Role of the mid-Holocene environmental transition in the decline of late Neolithic cultures in the deserts of NE China

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A B S T R A C T
The mid-Holocene environmental transition was characterised by global cooling and the abrupt weakening of the Northern Hemisphere monsoon systems. It is generally considered the key driver of the collapse of several mid-Holocene agricultural societies, on a global scale. However, only a few previous studies have tried to verify the climatic origin of the collapse of these societies, using the compilation of spatiotemporal data at a large scale. Especially, the nature of mid-Holocene human-environment interactions in the climatically-sensitive margin of the East Asian summer monsoon front remains to be thoroughly understood. However, a systematic compilation of archaeological data at a regional scale can be used to verify the role the mid-Holocene environmental transition played in the collapse of late Neolithic cultures in China. Here, we present a regional compilation of Holocene records from sub-aerial sedimentary deposits, lake sediments, and archaeological sites in the deserts of NE China and the adjacent regions to explore human-environment interactions during the mid-Holocene. Comparison of the records of Holocene climate change with the evolution of archaeological sites reveals that the mid-Holocene environmental transition resulted in ecosystem degradation in the deserts of NE China, rendering these areas much less habitable. Faced with substantially increased environmental pressures, the late Neolithic inhabitants used several subsistence strategies to adapt to the environmental transition, including change in agricultural practices and ultimately migration. Overall, our results support the view that a widespread mid-Holocene drought destroyed the rain-fed agricultural and/or plant-based subsistence economies, ultimately contributing to the collapse of late Neolithic cultures in NE China.

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1. Introduction
The global climate during the current Holocene interglacial is usually considered to be substantially warmer than that of the Younger Dryas event (Dansgaard et al., 1989). Moreover, it has provided a relatively stable environmental context for the growth and development of human society. However, when thresholds of the Earth system were crossed (Alley et al., 2003), abrupt and widespread climate changes with major impacts on social-ecological systems occurred repeatedly during the Holocene (Weiss et al., 1993; O’Brien et al., 1995; Alley et al., 1997; Cullen et al., 2000; deMenocal et al., 2000a; Thompson et al., 2002; Morrill et al., 2003; Staubwasser et al., 2003; Marchant and Hooghiemstra, 2004; Mayewski et al., 2004; Alley and Ágústsdóttir, 2005; Booth et al., 2005; Drysdale et al., 2006; Wanner et al., 2008, 2011; Moros et al., 2009; Zhao et al., 2009; Macdonald, 2011; de Boer et al., 2014; Sarkar et al., 2015; Shanahan et al., 2015; Solomina et al., 2015; Lillios et al., 2016; Saraswat et al., 2016). In addition, severe climatic deterioration has often been regarded as the determining factor leading to the collapse of several ancient agriculturally-based civilizations (Hsu, 1998; Weiss and
Bradley, 2001). Clearly, detailed spatiotemporal information concerning abrupt and widespread climate change is important for improving our understanding of climate forcing and human responses during the Holocene, and for appraising the possible consequences of extreme climate events under a global warming scenario.

The mid-Holocene environmental transition has attracted much attention from climate scientists and archaeologists, especially Holocene event 3 (HE3, ~4.2 ka), as termed by Bond et al. (1997), because it marks the termination of the Holocene climatic optimum (Perry and Hsu, 2000) and the initiation of the Neoglacial (Solomina et al., 2015). Existing records reveal that ocean surface temperatures decreased by ~1–2°C during HE3 (Bond et al., 1997; deMenocal et al., 2000b), which persisted for ~300–600 years (Cullen et al., 2000; Perry and Hsu, 2000); while a total duration of up to ~1500 years was recorded in the North Atlantic (Bond et al., 1997, 2001). In addition, HE3 was punctuated by a series of geologically-rapid global cooling and/or dry events (Morrill et al., 2003; Marchant and Hooghiemstra, 2004; Booth et al., 2005; Shanahan et al., 2015) which were superimposed on the gradual drying trend of the mid-Holocene (Morrill et al., 2003; Majewski et al., 2004; Wanner et al., 2008, 2011; Roberts et al., 2011). Associated with this mid-Holocene cooling event was an increase in eolian dust (Staubwasser et al., 2003; Madella and Fuller, 2008; Macdonald, 2011; Giosan et al., 2012; Ponton et al., 2012; Leipe et al., 2014; Menzel et al., 2014; Prasad et al., 2014a), Mesopotamia (Weiss et al., 1993; Cullen et al., 2000; deMenocal, 2001), China (Jin and Liu, 2002; Wu and Liu, 2004; An et al., 2005; Innes et al., 2014; Zeng et al., 2016; Zhu et al., 2017) and Egypt (Thompson et al., 2002; Marshall et al., 2011; Phillips et al., 2012).

In high latitudes of the Northern Hemisphere, a peak in detrital carbonate flux on the East Greenland Shelf at 4.7 ka signaled both the beginning of the Neoglacial and a southward expansion of the Arctic sea ice (Jennings et al., 2002). In Europe, a 4.2 ka drought event is recorded by multi-proxy data from a cave flowstone in Italy (Drysdale et al., 2006); diatom assemblages from Montcortès Lake in the Iberian Peninsula indicate that lake levels were lower during a pronounced dry interval from 2360 to 1850 BCE (Scussolini et al., 2011); a decrease in deciduous Quercus and Pinus pinea-type percentages in Southwest Iberia at ~4.2 ka suggests an abrupt shift to dry conditions (Lillios et al., 2016); and a synthesis of records from the Mediterranean reveals an unusually dry interval from 4.5 to 3.9 ka (Mercuri et al., 2011; Roberts et al., 2011). Evidence from eastern tropical Africa indicates a shift to drier conditions at ~4.0 ka (Marchant and Hooghiemstra, 2004), although at this time wetter conditions were maintained in West Africa (Russell et al., 2003) and in parts of South America (Marchant and Hooghiemstra, 2004); and magnetic and geochemical data from the Holocene sediments of Lake Tana in northern Ethiopia confirm that the driest interval occurred at ~4.2 ka (Marshall et al., 2011), which is also identified in the Mount Kilimanjaro ice core (Thompson et al., 2002) and in the Mauritian lowlands (de Boer et al., 2014). In eastern Russia, evidence of a cold spell between 4.5 ka and 3.5 ka is provided by a multi-proxy record from Two-Yurts Lake (Hoff et al., 2015); A severe centennial-scale megadrought in mid-continental North America occurred between 4.1 and 4.3 ka (Booth et al., 2005).

In Asia, a record of the concentration of eolian minerals in core M5–422 from the Gulf of Oman reveals an abrupt increase in the content of eolian dolomite and CaCO3 at ~4.1 ka, indicating the onset of dry conditions in Mesopotamia (Cullen et al., 2000); a planktonic oxygen isotope record from core 135A in the Arabian Sea shows a shift to heavier δ18O values at ~4.2 ka, indicating dry conditions in the Indus valley (Staubwasser et al., 2003); multiple lines of evidence from Loran Lake indicate that the driest conditions in central India occurred from 4.8 to 4.0 ka (Prasad et al., 2014b; Sarkar et al., 2015), in agreement with records from Wadhwana Lake of very dry conditions at ~4.3 ka. (Prasad et al., 2014a); a Holocene pollen record from the northwestern Himalayan lake Tso Moriri suggests that the prolonged Holocene trend towards aridity was punctuated by an interval of increased dryness between ~4.5 ka and 4.3 ka (Leipe et al., 2014); after ~5 ka, the forest vegetation in the Mongolian Altai began to give way to a predominance of open vegetation types as the precipitation amount decreased from ~450 to 550 mm/yr to 250–300 mm/yr (Rudaya et al., 2009); the stable oxygen isotopic composition of authigenic lacustrine calcite from Xingyun Lake, in Yunnan Province in China, recorded a substantial positive shift from 5.0 to 4.3 ka, which is coincident with aridity in India and the Tibetan Plateau (Hillman et al., 2017); vegetation history during the Baodun period (~4.5–3.7 ka) in the Chengdu Plain reveals that the dry and cool climate conditions occurred at this period (Zeng et al., 2016); an abrupt climatic transition from wet to dry conditions at ~4.1 ka in the western part of the Chinese Loess Plateau (An et al., 2005), and an exceptional cold event at 4.6–4.3 ka in Hebei Province (Jin and Liu, 2002), indicate short-duration cold and dry events during the mid-Holocene in northern China; at ~4.2 ka there was an increase in cold-tolerant trees at Taihu Lake in the Yangtze coastal plain (Innes et al., 2014) and the climate of the northern Chinese region became rather dry and cold (Zhu et al., 2017); and a rapid and catastrophic fall of the groundwater table of up to ~30 m in the Otindag Desert at ~4.2 ka marks the onset of irreversible desertification in northern China (Yang et al., 2015).

Furthermore, several comprehensive reviews at a regional or global scale of Holocene glacier fluctuations (Solomina et al., 2015) and Holocene climate changes (An et al., 2006; Wanner et al., 2008, 2011; Rudaya et al., 2009; Zhao et al., 2009; Zhao and Yu, 2012; Wang and Feng, 2013) suggest that various climatic proxies recorded a cool and/or dry event in middle to low latitudes of Eurasia at ~5–4 ka. In addition, the wet status during this interval was confirmed in high latitudes of Eurasia (e.g., northern Xinjiang, the northern Mongolian Plateau, the Lake Baikal region and western Russia) as evaporation decreased (Rudaya et al., 2009).

Collectively, these cool and/or dry events in monsoon-influenced regions demonstrate that from 5 to 4 ka a significant large-scale drought in middle to low latitudes of the Northern Hemisphere was a primary response to an interval of weak monsoon strength. The consensus indicates that the mid-Holocene weak monsoon likely resulted from interacting ocean-atmosphere processes in the western tropical Pacific and the equatorial Indian Ocean, such as the El Niño Southern Oscillation (ENSO) (Moy et al., 2002; Marchant and Hooghiemstra, 2004; Macdonald, 2011) and the Indian Ocean Dipole events (Abram et al., 2007; de Boer et al., 2014); and from the southward migration of the Inter tropical Convergence Zone (ITCZ, Haug et al., 2001; Wanner et al., 2008; Abram et al., 2009; Sarkar et al., 2015; Shanahan et al., 2015) or cold climatic conditions at high latitudes of the Northern Hemisphere (Bond et al., 1997; Menzel et al., 2014; Fan et al., 2016). In addition, a regional interpretation considered this to be an irreversible region-wide hydrologic event (Yang et al., 2015). Ecosystem degradation was one of the most important effects of HE3, resulting in the abandonment of dwellings and the migration of Neolithic peoples to more habitable areas (Hsu, 1998; Perry and Hsu, 2000; Giosan et al., 2012; Jia et al., 2016), and the forced modification of agricultural systems such as the increased cultivation of drought-tolerant crops like millet (Giosan et al., 2012) and the spread of wheat in East Asia (Dodson et al., 2013; Chen et al., 2015a); Giosan et al. (2012) suggested that the effects of HE3 caused a decrease in the total settled area and in settlement sizes in the Indus Valley since 3.9 ka. In addition, the combination of decreased agricultural productivity and increased population in habitable areas triggered...
regional warfare during HE3, contributing to the decline and demise of several agriculturally-based civilizations.

Previous studies have used well-dated and high-resolution climatic sequences to decipher the relationship between late Neolithic cultural collapse and the mid-Holocene environmental transition. Several researchers argue that previous studies directly link the effects of the mid-Holocene environmental transition by one or multiple sequences to the late Neolithic cultural collapse. However, only a few studies have tried to verify comprehensively the mid-Holocene climatically-forced nature of the cultural collapses, using the compilation of spatiotemporal data at a large scale (An et al., 2005; Leipe et al., 2014; Lillios et al., 2016; Jia et al., 2017). Consequently, further work is needed to fully understand and explore how the mid-Holocene environmental transition affected civilizations in sensitive ecological environments, such as the desert-grassland border in the deserts of NE China. A compilation of archaeological data at a regional scale can be used to verify some of the hypotheses concerning past human-environment interactions in ecologically fragile environments (Hosner et al., 2016). For example, An et al. (2005) demonstrated that a decrease in the number of archaeological sites at ~4.0 ka in the western part of the Chinese Loess Plateau was a direct response to widespread aridification, with a shift from settled, rain-fed agriculture to migratory pastoralism. However, this work emphasized the cultural response within a small area, and it did not consider archaeological signatures at a large scale, such as those associated with, for example, long-term migration. Clearly, more work is needed which undertakes a large-scale compilation of archaeological data. The present research seeks to investigate human-environment interactions in the deserts of NE China during the mid-Holocene, using a regional compilation of Holocene records from sub-aerial sedimentary deposits, lake sediments, and archaeological sites in these deserts and the adjacent regions.

2. Regional setting

The deserts of NE China are in the northern margin of the region of influence of the East Asian summer monsoon (EASM); from east to west they are the Hulun Buir, Horqin, Otindag, Hobeq and Mu Us deserts (Fig. 1). They are quite different from the large deserts situated to the west of the north-south-oriented Helan Mountains (~106°E), because the current climate of these deserts is semi-arid, dominated by a wet, warm EASM and a dry, cold East Asian winter monsoon (EAWM, Fig. 1). The annual precipitation of the entire area of these deserts decreases from 400 to 500 mm in the southeast to 200 mm in the northwest (Ren et al., 1985). EASM precipitation, from June to September, contributes as much as 65–75% to total annual precipitation (Liu, 2010). The natural vegetation of these deserts is temperate steppe (Ren et al., 1985), with for example Needlegrass (Stipa sp.) and Chinese wild rye (Aneurolepidium chinense). As an agro-pastoralism transitional zone, these deserts are a crucial area of cultural interaction and dispersal. In addition, several rivers flow through them, including the Yellow River and the Xilamulun, Xiliaohe and Hailar Rivers, which support irrigation agriculture which enabled the region to be one of the cradles of ancient Chinese civilization (Liu and Chen, 2011).

3. Material and methods

3.1. Holocene dated records from sub-aerial sedimentary deposits in the deserts of NE China

EASM precipitation has a major effect on the vegetation distribution and dune activity in the deserts of NE China (Yang et al., 2011). Abundant EASM precipitation favors plant growth and the development of paleosols and lakes, while a deficit of EASM precipitation results in dune reactivation; moreover, reactivated dunes are the major source of loess deposits in the margin of the deserts of NE China. Thus, paleosols and lacustrine and peat deposits (which are the sources of dated records of environmental stability in this research) are characteristic of intervals of relatively warm and wet climate; and conversely, associated with eolian sand and loess (the source of dated records for a sediment accumulation state) are a dry and cold climate, mainly due to the increased aridity resulting from reduced EASM precipitation and/or effective moisture (Lu et al., 2005; Mason et al., 2009). Furthermore, during the last two decades, paleoenvironmental and palaeoclimatic studies in these deserts have yielded a very large number of dated records indicating accumulation and environmental stability, corresponding to dune mobile and stable states, respectively (Lu et al., 2011, 2012).

It should be noted that (i) we selected published actual ages determined by radiocarbon or luminescence methods, (ii) used one dated record when multiple ages or similar ages were measured from the same layer at a site, and (iii) rejected ages that were not in stratigraphic order. This resulted in a total of 811 published dated records (529 dated records indicating dune mobile states and 482 dated records indicating dune stable states) from 268 sections (Fig. 1). Detailed information on these dated records is listed in Table 1. In addition, uncalibrated radiocarbon ages were calibrated to calendar years before present (BP) (BP = 1950 CE) using the Calib Rev 7.0.4 radiocarbon age calibration program (Stuiver and Reimer, 1993) with the IntCal13 curve (Reimer et al., 2013), prior to statistical analysis. The dated records are plotted as histograms with a bin width of 200 years, rather than with the Gaussian distribution approach (Singhvi et al., 2001) because in some areas there are intervals for which no dated records are available. The spatiotemporal distribution patterns of these dated records were illustrated using ArcGIS 10.2 with a Universal Transverse Mercator Projection coordinate system, based on the World Geodetic System 1984.

3.2. Holocene lake records from the deserts of NE China and adjacent regions

We compiled published records from 22 lake sections, including paleolake and peat sections, in the deserts of NE China and the adjacent regions (Fig. 1) to assess Holocene hydrological changes driven by variations in EASM precipitation. All the sections are listed in Table 2. A graphical synthesis of the data is used to illustrate the hydrological changes.

3.3. Archaeological data: sources and mapping

A total of 51,074 archaeological sites, ranging mainly from early Neolithic to early Iron Age, and covering most of the regions of China, has been published (Wagner et al., 2013; Hosner et al., 2016; https://doi.pangaea.de/10.1594/PANGAEA.860072). The resulting database increases our understanding of the evolution of Chinese civilization, especially changes in population, agricultural practices and subsistence strategies (Hosner et al., 2016). We used part of the database (30,519 archaeological sites) to establish the spatiotemporal distribution patterns of Holocene archaeological sites in the deserts of NE China and the adjacent regions using ArcGIS 10.2 with a Universal Transverse Mercator Projection coordinate system, based on the World Geodetic System 1984.

The ages of archaeological sites in each map, with a bin width of 1000 years, are constrained by 14C-dated cultural intervals and additional published data. Although the spatiotemporal
4. Results

4.1. Holocene dune activity in the deserts of NE China

The spatiotemporal distribution of states of dune stability and mobility in the deserts of NE China during the Holocene are shown in Figs. 2 and 3. For the five deserts, the numbers of dated records indicating dune mobile states exhibit relatively high values with a decreasing trend from ~12 to 9 ka; they then decrease for the interval of ~9 to 4.5 ka, with a minimum at ~4.5 ka, and gradually increase since ~4 ka. However, the numbers of dated records indicating dune stable states is lower, with an increasing trend from ~12 to 9 ka; they then increase rapidly and maintain relatively high values during the interval from ~9 to 5 ka. From ~5 to 4 ka, a minimum in the number of stable state records is documented. Subsequently, since ~4 ka, the numbers of ages for stable states are relatively high and fluctuate with a large range. In addition, during

<table>
<thead>
<tr>
<th>Region</th>
<th>Luminescence dates</th>
<th>Radiocarbon dates</th>
<th>Total</th>
<th>Number of sites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OSL</td>
<td>IRLS</td>
<td>TL</td>
<td></td>
</tr>
<tr>
<td>Hulun Buir</td>
<td>75</td>
<td></td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>Horqin</td>
<td>204</td>
<td>2</td>
<td>87</td>
<td>293</td>
</tr>
<tr>
<td>Otindag</td>
<td>173</td>
<td>2</td>
<td>42</td>
<td>217</td>
</tr>
<tr>
<td>Hobq</td>
<td>28</td>
<td>7</td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Mu Us</td>
<td>97</td>
<td>2</td>
<td>70</td>
<td>175</td>
</tr>
<tr>
<td>Total</td>
<td>560</td>
<td>2</td>
<td>222</td>
<td>811</td>
</tr>
</tbody>
</table>

Note: '-' indicates no data.
Abbreviations: OSL, Optically Stimulated Luminescence; IRLS, Infrared-stimulated luminescence; TL, Thermoluminescence.
the late Holocene, there are few documented stable state records for the Mu Us desert, which likely results from local human activity involving over-grazing and over-cultivation. The synthesis of states of Holocene dune stability and mobility from the five deserts emphasizes several broad trends: a regional reversal of dune mobility and/or semi-stability (~12–9 ka) to dune stability and paleosol development (~9–5 ka); and spadonic dune re-mobilization beginning at ~5 ka, and dune re-mobilization throughout the entire study region since ~4 ka.

In addition, although Holocene dated records of sub-aerial sedimentary deposits should be documented in all the selected sections in the deserts of NE China, in practice, stratigraphic discontinuities in the various geomorphic units and limitations of the sampling strategies somewhat limit the utility of the data set (Li and Yang, 2016). Thus, the maximum in the number of total dated records is treated as the upper limit of the number of dated records for each time slice in these deserts. Based on this approach, a new proxy, the activation ratio, was calculated, as follows: activation ratio = number of dated records/max [number of total dated records], and it can be used to evaluate the number of occurrences of a potentially reactivated state. The activation ratio has relatively high values from ~12 to 9 ka, lower values from ~9 to 4 ka, and increases gradually since ~4 ka. Comparison of the activation ratio with the spatiotemporal distribution of Holocene dune stable and mobile states in these deserts, leads to the conclusion is that the onset of widespread dune re-mobilization occurred at ~4 ka (Fig. 4).

Table 2
Holocene lake and peat records from the deserts of NE China and the adjacent regions.

<table>
<thead>
<tr>
<th>No.</th>
<th>Site</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Elevation (m a.s.l.)</th>
<th>Archive</th>
<th>Present lake area (km²)</th>
<th>Age range (cal. kyr BP)</th>
<th>Dating method</th>
<th>Number of dates</th>
<th>Proxy</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hulun Lake</td>
<td>49.127</td>
<td>117.506</td>
<td>545</td>
<td>Lake core</td>
<td>2339</td>
<td>11.1–0</td>
<td>AMS¹⁴C</td>
<td>14</td>
<td>GC, GS, OS, P</td>
<td>Xiao et al., 2009a; Wen et al., 2010; Zhai et al., 2011</td>
</tr>
<tr>
<td>2</td>
<td>Dali Lake</td>
<td>43.261</td>
<td>116.604</td>
<td>1226</td>
<td>Lake core</td>
<td>238</td>
<td>11.5–0</td>
<td>AMS¹⁴C</td>
<td>15</td>
<td>Ca, GC, GS, OM, P</td>
<td>Fan et al., 2008, 2009b; Yan et al., 2016, 2017; Wen et al., 2017 Goldsmith et al., 2017a, b</td>
</tr>
<tr>
<td>3</td>
<td>Dali Lake</td>
<td>43.15</td>
<td>116.29</td>
<td>1226</td>
<td>Outcrop 238</td>
<td>16.0–0</td>
<td>OSL, AMS¹⁴C</td>
<td>41</td>
<td>Lithology</td>
<td>Ca, GS, OM, P</td>
<td>Wang et al., 2001; Liu et al., 2002; Guan et al., 2010; Wang et al., in press</td>
</tr>
<tr>
<td>4</td>
<td>Haoluku</td>
<td>42.96</td>
<td>116.75</td>
<td>1295</td>
<td>Outcrop dry</td>
<td>10.3–0</td>
<td>AMS¹⁴C</td>
<td>3</td>
<td>CN, EM, GC, GS, LOI, OM, P</td>
<td>Wang et al., 2001; Liu et al., 2002; Guan et al., 2010; Wang et al., in press</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Haddahure paleolake</td>
<td>42.951</td>
<td>116.794</td>
<td>1295</td>
<td>Outcrop dry</td>
<td>12.2–0</td>
<td>AMS¹⁴C, OSL</td>
<td>13</td>
<td>CN, D, GC, GS, OM</td>
<td>Wang et al., 2001</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Liuzhouwan</td>
<td>42.71</td>
<td>116.67</td>
<td>1365</td>
<td>Outcrop dry</td>
<td>13.5–0</td>
<td>AMS¹⁴C</td>
<td>3</td>
<td>CN, EM, GC, GS, LOI, OM, P</td>
<td>Liu et al., 2002; Wang et al., 2004</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Xiaoniuangang</td>
<td>42.62</td>
<td>116.83</td>
<td>1460</td>
<td>Outcrop dry</td>
<td>10.0–0</td>
<td>AMS¹⁴C</td>
<td>3</td>
<td>Ca, GC, OM, P</td>
<td>Wang et al., 2015</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Xiajinur Lake</td>
<td>42.6</td>
<td>115.47</td>
<td>1225</td>
<td>Lake</td>
<td>3.1</td>
<td>15.6–0</td>
<td>AMS¹⁴C</td>
<td>17</td>
<td>EM, GS, P</td>
<td>Yang et al., 2016</td>
</tr>
<tr>
<td>9</td>
<td>Jiangjunpaozi</td>
<td>42.374</td>
<td>117.47</td>
<td>1490</td>
<td>Outcrop dry</td>
<td>11.5–0</td>
<td>AMS¹⁴C</td>
<td>2</td>
<td>CN, EM, GC, GS, LOI, OM, P</td>
<td>Wang et al., 2004</td>
<td></td>
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<tr>
<td>10</td>
<td>Ulán Nuur</td>
<td>41.737</td>
<td>115.094</td>
<td>1246</td>
<td>Outcrop &lt;8.9</td>
<td>8.6–6.1</td>
<td>AMS¹⁴C</td>
<td>4</td>
<td>CN, EM, GC, GS, LOI, OM, P</td>
<td>Wang et al., 2012a; Jia et al., 2006</td>
<td></td>
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<tr>
<td>11</td>
<td>Bayanchagang Lake</td>
<td>41.65</td>
<td>115.21</td>
<td>1355</td>
<td>Lake core</td>
<td>8.6–6.1</td>
<td>AMS¹⁴C</td>
<td>9</td>
<td>CN, EM, GC, GS, LOI, OM, P</td>
<td>Wang et al., 2012a; Jia et al., 2006</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Bai Nuur</td>
<td>41.643</td>
<td>114.515</td>
<td>1346</td>
<td>Outcrop &lt;2.3</td>
<td>10.6–6.4</td>
<td>AMS¹⁴C</td>
<td>5</td>
<td>CN, EM, GC, GS, OM, P</td>
<td>Wang et al., 2012a; Liu et al., 2010; Wang et al., 2010; Yin et al., 2011</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Anguli Nuur</td>
<td>41.3</td>
<td>114.4</td>
<td>1315</td>
<td>Lake pool</td>
<td>10.9–0</td>
<td>AMS¹⁴C</td>
<td>10</td>
<td>CN, EM, GC, GS, OM, P</td>
<td>Wang et al., 2012a; Liu et al., 2010; Wang et al., 2010; Yin et al., 2011</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Diaojiao Lake</td>
<td>41.3</td>
<td>112.35</td>
<td>1800</td>
<td>Lake pool</td>
<td>0.3</td>
<td>10.2–2.1</td>
<td>¹⁴C</td>
<td>4</td>
<td>P</td>
<td>Shi and Song, 2003</td>
</tr>
<tr>
<td>15</td>
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<td>40.8</td>
<td>113.3</td>
<td>1277</td>
<td>Outcrop Lake pool</td>
<td>8.2–2.2</td>
<td>AMS¹⁴C, OSL</td>
<td>6</td>
<td>EM, GC</td>
<td>Chen et al., 2005, 2010; Chen et al., 2008</td>
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</tr>
<tr>
<td>16</td>
<td>Chasuaqi</td>
<td>40.67</td>
<td>111.12</td>
<td>1000</td>
<td>Outcrop Lake pool</td>
<td>9.1–0</td>
<td>¹⁴C</td>
<td>4</td>
<td>P</td>
<td>Wang et al., 1999</td>
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<tr>
<td>17</td>
<td>Dahai Lake</td>
<td>40.586</td>
<td>112.668</td>
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<td>Lake pool</td>
<td>12.3–0</td>
<td>AMS¹⁴C</td>
<td>8</td>
<td>Ca, GS, OM, P</td>
<td>Xiao et al, 2004, 2006; Peng et al., 2005; Xu et al., 2010; Chen et al., 2003</td>
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<tr>
<td>18</td>
<td>Yanhaizi Lake</td>
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<td>108.4</td>
<td>1180</td>
<td>Lake pool</td>
<td>&lt;18</td>
<td>17.0–0</td>
<td>AMS¹⁴C</td>
<td>15</td>
<td>EM, GC, Lithology, OM GS, LOI, P</td>
<td>Yang et al., 2014</td>
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<td>19</td>
<td>Bojihaizi Lake</td>
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<td>109.309</td>
<td>1365</td>
<td>Lake pool</td>
<td>1.2</td>
<td>11.8–0</td>
<td>AMS¹⁴C</td>
<td>10</td>
<td>P</td>
<td>Sun and Feng., 2013</td>
</tr>
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<td>Qigai Nuur</td>
<td>39.5</td>
<td>109.5</td>
<td>1403</td>
<td>Lake pool</td>
<td>5</td>
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<td>Ca, EM, GC, GS, OM, P</td>
<td>Fang et al., 2005; Guo et al., 2007; Huang and Guo, 2017</td>
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<td>109.27</td>
<td>1278</td>
<td>Lake pool</td>
<td>11.9–0</td>
<td>AMS¹⁴C</td>
<td>15</td>
<td>Ca, EM, GC, GS, OM, P</td>
<td>Chen et al., 2013, 2015b; Rao et al., 2016; Liu et al., 2018</td>
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<td>112.233</td>
<td>1860</td>
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<td>14.7–0</td>
<td>AMS¹⁴C</td>
<td>25</td>
<td>Ca, EM, GC, GS, OM, P</td>
<td>Yin et al., 2011</td>
</tr>
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Abbreviations: Ca—Carbonate content, D—Diatoms, EM—Environmental magnetic proxies, GC—Geochemical proxies, GS—Grain size, OM—Organic matter content, OS—Ostracod assemblage, P—Pollen.
4.2. Holocene hydrological changes in the deserts of NE China and adjacent regions

The Holocene hydrological changes in the deserts of NE China and the adjacent regions are summarized in Fig. 5; the data comprise 22 lake records (Table 2). Analysis of climatically-sensitive proxies (e.g., pollen and ostracod assemblages, organic matter and carbonate content, grain size, and geochemical parameters) enables four shifts to be observed, at around 11, 9, 6, and 4.3 ka. A warmer and wetter climate at Daihai lake and a high lake level in Hulun and Dali lakes confirm that the timing of the wettest climate along the margin of the EASM front was from ~9 to 6 ka. However, during the interval from ~11 to 9 ka, Hulun and Dali lakes maintained a high stand, in response to inflowing water to both lakes which resulted from insolation-driven snow/ice melt from the surrounding mountains and/or groundwater (Wen et al., 2010, 2017). During the mid-Holocene, conditions became drier and lake shrinkage occurred, starting at ~6 ka; this was followed by a semiarid interval from ~6 to 4 ka. The other prominent feature of the data is that from ~4.3 ka the lakes in these deserts and the adjacent regions shifted entirely to a low lake level state in response to an intensification of aridification. The shrinkage of the lakes continued towards the present. In addition, when the lake area is too small or the number of dates less is than 4, the lake records exhibit several asynchronous shifts (e.g., at Baahar Nuur, Jiangunpaozi, Xiaoniuchang, and Liuzhouwan).

4.3. Spatiotemporal distribution of archaeological sites in NE China during the Holocene

Seven time-slices from the selected 30,519 archaeological sites in NE China are used to establish the spatiotemporal distribution patterns of archaeological sites in NE China during the Holocene (Fig. 6). They show a long-term trend of an increase in the number of archaeological sites in NE China. From ~7 to 5 ka, the number of archaeological sites in the deserts of NE China reached a maximum. Comparison of the late Neolithic (5–4 ka, Fig. 6) and early Bronze Age (4–3 ka, Fig. 6) time slices, reveals that the number of archaeological sites decreased in the deserts, but increased substantially in the middle to lower reaches of the Yellow River. In contrast to the late Neolithic time slice, a similar distribution pattern of archaeological sites in NE China occurred from ~3 to 2 ka,
with the difference resulting from a substantial increase in the number of archaeological sites in the North China Plain.

It is noteworthy that the age of each archaeological site was constrained by one dated interval; thus, we used the median age to confirm the time slice for each site. The dating half-intervals of the selected 30,519 archaeological sites in NE China are shown in Fig. 7; they are less than 600 years from ~5 to 4 ka, although there is a large half-interval of up to 3000 years at ~7 ka. The large half-interval from ~7 to 5 ka (Fig. 7) also yields a data artifact in that the site distribution in NE China during the period of ~7–6 ka is much denser than during the subsequent period (~6–5 ka). In fact, the former period was when Zhaobaogou and probably the early Hongshan culture developed, while the latter period was when the Hongshan culture flourished, with site numbers multiplying from...
the previous period. Thus, the millennial-scale spatiotemporal distribution of archaeological sites in the deserts of NE China can be confirmed during the mid-Holocene and we suggest that it confirms the impact of climate on prehistoric cultures of the late...
et al., 2009a; Yang et al., 2013; Fan et al., 2016), in response to the transition in the deserts of NE China and the adjacent regions (Xiao et al., 2018). EASM is considered the cause of the mid-Holocene environmental transition in the deserts of NE China, which suggests a lag of ~1–2 kyr compared with our own conclusions. The pollen-based proxies are underpinned by the fact that effective moisture limits the growth and distribution of plants (Mason et al., 2009; Lu et al., 2011). When the Northern Hemisphere summer insolation decreased during the mid-Holocene, the temperature of the deserts of NE China decreased synchronously, which slightly altered effective moisture levels, but the thresholds of the ecological system were not crossed. Thus, tree pollen percentages and estimated C4 biomass maintained relatively high values (Fig. 9) which was accompanied by dated records for dune stable states (Figs. 2 and 3) from ~6 to 5 ka, which explains the ~1–2 kyr lag observed in our data compared to that derived from pollen-based reconstructions.

5.2. Onset of dune re-mobilization in the deserts of NE China

The onset of dune re-mobilization in the deserts of NE China inferred from our results was at ~4 ka, in agreement with records from shoreline dunes from the Otindag Desert (Yang et al., 2015), coincident with a drastic decrease in EASM precipitation during the mid-Holocene. However, an important question is why dune re-mobilization throughout the entire study region did not begin at ~5 ka, because our conclusion suggests that the climate was rather cold and dry during the interval from ~5 to 4 ka, and that the onset of dry conditions occurred at ~6 ka.

Several factors affect the development of dunes that reflect the onset of dune re-mobilization, including sand source, wind, landforms and local climate. The deserts of NE China are in endorheic basins which are well-supplied with sand derived from fluvial and alluvial sediments brought by rivers and streams from the surrounding mountains (Yang et al., 2012). Thus, climatic conditions in the sand source and depositional regions are often considered one of the limiting factors for the development of dunes in these deserts. Precipitation in sand source regions affects the development of fluvial and alluvial sediments and indirectly determines the supply of sand; and in depositional regions it influences the development of vegetation which is regarded as a major factor determining the sand transport rate (Liu et al., 2005).

During the interval from ~6 to 5 ka, the EAWM intensity decreased abruptly but still maintained a relatively high level (Fig. 8b, Wang et al., 2012b), with sparse vegetation cover in these deserts (Fig. 9), which prevented the dunes from expanding. Subsequently, the EAWM reached its weakest state during HE3 when the severe cold and dry conditions in the surrounding mountains resulted in insufficient sand supply for the development of dunes from ~4.2 ka. In contrast, at ~5 ka, the relatively stronger EAWM, with semiarid conditions in the surrounding mountains, was still able to supply sufficient sand to enable partial reactivation of those dunes which were not vegetation covered. Although vegetation covered part of these deserts after ~4 ka (Fig. 3), the thresholds of the ecological system were crossed, as indicated by the evidence of dune re-mobilization in the deserts of NE China.
Fig. 8. Holocene dated records of sub-aerial sedimentary deposits (a, this study) in the deserts of NE China compared with the frequency distribution of Chinese Loess Plateau loess and palaeosol dates (b, Wang et al., 2014a); humidity indicators of deserts in northern China and the Sahara (c, Guo et al., 2000); July (China summer) insolation at 65°N (W/m²) (d, Laskar et al., 2004); concentration of hematite-stained quartz grains in North Atlantic sediments (e, Bond et al., 2001) with 0–8 designating millennial-scale cycles; red colour intensity of a sediment core from Laguna Pallcacocha, southern Ecuador (g, Moy et al., 2002); sea surface temperature (SST) of the western tropical Pacific (f, Stott et al., 2004); and positive index for the strength of the EAWM inferred from the AG/CS ratio, A. granulata/C. stelligera (h, Wang et al., 2012b). Rectangle colors are the same as in Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
presented herein for severe cold and dry conditions from ~4.2 ka (Yang et al., 2015), which weakened the effect of vegetation on the sand transport rate. Thus after ~4 ka, the severe environmental conditions began to ameliorate slightly in the sand source regions with the gradual increase in EAWM intensity and/or human activities, which favored the development of dunes.

5.3. Effect of the mid-Holocene environmental transition on late Neolithic cultures in NE China

During the Holocene Thermal Optimum, warm and wet conditions along the margin of the EASM front favored the development of rain-fed agriculture in many flat and fertile terraces and alluvial fans, which provided a large area of arable land and a favorable habitat for Neolithic peoples. Thus, rain-fed agriculture played a major role in the flourishing of the Yangshao and Hongshan cultures (~5000–3000 BCE) in northern China (Crawford, 2009; Liu and Chen, 2012; Jia et al., 2017). The climate in northern China became slightly drier and cooler from ~6 to 5 ka, but this did not adversely affect the rain-fed agriculture of the Yangshao and Hongshan cultures. In addition, since the hydrothermal configuration in northern China meets the needs of rain-fed agriculture, the slightly drier and cooler climate stimulated the expansion and communication of the Yangshao and Hongshan cultures, which promoted the appearance of the short-lived culture in the Huangqihai (Mo et al., 2003). In the case of the Yangshao culture, the size of settlements ranged from ~100 m² to more than 100 ha, the number of sites increased dramatically, and the distribution of sites expanded northwards to Inner Mongolia during this interval. The remains of domesticated plants (millet and rice) and animals (pigs and dogs) indicate that farming societies in central to southern Inner Mongolia were established (Ren and Wu, 1999). The quantity of the bones of domestic pigs and dogs at Miaozigou site in the Huangqihai from ~3500 to 3000 BCE was 13% greater than in the same region at ~4500 BCE (Huang, 2003), and a possible interpretation of this is that the domesticated animals were fed on the abundant cereal crops (Zhang et al., 2010a). In addition, before 3500 BCE in central-south Inner Mongolia, subsistence strategies based on plants with various underground storage organs provided staple foods (Liu et al., 2016a). In contrast to the Yangshao culture, the Hongshan culture was the first complex society to develop in NE China, indicated by a dramatic increase in the number of sites and many new pottery types and a highly specialized type of jade work (Liu and Chen, 2012; Drennan et al., 2017). In addition, the earliest leaf-shaped and rectangular stone knives at Niheliang site of the Hongshan culture likely were used to harvest cereal crops (Mo et al., 2003; Li, 2008), which demonstrates that the Hongshan people were cultivators. Evidence from paleodiet studies at several sites in the Liao River region of NE China reveal that during Hongshan culture, C₄-plant-based foods were primarily consumed for subsistence (Zhang et al., 2003; Liu et al., 2012). The main contribution of C₄-plant-based in the paleodiet is from millet agriculture (Zhao, 2004, 2011; Li, 2008). However, investigations of the functions of grinding stones recovered at Baiyinchanghan site of the Hongshan culture suggest that the people utilized a broad-spectrum subsistence strategy using various wild, cultivated, and domesticated plants (Liu et al., 2016b).

During the subsequent Laohushan (~2500–2300 BCE) and Xiaoheyan (~3000–2000 BCE) cultures in northern China (Liu and Chen, 2012), the EASM weakened and dunes began to be reactivated in the deserts of NE China. Thus, during the interval from ~5 to 4 ka, the mid-Holocene environmental transition undoubtedly would have led to the failure of rain-fed irrigation agriculture and thus to a conflict between decreased agricultural productivity and

![Fig. 9. Holocene vegetation records from estimated C₄ biomass of the MTG section in the Horqin Desert (Guo et al., 2018) and tree pollen percentages at Hulun Lake (Wen et al., 2010), Dali Lake (Wen et al., 2017) and Daihai Lake (Xiao et al., 2004) in the northern margin of the East Asian summer monsoon, in response to monsoon intensity changes. Rectangle colors are the same as in Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)](image-url)
the increased population of previously habitable lands. Drier and cooler conditions in Inner Mongolia resulted in the disappearance of the short-lived culture in the Miaozigou area and the ensuing cultural hiatus lasted some 1500 years (Mo et al., 2003). In addition, studies of past human-environment interactions in the Otinidag Desert (Yang et al., 2015) and in the Taishizhuang section (Jin and Liu, 2002) reveal that a cold and dry event caused a reduction in the size of settlements, rapid abandonment of dwellings, and migration to the moister monsoon regions at ~4.2 ka. To adapt to the transition to the cold and dry environment of the mid-Holocene, frost-resistant wheat and/or barley likely were introduced to central-southern Inner Mongolia as the basis for subsistence during the late Neolithic period (Dodson et al., 2013; Liu et al., 2016a). In addition, the late Neolithic peoples on the eastern margin of the Mu Us Desert used vegetation to provide fuel for pottery manufacture, cooking and for heating (Miao et al., 2016). However, the development of the Hongshan culture in some regions relied mainly on millet cultivation (Zhang et al., 2003; Zhao, 2004, 2011; Li, 2008; Liu et al., 2012), and the cold and dry conditions during the subsequent Xiaoheyan culture impeded millet cultivation. Although the Neolithic peoples used a broad-spectrum subsistence strategy in central-southern Inner Mongolia and the Liao River region, such as the consumption of roots, tubers and nuts (Liu et al., 2016a, 2016b), the mid-Holocene environmental transition may have also affected the yields of oak and other nut-bearing trees as well as that of tuberiferous plants. Thus, the Xiaoheyan culture exhibited a lower level of social complexity with smaller populations, pastoralism, greater mobility of dwelling sites, abandonment of large ritual sites and limited jade-making (Li, 2008; Liu and Chen, 2012). Furthermore, several researchers have attributed the collapse of the Hongshan complex society to a large-scale drought event in northeast China (Jin, 2004; Li, 2008), where the summer monsoon rainfall reached a minimum at ~4.9 ka, as recorded at Lake Silaihongwan (Schettler et al., 2006).

Based on the regional compilation of records, a drastic decrease in the number of archaeological sites in the deserts of NE China during ~5–4 ka (Fig. 6) confirms that the mid-Holocene environmental transition resulted in ecosystem degradation (Jin and Liu, 2002; Tarasov et al., 2006), rendering land that was agriculturally productive during the Holocene Thermal Optimum subsequently unproductive, and reducing the overall habitability of the region.

Faced with the environmental severity, the late Neolithic farmers likely migrated from the deserts to the middle and lower reaches of the Yellow River or other habitable areas during ~5–4 ka. The reasons for these chosen destinations were that the middle and lower reaches of the Yellow River were warmer and moister and thus more favorable for cultivation and farming compared with the northern deserts (Jin and Wang, 2010; Liu, 2010; He et al., 2017); human societies prospered relatively in these chosen destinations since ~5 ka, as inferred from the dated records of deposits in the Mu Us desert (Figs. 2 and 3) and the spatiotemporal distribution of archaeological sites (Fig. 6). In the middle and lower reaches of the Yellow River, the density of archaeological sites was substantially higher both before and after ~5–4 ka, leading to a greatly increased population and increased demand for food resources. The dominant dry-land crops (e.g., millets) and locally cultivated rice supported an enormous population (Jin et al., 2007, 2016; Zhang et al., 2016a). A similar example is the deteriorating climate during the early Bronze Age in the West Liao River Basin which forced the population to migrate southwards, to the relatively flat loess tableland that was more suitable for millet farming; and westwards to the foothills of the Greater Khingan Mountains that favored the development of animal husbandry and hunting (Jia et al., 2016). Above all, there existed cultural exchange between the Yangshao and Hongshan cultural domains (Mo et al., 2003) which facilitated migration during the mid-Holocene.

From 5 to 4 ka, the cold and/or dry environmental conditions noted in the introduction indicate that a hemisphere-wide megadrought occurred in middle to low latitudes of the Northern Hemisphere which triggered the collapses of mid-Holocene cultures (Hsu, 1998; Weiss and Bradley, 2001). It should be noted that the indicators of cultural collapse include (1) a rapid reduction in the number of archaeological sites, (2) a reduction in the quality of the archaeological artifacts compared to the previous culture, and (3) the shift from a predominantly arable economy to pastoralism in northern China (Wu and Liu, 2004; Liu and Feng, 2012). Our conclusions suggest that the number of archaeological sites in NE China decreased during the interval from ~5 to 4 ka (Fig. 6), in accord with a low population level at ~4.5 ka inferred by a pre-historic demographic study in northern China (Wang et al., 2014b) and the distribution of archaeological sites in northern China during the late Neolithic—Bronze Age transition (Liu and Feng, 2012; Wagner et al., 2013). The absence of reaping knives and the presence of tools associated with hunting and gathering (e.g., arrowheads and grinding stones; Liu and Chen, 2012) during the Xiaoheyan cultural period suggest that pastoralism was the economic foundation with a small contribution from cultivation (Liu et al., 2016a). In addition, the disappearance of high-quality black-surface pottery in ritual burials at ~4 ka indicates that the Longshan population decreased sharply in the lower reaches of the Yellow River (Liu and Feng, 2012). Thus, our results support the view that a widespread drought destroyed the rain-fed agricultural and/or plant-based subsistence economies, ultimately contributing ultimately contributed to the collapse of the late Neolithic cultures in NE China.

6. Conclusions

Our analysis of a compilation of Holocene records of sub-aerial sedimentary deposits and lake sediments from the deserts of NE China and the adjacent regions demonstrates that the mid-Holocene environmental transition interrupted a period of relatively stable and warm climate. Our results indicate that the Holocene climate in these deserts can roughly be divided into four periods: early Holocene anathermal (~12–9 ka), Holocene Thermal Optimum (~9–6 ka), mid-Holocene environmental transition (~6–4 ka) and late Holocene deterioration (~4 ka onwards). Most likely, decreases in Northern Hemisphere summer insolation played the dominant role in weakening the EASM intensity and reducing precipitation along the margin of the EASM front, which in turn triggered the mid-Holocene environmental transition in these deserts.

During the interval from ~5 to 4 ka, the numbers of archaeological sites decreased in the study regions but they increased substantially in the middle to lower reaches of the Yellow River. An investigation of the published literature relating to late Neolithic cultures in NE China leads to the conclusion that the mid-Holocene environmental transition contributed substantially to ecosystem degradation in the deserts of NE China and the adjacent regions, which transformed land which was agriculturally productive and habitable during the Holocene Thermal Optimum to an uninhabitable state during the mid-Holocene. In response, the late Neolithic peoples likely migrated to moister and warmer regions to the south, in the middle and lower reaches of the Yellow River. Overall, a widespread mid-Holocene drought destroyed the rain-fed agricultural and/or plant-based subsistence economies, ultimately contributing to the collapse of late Neolithic cultures in NE China. If correct, this conclusion supports the speculation that one of the origins of Chinese civilization may be rooted in the adjacent regions of the deserts of NE China.
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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quascirev.2018.04.017.

References


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