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Spatial and temporal patterns of Holocene vegetation and climate changes in arid and semi-arid China

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Abstract

Pollen data from 30 sites in arid and semi-arid regions of China were reviewed to document regional patterns of Holocene vegetation and climate change and to understand the large-scale controls on these changes. Vegetation at most sites in eastern Inner Mongolia switched between forest, forest steppe, and typical steppe, showing maximum moisture conditions before 6 ka (1 ka = 1000 cal yr BP) and a dry climate after ~6 ka. Vegetation in the northwestern Loess Plateau changed between desert steppe, forest steppe and steppe, suggesting wet–dry oscillations, from an initial dry to wet climate at ~9–4 ka and then back to a dry climate. In the northern Tibetan Plateau, vegetation was characterized by steppe desert, steppe or desert, indicating a wet climate in the early and mid-Holocene until 6–4.5 ka. In western Inner Mongolia and Xinjiang, pollen assemblages show changes between desert, steppe desert and steppe, with a wet period occurring during 8.5–5.5 ka at most sites. All the four regions show a drying trend during the late Holocene. The complex climate patterns suggest that regional climate responses to large-scale climate forcing were controlled by interactions of competing factors, including the monsoons, westerlies and topography-induced regional atmospheric dynamics. The role of human activity in vegetation change requires further investigation.

1. Introduction

The Asian summer monsoons (including the Indian and East Asian monsoons) have been dominant driver of climate changes, especially change in precipitation and moisture conditions, in the southeastern part of the Eurasian continent at various timescales. During the Holocene, the monsoon intensity followed the summer insolation trend of the northern Hemisphere, with the maximum monsoon occurring in the early Holocene and decreasing afterwards (Kutzbach, 1981; COHMAP, 1988). This general pattern has been well documented in various proxy records, mostly in east and south China (e.g., An et al., 2000; He et al., 2004; Wang et al., 2005; Shao et al., 2006). However, monsoonal influence on regional climate in other parts of China is still poorly understood, especially further inland in north and northwest China located near and beyond the present limit of summer monsoon influence. In addition, the climates in northwest and north China are also influenced by the westerlies (Vandenberghe et al., 2006). The interactions between the subtropical monsoon system and the mid-latitude westerlies might have induced regional variations in climate change and vegetation responses.

This paper reviews fossil pollen records from 30 sites in arid and semi-arid areas of China. The region covered in this review includes semi-arid eastern Inner Mongolia and northwestern Loess Plateau (influenced by the East Asian summer monsoon), arid and semi-arid northern Tibetan Plateau (by both the summer monsoon and westerlies), and hype-arid western Inner Mongolia (including the Hexi corrider) and Xinjiang (mainly controlled by the westerlies). The climate of the regions should show sensitive response to large-scale climate forcing, including the Indian Monsoon, the Southeast Asian Monsoon, and the prevailing westerly atmospheric circulation (Herzschuh, 2006). The vegetation across this region should be sensitive to changes in effective moisture, induced by interplay between these circulation systems. Pollen data have been frequently

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used in vegetation and climate reconstructions, as they tend to reflect vegetation and climate changes at a regional scale. As a result, fossil pollen has become one of the most widely used and available paleoclimatic proxies in that part of China. There are, however, few syntheses of pollen data available in dryland regions of China. The objectives of this paper are to review the fossil pollen data from arid and semi-arid regions of China, to document regional patterns of Holocene vegetation and climate changes on millennial scale, and to understand the large-scale controls of these changes. Building upon an earlier synthesis (Zhao et al., 2007b) that was published in a book mainly focusing on human adaptation and impacts in arid China, this paper expands the synthesis and places more emphasis on regional vegetation and climate patterns by using a more climatically meaningful division of the regions and a semi-quantitative method to quantify moisture changes.

2. Modern environmental settings

The geographical region considered in this review covers northern China (31–49°N; 79–118°E) (Fig. 1). Altitude ranges from 194 to 5325 m above sea level (Table 1). The East Asian summer monsoon, Indian monsoon, and the westerlies play a significant role in controlling the hydrologic balance and effective moisture of the region. Most of the sites are near the present-day northern limit of monsoonal influences (Fig. 1). North of 40°N latitude, the mid-latitude westerlies prevail and bring relatively dry air from Central Asia to northwest China (Li, 1996). The transitional area between the monsoon front and the westerly dominance is very sensitive to changes in

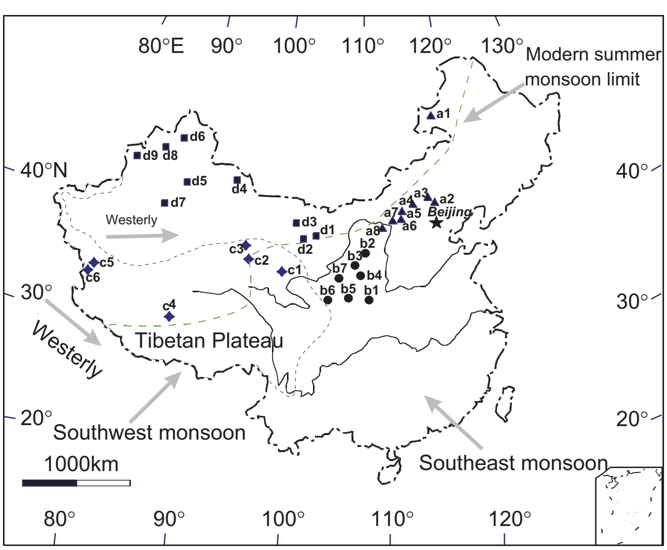

Fig. 1. Map showing the locations of fossil pollen sites in north and northwest China (see Table 1 for site information and references). Sites a1–a8 in Eastern Inner Mongolia; b1–b7 in NW Loess Plateau; c1–c6 in northern Tibetan Plateau; and d1–d9 in western Inner Mongolia and Xinjiang. The short dashed line indicates the boundary of the Tibetan Plateau and the long dashed line the rough northern boundary of East Asian summer monsoon influence.

monsoonal dynamics and interactions between monsoon and westerlies.

Under the influence of the monsoon systems, annual precipitation decreases sharply from the southeast to the northwest. Most of the study sites are situated in areas with <400 mm of annual precipitation. In eastern Inner Mongolia and the northwestern Loess Plateau, annual precipitation mostly ranges from 500 to 300 mm. On the northern Tibetan Plateau, the precipitation decreases from >300 mm in the northeast (e.g., at Qinghai Lake) to <50 mm in the northwest (e.g., at Sumxi Lake). Monsoonal air streams rarely reach western Inner Mongolia and the low-elevation part of Xinjiang, and the annual precipitation is less than 100 mm. At most of the sites, the precipitation of the three summer months (June, July, and August) usually accounts for more than 80% of the total annual precipitation, leaving winter and spring extremely dry (Ren and Beug, 2002).

The study sites are located in one of three vegetation zones: steppe, desert, and highland vegetation. A typical temperate steppe occurs in eastern Inner Mongolia and the northwestern Loess Plateau where the annual precipitation is 300–500 mm. The floristic composition mainly includes *Artemisia arenaria*, *Artemisia salsoloides*, *Stipa* spp., *Leymus chinensis*, *Achnatherum splendens*, *Carex* spp. Patches of woodlands dominated by *Quercus mongolica*, *Betula platyphylla*, *B. dadurica*, *Populus davidiana*, *Pinus tabulaefomis* and *Picea meyeri* occur in eastern Mongolia in the steppe (Hou, 2001; Liu et al., 2002). In western Inner Mongolia and Xinjiang where precipitation is less than 100 mm, desert and desert steppe are main vegetation types dominated by *A. splendens*, *Stipa* spp., *Ajania fastigiata*, *Artemisia argyi*, *Ceratoides latens*, *Haloxylon ammodendron*, *Ephedra prezewalskii*, *Tamarix* spp., *Suaeda dendroides*, and *Kalidium schrenkianum* (Hou, 2001). Vegetation in the northern Tibetan Plateau changes from highland steppe in the east to highland desert in the west, as a result of the decrease in precipitation. In the eastern part of the plateau, arboreal taxa are frequently found in mountainous valleys, including *Picea crassifolia*, *Abies likiangensis*, *Sabina przowalskii*, *Pinus tabulaeformis*, *B. platyphylla*, and *Quercus* spp. The highland steppe is dominated by *Stipa subsessiliflora*, *Stipa purpurea*, *Artemisia* spp., *Kobresia littledalei*, *Carex moorcroftii*, and *Polygonum* spp. The highland desert, where the climate is extremely dry, with an annual precipitation of less than 100 mm, is covered by a sparse vegetation, characterized by Chenopodiaceae (*H. ammodendron*, *Salsola abrotanoides*, *Kalidium spp.* and *Ceratoides compacta*), *Zygophyllum xanthoxylon*, *Artemisia* spp., *Stipa spp.*, *A. splendens*, *Ephedra przewalskii* and *Nitraria* spp. (Yu et al., 2001).

3. Data sources and methods

The criteria for site selection included a reliable chronology with a minimum of three dating control points (but with several exceptions if there were no pollen

Table 1
List of fossil pollen sites from arid and semi-arid China used in this review

Site no.	Site name	Province/ region	Location	Elevation (m a.s.l.)	No. of dates[a]	Type of archives	Climate proxy[b]	Reference
a1	Hulun Lake	Inner Mongolia	E116°58′, N48°30′40″	545	4	Lake section	A/C ratio; pollen concentration	Yang and Wang (1996)
a2	Xiaoniuchang	Inner Mongolia	E116°49′, N42°37′	1460	3	Lake section	A/C ratio; AP/NAP	Liu et al. (2002)
a3	Haoluku	Inner Mongolia	E116°45.42′, N42°57.38′	1295	4	Lake section	A/C ratio; AP/NAP	Liu et al. (2002)
a4	Bayanchagan	Inner Mongolia	E115.21°, N41.65°	1355	7	Lake core	Tree percentage; concentration	Jiang et al. (2006)
a5	Huangqihai	Inner Mongolia	E113°10′, N40°48′	1264	4	Lake section	Pollen percentage	Li et al. (1992)
a6	Daihai	Inner Mongolia	E112°33′, N40°29′	1221	8	Lake core	Tree percentage	Xiao et al. (2004)
a7	Diaojiao Lake	Inner Mongolia	E112°21′, N41°18′	1800	4	Lake core	Pollen percentage; pollen flux	Shi and Song (2003)
a8	Chasuqi	Inner Mongolia	E111°08′, N40°40′	1000	4	Peat section	Tree percentage	Wang and Sun (1997)
b1	Fuping	Shan'xi	E 109°50′, N 34°50′	400	2	River section	Broad-leaf trees	Sun and Zhao (1991)
b2	Sandaogou	Shan'xi	E109.25°, N38.4°	1049	6	Loess section	Pollen percentage	Gao et al. (1993)
b3	Yaoxian	Shan'xi	E108°50′, N34°56′	667	2	Loess section	Pollen percentage; A/C ratio	Li et al. (2003a)
b4	Midiwan	Shan'xi	E108°37′, N37°39′	1400	23	Peat section	Concentration; tree pollen	Li et al. (2003b)
b5	Dadiwan	Gansu	E105°54′, N35°01′	1400	3	Marsh section	Tree pollen percentage	An et al. (2003)
b6	Shujiawan	Gansu	E104°31′22″, N35°32′20″	1700	3	Marsh section	Tree pollen percentage	An et al. (2003)
b7	Lanzhou	Gansu	E103°73′, N36°03′	1500	6	Loess section	Pollen percentage	Wang et al. (1991)
c1	Qinghai lake	Qinghai	E99°36′, N36°32′	3200	7	Lake core	Tree percentage; concentration	Shen et al. (2005)
c2	Hurleg Lake	Qinghai	E96°54′, N37°19′	2809	7	Lake core	A/C ratio	Zhao et al. (2007a)
c3	Dunde	Qinghai	E96°24′, N38°06′	5325		Ice core	Concentration; A/C ratio	Liu et al. (1998)
c4	Selin Co	Qinghai	E88°31′, N31°34′	4530	5	Lake core	*Artemisia* percentage	Sun et al. (1993)
c5	Sumxi Co	Qinghai	E81°00′, N35°30′	5058	6	Lake core	A/C ratio	Van Campo and Gasse (1993)
c6	Bangong Lake	Qinghai	E79°00′, N33°40′	4241	25	Lake core	A/C ratio; Cyperaceae	Van Campo et al. (1996)
d1	Sanjiaocheng	Hexi Corridor	E103°20′, N39°00′	1325	13	Lake bank	Pollen concentration;	Chen et al. (2006)
d2	Hongshui River	Hexi Corridor	E102°45′53″, N38°10′46″	1460	9	River section	Percentage; concentration; A/C ratio	Zhang et al. (2000)
d3	Eastern Juyanze	Inner Mongolia	E101.85°, N41.89°	892	5	Lake	Concentration; A/C ratio, *Ephedra fragilis*	Herzschuh et al. (2004)
d4	Balikun	Xinjiang	E86°40′, N41°56′	1580	8	Lake core	Pollen percentage	Han (1992)
d5	Chaiwopo	Xinjiang	E87°15′, N43°25′	1115	8	Peat section	Percentage	Shi (1990)
d6	Wulun Lake	Xinjiang	E87°00, N46°59′	1374	2	Lake core	A/C ratio	Yang and Wang (1996)
d7	Boston Lake	Xinjiang	E86°40′, N41°56′	1048	4	Lake section	Percentage; concentration	Xu (1998)
d8	Manas Lake	Xinjiang	E86°00′, N45°45′	257	7	Lake core	A/C ratio; pollen influx	Sun et al. (1994)
d9	Aibi Lake	Xinjiang	E82°35′, N44°54′	194	2	Lake section	Pollen percentage	Wu et al. (1996)

[a]Dated by ^{14}C except at b3 by thermal luminescence and at c3 by annual layer and ice model.
[b]A/C ratio—*Artemisia*-to-Chenopodiaceae ratio; AP/NAP—aboreal pollen to non-aboreal pollen ratio.

diagrams for a given region) and high sampling resolution with a minimum of 40 pollen samples during the Holocene. Thirty fossil pollen sites were selected from the four regions based on these criteria (Table 1). In cases where there was more than one diagram available from a site, the one with better dating control and higher pollen sampling resolution was used.

Radiocarbon dating was the geochronological technique used to date all the profiles in this paper, except for Yaoxian (dated by thermoluminescence) and Dunde ice core (dated by ice layer counting and ice flow modeling). Organic materials or carbonates were used for ^{14}C dating from loess, lacustrine deposits, and peat. No attempt was made to correct for potential old carbon problems at individual sites. In this paper, all ages for all reviewed sites have been calibrated to calendar years before present (BP = 1950 AD) using the most recent IntCal04 calibration dataset (Reimer et al., 2004).

Six summary pollen diagrams that are representative of vegetation changes in different regions are discussed. The pollen diagrams are used to discuss spatial and temporal patterns of vegetation change across arid and semi-arid China. In arid or semi-arid regions, vegetation is mostly dependent on effective moisture rather than temperature. This discussion focuses on changes in effective moisture. The main pollen indices used are tree pollen percentage (a moist climate indicator), pollen concentration (a pollen production indicator), *Artemisia*-to-Chenopodiaceae A/C ratio (measuring relative dominance of steppe vs. desert pollen types) (El-Moslimany, 1990), and *Ephedra* and *Nitraria* percentages (as characteristic desert indicators). These pollen indices provide a semi-quantitative estimate of relative moisture conditions, despite potential interpretation problems. Pollen indices from the 30 sites were used to quantify dry–wet climate fluctuations semi-quantitatively at individual sites during the Holocene. The four moisture classes were assigned for each individual site from the wettest (score 4) to the driest period (score 1). Time series of relative moisture changes at a 100-year interval for each of the four regions were generated using this approach. These synthesized time series help detect and understand spatial and temporal variations of effective moisture along an east to west transect.

4. Records of Holocene vegetation and climate changes

4.1. Semi-arid eastern Inner Mongolia

Eight well-dated pollen records were used for the synthesis in eastern Inner Mongolia (sites a1–a8; Fig. 1 and Table 1). Daihai Lake (site a6; Xiao et al., 2004) provides a high-resolution pollen record that is representative of the pollen sites from Inner Mongolia (Fig. 2). The pollen assemblages are dominated by herbs and shrubs typical of arid conditions, especially *Artemisia* at 30–70%. At 11–8 ka (1 ka = 1000 cal yr BP), pollen assemblages have ~65% *Artemisia*, ~10% Chenopodiaceae, 5% *Ephedra*, and about 20% tree pollen mostly from *Pinus*, *Betula*, and

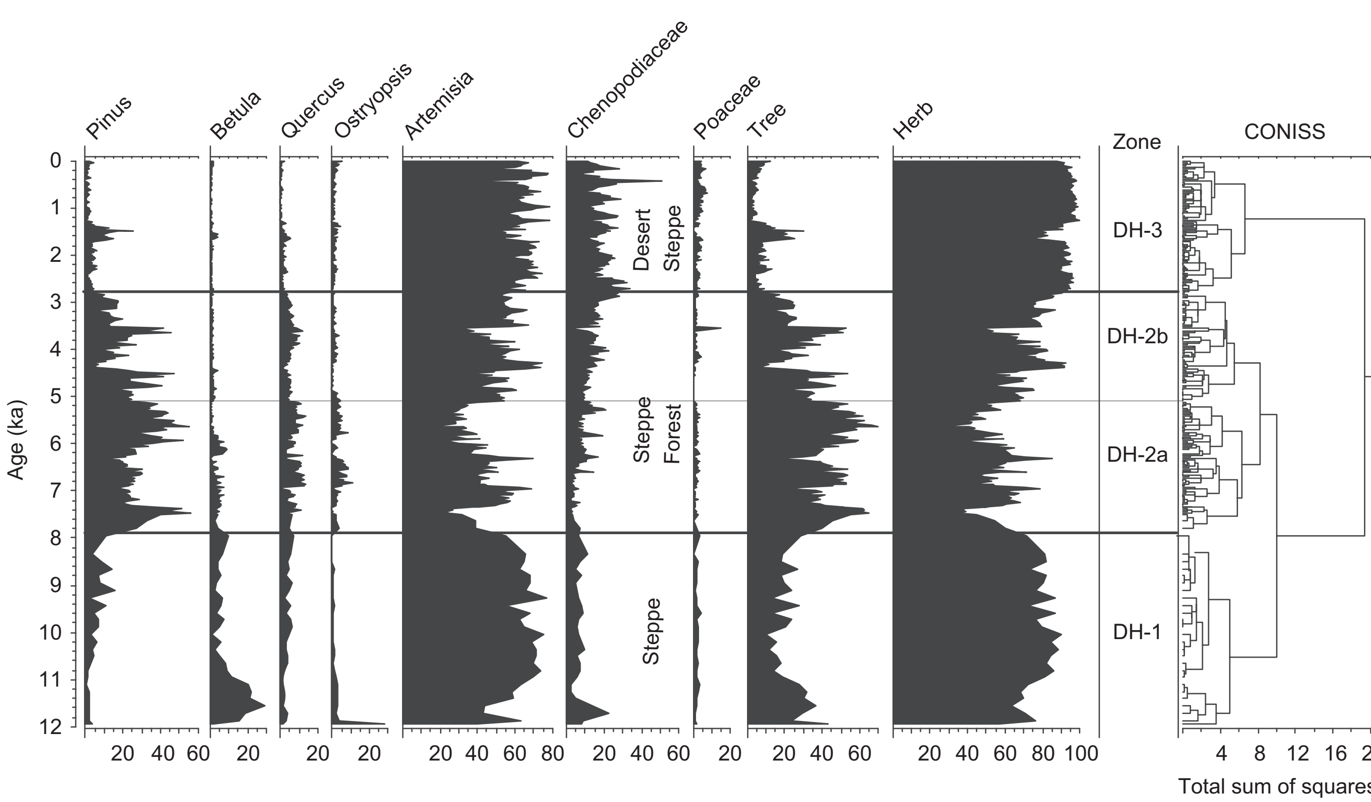

Fig. 2. Summary percentage pollen diagram from Daihai Lake, Inner Mongolia (redrawn from Xiao et al., 2004). Only selected taxa shown.

Quercus. Between 8 and 5 ka, tree pollen reaches the maximum level of 40–60% for the entire Holocene, characterized by *Pinus* (20–50%), *Quercus*, *Betula* and *Ulmus*. At 5–3 ka, tree pollen decreases to <20%, while Chenopodiaceae increases gradually from 10% to >20% and *Artemisia* increases to its early Holocene level of ~65%. After 3 ka, pollen assemblages are characterized by consistently high *Artemisia* (~70%) and Chenopodiaceae (~20%), with some increases in Poaceae (to ~8%) (Xiao et al., 2004). The pollen record from Daihai indicates that vegetation around Daihai Lake changed from steppe at 10–8 ka, through *Pinus*- and *Quercus*-dominated steppe forest at 8–3 ka, to desert steppe after 3 ka. This vegetation sequence suggests that climate changed from a dry climate in the early Holocene, through a moist mid-Holocene, to drier conditions in the late Holocene.

Other pollen records from eastern Inner Mongolia show diverse Holocene vegetation history. During the early Holocene, pollen assemblages are generally dominated by *Betula*, *Picea*, and *Ulmus* in the southeast. During the middle Holocene at 7–5 ka, pollen assemblages tend to be dominated by *Artemisia* with some tree pollen including *Betula*, *Quercus*, *Ulmus*, and *Pinus*. After 5 or 4 ka, pollen assemblages change to *Artemisia*-dominated with some tree pollen. Vegetation around Xiaoniuchang (a2) (Liu et al., 2002), Haoluku (a3) (Liu et al., 2002) and Huangqihai (a5) (Li et al., 1992) changed from forest in the early Holocene, through steppe forest during the middle Holocene, to forest steppe in the late Holocene. Vegetation at Bayanchagan (a4) (Jiang et al., 2006) changed from steppe in the early Holocene, through forest steppe from the late early-Holocene to early mid-Holocene, to steppe afterwards. At Hulun Lake (a1) (Yang and Wang, 1996), Diaojiao Lake (a7) (Shi and Song, 2003), Chasuqi (a8) (Wang and Sun, 1997), vegetation changed from steppe in the early Holocene, through forest steppe in the middle Holocene, to steppe in the late Holocene. These vegetation sequences indicate that climate changed generally from a wet climate in the early mid-Holocene to drier conditions after 7 ka.

4.2. Semi-arid northwestern Loess Plateau

Seven records that cover the entire Holocene (sites b1–b7) are available from the northwestern Loess Plateau. Dadiwan (b5) is representative of the pollen sites in this region with a high sampling resolution of ca. 50 years (Fig. 3; An et al., 2003). At 12–8.5 ka, the pollen assemblages are dominated by *Artemisia* (30%), other Asteraceae (30%), and *Zygophyllum*. From 8.5 to 6.5 ka, the pollen assemblages are characterized by up to 80% tree pollen, predominantly from *Pinus*, with some *Betula*, *Ulmus*, and *Quercus*. After 6.5 ka, Poaceae (up to 80%), Asteraceae, *Artemisia*, and Chenopodiaceae dominate the pollen diagram. The pollen data thus indicate that vegetation around Dadiwan changed from a desert steppe at 12–8.5 ka, through *Pinus*-dominated steppe woodland (steppe forest) at 8.5–6.5 ka, to desert with sparse steppe after 6.5 ka. This vegetation sequence suggests that a relatively humid climate during the mid-Holocene at 8.5–6.5 ka was favorable for the development of woodland,

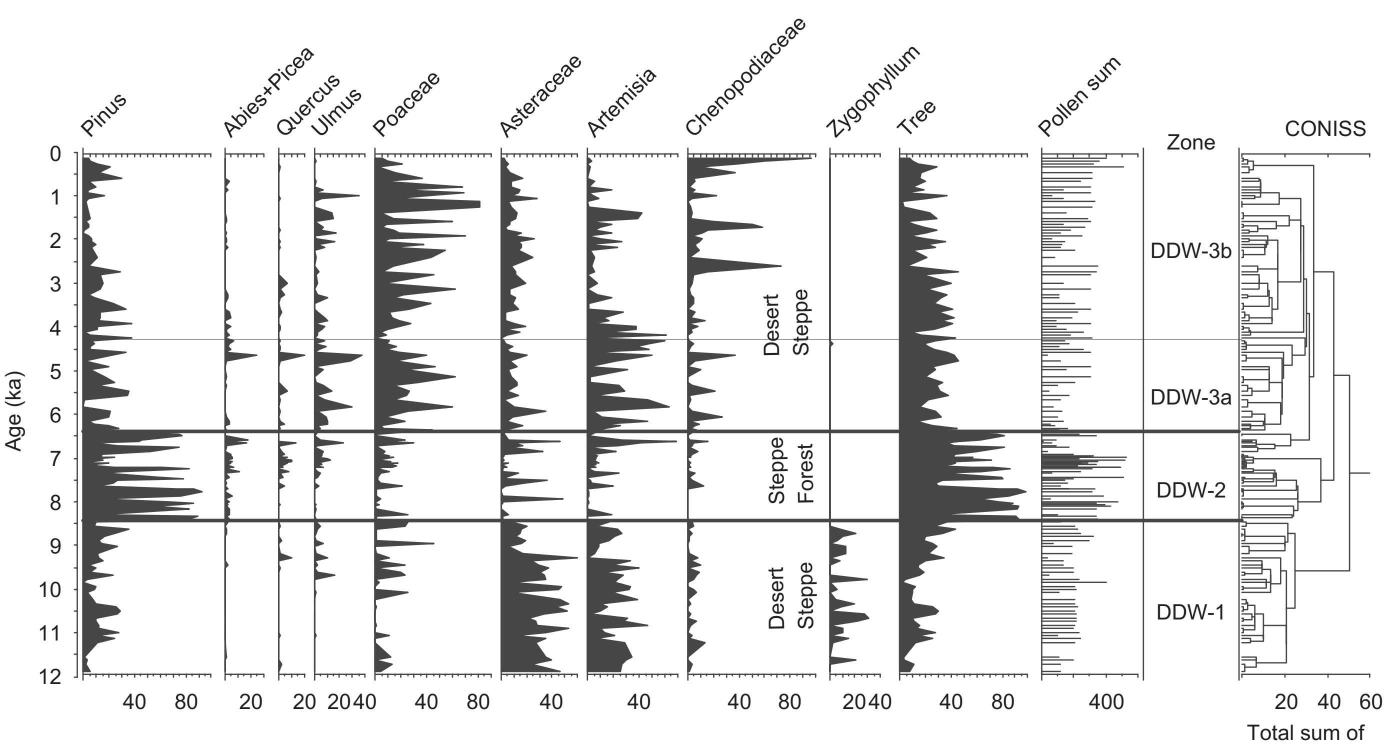

Fig. 3. Summary percentage pollen diagram from Dadiwan, NW Loess Plateau (redrawn from An et al., 2003). Only selected taxa shown.

while a relatively dry early and late Holocene allowed open vegetation representative of arid conditions to develop.

Pollen data from Midiwan (b3), in the desert and loess transition zone, show a different pattern of Holocene vegetation and climate change. Vegetation changed from sparse forest steppe, consisting mainly of *Thalictrum*, Cyperaceae, *Betula*, and *Quercus* at 11.5–8.5 ka, through a desert steppe composed of *Artemisia* and Chenopodiaceae during 8.5–5.3 ka, to a humid steppe with some tree pollen at 5.3–3 ka and finally to *Artemisia*-dominated desert steppe after 3 ka (Li et al., 2003b). These vegetation changes indicate climate changed from a warm and humid early Holocene, through a dry mid-Holocene and a wet early late-Holocene, to drier conditions in the late Holocene.

Pollen data from other sites in the NW Loess Plateau show that between 12 and 9 (or 8.5) ka, the pollen assemblages mainly contain Chenopodiaceae, *Artemisia*, *Reaumuria*, *Ephedra*, Asteraceae, and *Ranunculus*, with some tree pollen from *Pinus*, *Picea*, *Abies*, and *Ulmus*. From 9/8.5 to 6 ka, pollen assemblages are characteristic of *Quercus*, *Betula*, and *Pinus* at Fuping (Sun and Zhao, 1991), Dadiwan, and Shujiawan (An et al., 2003), all of which are located in river valleys and terraces. At other sites (Lanzhou: Wang et al., 1991; Sandaogou: Gao et al., 1993; Yaoxian: Li et al., 2003a) *Artemisia*, Chenopodiaceae, Asteraceae, and Poaceae are the main pollen types. Pollen record from the southeast site of Yaoxian showed a different herb component from other sites, dominated by *Polygonum*, Lamiaceae, *Ulmus*, *Quercus*, and *Betula* (Li et al., 2003a). After ~5 ka, drought-tolerant plants such as Chenopodiaceae and *Ephedra* dominated (Fuping: Sun and Zhao, 1991; Lanzhou: Wang et al., 1991; Sandaogou: Gao et al., 1993; Dadiwan and Shujiawan: An et al., 2003; Yaoxian: Li et al., 2003a). Vegetation around these sites changed from desert steppe before 9 (or 8.5) ka, through shrub steppe or steppe with sparse trees from 9 (or 8.5) to 6 ka, to desert steppe or semi-desert over the last 5 ka. At the sites in the river valleys and terraces, vegetation changes are somewhat different, changing from steppe/forest and steppe with sparse trees, through forest, to steppe or forest steppe. Climate in the NW Loess Plateau was generally dry during the early Holocene before 9 (or 8.5) ka, became wet from 9 (or 8.5) to 6 ka, and was dry again after 5 ka.

4.3. Arid and semi-arid northern Tibetan Plateau

Six pollen diagrams from the Northern Tibetan Plateau (from c1 to c6) were used for this synthesis. The pollen diagram from Qinghai Lake (c1; Fig. 4; Shen et al., 2005) can be divided into three pollen assemblage zones. Before 10.6 ka, pollen assemblages are characterized by *Artemisia* (~60%), tree pollen (~20%), Poaceae (~10%), and Chenopodiacece (~10%). At 10.6–4.2 ka, *Artemisia* decreased to less than 40%, *Pinus* increased up to ~30% and

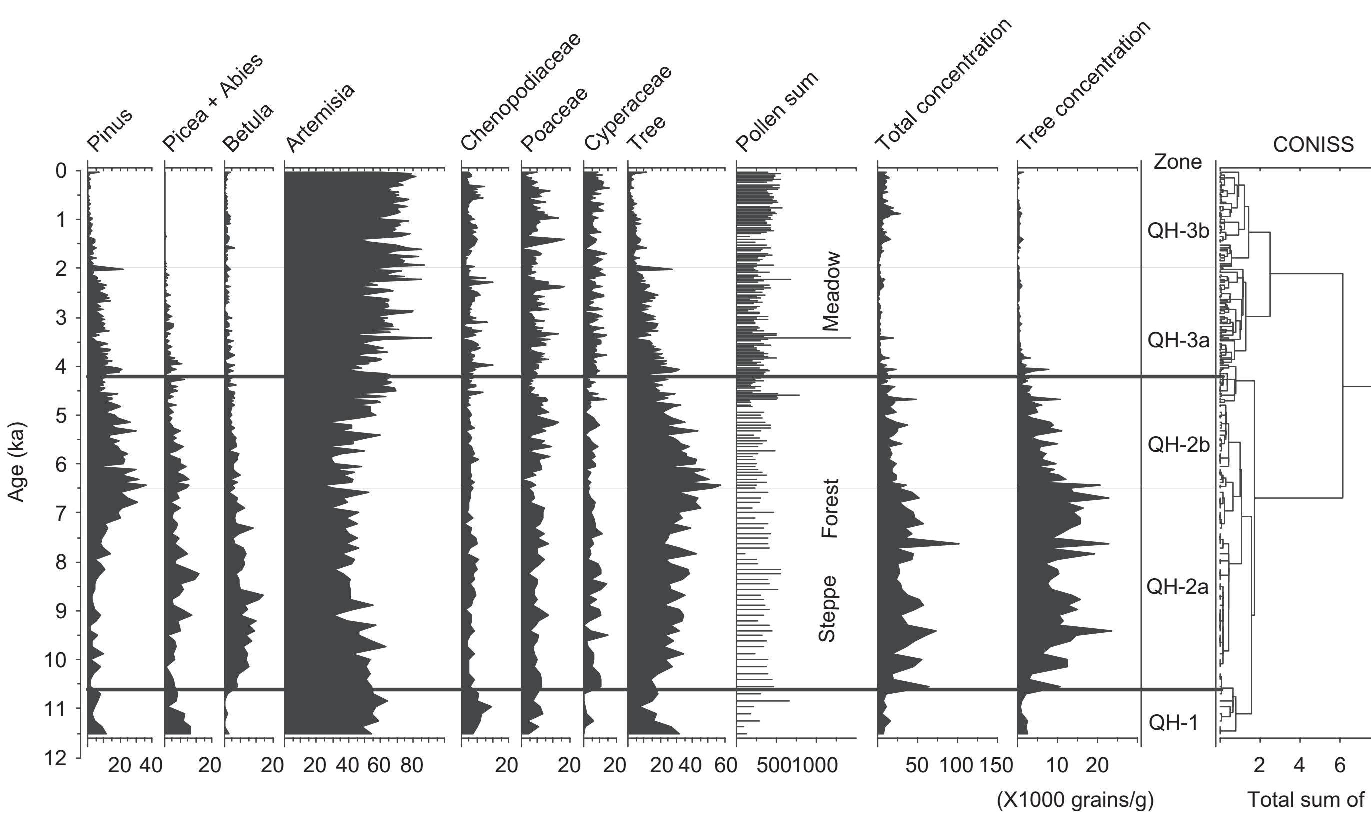

Fig. 4. Summary percentage pollen diagram from Qinghai Lake, N. Tibetan Plateau (redrawn from Shen et al., 2005). Only selected taxa shown.

Betula was up to 20%. The highest pollen concentrations occur in this zone. After 4.2 ka, *Artemisia* increased again (up to 80%) and *Pinus* decreased from 15% to 0% (Shen et al., 2005). Vegetation around Qinghai Lake changed from steppe before the Holocene, through steppe forest in the early and mid-Holocene at 10.6–4.2 ka, to *Artemisia*-dominated steppe in the late Holocene. This vegetation sequence suggests a dry climate before the Holocene, a wet climate in the early and mid-Holocene, and a dry climate in the late Holocene.

Pollen assemblages from other sites in the northern Tibetan Plateau (Dunde ice core, Selin Co, Sumxi Co, and Bangong Co) are dominated by *Artemisia* and are characterized by higher pollen concentrations and higher A/C ratios during the early and early middle Holocene. At Selin Co (Sun et al., 1993), Sumxi Co (Van Campo and Gasse, 1993) and Bangong Co (Van Campo et al., 1996), this pollen assemblage lasted until 6.8 ka, with a peak A/C ratio between 8.4 (or 8) and 7.4 (or 6.8) ka, while at Dunde (Liu et al., 1998), it lasted until 4.5 ka. After that period, *Artemisia*, Chenopodiaceae, *Ephedra*, and *Nitraria* dominate the pollen assemblages. Arboreal pollen was never the main component throughout the Holocene at any of the sites. Vegetation switched between desert, desert steppe and steppe. The abundant tree pollen at Selin Co during the late Holocene probably resulted from aerial transport from the south and east, instead of indicating local trees. The vegetation suggests a consistently wet climate in the early and middle Holocene and a progressive drying trend during the late Holocene. It seems that the modern environmental conditions were established time-transgressively at 6.8, 4.5, and 4 ka from west to east in the northern Tibetan Plateau.

The pollen results from Hurleg Lake (c2) in the Qaidam Basin are in sharp contrast to the records from other sites, including Qinghai Lake (only ~300 km to the east) (Fig. 5; Zhao et al., 2007a). A revised chronology for core HL05-2 at Hurleg Lake is presented, as corrected by 2758 years of old carbon reservoir effect from the chronology presented in Zhao et al. (2007a, b), on the basis of the paired dating of ^{14}C and ^{210}Pb dating of a short core (unpublished data). Hurleg fossil pollen data showed that *Artemisia*, Chenopodiaceae, and Poaceae were the dominant pollen types over the entire Holocene, with relatively low *Ephedra* and *Nitraria* pollen percentages. Before 9 ka, pollen assemblages are dominated by Chenopodiaceae (up to 50%), *Artemisia* (20%), and *Ephedra* (up to 20%), except at 13–11 ka with higher *Artemisia*. Pollen assemblages during 9–6 ka are characterized by higher *Artemisia* (~35%), leading to higher A/C ratios. At 6–3.5 ka, Chenopodiaceae reaches the maximum value (~80%), with low and fluctuating A/C ratios. Poaceae starts to increase during this period. After 3.5 ka, pollen assemblages are dominated by consistently high Poaceae (30–40%), and Chenopodiaceae decreases to 35%. Vegetation around Hurleg Lake changed from Chenopodiaceae-dominated desert before 9 ka, through steppe desert at 9–6 ka, desert at 6–3.5 ka, and back to steppe desert after 3.5 ka. This vegetation sequence indicates that in a generally arid context, climate was dry at the beginning of the early Holocene, relatively

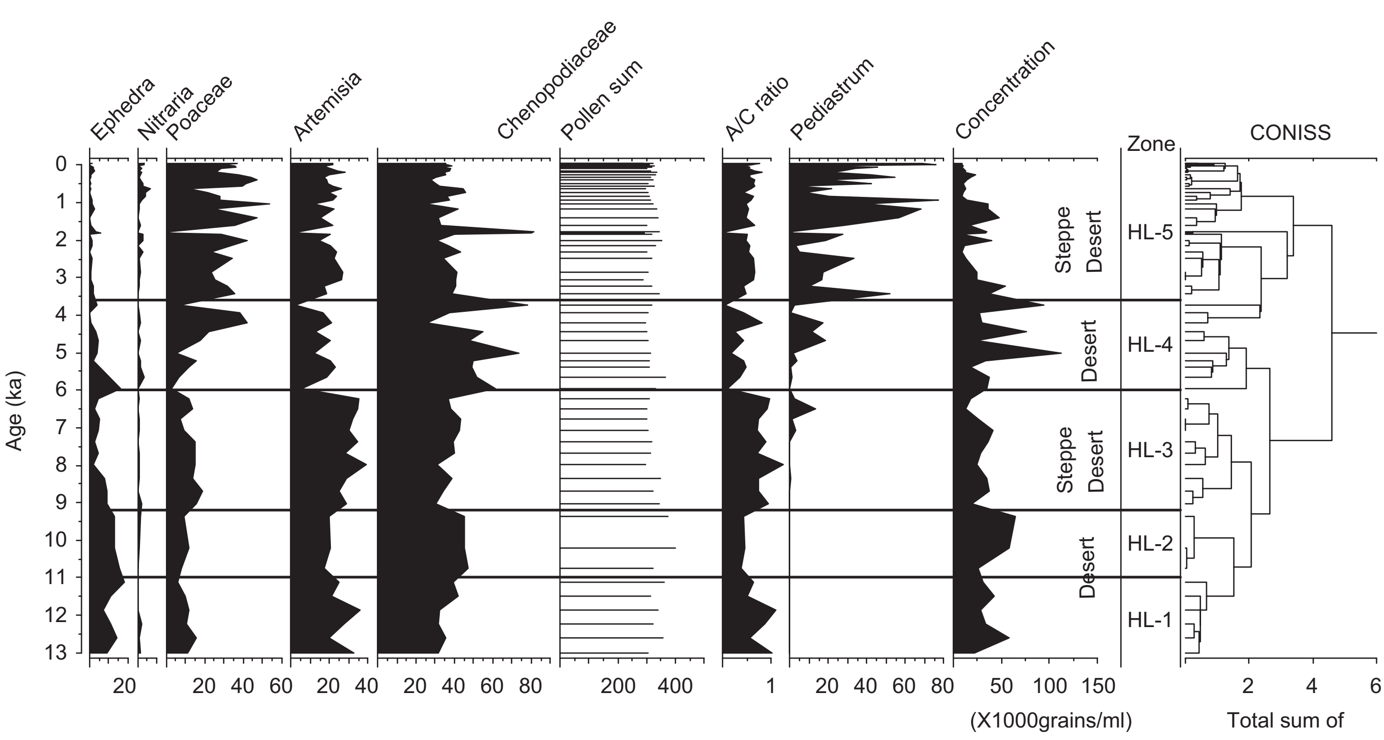

Fig. 5. Summary percentage pollen diagram from Hurleg Lake, N. Tibetan Plateau. Chronology was revised from Zhao et al. (2007a) after considering old carbon reservoir effect. Only selected taxa shown.

wet at 9–6 ka, dry and variable at 6–3.5 ka, and relatively wet and stable after 3.5 ka.

4.4. Hyper-arid Xinjiang and western Inner Mongolian Region

Nine pollen sites from this region were selected to discuss changes in fossil pollen assemblages during the Holocene (sites d1–d9). The Sanjiaocheng site (d1) is an exposed section in a dried-up lake basin in the western Hexi Corridor, which is located near the present-day boundary between desert and steppe. At 11.6–7 ka, conifer tree pollen, mainly from *Sabina* (also called *Juniperus*) (40–60%), *Picea* (up to 80%) and *Pinus* (20–40%), dominates the pollen assemblages, with consistently high total pollen concentrations (Fig. 6; Chen et al., 2006). Pollen assemblages are characterized by xerophyte pollen types from 7 to 3.8 ka, including *Nitraria* (up to 90%) at the expense of *Sabina* (<20%), *Picea* (<5%) and *Pinus* (<10%). Pollen concentration is at the lowest level for the entire diagram at this interval. After 3.8 ka, pollen assemblages mainly contain Chenopodiaceae (up to ~40%), Poaceae (~30%), and *Artemisia* (~20%), with large fluctuations both in pollen percentages and in concentration (Chen et al., 2006). The pollen diagram suggests that Sanjiaocheng was covered by steppe at 11.6–7 ka, desert or desert steppe at 7–3.8 ka and desert after 3.8 ka, indicating a wet early Holocene, a dry mid-Holocene, and variable late Holocene. Tree pollen grains from *Sabina*, *Picea*, and *Pinus* were likely transported by rivers from the Qilian Mountains, especially in the early Holocene when the summer monsoon precipitation was greater (Zhu et al., 2003).

Pollen assemblages at sites d2 (Ma et al., 2003), d3 (Herzschuh et al., 2004), d4 (Han, 1992), d5 (Shi, 1990), d6 (Yang and Wang, 1996), d7 (Xu, 1998), and d9 (Wu et al., 1996) show that vegetation changed between desert, steppe desert and steppe during the Holocene, based on the criteria proposed by Li (1996). Using these criteria, desert is defined by Chenopodiaceae pollen abundance ranging from 35% to 55%. For steppe desert, Chenopodiaceae percentage is <35% and is lower than *Artemisia*. For steppe, Chenopodiaceae, and *Artemisia* pollen together account for less than 35% of total pollen. Desert or steppe desert dominates the assemblages at these sites from the beginning of the Holocene until 9.5/8.5 ka. Vegetation was dominated by *Artemisia* steppe at the expense of Chenopodiaceae or steppe desert (at Eastern Juyanze) from 9.5 (or 8.5) to 4.5 (or 3) ka, while desert returned to dominance after 4.5 (or 3) ka. Vegetation reconstructions from fossil pollen data indicate that the climate was dry during the first 2000 years of the Holocene and became wetter from 9.5 (or 8.5) to 4.5 (or 3) ka. All the records indicate that effective moisture decreased after 4 or 3 ka, though with some fluctuations.

The pollen diagram from Manas Lake (d8) shows a somewhat different vegetation history in this region (Fig. 7; Sun et al., 1994). At 10.5–7.5 ka, the pollen assemblages are

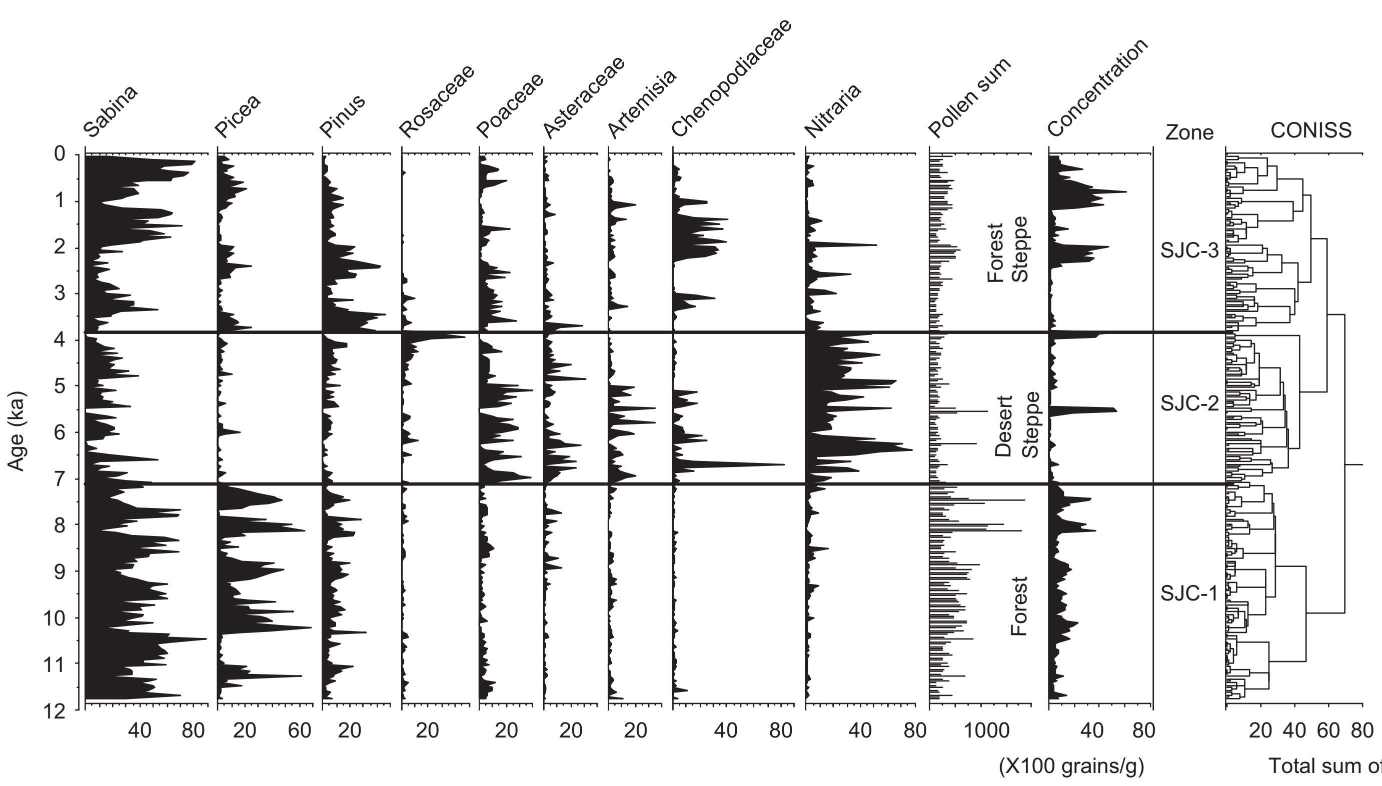

Fig. 6. Summary percentage pollen diagram from Sanjiaocheng, Inner Mongolia (redrawn from Chen et al., 2006). Only selected taxa shown.

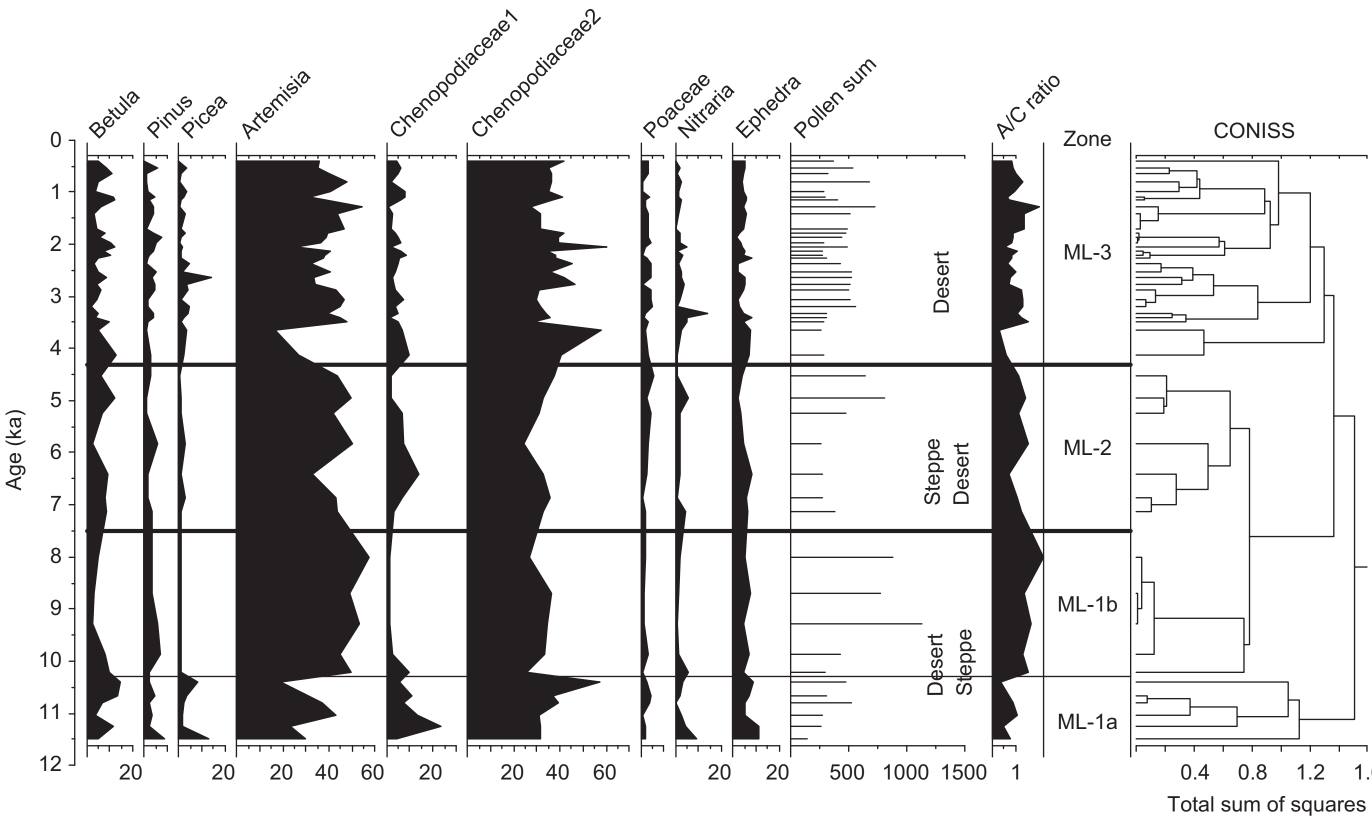

Fig. 7. Summary percentage pollen diagram from Manas Lake, Xinjiang (redrawn from Sun et al., 1994). Only selected taxa shown.

characterized by higher *Artemisia* (up to 55%) and the highest A/C ratios. From 7.5 to 4.3 ka, Chenopodiaceae increases to 45%, *Artemisia* decreases from 40% to 30%, and Poaceae increases slightly to ~5%. After 4.3 ka, *Artemisia* stays at 40% and Chenopodiaceae increases to 50%. Manas Lake was surrounded by desert steppe before 7.5 ka and by desert after 4 ka, with a transition from steppe desert to desert from 7.5 to 4.3 ka. This vegetation change suggests that climate varied from a slightly dry climate in the early Holocene, through a drying period in the mid-Holocene, to a very dry climate in the late Holocene.

5. Synthesis and discussion

5.1. Spatial and temporal patterns of Holocene vegetation and climate changes

The 30 fossil pollen records were used to detect and discuss the spatial and temporal patterns of Holocene vegetation (Fig. 8) and climate changes (Fig. 9) in arid and semi-arid China. Vegetation showed different changes in various regions during the Holocene. Forest, forest steppe, steppe dominated the vegetation in eastern Inner Mongolia, whereas steppe/desert, forest steppe/desert steppe, steppe/desert occupied the west part of Inner Mongolia. Vegetation in the northwestern Loess Plateau changes between desert steppe, forest steppe, and steppe, with forests prevailing in loess valleys during the mid-Holocene. In the northern Tibetan Plateau, vegetation is characterized by steppe, steppe desert or desert, while the Qinghai Lake area was dominated by forest during the early and mid-Holocene. In western Inner Mongolia and Xinjiang, vegetation changes between desert, steppe desert, and steppe during the Holocene.

The semi-quantitative moisture classes obtained from interpreted fossil pollen records in the four regions reveal different wet–dry climate changes during the Holocene (Fig. 9). In the northern Tibetan Plateau, a wet climate occurred in the early and mid-Holocene before 5 ka, with the maximum moist period at 11–8 ka. The northern Tibetan Plateau appears to be the region showing the earliest occurrence of the maximum moist period at the onset of the Holocene, while other regions appear to show delays of several thousand years (Fig. 9). Most sites in eastern Inner Mongolia show a relatively wet climate during the early Holocene, the wettest climate during the mid-Holocene, and a dry climate since ~6 ka. In the NW Loess Plateau, all the sites appear to show wet–dry oscillations, from an initial dry climate in the early Holocene to a wet climate at 9–4 ka and then return to a dry climate after 4 ka, which is generally consistent with climate change as inferred from paleosol/peat and loess/aeolian layers (Porter and Zhou, 2006). The maximum moisture period occurred at 8.5–5.5 ka in the NW Loess Plateau. In western Inner Mongolia and Xinjiang, a wet

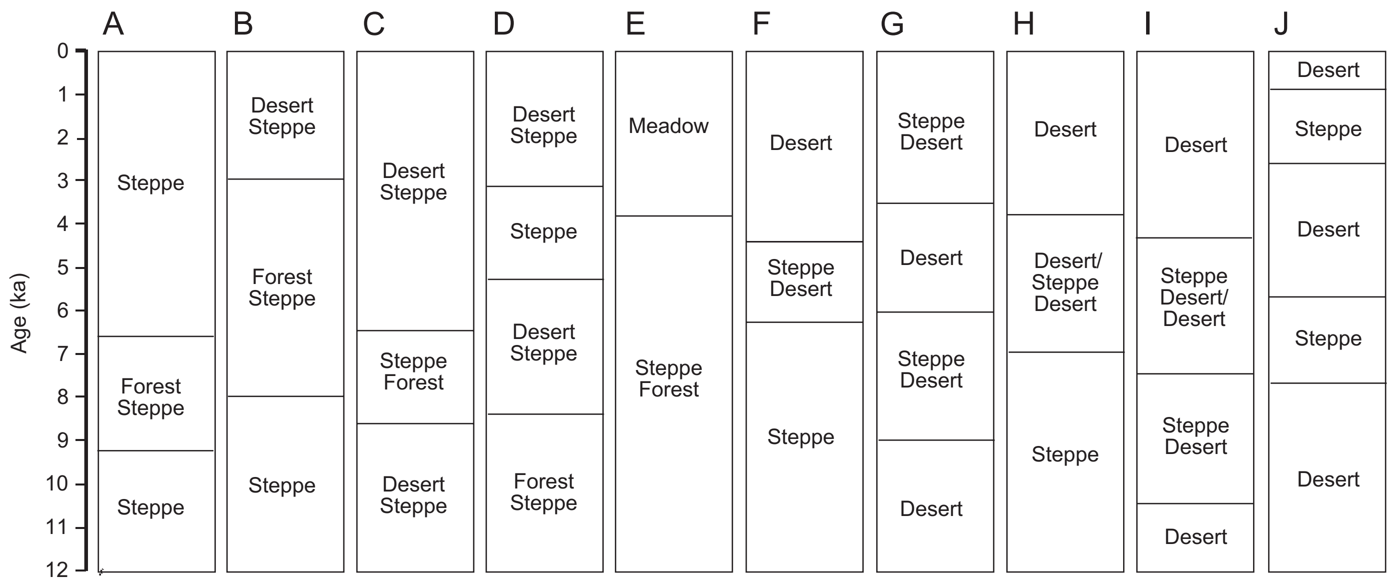

Fig. 8. Summary of vegetation history derived from fossil pollen records in arid and semi-arid China. (A) Bayanchagan (Jiang et al., 2006); (B) Daihai Lake (Xiao et al., 2004); (C) Dadiwan (An et al., 2003); (D) Midiwan (Li et al., 2003b); (E) Qinghai Lake (Shen et al., 2005); (F) Sumxi Co (Van Campo et al., 1996); (G) Hurleg Lake (Zhao et al., 2007a); (H) Sanjiaocheng (Chen et al., 2006); (I) Manas Lake (Sun et al., 1994); (J) Wulun Lake (Yang and Wang, 1996).

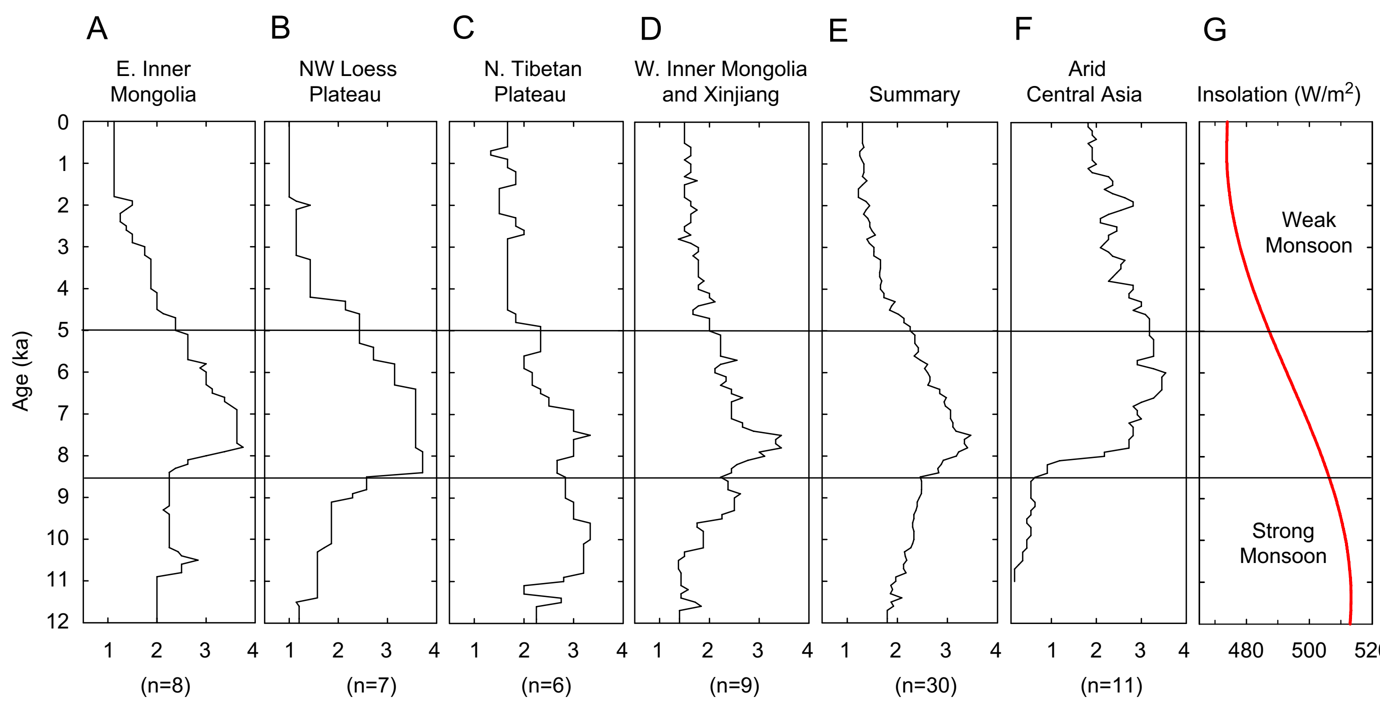

Fig. 9. Correlations of synthesized overall and regional time series of relative moisture conditions as inferred from fossil pollen data across arid and semi-arid China. (A) Eastern Inner Mongolia; (B) NW Loess Plateau; (C) N. Tibetan Plateau; (D) W. Inner Mongolia and Xinjiang; (E) summary of the four regions; (F) synthesis moisture pattern from arid Central Asia (Chen et al., in press); (G) insolation at 40 °N (May–September; data from Berger and Loutre, 1991). The moisture conditions were averaged at every 100 year and coded by four classes, from 1 (driest) to 4 (wettest).

period occurred during 8.5–5.5 ka at most sites, as also shown further to the west in arid central Asia (Chen et al., in press, Fig. 9F). All four regions show a consistently dry climate during the late Holocene.

The climate pattern inferred from fossil pollen records as presented in this paper is generally consistent with the results from previously published syntheses, also based on other independent climatic proxies (An et al., 2006; Feng et al., 2006; Chen et al., in press). For example, at Daihai Lake the climate was warm and dry during the early Holocene (11.5–8 ka), warm and wet during the mid-Holocene (8.1–3.3 ka), and cooler and drier during the late Holocene (3.3–0 ka), based on interpretations of total inorganic and organic carbon variations (Xiao et al., 2006).

Oxygen isotopes from ostracode shells at Qinghai Lake also suggest a moister early Holocene (Lister et al., 1991). At Dadiwan, a wet mid Holocene was suggested by organic matter content, grain size, mollusc as well as pollen data (An et al., 2003). Geochemical data in Xinjiang also showed a dry early Holocene, wet mid Holocene and fluctuating late Holocene (Feng et al., 2006). Eleven records from lakes in arid central Asia showed maximum effective moisture at 8–4 ka in the mid-Holocene (Chen et al., in press; Fig. 9F) based on pollen and other proxies. The generally consistent conclusions drawn from palynological data and other climatic proxies suggest that vegetation in arid and semi-arid China sensitively responded to regional climate, particularly to effective moisture, and that vegetation change during the late Holocene was also induced by climate change.

In the arid and semi-arid regions of China, however, human disturbance may also have contributed to late Holocene vegetation change. Unfortunately, the pollen evidence for human impacts on vegetation and methods to distinguish the anthropogenic from the climatic signal require further research (Liu and Qiu, 1994; Ren and Beug, 2002). For example, many researchers argue that human activities caused vegetation deterioration, especially in the Loess Plateau and Ordos Plateau (e.g., Shi, 1984; Ren and Beug, 2002), but the pollen records are scarce or limited by inadequate dating control, coarse sampling intervals and insufficient taxonomic details (Liu and Qui, 1994). Zhao et al. (2007b) discussed in more detail about the possible human impacts on vegetation change at some sites.

Climate change is one of the major candidates for explaining vegetation change during the late Holocene. Drying during that period was indicated by other independent climatic proxies as discussed above. This was also supported by the evidence of the cultural responses to prolonged drought during the late Holocene in Asia and Africa, including population dislocations, urban abandonment and state collapse (deMenocal, 2001), for example, the collapse of Neolithic culture around the Central Plain in China (Wu and Liu, 2004).

5.2. *Possible forcing mechanisms for Holocene climate patterns*

The sites in the northern Tibetan Plateau and eastern Inner Mongolia that are strongly influenced by summer monsoons show a wet early and early mid-Holocene and a continued drying trend afterwards, which is likely in response to the general weakening of the East Asian summer monsoon as predicted by the insolation hypothesis (Kutzbach, 1981; COHMAP, 1988). This pattern has been documented by many records from east monsoonal China (e.g., An et al., 2000; Morrill et al., 2003; Wang et al., 2005; Shao et al., 2006). In addition, the Tibetan Plateau plays a major role in driving the Asian monsoon circulation through the intense heating of the plateau surface during the summer. Maximum moisture conditions occurred earliest on the Tibetan Plateau at the onset of the Holocene, probably in response to rapid and intense heating of the plateau during summer insolation maximum.

Most sites in western Inner Mongolia, the northwestern Loess Plateau, and Xinjiang showed a dry early Holocene, wet mid-Holocene, and dry late Holocene. This inconsistency in timing of Holocene moisture maximum climate could either be due to poor dating and limited sampling resolution or be a real feature of regional climate changes in northern and northwestern China. If the latter, the delayed moisture maximum in these regions might have been caused by the orographic effect of the Tibetan Plateau (Herzschuh, 2006). Climate modeling and observational studies (Broccoli and Manabe, 1992) show that the heating and upward motion of air over the plateau causes strong air subsidence to the northwest and north of the Tibetan Plateau, inducing dry climate in central Asia. This mechanism could have induced the wettest period on the Tibetan Plateau at 11–9.5 ka, while Xinjiang and other regions were still dry. It appears that an orographically induced uplift-subsidence mechanism also works at a fine spatial scale as demonstrated in climate simulations. High spatial resolution simulations show that the subsidence extends into the Qaidam Basin, especially in simulations with no condensation (Sato and Kimura, 2005). This uplift-subsidence mechanism could be responsible for the wet–dry change at Hurleg Lake, the only site available from the Qaidam Basin, which appears to be the most noticeable exception among all the sites reviewed in the northern Tibetan Plateau.

The moisture maximum during the Holocene in arid and semi-arid China could also have been strengthened by reduced albedo induced by denser vegetation cover (Feng et al., 2006). Vegetation and climate modeling showed that the increase in vegetation cover reduced albedo and absorbed more energy in the soil–vegetation–air coupled systems, leading to a reduced seasonal temperature difference (i.e., higher winter temperature and lower summer temperature) (Ganopolski et al., 1998). This reduced seasonal temperature difference might have weakened the winter monsoon and strengthened the summer monsoon, which might be responsible for bringing more water vapor from ocean to land via the enhanced East Asian Monsoon. This scenario is supported by Holocene vegetation and climate modeling in China, showing a northwest shift of forest zones in China during the mid-Holocene (Yu et al., 1998).

All four regions show a drying trend after 6–4 ka. This drying pattern has also been documented by higher $\delta^{18}O$ values in stalagmites from eastern China (e.g., Zhang et al., 2004; Wang et al., 2005; Shao et al., 2006) and by lake and peat records from other parts of the Tibetan Plateau (Wang and Fan, 1987; An et al., 2000; He et al., 2004), showing an intensification of the monsoon in the early Holocene and subsequent weakening around 5–4 ka. The drying trend after 6–4 ka in the study regions was possibly in response to decreased summer insolation, subsequent weakened monsoon and less moisture transport by the westerlies. In the Tibetan Plateau, the major change to dry conditions began as early as 6 ka in the northwestern plateau, as indicated by decreasing A/C ratio and lake levels, which is roughly coincident with records outside the plateau. The major decrease in monsoon rainfall happened at ca. 4.5 ka at Dunde and at 4 ka at Qinghai Lake. It seems that the timing of monsoon weakening lagged from northwest to east, suggesting that the summer monsoon retreated southeastward gradually (Liu et al., 1998; Shen, 2003). In western Inner Mongolia and Xinjiang, the drying trend in the late Holocene probably is due to less moisture transport by the westerlies from the North Atlantic and central Asia. Understanding the complexity in spatial and temporal patterns in arid and semi-arid regions of China will require additional well-dated, high-resolution paleoclimate records from many locations.

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