2% O_2) at 550 °C, 700 °C, and 800 °C, and three BC fractions were produced: BC_1, BC_2, and BC_3. Pyrolyzed organic carbon (POC) was also produced. Duplicate analyses of samples showed that the precisions of BC ($BC = BC_1 + BC_2 + BC_3 - POC$) and OC ($OC = OC_1 + OC_2 + OC_3 + OC_4 + POC$) were 94% and 95%, respectively.

The magnetic susceptibility (MS) and grain size were analyzed at the Institute of Geology and Geophysics, Chinese Academy of Sciences. The MS was measured using a Barrington MS2 magnetic susceptibility meter, using 10-g air-dried samples. Each sample was tested three times, and the average value for each sample was determined.

The grain size distribution was determined using a Master Size 2000 Laser Particle Size Analyzer (Qin et al., 2005; Xiao et al., 2009). Approximately 200 mg of sediment from each air-dried, disaggregated sample was pretreated with 10–20 ml of 30% H_2O_2 to remove organic matter and then with 10 ml of 10% HCl, with the sample solution boiled to remove carbonates. Approximately 2000 ml of deionized water were added, and the sample solution was maintained for approximately 24 h to rinse acidic ions. The sample residue was dispersed with 10 ml of 0.05 M $(NaPO_3)_6$ on an ultrasonic vibrator for 10 min before the grain size analysis. The analysis was performed with a Malvern Instruments Mastersizer 2000 with a size measurement range from 0.02 to 2000 μm.

3.3. Chronology

Twelve radiocarbon samples from this loess/paleosol section were dated using an Accelerator Mass Spectrometry (AMS) system at Beta Analytic Inc., Miami, Florida, United States.

The sample dated was the organic fraction that remained after sieving the sediment to <180 μm to remove any roots or macrofossils and then washing with acid to remove carbonates. To provide radiocarbon determinations that are both accurate and precise, it is necessary to measure the stable isotopes of ^{13}C and ^{12}C and their ratio. This is performed by extracting a small amount of the CO_2 generated during combustion or acid hydrolysis and measuring the $^{13}C/^{12}C$ ratio relative to the Pee Dee Belemnite (PDB) mass spectrometry standard. This ratio was used later in the calculation of the radiocarbon age and error to correct for isotopic fractionation in nature. The parameters used for the corrections were obtained through precise analyses of hundreds of samples taken from known-age tree rings of oak, sequoia, and fir up to approximately 12,000 BP. Beyond that, back to approximately 42,000 BP, correlations were made using multiple lines of evidence. These older data are nonetheless subjective and should be interpreted conservatively.

The Pretoria Calibration Procedure program was chosen for use in these calendar calibrations. This program uses splines through the tree-ring data as calibration curves, which eliminates a large part of the statistical scatter of the actual data points. The spline calibration allows adjustment of the average curve by a quantified closeness-of-fit parameter to the measured data points. The calibration database used was INTCAL13.

For the WNT Section, the positions of these radiocarbon samples were 0 cm, 10 cm, 28 cm, 48 cm, 88 cm, 118 cm, 160 cm, 186 cm, 214 cm, 250 cm, 264 cm, and 292 cm from the surface of the section (Table 2).

To parameterize this paleoenvironmental information, a precise timescale had to be established (Fig. 2).

4. Results and interpretation

The MS, TOC, grain size distribution, and BC records of the WNT section spanning the last 11,600 cal yr BP were plotted against the calibrated radiocarbon age (Fig. 3).

(1) Fluctuation of the Asian summer monsoon (ASM) during the Holocene period

MS is the proxy most widely used to investigate Quaternary climate change by loess/paleosol sequences on the Loess Plateau

Table 2
AMS radiocarbon dates of samples.

Sample number	Depth (cm)	Dating material	AMS ^{14}C (age/a. BP)	Calibrated ^{14}C age (2σ) (cal a. BP)
WNT-2011I-3	0	Organic matter	1060 ± 30 BP	1170–1050/1040–980
WNT-2011I-8	10	Organic matter	1910 ± 30 BP	1990–1870
WNT-2011I-17	28	Organic matter	2280 ± 30 BP	2430–2420/2360–2340
WNT-2011I-27	48	Organic matter	3250 ± 30 BP	3630–3460
WNT-2011I-47	88	Organic matter	3310 ± 30 BP	3690–3560
WNT-2011I-62	118	Organic matter	3040 ± 30 BP	3380–3260
WNT-2011I-83	160	Organic matter	4290 ± 30 BP	4970–4840
WNT-2011I-96	186	Organic matter	4430 ± 40 BP	5310–5040/5010–4980
WNT-2011I-110	214	Organic matter	6950 ± 40 BP	7940–7790/7770–7760
WNT-2011I-128	250	Organic matter	10,390 ± 50 BP	12,540–12,100
WNT-2011I-135	264	Organic matter	8380 ± 40 BP	9530–9440
WNT-2011I-149	292	Organic matter	10,150 ± 50 BP	12,040–11,620

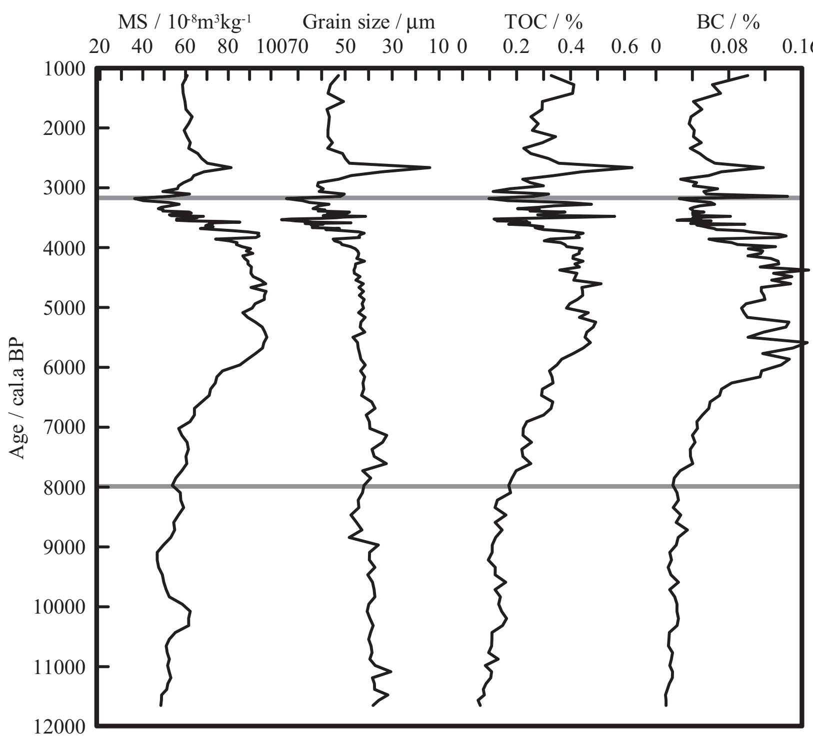

Fig. 3. BC, MS, TOC, and grain size distribution for the section in the study area.

(Balsam et al., 2004; Heller and Tungsheng, 1986). The MS record indicates changes in the intensity of pedogenesis resulting from precipitation changes connected with summer monsoonal climatic variations (An et al., 1991; An and Xiao, 1990).

As Fig. 3 shows, lower MS values ($\sim 55 \times 10^{-8}$ m^3 kg^{-1}) occurred during the early Holocene, from 11,600 to 8000 cal yr BP, indicating low pedogenesis under the arid climate conditions prevalent during that era. The MS record begins to increase slightly over approximately 8000 cal yr BP and reaches its highest value ($\sim 100 \times 10^{-8}$ m^3 kg^{-1}) ca. 5600 cal yr BP, subsequently declining ca. 3900 cal yr BP. During the interval of 3900–3200 cal yr BP, the MS values decreased sharply, with five dramatic centennial-scale fluctuations, and reached their lowest value ($\sim 40 \times 10^{-8}$ m^3 kg^{-1}) ca. 3200 cal yr BP. The fluctuations in the MS values suggest a warmer and moister climate, and the ASM reached a maximum during the interval between 8000 and 3200 cal yr BP. The decrease in the MS values ca. 3900 cal yr BP may have corresponded to climatic cold events ($\sim$4000 years BP) during the Holocene (Huang and Pang, 2002). The sharp decline in the MS values during the interval of 3900–3200 cal yr BP suggests a climatic deterioration. A high peak value of MS at a depth of approximately 30 cm (at 2700 cal yr BP) was detected, indicating a rapid rise in both temperature and precipitation. The MS values then decreased, indicating that the climate became drier and colder after the sudden climate warming at approximately 2700 cal yr BP.

(2) Variations in vegetation coverage in the Holocene

The TOC content of aeolian deposits can be used as an indicator of vegetation cover, and vegetation cover becomes more dense when the climate is more humid. Therefore, the TOC can be linked to the summer monsoon intensity: an increase in the TOC content is associated with an increase in the intensity of the summer monsoon (Xiao et al., 2002; Zhou et al., 1996).

As Fig. 3, the fluctuation in the TOC results for the Holocene was also characterized by three stages. During the interval between 11,600 and 8000 cal yr BP, the TOC value was low ($\sim$0.15%). It then exhibited an increasing trend until 5600 cal yr BP, reached a high value of 0.45%, and declined to 0.3% at approximately 3900 cal yr BP. The interval of 3900–3200 cal yr BP was also characterized by five dramatic centennial-scale TOC fluctuations. The TOC content then reached its lowest value at approximately 3200 cal yr BP. Between 2800 and 2600 cal yr BP, the TOC value increased dramatically. Subsequently, the TOC values declined, and then remained at a low level. The fluctuations in the TOC values indicate changes in vegetation and climate in the study area during the Holocene.

The vegetation coverage was low between 11,600 and 8000 cal yr BP and then increased ca. 8000 cal yr BP. Between 8000 and 3200 cal yr BP, the greater density of vegetation coverage was associated with the climate being warmer and more humid, which is also one reason why the Holocene optimum possibly occurred within this period. Climatic "deterioration" events (~4000 yr BP) might also have influenced the vegetation coverage, because the lowest level of vegetation was at 3900 cal yr BP. Vegetation coverage during the interval of 3200–1160 cal yr BP was at a relatively low level, except during 2800–2600 cal yr BP.

(3) Variations in the Asian winter monsoon (AWM) in Holocene

The grain size distribution of the loess/paleosol sequence in the Chinese Loess Plateau can be used to describe paleoclimate change and has long been used as a proxy of AWN (An et al., 1991; Ding et al., 2001; Qin et al., 2005). In addition, changes in the grain size record can reflect fluctuations between cold/warm and dry/wet conditions. Sun and Ding (1998) and Sun et al. (1999) used grain size distributions to study environmental evolution in the desert–loess transition zone.

As Fig. 3 shows, the fluctuation trends in the grain size distributions since 6000 cal yr BP have been different from those of the MS and OC. However, the differences are not easily explained, because grain size distributions are influenced by many factors in sandy regions, including the distance from the source, the wind speed and direction, and others.

The grain size values exhibited an increasing trend, with five significant fluctuations, during the interval of 3900–3200 cal yr BP, reaching their peak values ca. 3200 cal yr BP. During the late Holocene, the grain size values reached their lowest levels ca. 2700 cal yr BP and then begin to increase.

The fluctuation in the AWM during the early Holocene cannot be explained clearly on the basis of the grain size distribution record and requires further study in the future. Since 6000 cal yr BP, the intensification of AWM has been low, although it began to strengthen ca. 3900 cal yr BP. After five fluctuations, the AWM reached its peak level ca. 3200 cal yr BP. During the late Holocene, the AWM decreased sharply to its lowest value and then began to increase.

(4) Variation in BC

The BC preserved in loess sediments can be used as a record of changes resulting from occurrences of fire, which can be caused by changes in climate, vegetation coverage, and human activities.

The trends exhibited by the BC content were similar to those of the TOC values. At approximately 8000 cal yr BP, the BC values began to increase gradually and reached their highest value (~0.16%) ca. 5600 cal yr BP. During the interval of 5600–4000 cal yr BP, the BC content fluctuated between 0.1% and 0.16% and then suddenly decreased to a lower value (~0.06%) ca. 3900 cal yr BP. The BC record between 3900 and 3200 cal yr BP was characterized by a decreasing trend with five dramatic centennial-scale fluctuations, a subsequent sharp decline, and the lowest value being reached at approximately 3200 cal yr BP. After that time, the BC record was characterized by a high-amplitude fluctuation with a high-value peak occurring approximately 27,007 cal yr BP and a subsequent slight decreasing trend.

The lower values of BC between 11,600 and 8000 cal yr BP, can be attributed mainly to the vegetation coverage. The high-frequency BC variation since 8000 cal yr BP may have been influenced mainly by climate change and human activities.

5. Discussion

5.1. Holocene climate change in the Horqin dunefield

Based on the data (Fig. 3), three intervals of time can be considered: the early Holocene (11,600–8000 cal yr BP), the mid-Holocene (8000–3200 cal yr BP), and the late Holocene (3200–0 cal yr BP) (Dykoski et al., 2005; Tan et al., 2015). Analyses of grain size, MS, and TOC content revealed that there have been many dry/cold and warm/moist climate cycles in the Horqin area during the Holocene. A warm/moist climate is associated with a more intense ASM, with a high degree of pedogenesis and vegetation cover density.

(1) The early Holocene

During the period from 11,600 to 8000 cal yr BP (the early Holocene), the degree of pedogenesis and the vegetation coverage were low. Analysis of the total organic carbon (TOC) and total inorganic carbon (TIC) during the early Holocene indicates that the Dali Lake expansion was due to snow/ice melt input, rather than monsoon precipitation, because of the dry climatic conditions and weak monsoonal precipitation (Xiao et al., 2008) (Fig. 4). Based on studies of the drill core record from Dabusu Lake, Li et al. (2000) and Jie et al. (2001) argued that, during the period from 10,450 to 7260 cal yr BP, the lake level was high, which may also have been due to snow/ice melt input. These findings support the notion that the climate of the study area was characterized by less rainfall during the early Holocene.

However, there are also findings from some other studies that are inconsistent with ours. An et al. (2000) reconstructed the summer monsoon record on the basis of pollen profiles from Qindeli in northeastern China and determined that the Holocene optimum in northeastern China reached a maximum between 10,000 and 8000 yr ago. Based on an analysis of pollen from Bayanchagan Lake in Inner Mongolia, Jiang et al. (2006) found that a warmer and moister climate prevailed beginning ca. 11,000 cal yr BP. The period of 10,500–6500 cal yr BP was strongly influenced by the ASM (Fig. 4).

(2) The mid-Holocene

From approximately 8000 cal yr BP onwards, the ASM began to increase, and the climate became warmer and moister; at approximately 6000 cal yr BP, the ASM reached its peak. The period from 3900 to 3200 cal yr BP was characterized by five centennial-scale climate fluctuations, and the ASM intensity decreased to its minimum at ca. 3200 cal yr BP. The Holocene optimum in this region possibly occurred during this period.

(3) The late Holocene

During the period 2800–2400 cal yr BP, a warmer and moister climate was associated with a more intense EASM and a high degree of pedogenesis and vegetation cover density at approximately 2700 cal yr BP. Subsequently, the EASM intensity decreased, and the climate became drier and colder.

Our results are consistent with that of previous studies on Horqin sandy dunefield. Based on optical dating of Holocene sandy dunes in Horqin, some scientists found that dunes solidified and soils developed during the mid-Holocene, implying that the

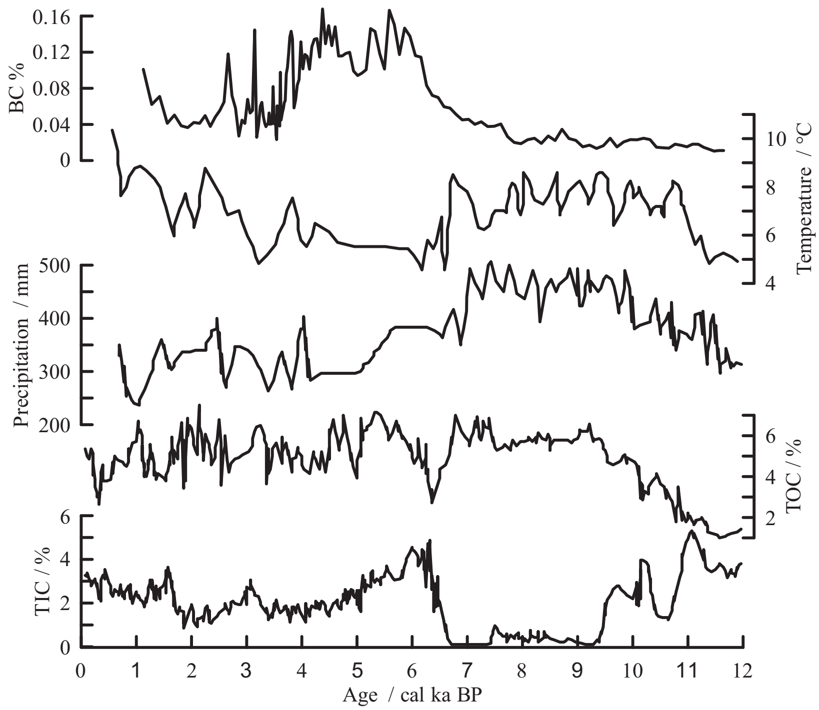

Fig. 4. Comparison of concentrations of total organic carbon (TOC, %) and total inorganic carbon (TIC, %) from Lake Dali (Xiao et al., 2008); the variations in precipitation and temperature are for Lake Bayanchagan (Inner Mongolia) (Jiang et al., 2006; Jiang and Liu, 2007); and BC content (BC%) from Horqin profile.

climate was warm and moist, and the summer monsoon strongly influenced this region during this period. During the late Holocene, re-mobilization of dunes occurred due to the weak summer monsoon (Yang et al., 2012; Zhao et al., 2007). Hu et al. (2002) also believed that the climate was warm-wet during 7.6–2.8 ka, and had been dry since 2.8 ka, on the basis of the archaeological and geological records.

Our profile is located downwind of the Horqin dunefield, and aeolian deposition can reflect the occurrence of dust storms in sandy areas. Qindeli is located in Heilongjiang, and Banyanchagan is located in the Otindag sandy area in southern Inner Mongolia. The intensity of the influence of the Asian monsoon may be different for these different regions. We speculate that regional differences may have arisen from an increase in evaporation over the Horqin Desert during the early Holocene. An et al. (2000) have suggested that the Holocene optimum may be asynchronous in different regions of China.

5.2. Linkage with monsoon climate change, vegetation, and human activity

Vegetation and climate change are likely to affect BC as a result of biomass burning. Human activity developed rapidly in the study region during the Holocene period. Frequent large fires have been linked to human activity, which may be another important reason for the increase in the BC content. Therefore, natural and anthropogenic fire can be presumed to have affected the BC content in our study section.

The BC records from our study section began to increase ca. 8000 cal yr BP. High values of BC appeared during the mid-Holocene, from 6000 to 4000 cal yr BP. After 3200 cal yr BP, a peak value occurred during the interval between 2800 and 2600 cal yr BP.

In previous studies, natural fires have been found to occur frequently and BC content values have been found to be high under arid and cold climate conditions (Wang et al., 2005). However, the findings of our study are not completely consistent with those of previous studies in this regard. During the early Holocene, based on the low MS values, the climate appears to have been dry and cold, and the low BC values indicate that fire activities were not frequent. Natural fires may occur frequently in cold arid climates, but the lower vegetation cover suggested by the OC values during this period may have influenced the extent of fire. This may be the reason why the BC values were low during the early Holocene.

During the mid-Holocene (the “Holocene optimum period”), the climate became warmer and wetter, and the vegetation coverage became very high. Natural fire does not occur frequently in moist climates. However, anthropogenic fires may have contributed to BC preservation during this period because of the development of human activities (Hu et al., 2002). During the period from 6000 to 5000 cal BP, the Hongshan culture, a significant archeological culture in China, arose. Tillage agriculture became dominant during this cultural period. During the interval of 5000–3900 cal yr BP, the Xiaoheyan culture replaced the Hongshan culture. Even though the Hongshan culture declined and extreme event happened at around 3900 cal yr BP, agriculture remained an important part of human activities. The higher fire occurrence and BC content were caused mainly by the cooking of food and slash-and-burn cultivation. Under the sharp decline of the monsoon climate ca. 3200 cal yr BP, human activities changed from developed farming to pastoralism, so the intensity of slash-and-burn cultivation decreased. Therefore, the BC produced by anthropogenic fires declined. Lower vegetation coverage may also have influenced the fire extent, which in turn affected the BC content.

During 3200–1160 cal yr BP in the late Holocene, human activity in the region was mainly based on pastoralism. Between 2800 and 2600 cal yr BP, the number of human settlements in the region increased, and the population may also have grown significantly, because the climate was warm and moist. Fire may have contributed to human development in the region by enabling the cooking of food. Beginning ca. 2000 cal yr BP, the climate became relatively cold and dry. The high OC content during this period may have been associated with the rate of OC decomposition under arid climate conditions. With rapid population growth, cultivation became more intensified as humans from the Central Plains migrated north to the Horqin region. Fire linked to agriculture may have led to an increase in biomass burning.

6. Conclusions

Based on the results of analyses of paleoclimate proxies (including MS, TOC, and grain size distribution) in loess sediments in the Horqin dunefield, we were able to characterize climate changes in the region during the Holocene and their linkages to fire–climate–human activities.

Before 8000 cal yr BP (the early Holocene), the climate of the region was mainly dry. Limited vegetation coverage during this period may have limited the extent of fire. The Holocene optimum period in this region possibly occurred between 8000 and 3200 cal yr BP. During this period, the summer monsoon influenced this region quite strongly, and the climate was warm and wet. Natural fire does not occur frequently in a moist climate. More frequent occurrence of fire can therefore be attributed mainly to the cooking of food and slash-and-burn cultivation associated with the development of human civilization in the region. Fire may have contributed to human development by enabling the cooking of food in the warm and wet climate that prevailed in the region during the interval from 2800 to 2600 cal yr BP. Since 2000 cal yr BP, fire linked to agriculture may have led to increased biomass burning associated with agriculture.

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