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Modern pollen assemblages from surface lake sediments in northwestern China and their importance as indicators of vegetation and climate

QIN Feng, ZHAO Yan*, LI Quan & CAI MaoTang

Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Nature Resources Research, Chinese Academy of Sciences, Beijing 100101, China

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The modern pollen assemblages of surface lake sediments and topsoils in northwestern China were studied to understand the relationship of modern pollen data with contemporary vegetation and climate, and the differences between the pollen assemblages of surface lake sediments and topsoils. The results show that Chenopodiaceae and *Artemisia* are dominant elements in the pollen assemblages of northwestern China. Additionally, *Ephedra*, Cyperaceae, Asteraceae, Poaceae, *Picea*, *Pinus*, and *Betula* are also important pollen taxa. Both pollen assemblages and principal component analysis indicate that pollen data from surface lake sediments and topsoils can be used to differentiate the main vegetation types of this region (desert, steppe, meadow and forest). However, differences exist between modern pollen assemblages of the two types of sediments due to the different relevant source areas of pollen and degrees of pollen preservation. For example, the larger relevant source area of surface lake sediment results in a higher abundance of *Betula* in pollen assemblage from surface lake sediment, whereas the tendency to disintegrate thin-walled pollen types in topsoil leads to a higher proportion of resistant pollen, such as Asteraceae. Linear regression analysis indicates that the *Artemisia*/Chenopodiaceae (A/C) ratio in pollen assemblages of surface lake sediments can be used to indicate humidity changes in the study area. However, the A/C ratio in topsoils should be used carefully. Our results suggest that pollen data from surface lake sediments would be better references for interpreting the fossil pollen assemblages of lake cores or lacustrine profiles.

modern pollen assemblage, surface lake sediment, topsoil, vegetation, climate, northwestern China

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Pollen data have been used to unravel the vegetation succession and climatic changes of the past since the pioneering work of von Post in 1916 (Davis, 2000). The deciphering of fossil pollen data must be performed on the basis of the investigation of modern pollen assemblages. Numerous studies (e.g., Wright et al., 1967; Gaillard et al., 1992; Sugita, 1994; Cour et al., 1999; Davis, 2000; Shen et al., 2006; Ma et al., 2008; Zhao and Herzschuh, 2009; Zhao et al., 2009; Herzschuh et al., 2010; Lu et al., 2011; Fall, 2012; Zheng et al., 2013; Tian et al., 2014) have been conducted to understand the relationship of modern pollen assemblages with contemporary vegetation and climate. Modern pollen assemblages are mainly collected from airborne pollen collectors (e.g., Cour et al., 1999; Giesecke et al., 2010), moss polsters (e.g., Hicks and Birks, 1996; Mazier et al., 2006), topsoils (e.g., Xu et al., 2009; Zhang et al., 2010) and surface lake sediments (e.g., Herzschuh, 2007; Seppa et al., 2004). However, the four types of pollen traps always yield different pollen assemblages even if they are collected from

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*Corresponding author (email: zhaoyan@igsnrr.ac.cn) the same site (e.g., Fall, 1992; Wilmshurt and McGlone, 2005a; Zhao et al., 2009; Lisitsyna et al., 2012;). Consequently, many palynologists (e.g., Seppa et al., 2004; Birks et al., 2010) emphasize that the modern pollen calibration set for quantitatively reconstructing palaeoclimate should be established based on the pollen data from surface lake sediments because most fossil pollen data are extracted from lacustrine sediments (such as lake cores).

Modern pollen databases from North America (www.ncdc.noaa.gov/paleo/gpd.html) and Europe (www.europeanpollendatabase.net) have compiled numerous pollen data from surface lake sediments. These pollen data have been successfully used as modern calibration sets for quantitatively reconstructing the late Quaternary climatic changes in North America and Europe (e.g., Bartlein et al., 2011). In East Asia, many modern pollen databases have also been established (e.g., Sun et al., 1999; Lu et al., 2011; Zheng et al., 2013), and they have provided robust references to help interpret fossil pollen assemblages. However, most pollen data in these East Asia databases are derived from topsoils and moss polsters, whereas only a few of them are derived from surface lake sediments.

Recently, pollen assemblages of surface lake sediments have received more attention in East Asia. Herzschuh (2007) investigated the modern pollen assemblages of 113 lakes, and established a surface lake sediment pollen database in the northeastern Tibetan Plateau. Based on this database, Herzschuh and her colleagues (Herzschuh et al., 2009, 2010, 2014) developed pollen-climate transfer functions for the northeastern Tibetan Plateau, and used the transfer functions to quantitatively reconstruct the Holocene climatic changes in Lakes Koucha (Herzschuh et al., 2009), Luanhaizi (Herzschuh et al., 2010) and Ximencuo (Herzschuh et al., 2014). Tian et al. (2014) reported the pollen assemblages from surface lake sediments of 90 lakes in central-western Mongolia. Based on these data, they developed a transfer function for estimating late Quaternary precipitation changes in central-western Mongolia, and provide a case study that reconstructs the humidity oscillations since the late glacial period in Lake Bayan Nuur. Zhao et al. (2009) and Zhao and Herzschuh (2009) investigated pollen assemblages of surface lake sediments in the arid and semi-arid regions of northwestern China, and revealed the characteristics of pollen assemblages from surface lake sediments vs. topsoils. Xiao et al. (2011) studied the pollen assemblages from surface lake sediments in southwestern China, and found a strong influence of arboreal pollen at low elevation in alpine lakes. These pollen data have great potential to be used as a calibration set for reconstructing palaeovegetation and palaeoclimate in relevant regions. However, except for the aforementioned works, study of modern pollen in surface lake sediments is still rarely carried out in China.

Northwestern China is characterized by its dry environment. Many investigations of modern pollen assemblages have been carried out in this region, e.g., Tianshan Mountain (Pan, 1993; Xu et al., 1996; Yang et al., 2004, 2011), Kunlun Mountain (Weng et al., 1993), Yili Basin (Zhao and Li, 2013), the Alashan Plateau and Qilian Mountain (Herzschuh et al., 2003, 2004), the Shiyang River drainage (Cheng et al., 2004; Cheng and Chen, 2010), the Qaidam Basin (Chen et al., 2004; Zhao and Herzschuh, 2009), the eastern part of this region (Li et al., 2005; Wei et al., 2009; Zhao et al., 2012a), and Xinjiang Province (Yan, 1993; Yan et al., 2004; Luo et al., 2008). These studies provide important modern references for unraveling the vegetational and climatic information in fossil pollen assemblages from arid and semiarid regions. However, only a few of these studies (e.g., Zhao and Herzschuh, 2009; Zhao et al., 2009) investigated the modern pollen assemblages from surface lake sediments. Clearly, more research on pollen assemblages of surface lake sediments is needed to develop a modern pollen calibration set covering the complete ecological gradients of this region.

In this study, we presented pollen data from the surface sediments of 22 lakes and from 18 topsoil samples in northwestern China, and compared the differences of modern pollen data between surface lake sediment and topsoil. We investigated the relationships of modern pollen assemblages with contemporary vegetation and climate using principal component analysis. Indicator pollen taxa, which characterized different types of vegetation, were also examined. In addition, the significance of the *Arteimisia*/Chenopodiaceae (A/C) ratio and the arboreal/non-arboreal pollen (AP/NAP) ratio for indicating vegetational and climatic change was discussed.

1 Materials and methods

1.1 Study area

The study area is mainly in the arid region of northwestern China (35°–50°N, 73°–107°E), which is a vast region surrounded by Kunlun Mountain, Altun Mountain and Qilian Mountain to the north, and Helan Mountain and Yinshan Mountain to the west (Ni et al., 2005). Dry climate prevails in this region due to a long distance from the ocean and the influence of the surrounding mountains on atmospheric circulation (Shi et al., 2007). The ecosystem of this region is fragile and very sensitive to climatic changes (Zhang et al., 2000). Generally, four vegetation types are distributed in the arid region of northwestern China (ISTXCAS and IBCAS, 1978; Wu, 1980; Zhang, 2007). Desert is the major vegetation type of this region and is mainly dominated by xerophilous taxa such as Chenopodiaceae (*Anabasis*, *Ceratoides*, *Eurotia*, *Haloxylon*, *Kalidium*, *Kochia*, *Nanophyton*, *Salsola*, *Suaeda*, *Sympegma*), Zygophyllaceae (*Nitraria*, *Tetraena*, *Zygophyllum*), Tamaricaceae (*Reaumuria*, *Tamarix*), Ephedraceae (*Ephedra*), Polygonaceae (*Atraphaxis*, *Calligonum*, *Gymnocarpos*), Fabaceae (*Ammopiptathus*, *Caragana*), and Asteraceae (*Artemisia*, *Ajania*). Steppe, meadow and forest vegation occur in the mountainous areas with high precipitation and in humid lowland environments such as lake shores and river banks. The steppe vegetation type is mainly composed of Poaceae (*Agropyron*, *Cleistogenes*, *Festuca*, *Helictotrichon*, *Koeleria*, *Poa*, *Stipa*). Some desert components play important roles in relatively dry steppe (desert steppe), such as Chenopodiaceae (*Anabasis*, *Eurotia*, *Kochia*, *Nanophyton*, *Salsola*), and Fabaceae (*Caragana*). In contrast, in relatively wet steppe (meadow steppe), forbs such as Fabaceae (*Astragalus*, *Lathyrus*, *Trifolium*, *Vicia*), Geraniaceae (*Geranium*), Lamiaceae (*Phlomis*), Rosaceae (*Alchemilla*, *Fragaria*, *Sanguisorba*), and Rubiaceae (*Galium*) become important components. Meadow vegetation comprises much more diverse taxa than that of desert and steppe, and mainly includes Poaceae, Cyperaceae, Asteraceae, Fabaceae, Rosaceae, Polygonaceae, Apocynaceae, Geraniaceae, Iridaceae, Ranunculaceae, and Chenopodiaceae. In addition, Saxifragaceae, Lamiaceae, Scrophulariaceae, Getianaceae, Campanulaceae, Valerianaceae, Primulaceae, Apiaceae, Liliaceae, Juncaceae, and Juncaginaceae are also frequently observed in meadows. Alpine forest vegetation is usually dominated by Pinaceae (*Abies*, *Larix*, *Picea*, *Pinus*), Cupressaceae (Sabina), Salicaceae (*Populus*), Betulaceae (*Betula*), and Juglandaceae (*Juglans*), whereas forest patches in plain areas are mainly composed of Salicaceae (*Populus*, *Salix*), Elaeagnaceae (*Elaeagnus*), and Ulmaceae (*Ulmus*).

1.2 Materials

Surface lake samples were collected from twenty-two lakes in 2013. Among these lakes, nineteen are located in the arid region of northwestern China, whereas the other three are from nearby semi-arid regions (Figure 1, Table 1). The top 1 cm of sediment in the center of the lake center was collected by using a gravity corer. Eighteen topsoil samples (1 cm of topsoil) were also collected in this region, which enabled us to compare the pollen assemblages of surface lake sediments and topsoils. The studied sites were located in variety of vegetation zones, including desert, steppe, meadow and forest. The vegetation type of each site was assigned according to field investigation and regional vegetation literatures (ISTXCAS and IBCAS, 1978; Wu, 1980; Zhang, 2007). Mean annual temperature (MAT) and mean annual precipitation (MAP) of studied sites referred to the Earth Systems Modelling Results of Bristol Research Initiative for the Dynamic Global Environment (http://www.paleo.bris.ac.uk/ummodel/scripts/html_bridge/clamp_UEA.html), which were developed based on the datasets of New et al. (1999, 2002).

1.3 Laboratory methods

Pollen samples were treated by standard procedures (Faegri and Iversen, 1989) including chemical treatments with 10% HCl, 10% NaOH, and 40% HF, followed by acetolysis treatment (Moore et al., 1991), sieving in an ultrasonic bath to remove particles <10 µm, and mounting in glycerol. Prior to chemical treatment, one exotic *Lycopodium* spore tablet

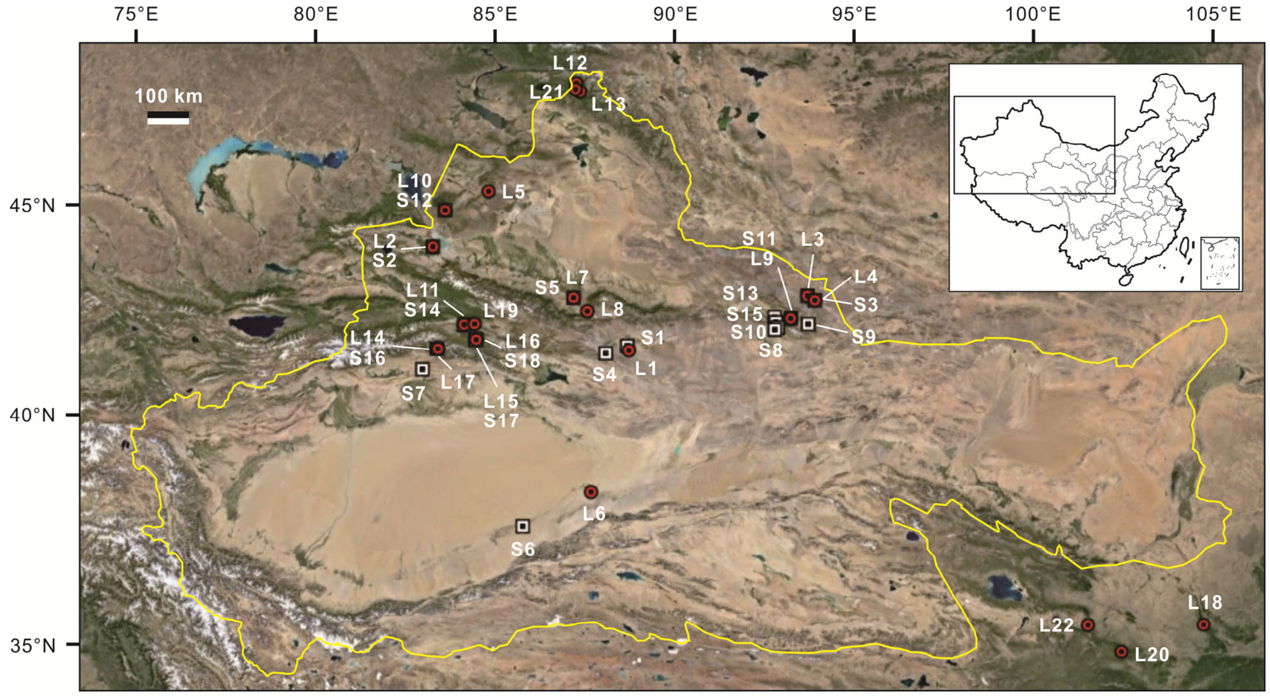


Figure 1 Map showing the study area, the sampling sites and the extent of the arid region of northwestern China (area enclosed by yellow line, refer to Ni et al., 2005). Red circles and white boxes represent the samples collected from surface lake sediments and topsoils, respectively.

Table 1 Location and surrounding vegetation types of studied samples from northwestern China

Sample code	Vegetation types	Sample type	Latitude (N)	Longitude (E)	Elevation (m a.s.l)	Mean annual temperature (°C)	Mean annual precipitation (mm)	Note
L1	Desert	Lake sediment	42.67°	89.25°	−159	15.4	16.7	Aidin Lake
L2	Desert	Lake sediment	44.79°	82.73°	207	8.8	106.2	Zhuangwan Lake
L3	Desert	Lake sediment	43.90°	94.82°	290	10.0	54.1	Yinggekule Lake
L4	Desert	Lake sediment	43.79°	95.04°	415	10.1	50.7	Naomao Lake
L5	Desert	Lake sediment	46.18°	84.37°	795	4.7	194.4	Yukunkake Lake
L6	Desert	Lake sediment	39.43°	88.26°	812	12.2	23.1	Taitema Lake
L7	Desert	Lake sediment	43.82°	87.44°	823	7.7	250.2	Bainiao Lake
L8	Desert	Lake sediment	43.53°	87.90°	1078	6.1	218	Chaiwobao Lake
L9	Steppe	Lake sediment	43.40°	94.26°	1899	2.2	128.4	Tuolekule Lake
L10	Steppe	Lake sediment	45.66°	82.98°	1877	−1.5	367.3	Tasier Lake
L11	Steppe	Lake sediment	43.06°	84.05°	2611	−5.0	294.3	Unnamed lake NO. 1
L12	Meadow	Lake sediment	48.87°	87.04°	1511	−1.6	360.9	Shuanghu Lake
L13	Meadow	Lake sediment	48.68°	87.19°	2180	−3.0	353.5	Heihu Lake
L14	Meadow	Lake sediment	42.45°	83.26°	2343	−2.6	280.7	Xiaolongchi Lake
L15	Meadow	Lake sediment	42.74°	84.45°	2395	−2.4	254.6	Tianehu Tongxin Lake
L16	Meadow	Lake sediment	42.73°	84.47°	2396	−2.5	255.2	Tianehu Neihu Lake
L17	Meadow	Lake sediment	42.45°	83.30°	2398	−3.1	283.7	Dalongchi Lake
L18	Meadow	Lake sediment	35.26°	106.31°	2450	5.1	590.2	Tianchi Lake
L19	Meadow	Lake sediment	43.09°	84.37°	2493	−4.4	283.2	Unnamed lake NO. 2
L20	Meadow	Lake sediment	35.02°	103.63°	2598	3.0	562.5	Yehai Lake
L21	Forest	Lake sediment	48.73°	87.03°	1375	−1.3	351.1	Kanas Lake
L22	Forest	Lake sediment	35.79°	102.67°	2515	5.3	444.4	Mengdatianchi Lake
S1	Desert	Topsoil	42.77°	89.19°	−142	15.5	16.9	Near Aiding Lake
S2	Desert	Topsoil	44.78°	82.73°	207	8.8	106.2	Near Zhuangwan Lake
S3	Desert	Topsoil	43.79°	95.04°	415	10.1	50.7	Near Naomao Lake
S4	Desert	Topsoil	42.58°	88.54°	543	10.8	80.8	Road side
S5	Desert	Topsoil	43.82°	87.44°	823	7.7	250.2	Near Bainiao Lake
S6	Desert	Topsoil	38.58°	86.31°	1061	11.0	27.1	Road side
S7	Desert	Topsoil	41.94°	82.88°	1485	7.4	142.2	Road side
S8	Desert	Topsoil	43.15°	93.75°	1602	5.1	133.1	Road side
S9	Desert	Topsoil	43.26°	94.80°	1655	4.3	81.7	Road side
S10	Steppe	Topsoil	43.20°	93.84°	1654	2.5	150.9	Road side
S11	Steppe	Topsoil	43.40°	94.26°	1899	2.2	128.4	Near Tuolekule Lake
S12	Steppe	Topsoil	45.66°	82.98°	1877	−1.5	367.3	Near Tasier Lake
S13	Steppe	Topsoil	43.44°	93.76°	2113	2.2	161.6	Road side
S14	Steppe	Topsoil	43.06°	84.05°	2611	−5.0	294.3	Near unnamed lake NO. 1
S15	Steppe	Topsoil	43.32°	93.79°	2173	−0.6	181.8	Road side
S16	Meadow	Topsoil	42.45°	83.26°	2343	−2.6	280.7	Near Xiaolongchi Lake
S17	Meadow	Topsoil	42.74°	84.45°	2395	−2.4	254.6	Near Tianehu Tongxinhu Lake
S18	Meadow	Topsoil	42.73°	84.47°	2396	−2.5	255.2	Near Tianehu Neihu Lake

(20848 grains/tablet) was added to each sample for estimating pollen concentrations. Pollen was counted under a Leica optical microscope at 400× magnification. Pollen identification was based on published palynological literature (e.g., Xi and Ning, 1994; Wang et al., 1995; Wan et al., 1999) and the pollen reference collection of western China. A minimum of 300 terrestrial pollen grains (344–2332 grains) were counted per sample, except for six samples (150–218 grains) with very low pollen concentration (553–2864 grains/g). The relative abundance (expressed as percentage) of each pollen taxon in a sample was calculated against the sum of terrestrial pollen. Tilia 1.7.16 (Grimm, 2011) was used to construct the pollen diagram (Appendix 1).

1.4 Numerical analysis methods

Ordination techniques were used to explore the potential gradients of modern pollen data, and their relationships with vegetation and climate. A preliminary detrended correspondence analysis (DCA) yielded a length of 2.44 standard deviation unit (SD) on the first axis. Consequently, principal component analysis (PCA) was adopted to analyse the pollen data. Only those pollen taxa with more than 2% relative abundance in at least one sample were included. Raw data were standardized using Hellinger transformation (Legendre and Gallagher, 2001) prior to ordination procedures. In PCA plots (Figure 2), scores of samples and pollen taxa were scaled symmetrically by the square root of eigenvalues. Linear regression was used to analyse the relationships of relative abundances of selected pollen taxa and *Artemisia*/Chenopodiaceae ratio (A/C) versus MAP (Figure 3). Moreover, Dufrêne-Legendre indicator species analysis (Dufrene and Legendre, 1997) was used to identify statistically significant indicator pollen taxa for different types of vegetations. This method combines the species relative abundance with its relative frequency of occurrence in different sample groups to calculate the indicator value for each species (Dufrene and Legendre, 1997). A higher indicator value for an individual species in a specific group suggests that relative abundance of the species in this group is higher than other groups, and it occurs in most samples of this group. All numerical analyses were conducted in R (ver. 3.1.2, R Core Team, 2014). The vegan 2.2-0 package (Oksanen et al., 2014) was involved in ordination, and labdsv 1.6-1 (Roberts, 2013) was employed in indicator species analysis.

2 Results

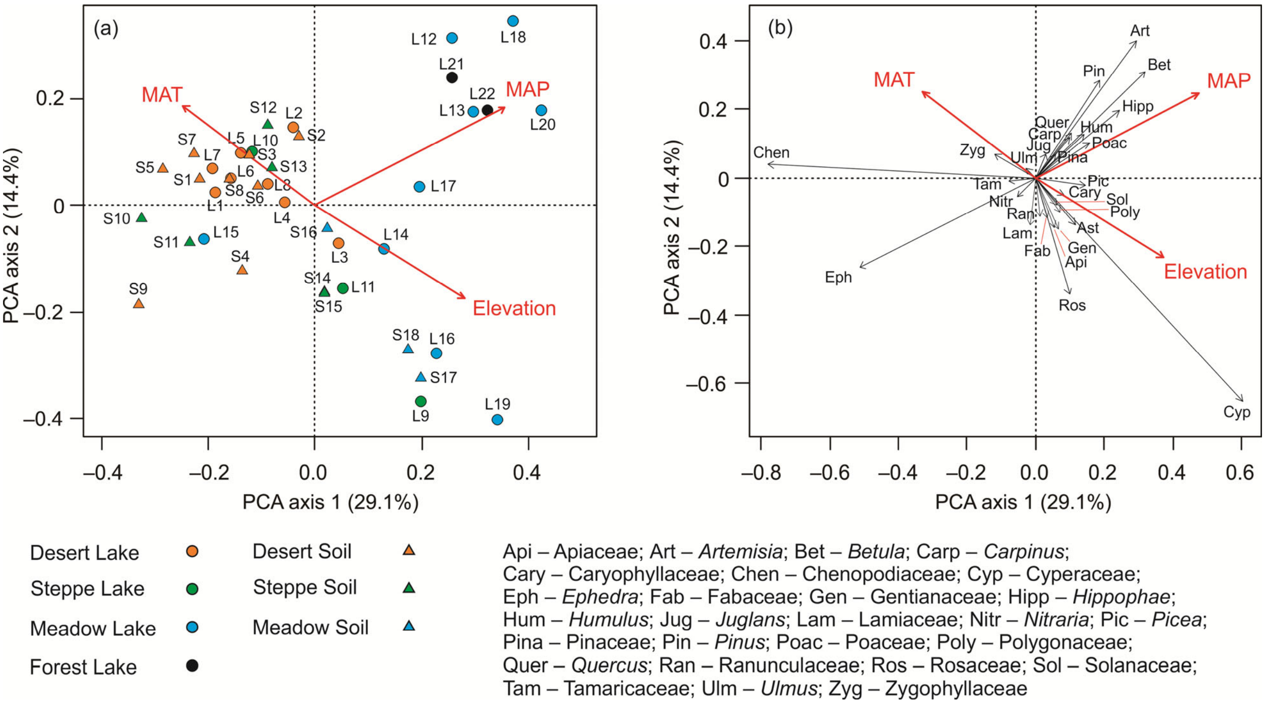
2.1 Pollen assemblages

2.1.1 Surface lake sediments

A total of 57 palynomorphs were identified from the 22 surface lake samples, among which *Artemisia*, Chenopodiaceae, Cyperaceae, *Ephdera*, and Poaceae were the most important non-arboreal elements, whereas *Betula*, *Picea* and *Pinus* dominated arboreal elements (Appendix 1). The relative abundance of these pollen taxa varied in different types of vegetations.

In the pollen assemblages of desert samples, Chenopodiaceae had an average abundance of 47.8%, and *Artemisia* contributed 18.6% on average. Poaceae (7.3%) and *Ephedra* (5.9%) were frequently observed. Arboreal pollen represented only 4.9%, mainly including *Betula* (1.7%), *Picea* (1.1%), *Ulmus* (0.9%), *Pinus* (0.6%) and *Juglans* (0.4%). The pollen assemblages of steppe were also dominated by Chenopodiaceae (37.2% on average) and *Artemisia* (15.7%). Additionally, Cyperaceae pollen (19.3%) was common in steppe samples. In comparison with desert samples, the average abundance of Poaceae (4.8%) and *Ephedra* (2.4%) decreased in steppe samples. Arboreal pollen had an average abundance of 2.6%, of which *Betula* contributed 1.3% and *Picea* 1.3%.

In meadow samples, *Artemisia* (28.5% on average), Chenopodiaceae (20%) and Cyperaceae (14.8%) dominated



Api – Apiaceae; Art – *Artemisia*; Bet – *Betula*; Carp – *Carpinus*; Cary – Caryophyllaceae; Chen – Chenopodiaceae; Cyp – Cyperaceae; Eph – *Ephedra*; Fab – Fabaceae; Gen – Gentianaceae; Hipp – *Hippophae*; Hum – *Humulus*; Jug – *Juglans*; Lam – Lamiaceae; Nitr – *Nitraria*; Pic – *Picea*; Pina – Pinaceae; Pin – *Pinus*; Poac – Poaceae; Poly – Polygonaceae; Quer – *Quercus*; Ran – Ranunculaceae; Ros – Rosaceae; Sol – Solanaceae; Tam – Tamaricaceae; Ulm – *Ulmus*; Zyg – Zygophyllaceae

Figure 2 Principal component analysis plots for samples (a) and pollen taxa (b) on axes 1 and 2. (a) Ordination biplot for samples of surface lake sediments (circle) and topsoils (triangle) from different vegetation types with 3 environmental variables; (b) Ordination biplot for major pollen taxa of the modern pollen assemblages from northwestern China. MAT, mean annual temperature; MAP, mean annual precipitation.

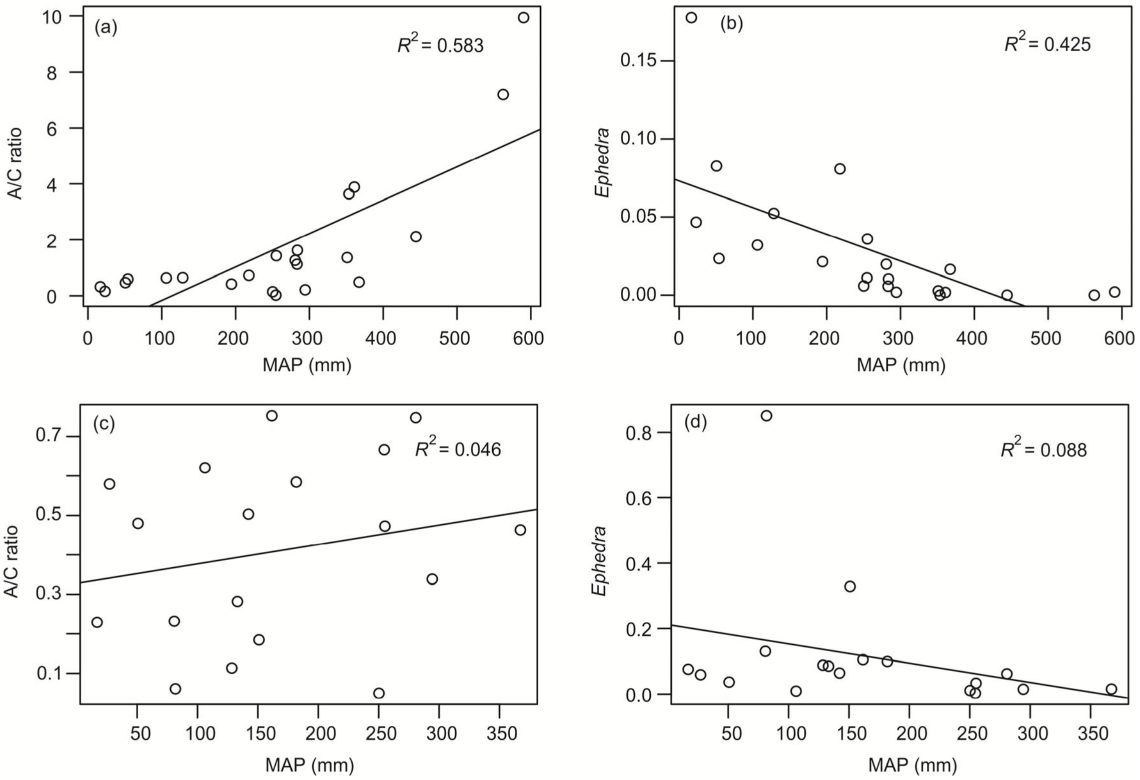


Figure 3 Scatter plots of *Artemisia*/Chenopodiaceae (A/C) ratio and the relative abundance of *Ephedra* versus mean annual precipitation (MAP) for surface lake sediment ((a), (b)) and topsoil ((c), (d)) samples. The results of linear regression (R^2 and fitted lines) are shown.

the pollen assemblages. Poaceae contributed 7.8% on average, and *Ephedra* only had an average abundance of 1%. Arboreal pollen (13%) was mainly composed of *Betula* (5.5%), *Picea* (3%), *Pinus* (1.4%) and *Quercus* (1.1%).

A high abundance of arboreal pollen (42.4% on average) was observed in forest samples, of which *Picea* (18.9%), *Pinus* (14.1%) and *Betula* (4.9%) were the most important. Non-arboreal pollen from forest samples was mainly composed of *Artemisia* (13%), Chenopodiaceae (7.2%), Cyperaceae (2.6%) and Poaceae (4.8%). In addition, a substantial amount of *Hippophae* pollen (33.4%) was found in one of the forest samples (L22).

2.1.2 Topsoil samples

Forty-one palynomorphs were identified from the 18 topsoil samples. *Artemisia*, Asteraceae, Chenopodiaceae, Cyperaceae, *Ephdera*, and Poaceae were the most important non-arboreal elements, whereas *Picea* dominated arboreal pollen (Appendix 1).

In desert samples, Chenopodiaceae dominated the pollen assemblages with an average abundance of 47.6%. *Artemisia* (15.8%) and *Ephedra* (14.7%) both showed high relative abundances. Poaceae (4.4%) and Asteraceae (2.2%) were abundant. Arboreal pollen represented only 3.7%, mainly including *Picea* (1.8%), *Betula* (0.7%) and *Ulmus* (0.6%).

Chenopodiaceae (42.1% on average), *Artemisia* (14.7%) and *Ephedra* (10.9%) dominated the pollen assemblages of steppe. Asteraceae (6%), Poaceae (4.7%) and Fabaceae (2.7%) were commonly observed. Arboreal pollen represented only 5.4%, of which Picea contributed 4.6%.

In meadow samples, Chenopodiaceae (22.7% on average), *Artemisia* (14.6%), Cyperaceae (13.1%) and Poaceae (8.1%) were the most important elements. *Ephedra* had an average relative abundance of 3.3%. Arboreal pollen (9%) was dominated by *Picea* (8.4%).

2.2 Numerical analysis results

2.2.1 PCA results for original data

PCA for original pollen data suggested that the first axis explained 29.1% of the variation in the pollen data, and the second axis accounted for 14.4%. Despite the differences between lake and soil samples, the PCA diagram (Figure 2) showed that samples of desert were located at the right side of the diagram, which corresponded to high pollen relative abundance of xerophilous taxa (e.g., Chenopodiaceae, *Ephedra*, *Nitraria*, Tamaricaceae, Zygophyllaceae). In contrast, most of the meadow samples and all forest samples were on the left side, corresponding to high pollen relative abundance of arboreal taxa (e.g., *Betula*, *Pinus*, *Quercus*) and the meadow component (e.g., Cyperaceae, Gentianaceae). Steppe samples showed indistinct characteristics, i.e., five of the steppe samples were located close to desert samples, and the other three are close to meadow samples.

Roughly, PCA axis 1 might represent a humidity gradient, which separated the desert samples from meadow and forest.

Three environmental variables (MAT, MAP and elevation) appeared to explain the variations in pollen assemblage of different vegetation types. In the PCA biplot of samples (Figure 2(a)), meadow and forest samples were generally correlated with higher MAP and elevation, and lower MAT. In contrast, desert samples were related to lower MAP and elevation, and higher MAT. In the PCA biplot of pollen taxa (Figure 2(b)), xerophilous elements (e.g., Chenopodiaceae, *Ephedra*, *Nitraria*, Tamaricaceae, Zygophyllaceae) showed negative correlation with MAP, whereas arboreal taxa (e.g., *Betula*, *Pinus*, *Quercus*) and some steppe components (e.g., *Artemisia*, Poaceae) were positively correlated with MAP. Meadow components (e.g., Cyperaceae, Gentianaceae) showed close positive correlation with elevation.

With respect to the same vegetation type, surface lake samples always fell on the right side of topsoil samples in the PCA diagram, except for desert (Figure 2(a)). Among surface lake samples, those from desert grouped together on the left side of PCA axis 1, and they were easily differentiated from samples of other vegetation types. Surface lake samples from meadow were mostly located at the right side of axis 1, and they were not easily differentiated from samples of forest. Roughly, surface lake samples from steppe were located between those from desert and meadow/forest, except for Sample L10, which was located close to desert samples. Among topsoil samples, those from desert were also on the left part of the diagram, whereas those from meadow were on the bottom right part. Among topsoil samples of steppe, three samples were located between desert and meadow/forest samples, whereas two were close to desert samples.

2.2.2 *Linear regression analysis*

Linear regression analysis results (Figure 3) showed a positive correlation (R^2=0.583, P<0.001) between the *Artemisia*/Chenopodiaceae (A/C) ratio and MAP when only the pollen data from surface lake sediments were involved. The relative abundance of *Ephedra* pollen in surface lake samples was negatively related to MAP (Figure 3(b), R^2=0.425, P<0.001). However, both the A/C ratio and *Ephedra* in topsoil samples showed weaker correlation with MAP (Figure 3(c), (d)).

2.2.3 *Indicator species analysis*

Indicator species analysis on surface lake pollen data (Table 2) showed that *Ephedra* pollen had a high indicator value (0.63) in desert; Apiaceae (0.76) and Gentianaceae (0.52) yielded high indicator values in steppe; whereas Ericaceae (1), *Pinus* (0.87), Saxifragaceae (0.74), Cupressaceae (0.72) and Pinaceae (0.49) had high indicator values in forest. When indicator species analysis was performed on topsoil pollen data, the results suggested that Tamaricaceae had a high indicator value (0.68) in desert, whereas Gentianaceae, Cyperaceae and Primulaceae yielded indicator values of 0.98, 0.88 and 0.61 respectively in meadow.

3 Discussion

3.1 Differentiation of vegetation types using pollen data

Pollen assemblages and PCA results suggest that both surface lake sediment and topsoil can be used to differentiate four vegetation types in the study region, i.e., desert, steppe, meadow and forest (Figure 2; Appendix 1). However, the two types of samples yield different pollen assemblages for the same vegetation type. With respect to pollen assemblages of surface lake sediments, Chenopodiaceae and *Artemisia* are dominant taxa in desert, steppe and meadow. However, desert is characterized by a high relative abundance of Chenopodiaceae, whereas a high relative abundance of *Artemisia* appears in meadow. Additionally, xerophilous taxa such as *Ephedra*, Tamaricaceae, and Zygophyllaceae contribute significantly to the pollen assemblage

Table 2 Indicator pollen taxa and their indicator values in two types of samples for different vegetation types [a)]

Taxa	Vegetation type	Sample type	Indicator value	*P* value	Frequency
Ephedra	Desert	Lake sediment	0.63	0.0484	19
Apiaceae	Steppe	Lake sediment	0.76	0.0418	10
Gentianaceae	Steppe	Lake sediment	0.52	0.0423	3
Ericaceae	Forest	Lake sediment	1	0.0043	2
Pinus	Forest	Lake sediment	0.87	0.0038	14
Saxifragaceae	Forest	Lake sediment	0.74	0.0129	6
Cupressaceae	Forest	Lake sediment	0.72	0.0217	5
Pinaceae	Forest	Lake sediment	0.49	0.048	3
Tamaricaceae	Desert	Topsoil	0.68	0.015	16
Gentianaceae	Meadow	Topsoil	0.98	<0.001	4
Cyperaceae	Meadow	Topsoil	0.88	0.0021	13
Primulaceae	Meadow	Topsoil	0.61	0.0192	3

a) Only statistically significant pollen taxa (P<0.05) are listed. Frequency represents the number of occurrences for the pollen taxa in specific sample types.

of desert, whereas Cyperaceae and Poaceae pollen play important roles in meadow. Pollen assemblages of steppe generally exhibit intermediate status between desert and meadow. This may reflect the moderate condition of steppe between relatively dry desert and relatively wet meadow. Arboreal pollen such as *Betula*, *Picea*, and *Pinus* can be found in desert, steppe and meadow, which suggests a long transport distance of these pollens. A higher relative abundance of arboreal pollen in meadow than in desert and steppe is due to the shorter distance from the forest in alpine region. It is easy to deduce that arboreal pollen has the highest relative abundance in forest, which is consistent with former investigations (Yan, 1993; Liu et al., 1999; Luo et al., 2008). Strangely, in one forest sample (L22), arboreal pollen, especially pollen with sacci (*Picea* and *Pinus*) had very low relative abundance, whereas a large amount of *Hippophae* pollen was found. This was possibly caused by the heterogeneity of vegetation around the lake and the *Hippophae* scrub close to the sampling site.

Topsoils produce somewhat different pollen assemblages, although they are also dominated by Chenopodiaceae and *Artemisia* (Appendix 1). In comparison with surface lake sediments, more Chenopodiaceae are found in pollen assemblages of topsoils from steppe and meadow (Figure 4). *Artemisia* pollen has similar relative abundance in desert, steppe and meadow. High relative abundances of *Ephedra*, Tamaricaceae and Zygophyllaceae appear in desert. Unlike in surface lake sediment, significant amounts of *Ephedra* pollen can be found in topsoils of steppe and meadow. Cyperaceae only showed high relative abundance

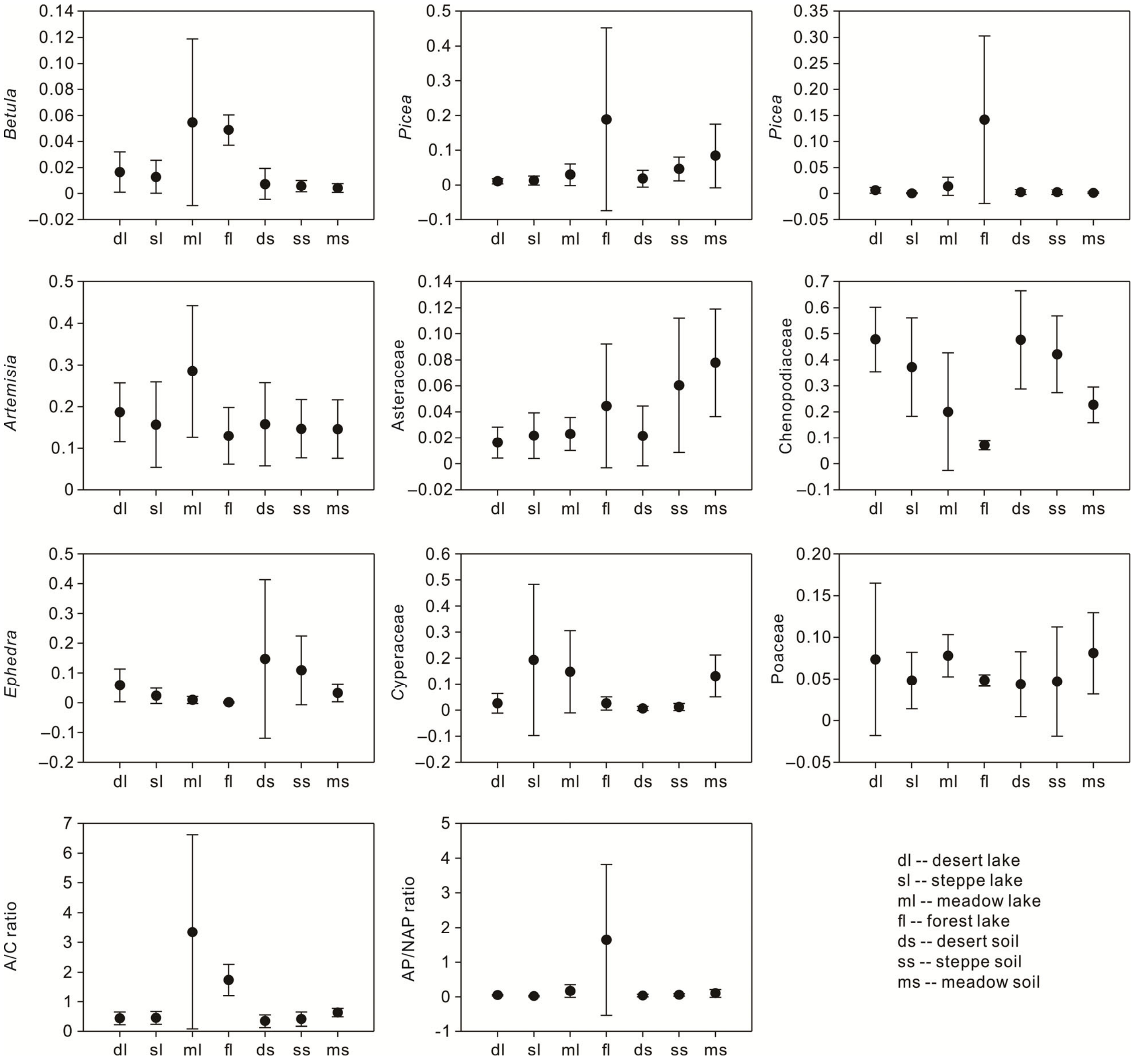


Figure 4 Scatterplots showing the mean and standard deviation of relative abundances of main pollen taxa, *Artemisia*/Chenopodiaceae (A/C) and arboreal/non-arboreal pollen (AP/NAP) ratios of modern pollen assemblages from different types of vegetations and samples in northwestern China.

in topsoils of meadow. In comparison, Cyperaceae pollen occasionally has high relative abundance in surface lake sediment samples from desert and steppe, which may be attributed to the Cyperaceae grown in the wetland of lake shore. Asteraceae (excluding *Artemisia*) shows higher relative abundance in topsoils than in surface lake sediments for all vegetation types. Arboreal pollen only has very low relative abundance in topsoil samples. High relative abundances of *Picea* pollen in several samples are derived from the *Picea* forest (mainly patchy) growing on mountains or hills near the sampling sites.

Indicator species are useful for distinguishing vegetation types using pollen data, especially when elucidating a fossil pollen assemblage. Here, a statistical procedure in community ecology (Dufrene and Legendre, 1997) was involved to objectively determine the indicator pollen taxa. The results show that pollen assemblages from different types of sediment have different indicator pollen taxa (Table 2). *Ephedra* and Tamaricaceae are indicator taxa for desert in pollen assemblage of surface lake sediments and topsoils, respectively. In steppe, Apiaceae and Gentianaceae are indicator taxa in pollen assemblages of surface lake sediments. However, Gentianaceae can be used to distinguish meadow based on pollen assemblages of topsoils together with Cyperaceae and Primulaceae in the studied region. No statistically significant indicator species were found for meadow based on pollen assemblages of surface lake sediments. High pollen relative abundances of Ericaceae and *Pinus* in surface lake sediments are an appropriate signal for the occurrence of forest, and Saxifragaceae, Cupressaceae and Pinaceae are also potential indicator taxa for forest. Note that some of the indicator pollen taxa (such as Saxifragaceae, Primulaceae, and Cupressaceae) only have low relative abundances in the pollen assemblages. This implies that the pollen taxa with low abundance may also be useful for indicating vegetation types, in addition to the dominate pollen taxa.

Several reasons are responsible for the differences between pollen assemblages of surface lake sediments and those of topsoils. On the one hand, previous researches suggested that the differences between pollen assemblages of surface lake sediments and those of topsoils are probably caused by their different relevant source area of pollen (RSAP) (Sugita, 1994, Zhao et al., 2009). Surface lake sediments have larger RSAP than topsoils, and their pollen assemblages contain more regional pollen. In contrast, pollen assemblages of topsoils contain more local pollen due to the smaller RSAP. In this study, higher relative abundance of *Betula* pollen in surface lake sediments from treeless regions may result from the larger amount of regional pollen, whereas higher abundances of *Ephedra* pollen in topsoils are probably attributed to the greater influence of local pollen. On the other hand, different degrees of pollen preservation involved in the two different types of sediment may also contribute to the differences between their pollen assemblages (Wilmshurt and McGlone, 2005a; Zhao et al., 2009). Wilmshurt and McGlone (2005a) indicated that pollen assemblages from topsoils contain a greater number of resistant pollen types because of the oxidation and microbial attack in the soil. Higher relative abundance of Asteraceae and Chenopodiaceae pollen in topsoil samples may result from this reason. In addition, surface lake sediment can derive pollen from inwashed material from catchment soil (Wilmshurt and McGlone, 2005b). This contributes a substantial amount of redeposited pollen to surface lake sediments. After all, pollen assemblages of both surface lake sediments and topsoils have advantages and weaknesses in regard to their use for investigating changes in vegetation. Pollen assemblages of topsoils better reflect local vegetation, but they are easily biased by the disintegration of thin-walled pollen. In contrast, pollen assemblages of surface lake sediments are better used to indicate regional vegetation, and the redeposited pollen from catchment soil will introduce a disturbance of contemporary pollen. Considering that most fossil pollen data are derived from lacustrine sediments, pollen assemblages of surface lake sediments are better references for interpreting fossil pollen records.

In general, variations of pollen data reflect the environmental gradients of the study area. PCA results indicate that desert samples are correlated with dryer conditions (lower MAP), whereas samples of meadow and forest are related to the wetter environments (higher MAP) in the high elevation regions (Figure 2(a)). Moreover, steppe samples are suggested to be correlated with intermediate humidity. Thus, the distributions of pollen assemblages from the four types of vegetations in the PCA diagram imply a humidity gradient (PCA axis 1), which is generally consistent with the humidity changes of the four types of vegetation in northwestern China. Noticeably, samples of surface lake sediments from steppe and meadow are generally located on the right side of those of topsoils from the same vegetation type on PCA axis 1 (Figure 2(a)). Therefore, in comparison with pollen assemblages of topsoils from steppe and meadow, those of surface lake sediments from the same vegetation types tend to indicate wetter conditions.

In summary, pollen assemblages of both surface lake sediment and topsoil show clear distinctions for four vegetation types. However, differences still exist between the modern pollen assemblages of the two types of sediments. Therefore, it is better to use pollen data from surface lake sediments as calibration sets for quantitative approaches, such as pollen-climate transfer function (Bartlein et al., 1984) and modern analogue technique (Overpeck et al., 1985), if palaeoclimate is to be estimated quantitatively based on fossil pollen assemblages from lake cores or lacustrine profiles.

3.2 Pollen ratios, vegetation and climate

The *Artemisia*/Chenopodiaceae (A/C) ratio has been frequently used to indicate humidity change in northern and western China (e.g., Liu et al., 1999; Herzschuh, 2007; Zhao et al., 2007; Zhang et al., 2010; Zhao and Li, 2013), after El-moslimany (1990) found that it is a good humidity indicator in the Middle East. Recently, Zhao et al. (2012b) reviewed the reliability of the A/C ratio as humidity indicator in the arid region of China. They suggested that the A/C ratio can only be used to evaluate the humidity variations in regions with precipitation <450–500 mm, and environmental factors such as soil salinity, vegetation community composition, and human activity can also affect the validity of the A/C ratio. However, nearly all previous research on the validity of the A/C ratio is based on pollen data from topsoils or moss polsters. As mention above, surface lake sediments and topsoils yield different pollen assemblages. Thus, it is necessary to evaluate the significance of the A/C ratio for the pollen assemblages of surface lake sediments.

Our results show that the average A/C ratios generally have higher values in pollen assemblages of surface lake sediments than in topsoils for the same vegetation type (Figure 4). However, in both surface lake sediments and topsoils, the average A/C ratio has an increasing trend from desert to steppe, then to meadow and forest. Despite the average value, it is important to note that the ranges of the A/C ratio are not clearly differentiated between desert and steppe or between meadow and forest in pollen assemblages of surface lake sediments (Appendix 1). Moreover, in topsoils, the A/C ratios of desert, steppe and meadow also show some overlapping intervals. Nevertheless, the general increasing trend of A/C ratio from dry habitat (desert) to wet (meadow and forest) habitat should still be reliable, as suggested by El-Moslimany (1990). Moreover, some distinct boundaries can still be found to delimit vegetation types. The A/C ratios of desert and steppe are <1 in both types of samples. The A/C ratios are >1 in both meadow and forest for pollen assemblages of surface lake sediments, but are still <1 for those of topsoils. Therefore, the A/C ratio may be a potential index for differentiating forest and meadow from steppe and desert when studying fossil pollen data from lake cores.

In the eastern Tibetan Plateau, Herzschuh (2007) found a positive correlation between the A/C ratio in surface lake sediment and MAP. It is clear that the A/C ratios in pollen assemblages of surface lake sediments can be used as humidity indicators in eastern Tibetan Plateau. Our results show that low values of A/C ratios are found in relatively dry habitats such as desert and steppe, whereas high values occur in relatively wet habitats such as meadow and forest (Appendix 1). Linear regression analysis supports that the A/C ratios of surface lake sediments are positively related to MAP, but those of topsoils seem not to correlate with MAP (Figure 3). Therefore, the A/C ratio is also valid in the pollen assemblages of surface lake sediments in the study area. However, the A/C ratio of topsoil should be used carefully in this region. In addition, *Ephedra* pollen is also a potential indicator of aridity in surface lake sediments because its relative abundance exhibits a negative correlation with MAP (Figure 3). Therefore, *Ephedra* can be used as an alternative indicator for interpreting humidity variations.

The arboreal/non-arboreal pollen (AP/NAP) ratio is a useful index for identifying forest. Studies of pollen assemblages of topsoils (Liu et al., 1999; Zhang et al., 2010; Zhao et al., 2012a) suggested that high AP/NAP ratios were always found in forest zones and zones with forest patches in northern and northwestern China. The investigation of the pollen assemblages of surface lake sediments in the eastern Tibetan Plateau indicated that a much higher AP/NAP ratio occurred in the patchy forested areas (Herzschuh, 2007). In this study, the average AP/NAP ratio in surface lake sediments increases from 0.05 in desert and 0.02 in steppe, to 0.17 in meadow, then to 1.64 in forest. Additionally, in pollen assemblages of topsoils, the average AP/NAP ratio increases from 0.04 in desert, to 0.05 in steppe, then to 0.11 in meadow. Generally, meadow samples can yield higher AP/NAP ratios than desert or steppe samples, but the values of the AP/NAP ratio in the three non-forest vegetation types never exceed 1. This phenomenon occurs in samples from both surface lake sediment and topsoil. Although the average value of the AP/NAP ratio in surface lake samples of forest is much higher than in those of other vegetation types, and its standard deviation is also high (Figure 4). Apparently, more work is still needed to test the validity of the AP/NAP ratio in the pollen assemblages of surface lake sediments to identify forest in northwestern China.

4 Conclusions

Our results show that pollen data of both surface lake sediment and topsoil in northwestern China can be used to differentiate desert, steppe, meadow and forest. However, differences exist between modern pollen assemblages of the two types of sediments, and they yield different indicator species for the same vegetation type. Different relevant source areas and degrees of preservation of pollen in the two types of sediments should be responsible for their different pollen assemblages. PCA results suggest that the variations of pollen assemblages generally reflect the humidity changes of the four types of vegetation. Moreover, in comparison with pollen data of topsoils from steppe and meadow, those of surface lake sediments from the same vegetation types tend to indicate wetter conditions. Thus, it is better to use pollen data from surface lake sediments as calibration sets for quantitative estimation of palaeoclimate based on the fossil pollen assemblages from lake cores or lacustrine profiles. Furthermore, the *Artemisia*/Chenopodiaceae (A/C) ratio in pollen assemblages of surface lake sediments can be used to indicate humidity changes in this region; however, the A/C ratio in pollen assemblages of topsoils should be used carefully.

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Bartlein P J, Harrison S P, Brewer S, et al. 2011. Pollen-based continental climate reconstructions at 6 and 21 ka: A global synthesis. Clim Dyn, 37: 775–802

Bartlein P J, Webb T, Fleri E. 1984. Holocene climatic-change in the Northern Midwest-Pollen-Derived Estimates. Quat Res, 22: 361–374

Birks H J B, Heiri O, Seppa H, et al. 2010. Strengths and weakness of quantitative climate reconstructions based on Late-Quaternary biological proxies. Open Ecol J, 3: 68–110

Chen H, Lu X M, Li S C. 2004. A study on topsoil pollens in the east of Qaidam Basin. Geogr Res, 23: 201–210

Cheng B, Chen F H. 2010. Pollen analysis of topsoil samples from Shiyang River drainage, Northwest China. J Desert Res, 30: 350–356

Cheng B, Zhu Y, Chen F H, et al. 2004. Relationship between the surface pollen and vegetation in Shiyang River drainage, Northwest China. J Glaciol Geocryol, 26: 81–88

Cour P, Zheng Z, Duzer D, et al. 1999. Vegetational and climatic significance of modern pollen rain in northwestern Tibet. Rev Palaeobot Palynology, 104: 183–204

Davis M B. 2000. Palynology after Y2K-Understanding the source area of pollen in sediments. Annu Rev Earth Planet Sci, 28: 1–18

Dufrene M, Legendre P. 1997. Species assemblages and indicator species: The need for a flexible asymmetrical approach. Ecol Monogr, 67: 345–366

El-Moslimany A P. 1990. Ecological significance of common nonarboreal pollen-examples from drylands of the Middle-East. Rev Palaeobot Palynol, 64: 343–350

Faegri K, Iversen J. 1989. Textbook of Pollen Analysis. 4th ed. Chichester: Wiley

Fall P L. 1992. Pollen accumulation in a montane region of Colorado, USA—A comparison of moss Polsters, atmospheric traps, and natural basins. Rev Palaeobot Palynol, 72: 169–197

Fall P L. 2012. Modern vegetation, pollen and climate relationships on the Mediterranean island of Cyprus. Rev Palaeobot Palynol, 185: 79–92

Gaillard M J, Birks H J B, Emanuelsson U, et al. 1992. Modern pollen/land-use relationships as an aid in the reconstruction of past land-uses and cultural landscapes: An example from south Sweden. Veg Hist Archaeobot, 1: 3–17

Giesecke T, Fontana S L, van Der Knaap W O, et al. 2010. From early pollen trapping experiments to the Pollen Monitoring Programme. Veg Hist Archaeobot, 19: 247–258

Grimm E C. 2011. Tilia 1.7.16. Springfield: Illinois State Museum

Herzschuh U. 2007. Reliability of pollen ratios for environmental reconstructions on the Tibetan Plateau. J Biogeogr, 34: 1265–1273

Herzschuh U, Birks H J B, Mischke S, et al. 2010. A modern pollen-climate calibration set based on lake sediments from the Tibetan Plateau and its application to a Late Quaternary pollen record from the Qilian Mountains. J Biogeogr, 37: 752–766

Herzschuh U, Borkowski J, Schewe J, et al. 2014. Moisture-advection feedback supports strong early-to-mid Holocene monsoon climate on the eastern Tibetan Plateau as inferred from a pollen-based reconstruction. Paleogeogr Paleoclimatol Paleoecol, 402: 44–54

Herzschuh U, Kramer A, Mischke S, et al. 2009. Quantitative climate and vegetation trends since the late glacial on the northeastern Tibetan Plateau deduced from Koucha Lake pollen spectra. Quat Res, 71: 162–171

Herzschuh U, Kurschner H, Ma Y Z. 2003. The surface pollen and relative pollen production of the desert vegetation of the Alashan Plateau, western Inner Mongolia. Chin Sci Bull, 48: 1488–1493

Herzschuh U, Tarasov P, Wunnemann B, et al. 2004. Holocene vegetation and climate of the Alashan Plateau, NW China, reconstructed from pollen data. Paleogeogr Paleoclimatol Paleoecol, 211: 1–17

Hicks S, Birks H J B. 1996. Numerical analysis of modern and fossil pollen spectra as a tool for elucidating the nature of fine-scale human activities in boreal areas. Veg Hist Archaeobot, 5: 257–272

ISTXCAS (Integrated Survey Team of Xinjiang, Chinese Academy of Sciences), IBCAS (Institute of Botany, Chinese Academy of Sciences). 1978. Vegetation of Xinjiang and Its Application. Beijing: Science Press

Legendre P, Gallagher E D. 2001. Ecologically meaningful transformations for ordination of species data. Oecologia, 129: 271–280

Li Y C, Xu Q H, Zhao Y K, et al. 2005. Pollen indication to source plants in the eastern desert of China. Chin Sci Bull, 44: 160–171

Lisitsyna O V, Hicks S, Huusko A. 2012. Do moss samples, pollen traps and modern lake sediments all collect pollen in the same way? A comparison from the forest limit area of northernmost Europe. Veg Hist Archaeobot, 21: 187–199

Liu H Y, Cui H T, Pott R, et al. 1999. The surface pollen of the woodland-steppe ecotone in southeastern Inner Mongolia, China. Rev Palaeobot Palynol, 105: 237–250

Lu H Y, Wu N Q, Liu K B, et al. 2011. Modern pollen distributions in Qinghai-Tibetan Plateau and the development of transfer functions for reconstructing Holocene environmental changes. Quat Sci Rev, 30: 947–966

Luo C X, Zheng Z, Pan A D, et al. 2008. Spatial distribution of modern pollen in Xinjiang region. Sci Geogr Sin, 28: 272–275

Ma Y Z, Liu K B, Feng Z D, et al. 2008. A survey of modern pollen and vegetation along a south-north transect in Mongolia. J Biogeogr, 35: 1512–1532

Mazier F, Galop D, Brun C, et al. 2006. Modern pollen assemblages from grazed vegetation in the western Pyrenees, France: A numerical tool for more precise reconstruction of past cultural landscapes. Holocene, 16: 91–103

Moore P D, Webb J A, Collinson M E. 1991. Pollen Analysis. 2nd ed. Oxford: Blackwell Scientific Publications

New M, Hulme M, Jones P. 1999. Representing twentieth-century space-time climate variability. Part I: Development of a 1961–90 mean monthly terrestrial climatology. J Clim, 12: 829–856

New M, Lister D, Hulme M, et al. 2002. A high-resolution data set of surface climate over global land areas. Clim Res, 21: 1–25

Ni J, Guo K, Liu H J, et al. 2005. Ecological regionalization of arid lands in northwestern China. Acta Phytoecol Sin, 29: 175–184

Oksanen J, Blanchet F G, Kindt R, et al. 2014. Vegan: Community Ecology Package. R package version 2.2-0

Overpeck J T, Webb T, Prentice I C. 1985. Quantitative interpretation of fossil pollen spectra-dissimilarity coefficients and the method of modern analogs. Quat Res, 23: 87–108

Pan A D. 1993. Research on sporo-pollen assemblages in surface soil of various vegetation in northern slope of the Tianshan Mountain. Sci Geogr Sin, 13: 227–233

R Core Team. 2014. R: A language and environment for statistical computing. Vienna, Austria, R Foundation for Statistical Computing

Roberts D W. 2013. Labdsv: Ordination and multivariate analysis for ecology. R package version, 1.6-1

Seppa H, Birks H J B, Odland A, et al. 2004. A modern pollen-climate calibration set from northern Europe: Developing and testing a tool for palaeoclimatological reconstructions. J Biogeogr, 31: 251–267

Shen C M, Liu K B, Tang L Y, et al. 2006. Quantitative relationships between modem pollen rain and climate in the Tibetan Plateau. Rev Palaeobot Palynol, 140: 61–77

Shi Y F, Shen Y P, Kang E, et al. 2007. Recent and future climate change in northwest china. Clim Change, 80: 379–393

Sugita S. 1994. Pollen representation of vegetation in Quaternary sediments-theory and method in patchy vegetation. J Ecol, 82: 881–897

Sun X J, Song C Q, Chen X D. 1999. "China Quaternary Pollen Database' (CPD) and "Biome 6000" Project. Adv Earth Sci, 14: 407–411

Tian F, Herzschuh U, Telford R J, et al. 2014. A modern pollen-climate calibration set from central-western Mongolia and its application to a late glacial-Holocene record. J Biogeogr, 41: 1909–1922

Wan T, Wei Z J, Yang J, et al. 1999. Pollen morphology of modern inner mongolia grassland. Plants. Beijing: China Agriculture Press

Wang F X, Chien N F, Zhang Y L, et al. 1995. Pollen Flora of China. 2nd ed. Beijing: Science Press

Wei H C, Zheng Z, Ma H Z, et al. 2009. Pollen distribution patterns of surface soil sample in Qinghai of China and their relationship with vegetation. Arid Land Geogr, 32: 932–940

Weng C Y, Sun X J, Chen Y S. 1993. Numerical characteristics of pollen assemblages of surface samples from the west Kunlun Mountains. Acta Botanica Sin, 35: 69–79

Wilmshurt J M, Mcglone M S. 2005a. Origin of pollen and spores in surface lake sediments: Comparison of modern palynomorph assemblages in moss cushions, surface soils and surface lake sediments. Rev Palaeobot Palynol, 136: 1–15

Wilmshurt J M, Mcglone M S. 2005b. Corroded pollen and spores as indicators of changing lake sediment sources and catchment disturbance. J Paleolimn, 34: 503–517

Wright H E, Mcandrew J H, Vanzeist W. 1967. Modern pollen rain in western Iran and its relation to plant geography and Quaternary vegetational history. J Ecol, 55: 415–443

Wu Z Y. 1980. Vegetation of China. Beijing: Science Press

Xi Y Z, Ning J C. 1994. Pollen morphology of plants from Chinese arid and semiarid areas. Yushania, 11: 119–191

Xiao X Y, Shen J, Wang S M. 2011. Spatial variation of modern pollen from surface lake sediments in Yunnan and southwestern Sichuan Province, China. Rev Palaeobot Palynol, 165: 224–234

Xu Q H, Li Y C, Tian F, et al. 2009. Pollen assemblages of tauber traps and surface soil samples in steppe areas of China and their relationships with vegetation and climate. Rev Palaeobot Palynol, 153: 86–101

Xu Y Q, Yan S, Jia B Q, et al. 1996. Numerical relationship between the surface spore-pollen and surrounding vegetaion on the southern slope of Tianshan Mountains. Arid Land Geogr, 19: 24–30

Yan S. 1993. The discussion on the pollen of pine family in surface soil in Xinjiang. Arid Land Geogr, 16: 1–9

Yan S, Kong Z C, Yang Z J, et al. 2004. Seeking relationship between vegetation and Picea pollen in surface soils of Xinjiang, northwestern China. Acta Ecol Sin, 24: 2017–2023

Yang Z J, Kong Z C, Yan S, et al. 2004. Pollen distribution in topsoil along the Daxigou Valley in the headwaters of the Urumqi River, the central Tianshan Mountains. Arid Land Geogr, 27: 543–547

Yang Z J, Zhang Y, Bi Z W, et al. 2011. Surface pollen distribution in the southern slope of Tianshan Mountains, Xinjiang. Arid Land Geogr, 34: 880–889

Zhang Q, Hu Y Q, Cao X Y, et al. 2000. On some problems of arid climate system of northwest China. J Desert Res, 20: 357–362

Zhang X S. 2007. Vegetation of China and Its Geographic Patterns. Beijing: China Geology Publishing House

Zhang Y, Kong Z C, Wang G H, et al. 2010. Anthropogenic and climatic impacts on surface pollen assemblages along a precipitation gradient in north-eastern China. Glob Ecol Biogeogr, 19: 621–631

Zhao K L, Li X Q. 2013. Modern pollen and vegetation relationships in the Yili Basin, Xinjiang, NW China. Chin Sci Bull, 58: 4133–4142

Zhao Y, Herzschuh U. 2009. Modern pollen representation of source vegetation in the Qaidam Basin and surrounding mountains, north-eastern Tibetan Plateau. Veg Hist Archaeobot, 18: 245–260

Zhao Y, Li F R, Hou Y T, et al. 2012a. Surface pollen and its relationships with modern vegetation and climate on the Loess Plateau and surrounding deserts in China. Rev Palaeobot Palynol, 181: 47–53

Zhao Y, Liu H, Li F, et al. 2012b. Application and limitations of the Artemisia/Chenopodiaceae pollen ratio in arid and semi-arid China. Holocene, 22: 1385–1392

Zhao Y, Xu Q H, Huang X Z, et al. 2009. Differences of modern pollen assemblages from lake sediments and surface soils in arid and semi-arid China and their significance for pollen-based quantitative climate reconstruction. Rev Palaeobot Palynol, 156: 519–524

Zhao Y, Yu Z C, Chen F H, et al. 2007. Holocene vegetation and climate history at Hurleg Lake in the Qaidam Basin, northwest China. Rev Palaeobot Palynol, 145: 275–288

Zheng Z, Huang K Y, Wei J H, et al. 2013. Modern pollen data in China and adjacent areas: Spartial distribution fearures and applications on quantitarive paleoenvironment reconstruction. Quat Sci, 33: 1037–1053

Appendix 1

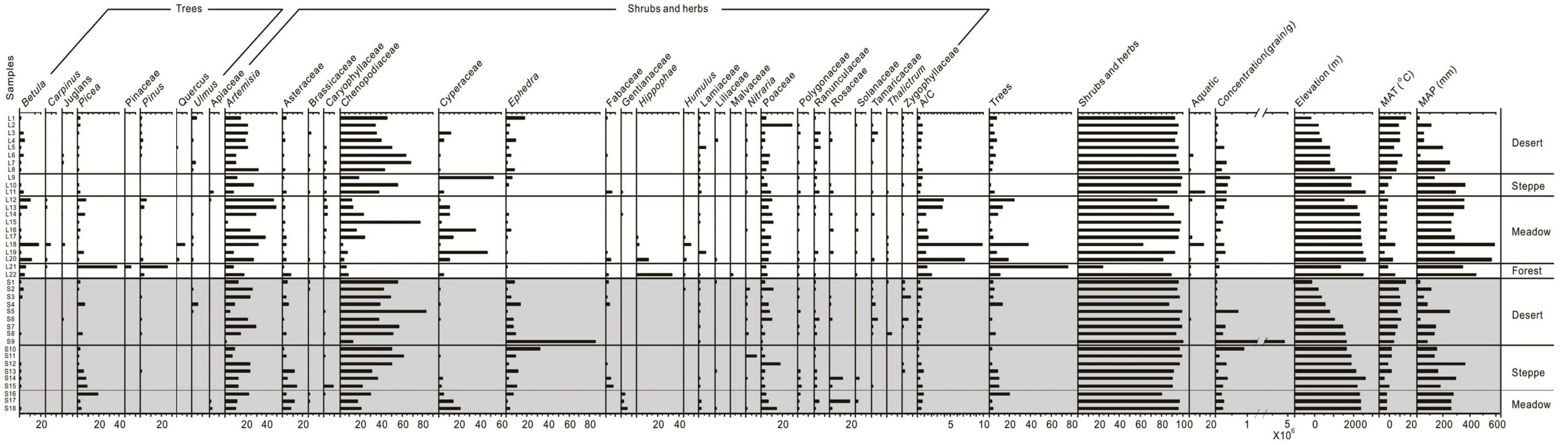

Figure A1 Pollen relative abundances of main taxa in the surface lake sediment (upper part) and topsoil (lower part with grey shadow) samples from northwestern China, and elevation, mean annual temperature (MAT), and mean annual precipitation (MAP) for each sample.