Article

The Possible Stimulation of the Mid-Holocene Period's Initial Hydrological Recession on the Development of Neolithic Cultures along the Margin of the East Asian Summer Monsoon

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Abstract: A better understanding of past East Asian summer monsoonal (EASM) variations, which play a key role in the development of the largely rain-watered agriculture in China, could contribute to better appraising potential impacts on EASM with regard to global climate change. However, our knowledge of the relationship between mid-Holocene hydrological recession and the development of Neolithic culture is limited due to a lack of joint studies and a compilation of spatiotemporal data, especially on the episode of ~6–5 ka from the mid-Holocene Optimum (HO) along the peripheral realm of the EASM. Here, we suggest that the hydrological recession between ~6–5 ka, on the basis of lithology and geochemical element analysis, occurred not only in the Horqin sandy land, but also in other fluvial-lacustrine, stalagmitic, loess, and aeolian records across the whole monsoon-influenced boundary belt. These records indicated varied, more or less synchronous, and coherent moisture changes, yet with not entirely consistent onsets, durations, and degrees. We attributed this spatiotemporal complexity to the orbit-induced weakening of summer solar insolation, and the interactions of the Asian monsoon (AM) and westerlies, as well as topography and regional vegetation factors. Furthermore, the mid-Holocene initial hydroclimatic recession during ~6–5 ka within the thresholds of an eco-environment bearing a capacity system, might have facilitated the development of mid-late Neolithic culture and stimulated the north and northwest expansion and integration of region-specific Neolithic culture.

Keywords: hydrological recession; mid-Holocene; geochemical elements; EASM margin; Neolithic culture

1. Introduction

The Neolithic age usually refers to the emergence of a set of technological innovations and social developments, including the domestication of animals and plants, the practice of settlement, and the use of pottery and ground stone tools [1,2]. Millet, rice, and wheat are the dominant crops in China [3]. Domesticated foxtail millet (*Setaria italica*) and broomcorn millet (*Panicum miliaceum*) became widespread by 6000 BC along the Yellow and Liao rivers [4,5]. Technological innovation and settlement were major characteristics in the rise and development of early Neolithic civilizations (7000–5000 BC) [2]. The Neolithic people in different regions of China adopted varied survival strategies

to cope with the diverse climate and complicated topographical features. In recent decades, numerous joint studies of the link between climatic and societal change have been conducted, especially on during the mid-Holocene (8–3 ka) due to the highly variable climate compared with the preceding and succeeding periods [6,7]. For example, widespread dramatic climatic transition of Holocene event 3 [8–13], HE3 (~4.2 ka) [14], has been intimately tethered to the collapse of the Harappan civilization [11,15], the domain of the Ancient Egypt [9], and the Akkadian empire [16]. As one of the cradles of ancient civilization, contemporaneous Chinese cultures also experienced the cultural decline and atavism of late-Neolithic cultures at ~4.2 ka in different regions with the exception of Erlitou Culture [17–24]. The decline of culture around 4.2 ka involved a drastic decrease in the number of archaeological sites, the disappearance of large-scale, sophisticated architectures, and the replacement of agricultural civilization by widespread pastoralism in northern semiarid China [25–27].

In comparison with the impact of HE3 on the decline of late-Neolithic culture, the role of climatic degeneration during ~6–5 ka from the Holocene Optimum (HO) is more complex and ambiguous in terms of the development of mid–late Neolithic culture. That is attributed to the following possible reasons: factors based on the spatiotemporal complexity of climatic change, such as not absolutely synchronous timing and various degrees of climatic degeneration, and complicated dynamic mechanisms of cultural evolution, such as the level of socio-economic resilience and the magnitude of capacity-related carrying [28,29].

Previously, multi-proxy records and synthesized data indicated an occurrence of climate deterioration during ~6–5 ka in many regions of the world. This was found not only in Asia [11,30,31], Africa [32], Europe [33–35], and the North Atlantic [14,36], but also in South and North America [37,38], and even in the southern hemisphere [39,40]. Especially in Asia and Africa, the hydrological degradation at 5.5 ka was very prominent [33].

In China, with a temporal resolution of 3–7 years, stalagmite $\delta^{18}\text{O}$ of the Tianmen cave recorded an obvious precipitation anomaly at 6.3 and 5.3 ka in the southern Tibetan Plateau [41]. The $\delta^{18}\text{O}$ record from Dunde ice suggested sharp cooling events during 6.0–5.0 ka [42]. A multi-proxy record from Qixing cave indicated major climate deterioration at 6.5–5.9 ka, followed by water level further dropping and a significant reduction in lake productivity [43], which is identical to the Dahu swamp record [44] and the Dongge stalagmite record [45,46]. However, in Dajihu, principal component analysis denoted that a warm and wet condition dominated in 7.0–4.2 ka, with decreased precipitation beginning at 4.2 ka [47]. In northern China, Goldsmith [48,49] proposed a substantial decrease in rainfall at 5.5 ka in Dali lake, in broad agreement with the record from the Chinese Loess Plateau (CLP) [50]. Stalactite data from Wanxiang cave suggested a weakening intensity of the East Asian summer monsoon (EASM) at 5.7–4.9 ka, with an extreme event at 5.4 ka resulting in a significant reduction in precipitation in the western CLP of Gansu [51,52]. The pollen profile from Qinghai Lake demonstrated that HO vegetation began to shrink at ~6 ka, and tree-pollen concentration almost reached the Holocene minimum at ~4.0 ka [52]. In addition, numerous studies of synthesized data also suggested that effective moisture started to decrease from 6 ka, with an abrupt shift at 4.5 ka in northern China [53–57]. Simultaneously, it could be observed that climatic transition was punctuated and superimposed by a series of global cold/dry events [14,36,58,59].

Different from the rise and blossoming of the Mesopotamian civilization and pre-civilization Egypt under gradual climatic decline [60], Wu [61] proposed, on the basis of a large amount of archaeological evidence, that the 6–5 ka climate transition in China caused resource stress and competition increment, and the resultant formation of unequal and complex societies. Bai [51] suggested that the dramatic decline in precipitation at 5.4 ka may have been partly related to the decline of the Miaodigou, middle Yangshao, and early Dawenkou cultures. Previous climatic studies and archaeological surveys provided good opportunities to investigate how prehistoric human activities responded to ecological change and perceived human–nature interactions. However, only a few studies tried to comprehensively explore the relationship between the hydrological recession at 6–5 ka and mid–late Neolithic culture’s development [51,61]. Consequently, further work is needed to fully understand

how climatic degeneration during ~6–5 ka affected the development of mid–late Neolithic culture. Utilizing a compilation of archaeological data by Hosner [62], and combining the earlier paleoclimatic records with our recent research, we were able to delineate spatiotemporal properties of cultural evolution, agricultural development, and subsistence strategies of Neolithic humans, accompanied by paleoclimatic variation during ~6–5 ka along the peripheral realm of the EASM, which had the sensitivity needed for variations of EASM waxing and waning; it was the arena for the rise and fall of pristine civilizations [18,63]. Detailed spatiotemporal information about climatic change and the distribution of archaeological sites is important for improving the understanding of the climatic driving mechanism and human responses during the Holocene, and for providing advice for the sustainable development of humans.

2. Regional Setting

The peripheral realm of EASM, a broad transitional zone between the influence of Asian monsoon (AM) and westerly-dominated regions, sensitively reflects the spatial expansion or withdrawal of the dominated circulation systems during the Holocene (Figure 1) [53]; this is also a pastoral farming and ecologically fragile zone. Contemporary vegetation across the belt is characterized by ecological diversity, involving ecotones of major biomes between cold-temperate needle-leaf forests and temperate steppes, between temperate steppes and temperature deserts, and between temperature deserts and highland meadows/steppes from the east to the west [64,65].

Figure 1. Study area and location of various sites shown in Table 1 to infer mid-Holocene hydrological recession along margin of the East Asian summer monsoon (EASM, red dashed line). Blue triangles represent records of published fluvial-lacustrine and stalagmites with their numbers, and green circles represent the records of published aeolian and loess with their numbers, both of which correspond to the numbers of Table 1. Red stars are the study location. ISM represents the Indian summer monsoon.

Table 1. Results of optically stimulated luminescence (OSL) dating age and related parameters for Xinjiamu (XJM), Hanxiantun (HXT), and Yangxumu (YXM) profiles.

Lab No.	Depth (cm)	U (ppm)	Th (ppm)	K (%)	D _e (Gy)	D (Gy/ka)	Water Content (%)	Age (ka)
XJM-1	110	0.84 ± 0.05	3.67 ± 0.14	2.37 ± 0.07	7.31 ± 0.27	3.19 ± 0.13	5	2.3 ± 0.1
XJM-2	170	0.74 ± 0.04	3.29 ± 0.13	2.34 ± 0.07	12.72 ± 0.30	3.07 ± 0.12	3.4	4.1 ± 0.2
XJM-3	280	0.70 ± 0.04	3.09 ± 0.12	2.28 ± 0.07	13.97 ± 0.66	2.96 ± 0.12	5.5	4.7 ± 0.3
XJM-4	350	0.72 ± 0.04	3.38 ± 0.13	2.25 ± 0.07	17.40 ± 1.19	2.96 ± 0.12	5.0	5.9 ± 0.5
XJM-5	495	0.90 ± 0.05	3.65 ± 0.14	2.29 ± 0.07	20.13 ± 1.25	3.06 ± 0.12	6.6	6.6 ± 0.5
HXT-1	40	0.83 ± 0.05	3.91 ± 0.15	2.51 ± 0.07	16.82 ± 1.05	3.36 ± 0.13	3.3	5.0 ± 0.4
HXT-2	150	0.85 ± 0.05	3.88 ± 0.15	2.45 ± 0.07	21.88 ± 1.23	3.28 ± 0.13	3.4	6.7 ± 0.5
HXT-3	245	1.04 ± 0.05	4.90 ± 0.18	2.59 ± 0.07	24.04 ± 1.29	3.55 ± 0.14	5.8	6.8 ± 0.5
HXT-4	340	1.12 ± 0.05	5.38 ± 0.19	2.50 ± 0.07	36.60 ± 0.96	3.52 ± 0.14	4.9	10.3 ± 0.5
HXT-5	470	1.20 ± 0.06	4.97 ± 0.18	2.34 ± 0.07	44.66 ± 2.69	3.36 ± 0.13	4.2	13.2 ± 1.0
HXT-6	570	1.36 ± 0.07	5.74 ± 0.20	2.36 ± 0.07	47.56 ± 0.86	3.48 ± 0.14	5.9	13.7 ± 0.6
HXT-7	665	1.24 ± 0.06	5.15 ± 0.19	2.47 ± 0.07	56.80 ± 2.42	3.48 ± 0.14	5.4	16.3 ± 1.0
HXT-8	740	0.75 ± 0.05	2.92 ± 0.12	2.31 ± 0.07	61.45 ± 1.86	2.93 ± 0.12	5.0	20.9 ± 1.1
YXM-1	40	0.6 ± 0.04	2.6 ± 0.11	2.6 ± 0.07	1.95 ± 0.17	3.2 ± 0.13	5.0	0.6 ± 0.05
YXM-2	100	0.6 ± 0.04	2.9 ± 0.12	2.4 ± 0.07	2.36 ± 0.14	3.1 ± 0.13	5.0	0.7 ± 0.05
YXM-3	195	0.7 ± 0.05	3.5 ± 0.14	2.8 ± 0.07	2.84 ± 0.17	3.5 ± 0.14	5.0	0.8 ± 0.06
YXM-4	300	0.7 ± 0.05	3.5 ± 0.14	2.4 ± 0.07	5.11 ± 0.27	3.2 ± 0.13	5.0	1.6 ± 0.1
YXM-5	380	0.7 ± 0.05	3.5 ± 0.13	2.4 ± 0.07	13.7 ± 0.93	3.2 ± 0.13	5.0	4.3 ± 0.3
YXM-6	530	0.7 ± 0.05	3.5 ± 0.14	2.5 ± 0.07	17.4 ± 0.50	3.2 ± 0.13	4.0	5.4 ± 0.3
YXM-7	710	0.77 ± 0.05	4.05 ± 0.15	2.42 ± 0.07	56.56 ± 2.39	3.16 ± 0.13	5.2	17.9 ± 1.0
YXM-8	760	0.86 ± 0.05	4.67 ± 0.17	2.44 ± 0.07	112.4 ± 4.34	3.27 ± 0.13	6.3	34.4 ± 1.9

U—Uranium, Th—Thorium, K—Potassium, D_e—Equivalent dose, D—Dose rate.

The Horqin sandy land (42°40′–45°15′ N, 118°30′–124°30′ E; 120–800 m above sea level) is located in the northeast of the transitional zone (Figure 1) with an area of $21.68 \times 10^4 \text{ km}^2$ [66]. The climate dominated by the Asian Monsoon system is a temperate, semiarid environment. Annual average temperature varies from 3 to 7 °C, and average annual precipitation ranges from 350 mm to 500 mm, with about 70% of it being concentrated in summer [66]. The Western Liaohe river incises the region with many tributaries, such as the Xilamulun river in the west, the Laoha and Jiaolai rivers in the south, and the Uljimulun and Xinkai rivers in the north, with certain scattered lakes and ponds that are attributed to the frequent migration or diversion of paleo-channels [67]. The landform is predominated by fixed and semi-fixed dunes [66].

3. Material and Methods

3.1. Optically Stimulated Luminescence (OSL) Dating

OSL samples were collected from freshly cleaned excavated sections by hammering aluminum tubes into the exposure, and then sealing them with black plastic bags to avoid light exposure and moisture loss, in accordance with Zhao's protocol [68]. Samples were analyzed by the Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences. The OSL samples were extracted under subdued red light; then, separated by wet sieving with a 180-mesh sieve. The fine fraction (4–11 μm) of quartz grain was extracted according to Stokes' Law. The 4–11 μm fraction was handled with H₂O₂ (40%) and HCL (30%) to remove organic material and carbonate, and then etched with 15% H₂SiF₆ for 5 days to obtain the fine-grained quartz component. All samples were deposited on stainless-steel discs, and then dried at 40 °C in an oven prior to D_e measurement. All sample measurements were performed on an automated Daybreak 2200 OSL reader, which was equipped with a combined blue (470 ± 5 nm) and infrared (880 ± 80 nm) LED OSL unit, and a ⁹⁰Sr/⁹⁰Y beta source (dose rate 0.06 Gy/s). Luminescence emissions were detected by an EMI 9235QA photomultiplier tube and a 3 mm U-340 filter. The samples' equivalent doses (D_e) were measured using a sensitivity-corrected multiple aliquot regeneration (SMAR) protocol [69,70]. Subsequently, calculating the dose rates from the concentration of U, Th, and K was performed by neutron activation

analysis (NAA). For the fine-grained fraction (4–11 μm), the alpha-efficiency value was taken as 0.035 ± 0.003 [71]. Cosmic dose rate was calculated from present day burial depth [72]. The water content sample was poured into a beaker to get the wet weight, and then dried at a low temperature in the oven. Finally, the dry weight and the breaker weight were measured, and the water content was calculated [73]. All OSL results are presented in Table 1.

3.2. Measurements of Geochemical Elements in the Horqin Sandy Land

A total of 405 samples were collected at 2–5 cm intervals from top to bottom in the XJM, HXT, and YXM sections, and 157 samples were measured for geochemical elements: 50 samples from XJM, 31 samples from HXT, and 76 samples from YXM. All measurements of the geochemical elements were performed in the Key Laboratory of Desert and Desertification, Cold and Arid Regions, Environmental and Engineering Research Institute, Chinese Academy of Sciences. The procedures were as follows: First, samples were dried, ground, and sifted through a 200-mesh screen. Then, 4 g of powdered samples were pressed into round discs of 32 mm diameters with boric acid at the edges and bottoms under 30-ton pressure and at 105 °C. Finally, the discs were measured with the spectrometer using a super-long, sharp-pointed ceramic X-ray light tube (4.0 kW, 60 kV, 160 mA, 75 μ UHT Be end window). The estimated error of major elements was less than 5%, and for the trace elements it was less than 25% according to GB/T14506 28-93 (Silicate rocks: Determination of contents of major and minor elements—X-ray fluorescence spectrometric methods).

3.3. Holocene Lacustrine, Stalagmite, Loess, and Aeolian Records from the EASM Boundary

In order to investigate overall Holocene hydrological changes, we compared hydrographic recession with a synthesis of published paleoclimate records from 39 paleolake sections and peat sections, two stalagmite sections, and 22 aeolian (loess) records along the peripheral realm of the EASM. All sections are listed in Table 2.

3.4. The Munsell Soil Color Charts

Soil color was measured using the Munsell soil color charts [74]. The measurement of color was repeated twice with two different persons performing the visual measurements. Based on chroma and value, all measurement samples were found to belong the one Hue group; namely, 10YR.

4. Results

4.1. Chronology and Stratigraphy

The XJM, HXT, and YXM sections are located in the northern, central northern, and southern portion of Horqin sand land (Figure 1). Stratigraphy sequences are described in Figure 2. The XJM section consists of two units, aeolian sand (500–350 cm, 170–135 cm, 100–20 cm) and sandy paleosols (350–170 cm, 135–100 cm). In the XJM section, the aeolian sands (500–350 cm, 100–20 cm) are grayish yellow-brown (10YR 6/2) or brownish-gray (10YR 6/1); the two layers of paleosols are light gray (10YR 7/1) or brownish-gray (10YR 5/1), and generally developed discontinuously in spatial distribution because of the horizontal annihilation of the middle layer of aeolian sand observed on the field survey. The ages of the bottom sands are at 6.6 ± 0.5 ka and 5.9 ± 0.5 ka in the lower and top boundaries, respectively. The HXT section consists of aeolian sand (750–665 cm, 160–10 cm), sandy loess (665–470 cm), and sandy paleosols (470–160 cm). In the HXT section, the upper aeolian sands are brownish-gray (10YR 6/1), poor to medium sorted; the sandy paleosol is grayish-brown (10YR 5/2); the sandy loess is grayish-brown (10YR 6/2); the bottom sand is grayish-yellow (10YR 6/2), well-sorted, and exhibiting obvious differences with the upper sand, all of whose deposited ages were 6.7–5.0 ka ago. The YXM section, located in the Valley of Yangxumu River, is composed of the lower portion of fluvial-lacustrine facies (760–600 cm) that were deposited between the last glacial and early Holocene, and an upper portion (600–10 cm) of aeolian sedimentary facies since the middle Holocene. During

field research, we found that the upper and lower sedimentary facies presented an obviously angular unconformity contact, with the top age of the aeolian sand at 5.4 ± 0.3 ka at the transition site of the sedimentary facies.

Figure 2. The aeolian–paleosols sequences in the Horqin sandy land. The TQ section was provided by Guo [75].

Table 2. Non-exhaustive list for fluvial–lacustrine, stalagmitic, loess, and aeolian records of mid-Holocene climatic change along the EASM margin. Site locations shown in Figure 1.

No. site	Latitude	Longitude	Elevation	Archive	Proxy	Climate Signal	Onset Age (cal.kyr BP)	Dating Method	Reference
1. Hurlig Lake	37.28	96.9	2817	Lake	OM, Ca, MS, GE, $\delta^{18}\text{O}$,	dry	6.2–5.9, 5.3–4.9	AMS ¹⁴ C	[76]
2. Koucha Lake	34.01	97.24	4530	Lake	P, GE, TOC, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$,	dry	4.3	¹⁴ C	[77]
3. Huahai	40.43	98.07	1200	Lake	GS, Ca, TOC, C/N	dry	5.5	AMS ¹⁴ C	[78]
4. Kuhai Lake	35.30	99.18	4150	Lake	LOI, GS, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, P, GE	dry	6.1–5.4	¹⁴ C	[79]
5. Qinghai Lake	37.91	99.6	3200	Lake	P, Ca, TOC, TN, $\delta^{13}\text{C}$,	dry	6–4.5,	AMS ¹⁴ C	[52]
6. Genggahai	36.18	100.1	2860	Lake	GE, FO, TOC, TN, $\delta^{13}\text{C}$,	dry	6.3–5.5	¹⁴ C	[80]
7. Dalianhai	36.53	100.4	2850	Lake	Ca, GS, P	dry	5.7–3.9	AMS ¹⁴ C	[81]
8. Ximencuo Lake	33.38	101.1	4030	Lake	TOC, ¹³ C, C/N, GS, MS	cold	5.7, 4.2	¹⁴ C	[82]
9. Juyanze Lake	41.99	101.53	920	Lake	P, L,	dry	7–5	AMS ¹⁴ C	[83]
10. Hongyuan Peatland	32.78	102.51	3527	Outcrop	St, P	cold, dry	6.2, 5.9–4.1	¹⁴ C	[84]
11. Hongshui River	38.18	102.76	1460	Outcrop	GE, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, P,	dry, warm	6.2–5.6, 5.0–4.4,	¹⁴ C	[85,86]
12. Zhuyeze (Sanjiaocheng)	39.01	103.34	1320	Lake	L, P, LOI	dry	7–5	AMS ¹⁴ C	[87]
13. Qingtu Lake	39.07	103.61	1302	Outcrop	MS, GS, Ca, P	dry	4.7	AMS ¹⁴ C	[88]
14. Zhuyeze	39.05	103.67	1309	Outcrop	GS, P, GE,	dry	4.7	AMS ¹⁴ C	[89]
15. Wanxiang Cave	33.32	105	1200	Stalagmites	$\delta^{18}\text{O}$	dry	6.1–5.7, 5.7–4.9	²³⁰ Th	[51]
16. Toudaohu Lake	38.42	105.12	1300	Lake	P, L,	dry	7–5	AMS ¹⁴ C	[83]
17. Yanhaizi	40.13	108.45	1180	Lake	GS, TOC, TOC/TN, MS	dry	5.8–4.3	AMS ¹⁴ C	[90]
18. Midiwan	37.65	108.62	1400	Peat section	P, TOC, $\delta^{13}\text{C}$	dry, warm	7.5–4.5	AMS ¹⁴ C	[91]
19. Baihar Nuur	39.32	109.27	1278	Lake	P, L, Ca, TOC, $\delta^{13}\text{C}$	humid	6.3–4.4	AMS ¹⁴ C	[92]
20. Bojianghaizi Lake	37.97	109.31	1365	Lake	GS, LOI, P	dry	6.8	AMS ¹⁴ C	[93]
21. QigaiNuur	39.5	109.5	1403	Lake	P, GE, OM,	cold, dry	7.4–6	AMS ¹⁴ C	[94]
22. Qasq Peat	40.67	111.12	1000	Outcrop	P,	dry	4100–2400(¹⁴ C)	¹⁴ C	[95]
23. Gonghai lake	38.9	112.23	1860	Lake	Ca, EM, GC, GS, OM, P	warm, dry	5.5–4.8	AMS ¹⁴ C	[96,97]
24. Diaojiaohaizi Lake	41.3	112.35	1800	Lake	P,	warm, dry	4400–3000(¹⁴ C)	¹⁴ C	[98]
25. Daihai Lake	40.59	112.67	1230	Lake	P, Ma.	dry	6.45–2.9	AMS ¹⁴ C	[99–101]
26. Huangqihai	40.8	113.3	1277	Lake	GS, GE, MS	cold, dry	6.7–5.5, 5.0–4.0	AMS ¹⁴ C, OSL	[102]
27. Lianhua Cave	38.17	113.72	1200	Stalagmites	$\delta^{18}\text{O}$	dry	6.5	²³⁰ Th	[103]
28. AnguliNuur Lake	41.35	114.4	1315	Lake	MS, GS, P, TOC, C/N	dry	6.3–3.5	AMS ¹⁴ C, ²¹⁰ Pb/ ¹³⁷ Cs	[104,105]
29. BaiNuur	41.64	114.52	1346	Outcrop	MS, GS, P,	dry	6.9/6.8	AMS ¹⁴ C	[105,106]
30. UlanNuur	41.74	115.09	1246	Outcrop	MS, GS, P, TOC, C/N	dry	6.2/6.1	AMS ¹⁴ C	[105,106]
31. Bayanchagan Lake	42.08	115.35	1355	Lake	Pollen	dry	6.5–5.1	AMS ¹⁴ C	[107]
32. Xiarihur	42.6	115.47	1225	Lake	EM, GS, P	dry	4.9	AMS ¹⁴ C	[108]
33. Dali Lake	43.15	116.29	1220	Lake	GE, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, $\delta^{5}\text{N}$,	dry	5.9–4.8	AMS ¹⁴ C, OSL	[109–111]
34. Liuzhouwan	42.71	116.67	1365	Outcrop	GE, EM, GC, GS, LOI, OM, P	dry	4700(¹⁴ C)	AMS ¹⁴ C	[112]
35. Haoluku	42.96	116.75	1295	Outcrop	LOI, TOC, GE, MS	dry	5600(¹⁴ C)	AMS ¹⁴ C	[112]
36. Haolainure	42.95	116.79	1295	outcrop	P	warm, wet	5.8–2.9	AMS ¹⁴ C, OSL	[113]
37. Xiaoniuchang	42.62	116.83	1460	Outcrop	LOI, TOC, GE, MS, P	dry	5600–3000(¹⁴ C)	AMS ¹⁴ C	[114]
38. Jiangjunpaozi	42.37	117.47	1490	Outcrop	LOI, TOC, GE, MS, P	dry	6600–4300(¹⁴ C)	AMS ¹⁴ C	[114]
39. Hulun Lake	49.13	117.51	545	Lake	P	dry	6.4–4.4	AMS ¹⁴ C	[115]
40. Tiekui Desert	36.08	97.12	2800–3300	Aeolian	L	dry	4.5	OSL	[116]

Table 2. Cont.

No. site	Latitude	Longitude	Elevation	Archive	Proxy	Climate Signal	Onset Age (cal.kyr BP)	Dating Method	Reference
41. Donggi Cona	35.3	98.32	4090	Aeolian	GS	dry	6	AMS ¹⁴ C	[117]
42. Gonghe Basin	35.5–36.93	98.8–101.4	2400–3200	Aeolian	L, GS, GE	dry	5	OSL	[118]
43. Gonghe basin (LG)	35.80	100.33	3780	Aeolian	MS, TOC, Ca, GS, GE	cold, dry	5.3–4.7	OSL	[119]
44. Gonghe basin (DQ)	35.60	101.08	3534	Aeolian	MS, TOC, Ca, GE	dry	6.5–5.8	¹⁴ C	[120]
45. Gonghe basin (KE)	35.65	101.1	3780	Aeolian	MS, TOC, P	cold, dry	5.3–4.9	¹⁴ C	[121]
46. Badain(a)	39.3–42	99.8–104.2	1200–1700	Aeolian, Lake	GE	dry	5	AMS ¹⁴ C, TL	[122]
47. Badain(b)	38–40.5	102.5–106.5	1600	Aeolian	L	dry	6–5	OSL	[123]
48. Badain (Chagelebuuulu)	39.89	103.30	1800	Aeolian	GE	cold, dry	6.2	AMS ¹⁴ C	[124]
49. Tengger	37.45–40	102.2–105.2	1200–1400	Aeolian	GS, S	dry	6	AMS ¹⁴ C	[125]
50. Ulan Buh	39.8–40.6	105.7–106.5	1030	Aeolian, Lake	GS	dry	6.5	OSL, ¹⁴ C	[126]
51. Hobq	39.6–40.8	107.1–111.5	1200	Aeolian	GS, MS, TOC, TC, Ca,	dry	7–4	OSL	[127,128]
52. InnerMong (KB, JJ, TYG)	37.37–40.8	106.1–111.5	1000–1200	Aeolian	P	dry	5.6	OSL	[129]
53. CLP	33.68–41.27	100.8–114.5	1000–2000	Loess	L, S	dry	5.5	OSL, ¹⁴ C	[50]
54. Qingquicun	34.22	107.83	500	Loess	L, GS, GE, MS, TOC	dry	6–5	¹⁴ C	[130]
55. MuUs	37.27–39.22	107.2–111.30	1200–1600	Aeolian	L	dry	5	OSL	[131]
56. MuUs (JJ)	38.74	110.17	1159	Aeolian	GE	dry	6.6–5.4	OSL	[132]
57. MuUs	37.45–39.48	107.3–111.5	1000–1200	Aeolian	L, TOC, S	dry	6.4	¹⁴ C, OSL	[133]
58. Otindag (HSDK)	42.66	115.95	1100	Aeolian	L, MS, GS, S	dry	5	OSL	[134]
59. Otindag (Xilinhot)	43.88	116.093	960	Aeolian	MS, OM	dry	5.9	¹⁴ C	[135]
60. Horqin	42.67–45.25	118.5–124.5	120–800	Aeolian	L, $\delta^{13}\text{C}$, S	dry	6–4	OSL	[57,74]
61. Hulunbuir Dune	47.5–49.5	117.5–119.5	600–800	Aeolian	GS, MS, S	dry	5	OSL	[136]

Grain size—GS, geochemical elements—GE, magnetic susceptibility—MS, organic matter—OM, total carbon—TC, total organic carbon—TOC, carbonate—Ca, pollen—P, macrofossils—FO, lithology—L, mathematic method—Ma, synthesizing chronological data—S.

4.2. Arid Reconstruction and Rb/Sr Ratio

In Northern China, under dry climate conditions, K, Na, Ca, and Mg are concentrated, while under relatively wet conditions, sediments are rich in Fe and Mn [119,137]. Thus, the ratio of elements (Re), expressed by a ratio of (K + Na + Ca + Mg) to (Fe + Mn), was proposed to evaluate the regional drought and humidity degrees, which increase when the climate becomes drier and vice versa. The value of Re is higher in aeolian sand than in paleosols (Table 3), indicating relatively arid climate (Figure 3).

Table 3. Statistical analysis of geochemical-element contents and ratios in different sections and lithologies.

Section	Age (ka)	Lithology	Re	Rb/Sr ratio	Rb (ppm)	Sr (ppm)	CaCO ₃
XJM	6.6–5.9	Aeolian sand	6.06	0.725	93.5	129.6	0.44
	5.9–4.1	Paleosol	5.83	0.739	95.2	128.9	0.37
	4.1–?	Aeolian sand	5.96	0.762	93.3	122.6	0.35
	?–2.3	Paleosol	4.94	0.753	96.8	128.5	0.93
	<2.3	Aeolian sand	5.36	0.754	93.5	124.1	1.10
HXT	20.9–16.3	Aeolian sand	5.0	0.623	99.4	160.7	1.45
	16.3–13.2	Sandy loess	4.19	0.571	106.9	187.9	2.54
	13.2–6.7	Paleosol	4.50	0.498	109.5	221.0	2.99
	6.7–5.0	Aeolian sand	6.12	0.491	105.3	208.2	3.71
YXM	34.4–17.9	River sand	4.99	0.558	101.5	182.0	0.39
	17.9–?	Muddy sand	4.75	0.557	102.7	184.7	0.61
	?–5.4	Aeolian sand	5.58	0.585	102.1	174.6	0.60
	5.4–1.6	Paleosol	5.1	0.575	101.5	176.6	0.67
	1.6–0.6	Aeolian sand	6.6	0.597	101.2	169.7	0.48

Figure 3. Time series of the moisture change revealed by Re and Rb/Sr ratio in the Horqin sandy land.

Rubidium (Rb) and strontium (Sr) are easily fractionated in the process of chemical weathering due to their discrepant geochemical behavior [138]. Rb mainly disperses in potassium (K)-containing minerals, such as potassium feldspar, mica, and so on, while Sr usually exists in Ca-containing minerals of plagioclase feldspar, hornblende, crystal, and carbonate. The ratio of Rb/Sr in weathered clay minerals is relatively high in response to the preferential accommodation of Rb adsorbed by K-containing sites and rapid leaching of Sr [139]. Chen [140] suggested that Rb was stable and Sr easily passed into solution. Hence, the Rb/Sr ratio significantly increases with the enhancement of weathering intensity in northwestern, relatively arid aeolian sand profiles and loess–paleosol sequences [140,141]. However, in eastern China, especially in Horqin with semi-arid climatic conditions and several tributaries of the Western Liaohe crossing through it, the variation of Rb/Sr ratio was not entirely synchronized due to small-scale different physicochemical weathering conditions. It was not noticeable whether the Rb was relatively enriched or leached; the content of Rb was both low and relatively stable (Figure 4), while the Sr was leached and migrated in the paleosol in comparison with the underlying aeolian sand with a migration ratio of -3.1% in the XJM section, and relatively enriched and deposited in the HXT and YXM sections, with deposition ratios of 16.4% and 0.6% , respectively. This showed consistent geochemical behavior with Ca in the weathering process of the three sections (Figure 4). Pioneering studies suggested that calcium carbonate would be leached or deposited with various degrees of leaching [142]. In general, abundant precipitation would result in large quantities of carbonate leaching in paleosols; therefore, the low carbonate content in the paleosols indicated a relatively humid climate condition. In Horqin sandy land, on the other hand, even in the loamy stage, CaCO_3 did not move out of the paleosol layers due to relatively low precipitation, leading to the deposition of carbonate and increased contents of carbonate in the paleosols, which implied a variation of precipitation in the pedogenesis and multistage soil formation [143,144]. According to Zhao [143], CaCO_3 in paleosols appeared in the form of film, spots, and mycelia when annual average precipitation (Pa) was less than 400 mm, while CaCO_3 nodules appeared in paleosols when Pa was more than 400 mm. During the field survey, we found markedly white mycelium and CaCO_3 nucleation in the paleosols (470–160 cm) of the HXT section. Continuous CaCO_3 deposition indicated that the amount of precipitation during the soil-forming process was not enough to make CaCO_3 leach [143,144]. In the YXM section, the paleosols (530–305 cm) contain white mycelium and yellow rust spots, sandwiched with lenticle grayish-yellow, fine sand, sorted well, which might be affected by running water, leading to the relatively high content of CaCO_3 in the paleosols. The Rb/Sr ratio was mainly dependent on the change of Sr content (Figure 5), which also has consistent geochemical behavior with Ca, leading to Sr being deposited in the paleosols (Figure 4). Therefore, it was reasonable that the relatively low Rb/Sr ratio in the paleosols indicated a relatively humid condition compared with the high content of the Rb/Sr ratio with a relatively arid climatic condition in the HXT section. It was the same in the YXM section: the low content of Rb/Sr ratio in paleosols indicated the inadequate precipitation in pedogenesis. However, in the XJM section, the high content of Rb/Sr ratio in paleosols (350–170 cm) indicated a relatively humid condition resulting from the deep leaching of abounding precipitation during the mid-Holocene.

Figure 4. The average percentage change of Rb, Sr, and Ca in the XJM, HXT, and YXM sections in the Horqin sandy land.

Figure 5. The relationship of Rb/Sr ratio and Sr content in the Horqin sand land. (a) XJM (b) HXT (c) YXM.

4.3. Holocene Hydrological Changes Indicated by Fluvial-Lacustrine and Aeolian Records

The Holocene-synthesized arid–humid fluctuation from the published documents of lacustrine, stalagmite, loess, and aeolian sections are partly summarized in Figure 6. Clearly, most fluvial–lacustrine records broadly exhibited that the hydrological environment began to gradually increase in the early Holocene [145], reached optimum humidity conditions during the early-mid Holocene, and then commenced recession after a maximum period at ~6 ka, although not entirely consistent with the onset of hydrological recession. The hydroclimatic change of the aeolian deposits at the northwest EASM fringe demonstrated a consistent trend with the fluvial–lacustrine indicator. In comparison, the Holocene hydrological evolution of aeolian records on the northwest part exhibited relatively less effective moisture during the early-mid Holocene and more during late Holocene, such as in Gonghe basin and Qinghai Lake [119,146], which is probably attributed to the non-linear response of aeolian deposits to climate change and multiple factors of aeolian activities [118].

Figure 6. Synthetical published records of the Holocene hydroclimate variation from fluvio-lacustrine, stalagmite, and aeolian (loess) deposits along the EASM margin, shown in Table 1. Dashed lines indicate hydrological climate conditions 6 ka, 5 ka, and 4 ka ago. Data is provided by part of the published reference in Table 2.

5. Discussion

5.1. Asynchronous Onset of Mid-Holocene Moisture Decline

Aeolian deposits from the XJM, YXM, and HXT sections indicated that there was a remarkably arid interval at ~6–5 ka in the Horqin sandy land, which interrupted the development of paleosols (Figure 2). In addition, C4 biomass values from TQ (Figure 2) and the MTG section in the Horqin also abruptly decreased around 5.6 ka [74]. The episode of hydrological recession lasted from about several hundred years to a millennium from the west to the east along the EASM boundary belt. Semi-quantitative moisture reconstruction obtained from integrated pollen data along the belt implied a maximum moist phase at 9.5–6 ka, and then main changes primitively began at ~6–5 ka, mostly due to tree decline [54,55]. The analysis of recorded dates of aeolian deposits in northeastern sandy lands suggested mobile dune states at ~6–4 ka, and a substantial decline in dune stable states ~5–4 ka

ago [57]. On the CLP synthetic frequency distribution of ages from loess and paleosols, it suggests a significant retreat of the EASM, and consequentially, climatic fluctuations from around ~6 to 5 ka (Figure 6) [50].

In the western CLP, pollen assemblages, mollusk fauna, grain size, CaCO_3 , and organic matter indicated that the climate was wet at 8.3–7.4 ka, distinctly humid and warm at 7.4–6.7 ka, semi-humid from 6.7–6.3 ka, and semi-arid at 6.4–4 ka [25]. Furthermore, Guo [147] compared the arid climatic events at ~6 ka in northern China with northern Africa on a millennial-scale and suggested that the climatic fluctuation at ~6 ka in China was large-scale regional rather than local events. This confirms unambiguously that humidity recession was concentrated at ~6 ka in northern China, yet some sites retreated as early as ~8 ka, such as in Yanhaizi and Midiwan (Figure 6). Using numerical techniques, pollen-based quantitative climatic reconstructions demonstrated that from 6.2–5.1 ka was the wettest and warmest interval in Daihai Lake, with cold and dry events identified as occurring ~6 ka ago [99], which is generally in accordance with Xiao's studies [100,101]. However, pollen assemblages indicative of vegetation changes from sparse-wood grassland to mixed conifer, broad-leaved forests suggested that the HO occurred prior to 7 ka ago on the basis of the highest pollen concentrations of the period in Daihai Lake [148]. Both of the records originated from the same core and reached different results. The divergence of the results may be attributed to different analysis methods or different interpretations of pollen assemblages by different pollen analyzers [99].

Not only was the initial time of the hydrographic recession asynchronous, but the degeneration degree was also inconsistent. In Dali Lake, a significant variation of mineral content indicated dramatically decreased inflowing water and decreased lake levels from 5.9 to 4.8 ka ago. Since 4.8 ka, quartz and albite percentages recovered to higher levels compared with the preceding period of 5.9–4.8 ka, but were much lower than before 5.9 ka, which suggests that drainage losses of lake water were much less from 4.8 to 0 ka than from 5.9 to 4.8 ka [149]. Compared with Dali's relatively large-amplitude oscillation of the hydrographic environment at 5.9–4.8 ka, pollen-derived, reconstructed Pa in Hulun lake declined slightly (fluctuating at around 330 mm at 6.4–4.4 ka) compared to the last stage (around 340 mm); until the period of 4.4–3.3 ka, the lowest Pa of the entire Holocene with an average of 260 mm was registered [115]. Hence, we may not necessarily expect a uniform pattern of environmental deterioration in northern China. Large between-site variability may be a response to the interactions of large-scale generally dynamic mechanisms and regional controlling factors [66]. In addition, irregularity-sensitive responses of the climatic index to climate change, different temporal resolutions, or inadequate dating precision may partly amplify regional differences [33,99].

5.2. Possible Mechanism for Holocene Hydroclimate Change

In semiarid North China, along the peripheral realm of the EASM, climate is driven by large-scale climate forcing, including the EASM and the Indian summer monsoon (ISM). The relationship between EASM and ISM is dynamic and more complicated than synchronous or asynchronous, relating to atmosphere–land–ocean–vegetation interactions [150]. Aside from AM circulation, mid-latitude westerlies also played a part in mediating the influence of monsoon circulations. Concurrently, topography and regional vegetation factors might have amplified spatial complexity [53,66,151].

Earth's stronger orbital forcing of summer insolation during the early-mid Holocene enhanced monsoon activity and pulled the northerly shift from the Intertropical Convergence Zone (ITCZ) [152,153], leading to abundant precipitation. The decline in monsoonal precipitation during the middle-late Holocene may be intimately associated with steeper reductions in summer insolation after ~6 ka (Figure 7a) and the southerly shift of the ITCZ [154].

Figure 7. Possible relationship between culture rising and waning and climatic evolution along EASM margin. (a) 30° summer insolation [155]; (b) Dongge cave speleothem $\delta^{18}\text{O}$ records [45,46]; (c) westerlies' climate index in arid Asia [156]; (d) EASM index (SMI) in Qinghai lake [157]; (e) probability density of paleosols in Chinese Loess Plateau [50]; (f) pollen percentages at Daihai Lake [100]; (g) variation of C_4 biomass in the Horqin sandy land [74]; (h) multi-culture evolution along EASM margin. From left to right are the western, central, and eastern portions of the EASM margin.

In addition, the westerlies' mediating role should not be overlooked. During the early Holocene, still-large ice-sheets at high latitudes modulated and reduced air temperature, and discharges of large meltwater from the ice-sheets also reduced the Northern Atlantic Ocean's surface temperature, with an increased latitudinal temperature gradient. All factors worked together, resulting in relatively dry westerlies and little precipitation in central Asia [151]. An increasingly wet interval during the mid-late Holocene was associated with increased winter solar insolation (Figure 7c) [156] and the change of external boundary conditions, such as ice sheets, meltwater fluxes, and CO_2 concentration. The westerlies probably transported water vapor from the North Atlantic Ocean and inland seas and lakes, such as the Mediterranean, Black, and Caspian Seas, along the westerly cyclonic storm paths [158]. The influence of westerlies could penetrate eastwardly, even to northeastern China [159], which probably restricted the northward stretch of the subtropical monsoonal rain belt [160]. The interaction and competition of the monsoon and the westerlies may have led to complex changes and spatial heterogeneity along the transitional belt [66].

Complex geographical configuration is also related to the spatial asynchronization of climatic changes, especially in the Tibetan Plateau (TP). Between the low elevation in Hurleg lake (2800 m a.s.l.) and the high elevation in Qinghai lake (3200 m a.s.l.), inconsistent hydroclimate changes might be attributed to a topographically-caused, strong uplift motion of air mass over the TP, and consequently intensified subsidence of air mass in the surrounding low-elevation areas [71,151]. Similarly, aside from the influence of topographic differences, climatic deviation between Qinghai Lake and the Zoige Basin (3500 m a.s.l.) is also associated with the different relative position to the EASM and ISM [161]. In addition, vegetation growth and land-surface characteristics have significant effects on regional climate; accordingly, climate was sensitive to land-surface feedback, especially in semi-arid/arid regions [162]. The exchange of water and energy of vegetation-atmosphere-soil was affected by the intersection of vegetation types and leaf-area index. Feedback dynamically responded to regional climatic variations as vegetation changes. A slight modification in vegetation type would significantly change the surface albedo and near-surface potential heat to change the dynamic circulation of water and energy of each component; thus, influencing regional hydrothermal configuration [66,162]. Hence,

the irregular pattern of the Holocene hydroclimate condition was likely caused by different regional responses to the coupling of solar-driven AM circulation and the westerlies, as well as the differences in the re-arrangement of hydrothermal configuration.

5.3. Influence of Hydrographic Recession on Neolithic Culture's Development

Even though the vicissitudes of prehistoric culture were mainly driven by climate fluctuations [24,163], similar climatic conditions would generate distinct social outcomes (the flourishing or collapse of culture) because of imperative subsistence strategies regulating the relationship between humans and the environment [164,165], the various degrees of climatic deterioration, and the impact of the contextual factors of those cultures [24,164]. More economical and socially specialized societies might be more vulnerable to any abrupt environmental transition [29]. Under the background of HO, environmental degeneration at ~6–5 ka was probably of minor amplitude within the thresholds of Earth's ecosystem, when annual precipitation was less than 400 mm, and mean annual temperature was colder than 4.5 °C, a 1 °C decrease relative to the present in northern China [99].

Accurate spatiotemporal changes of archaeological sites (Figures 8 and 9) reflecting the prehistoric population dynamics are crucial for the proper evaluation of their driving mechanisms for ascribing paleoclimate changes to human-induced forcing [62]. In Figure 8, we can see that some regions did not allow for detecting differences between early and middle Neolithic time slices because of not subdividing the Neolithic into finer cultural units, while other regions with higher temporal resolution provided archaeological data for the middle Neolithic time slices. In the Shaanxi provinces, for example, an increment of archaeological sites from 159 to 341 sites marks a transition from the early Yangshao culture to the middle Yangshao culture [62]. In Figure 9, six time-slices from 41,260 archaeological sites along the EASM margin were used to re-establish the spatiotemporal distribution of archaeological sites of the region. A comparison of early Neolithic (8–6 ka) and mid–late Neolithic (6–4 ka) time slices revealed that the number of archaeological sites increased substantially and expanded from the south to the north within the Taihang Mountains [62]; the sites are mainly distributed in the middle to lower reaches of the Yellow River, even far into the upper reaches.

Figure 8. Chronological diagrams and change in the number of archaeological sites from the Neolithic and Bronze Ages and the early dynastic periods along the provinces of the EASM's margin. Data were provided by Hosner [62]. N, undistinguished Neolithic cultures; L-N, late Neolithic culture; DDY, Dadiwan culture; LGT, Laoguantai culture; PLG, Peiligang culture; HL, Houli culture; YS, Yangshao culture; E-YS, early Yangshao culture; M-YS, middle Yangshao culture; L-YS, late Yangshao culture; MJ, Majiayao culture; QJ, Qijia culture; DWK, Dawenkou culture; MDII, Miaodigou II culture; BX, Beixin culture; QJL, Qujialing culture; LS, Longshan culture; BA, Bronze culture; XSZ, undistinguished Xia-Shang-Zhou dynasty period. Numbers in the brackets represent number of archaeological sites.

Figure 9. Holocene spatiotemporal variation of archaeological sites along EASM margin. These maps were compiled according to data of archaeological sites provided by Honser [62].

During the HO in the northeastern fringe, the strengthened monsoon brought more precipitation to the Western Liaohe basin, and hence, favorable climate benefits for the thriving of early Neolithic cultures, such as during the Xinglongwa and Zhaobaogou periods. Rain-watered agriculture began to develop at the time [5] when fishing, hunting, and gathering were the primary subsistence strategies [27,164]. Analysis of stable carbon isotopes in human bones revealed that C3 plants obtained by gathering were part of the daily diet in the region [26,166]. Flotation results demonstrated that foxtail millet and broomcorn millet became the most important crops during the Hongshan phase in the West Liao River Basin [167]. As the hydroclimate was not humid enough for practicing large-scale agricultural activities, the mid-late Hongshan culture could have been sustained at a low production level for the long term, and Hongshan humans engaged in other subsistence strategies [164]. Rice-starch grains of the Hongshan phase from grinding stones indicated that, at 4000 BC—the earliest evidence, rice appeared in the Liaodong peninsula [168]. The rare appearance of rice in the Hongshan period denoted as an exotic food is possibly attributable to interactions with other contemporary communities, such as in the Yellow River basin [20], where domesticated rice had become more widespread during the Yangshao culture (5000–3000 BC) [26,169], demonstrating the development of social complexity and the emergence of elite groups in the Hongshan culture [20]. During the mid-late Hongshan culture, analysis of ceramic assemblages with relatively high proportions of exquisite, advanced ceramics, and the spatial patterning of house structures in archaeological sites of the northeastern region, indicated greater social prestige. Moreover, the interpretable multidimensional scaling results for lithic assemblages clearly reflected some degree of productive differentiation or low-intensity specialization, and economic interdependence between households, reflecting kinship links or other kinds of social bonds [170–172]. The most impressive complex ritual differentiation in death is connected with difference in prestige, which was reflected in platform burials with jade carved into

symbolic forms [171,172]. However, prestige difference seems to not have spilled over into every aspect of village interactions [172]. Obviously, the social change trajectories of mid-late Hongshan culture were identical with contemporaneous Yangshao culture in northern-central China, where productivity and wealth differentiation were considerably more strongly developed [172].

In the northern-central region, including the Wei River valley, the Guanzhong Basin, the Wei and Yellow River confluence, and Inner Mon (central and south), there are a high concentration of archaeological sites assigned to the mid-Yangshao culture (Figure 8) [62], indicating substantial population growth [61,62]. The Yiluo region, a core area of Chinese civilization in the Yellow River valley, experienced dramatic population growth, and a two-tiered settlement system spread to a large part of the region during the middle-late Yangshao periods [19,165]. Millet farming and pig domestication became more intensive in the meantime, while wild cereal and tubers collected were part of subsistence strategies [165,173]. Large-scale movements of populations from the southeastern regions to Henan during the late Yangshao periods, were evidenced by the presence of ceramics and typical cultural practices, such as tooth extraction, which came from the mid-late Dawenkou culture in Shangdong and Qujialing cultures in Hubei, confirming the development of greater social complexity, probably due to resource shortage as a result of environmental deterioration [19,174]. In the Gongzhong Basin, cereal-crop cultivation remained strong. Increased charcoal concentration at 3500 BC revealed the expansion of human populations and agricultural activities in the region. It should be particularly noted that *Poaceae* decreased while the *xeromorphic Fagopyrum* increased gradually around 3500 BC, which indicated that rain-watered crops, such as buckwheat (*Fagopyrum*), were selected for cultivation by Neolithic humans to adapt to the drier climate in Guanzhong Basin [175]. In central-south Inner Mongolia, starch and phytolith analyses, as well as use-wear analysis, suggested various underground storage organs, such as yams, lily bulbs, snake gourd roots, and cattail rhizomes. They were staple foods before 3500 BC; by 3500–3000 BC, cereal-based agriculture, such as millets and Job's tears, replaced tubers and roots, and became a more important source of starchy foods. The transformation of the diet structure can probably be attributed to climatic fluctuations that might have led to the depletion of wild resources around 3500 BC. An increased number of houses and settlement sizes indicated population growth in Miaoziyou village in central-south Inner Mongolia [165], where the developed Miaoziyou culture inherited the property of the Miaodigou culture from the Zhongyuan region, and reached its peak in the initial stage of environmental degradation [176]. A typical jade dragon was found in the Nihewan–Huliou Basin of Hebei with obvious characteristics of the Hongshan culture, also indicating geographically different cultures meeting and coexisting ~6.5–5 ka ago [177,178].

In the Gansu–Qinghai region of the northeastern Tibetan Plateau (NETP), the first emergence of millet-based agriculture was found during the early-mid Yangshao periods in Longdong basin [179]. When vegetation changed from forest-steppes to steppes in response to the climate transition from semi-humid to semi-arid during 6.3–4.0 ka in Western CLP [25], there was a rapidly increased number of archaeological sites and a dramatically expanded distribution of settlements, productive agriculture, and fine agriculture, all indicating the thriving of the Majiayao culture. Westward to the Guanting Basin in the NETP, four archaeological sites were located on the third terrace of the Yellow River during the late Yangshao period (~5.5 ka). During the Majiayao cultures (~5.3 ka), the number of sites evidently increased, and the scale and distribution of the settlements was expanded, with settlements generally shifting toward the lower elevation areas of the region [180]. Contemporaneously, the rate of excavation of charred seeds increased from 0.71 to 34.1 grains/liter, implying the intensification of agricultural activity [180]. Farming communities of the NETP settled along the Yellow River and its tributaries at altitudes below 2500 m a.s.l., and foxtail millet and broomcorn millet constituted the primary crops during the late Yangshao, Majiayao, and Qijia periods; that was all regarded as an upstream extension of the longstanding tradition of millet-based agriculture into the NETP, which developed and became widespread along the middle and lower reaches of the Yellow River at an earlier time [181]. Large-scale cultural expansion during the late Yangshao (3500 BC) and Majiayao (3300 BC) periods may be associated with the increase of population, and the relatively dry climate led

to the contradiction of Yangshao human-land utilization, stimulating the expansion of the Yangshao culture in central China [177].

In the fragile environmental areas of the north, northwest, and northeast in China, certain geographic limitations may be lessened due to climate deterioration at ~5.5 ka [61]. Changes in subsistence strategies represented adaptations to climate change and population growth, which promoted cultural richness and even political and economic development [61–63,182].

6. Conclusions

The deposition of aeolian sand and the change of Re and Rb/Sr ratio in the strata based on the OSL ages indicated the relative dry mid-Holocene climate 6–5 ka ago in the Horqin sand land. Synthetical records of Holocene fluvial-lacustrine, stalagmite, loess, and aeolian deposits indicated hydroclimatic recession between ~6–5 ka from the HO, although they were not entirely consistent in onset, time of duration, or degree of recession along the peripheral EASM realm. The spatiotemporal complexity may be attributed to orbit-induced weakening of summer solar insolation, and the interactions of the AM and westerlies, as well as topographical and regional vegetation factors.

In response to hydroclimatic recession from the HO and regional population–resource pressure, Neolithic humans adjusted their subsistence strategies, which involved intensive agricultural activities, increasing the complexity and spread of settlement systems, northern and northwestern expansion, and integration of region-specific Neolithic cultures.

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