Mid-Late Holocene Climate Change and Sandy Land Evolution in the Horqin Sandy Land: Postprint

Authors: Liao Wanyue, Jie Dongmei, Gao Guizai, Wang Jiangyong, Jie Dongmei

Date: 2024-12-04T00:00:00+00:00

Abstract

The Horqin Sandy Land exhibits an ecologically fragile environment and is highly sensitive to climate change; elucidating the evolution patterns of the sandy land and its response to climate change holds significant theoretical guiding importance for future sandy land conservation and management. This study systematically reconstructed climate change and sandy land evolution in the Horqin Sandy Land since the mid-to-late Holocene using grain size, loss on ignition, and phytolith indicators from an aeolian sand-paleosol profile on the northeastern margin of the region. The results indicate that during the period of 5700–2400 cal a BP, the Horqin Sandy Land experienced two stabilization periods and two expansion periods. The first stabilization period (5700–4800 cal a BP) was characterized by a strong East Asian summer monsoon and a warm, humid climate, with most dunes in the sandy land being stabilized; the first expansion period (4800–3900 cal a BP) witnessed continuous weakening of the summer monsoon and a shift toward cold, dry conditions, leading to gradual expansion of the sandy land; the second stabilization period (3900–3300 cal a BP) featured a warm, humid climate with soil development and reduced sandy land area; the second expansion period (3300–2400 cal a BP) was marked by cold, dry conditions, renewed sandy land expansion, and widespread aeolian sand coverage of paleosol layers. In summary, climate change driven by the East Asian summer monsoon controlled the mid-to-late Holocene evolution of the Horqin Sandy Land, and the formulation of sandy land management policies must pay special attention to future climate change trends.

Climate Change and Desert Evolution of the Horqin Sandy Land in the Mid-Late Holocene

LIAO Wanyue[1], **JIE Dongmei**[1,2,3,4], **GAO Guizai**[1,2,3,4], **WANG Jiangyong**[5]

[1]School of Geographical Sciences, Northeast Normal University, Changchun 130024, Jilin, China
[2]Key Laboratory of Geographical Processes and Ecological Security in Changbai Mountains, Ministry of Education, Changchun 130024, Jilin, China
[3]Institute for Peat and Mire Research, State Environmental Protection Key Laboratory of Wetland Ecology and Vegetation Restoration, Changchun 130024, Jilin, China
[4]Institute of Grassland Science, Key Laboratory for Vegetation Ecology, Ministry of Education, Changchun 130024, Jilin, China
[5]College of Geography and Remote Sensing Sciences, Xinjiang University, Urumqi 830017, Xinjiang, China

Abstract

The Horqin Sandy Land exhibits ecologically fragile characteristics and responds sensitively to climate change. Clarifying the evolutionary patterns of the sandy land and its response to climate variations holds significant theoretical importance for future conservation and management efforts. This study investigates an aeolian-paleosol profile on the northeastern margin of the Horqin Sandy Land, employing grain size analysis, loss on ignition, and phytolith indicators to systematically reconstruct climate change and sandy land evolution since the mid-late Holocene. The results reveal that between 5700 and 2400 cal a BP, the Horqin Sandy Land experienced two stabilization periods and two expansion phases. During 5700–4800 cal a BP, the East Asian summer monsoon was strong, creating warm and humid conditions that maintained predominantly fixed dunes. The first expansion phase occurred during 4800–3900 cal a BP, when the weakening summer monsoon led to increasingly cold and dry conditions, causing gradual sandy land expansion. The second stabilization period spanned 3900–3300 cal a BP, when warmer and more humid conditions promoted soil development and reduced sandy land area. The second expansion phase occurred during 3300–2400 cal a BP, when cold and dry conditions returned, leading to renewed sandy land expansion and widespread burial of paleosol layers by aeolian sand. In summary, climate change driven by the East Asian summer monsoon controlled the evolution of the Horqin Sandy Land during the mid-late Holocene, and sandy land management policies must pay particular attention to future climate change scenarios.

Key words: Horqin Sandy Land; climate change; desert evolution; phytolith analysis; grain-size analysis

---

1 Introduction

1.1 Study Area Overview

Deserts and sandy lands constitute important components of the natural environment in northern China. A series of sandy lands, including the Horqin, Hunshandake, and Mu Us, are distributed from northeast to southwest along the monsoon margin zone [Figure 1: see original paper]. These regions feature ecologically fragile environments that are highly sensitive to climate change and have accumulated alternating sequences of aeolian deposits and paleosols, making them ideal areas for paleoenvironmental research [1-3]. The expansion and contraction of sandy lands in monsoonal regions are closely related to the strength of the monsoon system [4-6]. Therefore, understanding the evolutionary processes of sandy lands and their relationship with climate change is crucial for predicting future climate scenarios, comprehending climate trends, and providing scientific support for effective desertification control and regional ecological protection, carrying significant economic and ecological implications.

The Horqin Sandy Land, covering an area of approximately 50,000 km^2, is China's largest sandy land. Located on the eastern margin of the agro-pastoral ecotone in northern China and adjacent to the agricultural region of Northeast China, it lies within the marginal zone of East Asian monsoon influence and is highly responsive to climate change [7-9]. Previous research has established a basic framework for Horqin Sandy Land evolution, but detailed resolution remains insufficient, particularly regarding the mid-late Holocene evolutionary processes and responses to climate change. This study aims to refine the understanding of climate change and sandy land evolution in the Horqin Sandy Land during the mid-late Holocene and further explore how aeolian activity responds to climate variations and human activities.

1.2 Sample Collection

The Haminmangha profile (43°58 59 N, 122°13 24 E) is located approximately 500 m east of the Haminmangha Heritage Park in Shebotu Town, Horqin Left Wing Middle Banner, Tongliao City, Inner Mongolia. The site is currently covered by artificially planted poplar forests, with herbaceous vegetation dominated by *Artemisia* species growing beneath the canopy. Field sampling collected 80 sediment samples at 5 cm intervals from a 400 cm profile, sealed in ziplock bags and numbered HM1–HM80. The profile consists primarily of grayish-yellow fine sand layers and paleosol layers, with its base at the same elevation as the Haminmangha archaeological site and more severe erosion at the top. To determine the chronology, six bulk sediment samples were selected for AMS^{14}C dating at the Guangzhou Institute of Geochemistry .

1.3 Experimental Methods

Phytolith Extraction: Phytoliths were extracted using wet oxidation [28]. Dried samples (0.5 g) were placed in 50 mL centrifuge tubes, treated with 15 mL of 10% HCl to remove carbonates, washed to neutral pH with distilled water, then oxidized with concentrated nitric acid until organic matter was completely removed. After further washing, samples were treated with 10% HCl to dissolve fluorides and brought to neutral pH. Zinc bromide solution (specific gravity 2.35) was added for phytolith flotation. The final product was washed and prepared for slide mounting and identification. Phytolith counting was performed under a Motic microscope at 400× magnification, with each slide containing at least 300 identified phytoliths.

Grain Size Analysis: Following standard procedures [29], samples were pretreated with 10% HCl to remove carbonates, washed to neutral pH, then treated with 10% H_2O_2 to remove organic matter. After ultrasonic dispersion with 0.5 $\mathrm{mol \cdot L^{-1}}$ sodium hexametaphosphate solution, samples were analyzed using a Mastersizer 2000 laser particle size analyzer. To minimize sampling errors, each sample was measured three times and averaged.

Loss on Ignition: Dried samples were weighed and combusted in a muffle furnace at 550°C for 4 hours to determine organic matter content from weight loss [30]. The residue was then heated at 950°C for 2 hours, with weight loss representing carbonate content [31].

---

2 Results

2.1 AMS ^{14}C Chronological Framework

To establish a robust age-depth model, we utilized the Bacon 2.5.5 package in RStudio 1.4.1 to process six AMS^{14}C dates from the Haminmangha profile [Figure 2: see original paper]. The model indicates continuous deposition from 5688 to 2171 cal a BP. Considering potential modern contamination, the top 30 cm was excluded, focusing discussion on the 5700–2400 cal a BP interval (400–30 cm depth).

2.2 Grain Size and Loss on Ignition Characteristics

The profile is dominated by coarse particles, with sand (>63 m) comprising 74.21%–94.54% (mean 87.08%). Silt (4–63 m) accounts for 5.46%–25.46% (mean 12.90%), while clay (<4 m) is minimal (average 0.02%). End-member analysis using the Weibull function distribution in Matlab 2022a identified three grain size components [Figure 3: see original paper]. EM1 (39.25–120.08 m, mean 33.80%) represents suspended load from distal sources, likely from the Songnen Sandy Land upwind. EM2 (116.12–326.13 m) and EM3 (151.8–530.61 m) represent saltation loads from local sources, primarily from the Horqin

Sandy Land itself and nearby river floodplains. EM2 and EM3 were combined due to their similar characteristics, with the combined EM2+3 fraction comprising 52.59%–80.28% (mean 66.20%) of the total.

The profile was divided into three zones based on cluster analysis [Figure 4: see original paper]:

Zone 1 (400–260 cm, 5688–3950 cal a BP): EM2+3 content is relatively high (mean 63.19%), with organic matter content also elevated (mean 1.39%), indicating finer sediments and better soil development. Carbonate content is low (mean 0.69%), likely due to enhanced leaching under wetter conditions.

Zone 2 (260–140 cm, 3950–3212 cal a BP): EM2+3 content decreases (mean 68.06%), organic matter declines (mean 1.00%), and carbonates remain low (mean 0.38%), indicating coarser sediments and weaker pedogenesis.

Zone 3 (140–30 cm, 3212–2420 cal a BP): EM2+3 content increases again (mean 70.29%), reaching maximum values, while organic matter drops to its lowest level (mean 0.38%), indicating intensified aeolian activity and sandy land expansion.

2.3 Phytolith Assemblage Characteristics

A total of 24,000 phytoliths were identified from 80 samples (average 300 per sample). Following the ICPN 2.0 classification system [35], 29 phytolith types were identified, including saddle, hat, dumbbell, tooth, rod, point, fan, square, flat, and hair forms, plus sponge spicules. Rod and point types dominate (23%–48% and 14%–36% respectively), followed by hat types (2%–17%).

Based on ordered cluster analysis, the profile was divided into three sub-zones [Figure 5: see original paper]:

Sub-zone 1 (400–260 cm, 5688–3950 cal a BP): Cold-indicating smooth rod and ordinary point types dominate (21.31% and 18.76% respectively), with low phytolith concentrations (mean 57.58 grains $\cdot$ g^{-1}). The climate index (Ic = C3/[C3+C4]) [36] is relatively low (mean 49.44%), indicating warmer conditions in the lower part (400–340 cm, 5688–4752 cal a BP) that gradually cool upward.

Sub-zone 2 (260–140 cm, 3950–3212 cal a BP): Cold-indicating types increase (24.08% and 21.84%), phytolith concentrations decrease (mean 67.13 grains $\cdot$ g^{-1}), and the climate index rises (mean 64.93%), indicating continued cooling.

Sub-zone 3 (140–30 cm, 3212–2420 cal a BP): Cold-indicating types remain dominant, the climate index reaches its highest values (mean 69.64%), and phytolith concentrations decline further, indicating the coldest and driest conditions.

3 Discussion

3.1 Mid-Late Holocene Paleoclimate Reconstruction in the Horqin Sandy Land

Located at the margin of East Asian monsoon influence, the study area's climate is largely controlled by summer monsoon intensity. Phytolith, grain size, and carbonate records show good overall consistency, reflecting regional climate conditions [Figure 6: see original paper]. Between 5700 and 2400 cal a BP, the phytolith climate index shows a gradual upward trend while carbonate content decreases, consistent with declining solar radiation and summer monsoon strength [37].

5700–4800 cal a BP: Fine grain sizes with clay fractions at minimum values, low climate indices, and high carbonate content indicate warm and humid conditions corresponding to the Holocene Climatic Optimum. Pollen records from Daihai Lake [39] and Sihailongwan Maar Lake [38] in the same region also show warm and humid conditions, confirming that the enhanced East Asian summer monsoon extended over a larger area.

4800–4000 cal a BP: Grain sizes increase to maximum values, the climate index rises, and carbonate content decreases significantly, indicating a transition to colder and drier conditions as the summer monsoon weakened. Regional records show synchronous climate deterioration [39, 40]. Around 4.2 ka, the cold and dry conditions peaked, coinciding with widespread climate deterioration recorded in Jingbo Lake [40] and Dali Lake [41] pollen records.

4000–3300 cal a BP: Grain sizes decrease, carbonate content briefly increases, and the climate index declines, suggesting a temporary return to warmer and more humid conditions, though overall conditions remained relatively cold and dry. This warming phase is supported by charcoal evidence from the West Liao River Basin [42] and pollen records from Sihailongwan Maar Lake [38] showing increased precipitation around 3500 cal a BP.

3300–2400 cal a BP: Grain sizes coarsen again, the climate index rises, and carbonate content reaches minimum values, indicating a return to cold and dry conditions. This phase represents the most arid period of the mid-late Holocene.

3.2 Mid-Late Holocene Evolution of the Horqin Sandy Land

Sandy land evolution primarily involves processes of fixation/contraction and activation/expansion, with aeolian sand layers and paleosols serving as key indicators [43]. Aeolian sand layers contain high coarse particle content, strong aeolian activity, sparse vegetation, weak pedogenesis, and low organic matter. Paleosol development periods feature higher fine particle content, stronger pedogenesis, denser vegetation, and higher organic matter content. Based on grain size end-member analysis and organic matter content, we reconstructed the sandy land evolution history [Figure 7: see original paper].

First Stabilization Period (5700–4800 cal a BP): The Horqin Sandy Land was predominantly fixed, with low coarse particle content, high organic matter, weak aeolian activity, and well-developed paleosols. The warm and humid climate of the Holocene Climatic Optimum favored dune stabilization. Contemporary records from the Mu Us [44] and Hunshandake [45] sandy lands also show dune fixation. During this period, the Hongshan Culture covered most of the Horqin Sandy Land, indicating favorable conditions for early agriculture [46]. The Haminmangha inhabitants lived during this phase, benefiting from the relatively superior natural environment [47].

First Expansion Period (4800–4000 cal a BP): The sandy land gradually expanded as coarse particle content increased and organic matter decreased, reflecting intensifying aeolian activity under a weakening summer monsoon. The climate transition from warm-humid to cold-dry conditions slowed paleosol development. Pollen studies from the Xar Moron River Basin show climate cooling during 5000–4000 cal a BP, with a corresponding sandy land activation event [48]. The deteriorating conditions led to agricultural decline and contributed to the collapse of the Hongshan Culture [49].

Second Stabilization Period (4000–3300 cal a BP): The sandy land contracted again as coarse particle content decreased and organic matter increased. Warmer and more humid conditions promoted soil development and reduced sandy land area. The Xiajiadian Lower Culture rapidly developed in the West Liao River Basin during this period, benefiting from climate conditions favorable for agriculture [50]. While the eastern Horqin Sandy Land developed paleosols on dune surfaces under humid conditions, the western Hunshandake Sandy Land remained under dry conditions with limited weathering [45].

Second Expansion Period (3300–2400 cal a BP): The Horqin Sandy Land expanded again, with coarse particle content reaching maximum values and organic matter dropping to minimum levels. Paleosol layers were widely buried by aeolian sand under the coldest and driest conditions of the period. This phase coincides with the end of the Holocene Climatic Optimum around 3000 cal a BP, when most sandy lands in northern China became activated [44, 45]. The transition to pastoralism in the Xiajiadian Upper Culture reflects adaptation to deteriorating conditions [51].

The analysis demonstrates that Horqin Sandy Land dynamics are synchronized with climate fluctuations: warm-humid periods correspond to weak aeolian activity and sandy land fixation, while cold-dry periods trigger activation and expansion. Climate change is thus the primary driver of large-scale aeolian activity in the Horqin Sandy Land. Spatially, the Horqin Sandy Land shows longer stabilization periods than the Hunshandake and Mu Us sandy lands, likely due to its more easterly location and stronger monsoon influence.

4 Conclusions

1) Multi-proxy analysis of the Haminmangha profile reveals that mid-late Holocene climate in the Horqin Sandy Land shifted from warm-humid to cold-dry conditions, with two warm-humid and two cold-dry sub-periods. This gradual drying trend aligns with decreasing solar radiation since the mid-Holocene, indicating that climate change in the region is primarily controlled by East Asian monsoon dynamics driven by solar radiation variations.

2) Corresponding to climate changes, the Horqin Sandy Land experienced two stabilization periods (5700–4800 cal a BP and 4000–3300 cal a BP) and two expansion phases (4800–4000 cal a BP and 3300–2400 cal a BP). The large-scale fixation during 5700–4800 cal a BP was closely related to a strong East Asian summer monsoon, while the expansion during 4800–4000 cal a BP corresponded to monsoon weakening. The temporary warming during 4000–3300 cal a BP promoted sandy land fixation, and the subsequent expansion during 3300–2400 cal a BP coincided with the coldest and driest conditions of the period.

3) The evolution of the Horqin Sandy Land during the mid-late Holocene was primarily constrained by climate changes controlled by the East Asian summer monsoon. These findings highlight the need for climate-sensitive management policies for sandy land conservation.

References

[1] Dong Guangrong. Study on climate change and desertification in desert formation and evolution in China[M]. Beijing: China Ocean Press, 2002: 212-232.

[2] Xue Wenping, Jin Heling, Liu Bing, et al. Advances in the study of sandy land evolution and its driving mechanism in the monsoonal marginal area in China during the Holocene epoch[J]. Journal of Desert Research, 2019, 39(3): 163-171.

[3] Liu Bing, Jin Heling, Sun Zhong. Desert evolution and climate change in the Horqin Sandy Land in middle and late Holocene[J]. Journal of Desert Research, 2013, 33(1): 77-86.

[4] Qiu Shanwen. Study on the formation and evolution of Horqin Sandy Land[J]. Scientia Geographica Sinica, 1989(4): 317-328, 97.

[5] Dong Guangrong, Jin Jiong, Li Baosheng, et al. Several problems on the desertification of Horqin Sandy Land, northeast China: A case study on its south area[J]. Journal of Desert Research, 1994(1): 1-9.

[6] Wulan Tuya, Lei Jun, Yu Shan. An advance on studies of formation and

environment evolution of Horqin Desert[J]. Journal of Arid Land Resources and Environment, 2002(1): 28-31.

[7] Zhang Qide, Wang Yuxiu. Horqin sandy land and atmospheric environment[M]. Beijing: Science Press, 1994: 14-16.

[8] Yang Lihua, Wang Tao, Zhou J, et al. OSL chronology and possible forcing mechanisms of dune evolution in the Horqin dunefield in northern China since the Last Glacial Maximum[J]. Quaternary Research, 2012, 78(2): 185-196.

[9] Yang Lihua, Zhou J, Lai Z P, et al. Lateglacial and Holocene dune evolution in the Horqin dunefield of northeastern China based on luminescence dating[J]. Palaeogeography, Palaeoclimatology, Palaeoecology, 2010, 296(1): 44-51.

[10] Zhuo Haixin, Lu Huayu, Jia Xin, et al. A preliminary study on human activities in sand fields of northern China and its relationship with the climatic variations in Holocene[J]. Quaternary Sciences, 2013, 33(2): 303-313.

[11] Xu D K, Lu H Y, Chu G Q, et al. Synchronous 500-year oscillations of monsoon climate and human activity in northeast Asia[J]. Nature Communications, 2019, 10(1): 4105.

[12] Xu Yujie, Liu Bing, Sun Aijun, et al. Research progress of Holocene environmental evolution in the Gurbantunggut Desert and its surrounding areas[J]. Arid Land Geography, 2023, 46(4): 550-562.

[13] Li S H, Chen Y Y, Li B, et al. OSL dating of sediments from deserts in northern China[J]. Quaternary Geochronology, 2007, 2(1): 23-28.

[14] Liu B, Zhang H, Li S H, et al. Asynchronous palaeosol development during the past 20 ka in response to climate change across the dune fields of the Asian summer monsoonal boundary, northern China[J]. Earth Science Reviews, 2022, 234: 104232.

[15] Zhang Lansheng, Fang Xiuqi, Ren Guoyu, et al. Environmental changes in the north China farming-grazing transitional zone[J]. Earth Science Frontiers, 1997(Suppl. 1): 131-140.

[16] Wang Peifang. Preliminary study on the environmental changes of Hulun Buir Sandy Land since the Holocene[J]. Journal of Desert Research, 1992(4): 16-22.

[17] Li Qusheng. A preliminary study on the evolution of Songnen Sandy Land[J]. Science Bulletin, 1990(11): 854-856.

[18] Qiu Shanwen, Li Ziting, Yang Xiaoping, et al. Paleosols of sandy lands and environmental changes in the western plain of northeast China during Holocene[J]. Quaternary Sciences, 1992(3): 224-232.

[19] Liu Bing, Zhu Bingqi. Reinterpretation of the chronological data of paleoenvironmental records in the Badain Jaran Desert and reconstruction of the Holocene climatic changes[J]. Quaternary Sciences, 2010, 30(5): 925-933.

[20] Jin H L, Sun L Y, Sun Z. Millennial-scale evolution of Hunshandake Desert and climate change during the Holocene in Inner Mongolia, northern China[J]. Sciences in Cold and Arid Regions, 2010, 2(6): 505-513.

[21] Miao R H, Liu Y Z, Wu L Q, et al. Effects of long-term grazing exclusion on plant and soil properties vary with position in dune systems in the Horqin Sandy Land[J]. Catena, 2022, 209: 105860.

[22] Guo L C, Xiong S F, Yang P, et al. Holocene environmental changes in the Horqin Desert revealed by OSL dating and δ^{13}C analyses of paleosols[J]. Quaternary International, 2018, 469: 11-19.

[23] Lu H Y, Zhou Y L, Liu W G, et al. Organic stable carbon isotopic composition reveals late Quaternary vegetation changes in the dune fields of northern China[J]. Quaternary Research, 2012, 77(3): 433-444.

[24] Yang S L, Dong X X, Xiao J L. The East Asian monsoon since the Last Glacial maximum: Evidence from geological records in northern China[J]. Science China Earth Sciences, 2019, 62(8): 1181-1194.

[25] He Jin, Liu Yan, Tian Yanguo, et al. Mid-late Holocene climate change and its impact on the agriculture-pastoralism evolution in the west Liaohe Basin[J]. Acta Geographica Sinica, 2021, 76(7): 1618-1633.

[26] Zhu Yonggang, Ji Ping. A prediction of the cause of death of a large number of human bones in the Haminmangha Site in Inner Mongolia: Exploration and reflection on the prehistoric disaster events[J]. Archaeology and Cultural Relics, 2016(5): 75-82.

[27] Gao Guizai. Phytolith reference for identifying typical plant communities in northeastern China and its implication in paleovegetation reconstruction since the Late Glacial Period[D]. Changchun: Northeast Normal University, 2019.

[28] Wang Yongji, Lü Houyuan. Phytolith study and its application[M]. Beijing: China Ocean Press, 1993: 48-118.

[29] Liu Ying, Jie Dongmei, Fang Qi, et al. Sediment grain size characteristics of the Changshan site and its environmental indication meaning[J]. Journal of Northeast Normal University (Natural Science Edition), 2020, 52(1): 136-143.

[30] Heiri O, Lotter A F, Lemcke G. Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results[J]. Journal of Paleolimnology, 2001, 25(1): 101-110.

[31] Blaauw M, Christen J A. Flexible paleoclimate age-depth models using an autoregressive gamma process[J]. Bayesian Analysis, 2011, 6: 457-474.

[32] Paterson G A, Heslop D. New methods for unmixing sediment grain size data[J]. Geochemistry, Geophysics, Geosystems, 2015, 16(12): 4494-4506.

[33] Madella M, Alexandre A, Ball T. International code for phytolith nomenclature 1.0[J]. Annals of Botany, 2005, 96(2): 253-260.

[34] Neumann K, Strömberg C, Ball T, et al. International code for phytolith nomenclature 2.0[J]. Annals of Botany, 2019, 124(2): 189-199.

[35] Bremond L, Alexandre A, Wooler M J, et al. Phytolith indices as proxies of grass subfamilies on east African tropical mountains[J]. Global and Planetary Change, 2008, 61: 209-224.

[36] Stebich M, Rehfeld K, Schlütz F, et al. Holocene vegetation and climate dynamics of NE China based on the pollen record from Sihailongwan Maar Lake[J]. Quaternary Science Reviews, 2015, 124: 275-289.

[37] Xu Q H, Xiao J L, Li Y C, et al. Pollen-based quantitative reconstruction of Holocene climate changes in the Daihai Lake area, Inner Mongolia, China[J]. Journal of Climate, 2010, 23(11): 2856-2872.

[38] Li C H, Wu Y H, Hou X H. Holocene vegetation and climate in northeast China revealed from Jingbo Lake sediment[J]. Quaternary International, 2011, 229(1): 67-73.

[39] Wen R L, Xiao J L, Fan J W, et al. Pollen evidence for a mid-Holocene East Asian summer monsoon maximum in northern China[J]. Quaternary Science Reviews, 2017, 176: 29-35.

[40] Ren X X, Huang X Z, Huang C, et al. Effects of human activities on mountain forest in northern China during the middle Holocene[J]. Quaternary Science Reviews, 2022, 288: 107580.

[41] Jia X, Wang S Z, Sun Y G, et al. Charcoal evidence for environmental change ca. 3.5 ka and its influence on ancient people in the west Liao River Basin of northeastern China[J]. Quaternary Research, 2021, 102: 142-152.

[42] Zhang Jiahua, Kong Zhaochen, Du Naiqiu. The respondence of loss-on-ignition range to past climate and environment in Beijing[J]. Acta Ecologica Sinica, 1998(4): 9-13.

[43] Dong Guangrong, Jin Jiong, Gao Shangyu, et al. Climate changes since the late Pleistocene in deserts of northern China[J]. Quaternary Sciences, 1990, 10(3): 213-222.

[44] Sun J M, Li S H, Han P, et al. Holocene environmental changes in central Inner Mongolia, based on single aliquot quartz optical dating and multi-proxy study of dune sands[J]. Palaeogeography, Palaeoclimatology, Palaeoecology, 2006, 233(1): 51-62.

[45] Gong Z J, Li S H, Sun J M, et al. Environmental changes in Hunshandake (Otindag) Sandy Land revealed by optical dating and multi-proxy study of dune sands[J]. Journal of Asian Earth Sciences, 2013, 76: 30-36.

[46] Xia Zhengkai, Deng Hui, Wu Honglin. Geomorphologic background of the prehistoric cultural evolution in the Xar Moron River Basin, Inner Mongolia[J]. Acta Geographica Sinica, 2000, 55(3): 329-336.

[47] Wang J Y, Gao G Z, Jie D M, et al. Aeolian soils on the eastern side of the Horqin Sandy Land, China: A provenance and sedimentary environment reconstruction perspective[J]. Catena, 2022, 210: 105945.

[48] Tang Zhuowei, Zhu Yonggang, Ji Ping, et al. Spore-pollen analysis of Haminmangha settlement and initial research on paleoecological environment of Hamin culture[J]. Research of China Frontier Archaeology, 2016, 19: 341-346.

[49] Guo L C, Xiong S F, Ding Z L, et al. Role of the mid-Holocene environmental transition in the decline of late Neolithic cultures in the deserts of NE China[J]. Quaternary Science Reviews, 2018, 190: 98-113.

[50] Liu L, Duncan N A, Chen X C, et al. Plant-based subsistence strategies and development of complex societies in Neolithic northeast China: Evidence from grinding stones[J]. Journal of Archaeological Science: Reports, 2016, 7: 247-261.

[51] Wang Lin, Wu Hong, Jia Xin. Study on the temporal-spatial evolution of prehistoric settlements and its correlation with subsistence strategy and climate history in the western Liao River area[J]. Advances in Earth Science, 2016, 31(11): 1159-1171.

Note: Figure translations are in progress. See original paper for figures.