Quaternary International 298 (2013) 134–140

Contents lists available at SciVerse ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Over-representation of *Picea* pollen induced by water transport in arid regions

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ARTICLE INFO

Article history:
Available online 3 December 2012

ABSTRACT

Picea pollen plays an important role for reconstructing a cold-humid climate or palaeo-elevations. However, research has not yet taken into account the pollen transportation pathways within rivers in arid regions. A sporopollen study of surface (the uppermost) river sediments and surface soils from the Heihe and Shiyang Rivers (originating in the Qilian Mountains) suggests that significant differences exist between *Picea* pollen percentages within these two different sediment types. In surface soils the *Picea* pollen fractions are low, representing transportation by wind. However, percentages of *Picea* pollen reach up to 15.9% of total pollen counts in surface river sediments, as far as about 120 km away from the lower spruce forest line. This result, together with the demonstrated enrichment of *Picea* pollen in water bodies that lie along those observed rivers, indicate an over-representation within fluvial and lacustrine sediments. Knowledge about these relationships provides fundamental information for the reconstruction of palaeo-vegetation, palaeo-climate or palaeo-elevations.

1. Introduction

With their high production and fine preservation within sediments, sporopollen provide one of the best proxies for reconstructing past climates and monitoring recent ones (e.g., Erdtman, 1969; Prentice, 1985; Tarasov et al., 1999; Lu et al., 2010). Many studies have shown the value of *Picea* pollen to provide information about past climates. *Picea* pollen can also indicate a cold and humid climate and is also frequently used to reconstruct palaeo-elevations, because of its specific growing range on mountain slopes (Song and Liu, 1982; Sun et al., 1984; Huang et al., 1996; Van Campo et al., 1996; Cour et al., 1999; Wu et al., 2006; Dupont et al., 2008). Most researchers base their findings on the representation of *Picea* pollen within modern surface soils. However, few studies exist on the capacity of flowing water to carry *Picea* pollen (Brown, 1985; Catto, 1985; Li and Yao, 1990; Xu et al., 1995, 1996; Zhu et al., 2002; Xiao et al., 2011), even though many sporopollen results were obtained from fluvial or lacustrine depositional strata (e.g., Song and Liu, 1982; Sun et al., 1984; Wu et al., 2006; Dupont et al., 2008). Especially in arid regions, the appearance of *Picea* pollen in these sporopollen records plays an essential role for interpreting palaeo-environments and palaeo-elevations. Therefore, carrying out basic work about the transport of *Picea* pollen in water streams provides critical information to improve the interpretation of palaeo-environmental and palaeo-elevation data.

Rivers originating in the Qilian Mountains (Fig. 1) flow past each vertical zone (Fig. 2) of the temperate arid mountain vegetation, until finally vanishing in the Badain Jaran Desert or the Tengger Desert. *Picea* dominates the tree species in the forest belt of the Qilian Mountains. Therefore, these rivers provide an ideal site for the study of *Picea* pollen transport.

2. Geography

The Qilian Mountains lie along the northeastern margin of the Tibetan Plateau (Fig. 1). The Heihe River and the Shiyang River are the two main rivers originating along the northern face of the Qilian Mountains. The westerlies provide a dominant influence within their drainage areas. The southern part of the drainage system falls under the influence of a cool temperate semi-arid climate, whereas the middle and northern parts are more influenced by a temperate arid climate. The mean annual precipitation increases with elevation, while the mean annual temperature decreases with elevation (Wang et al., 2001) (Fig. 2).

From south to north of the Heihe and Shiyang River drainage areas, the distribution of modern vegetation depends strongly on

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http://dx.doi.org/10.1016/j.quaint.2012.11.026

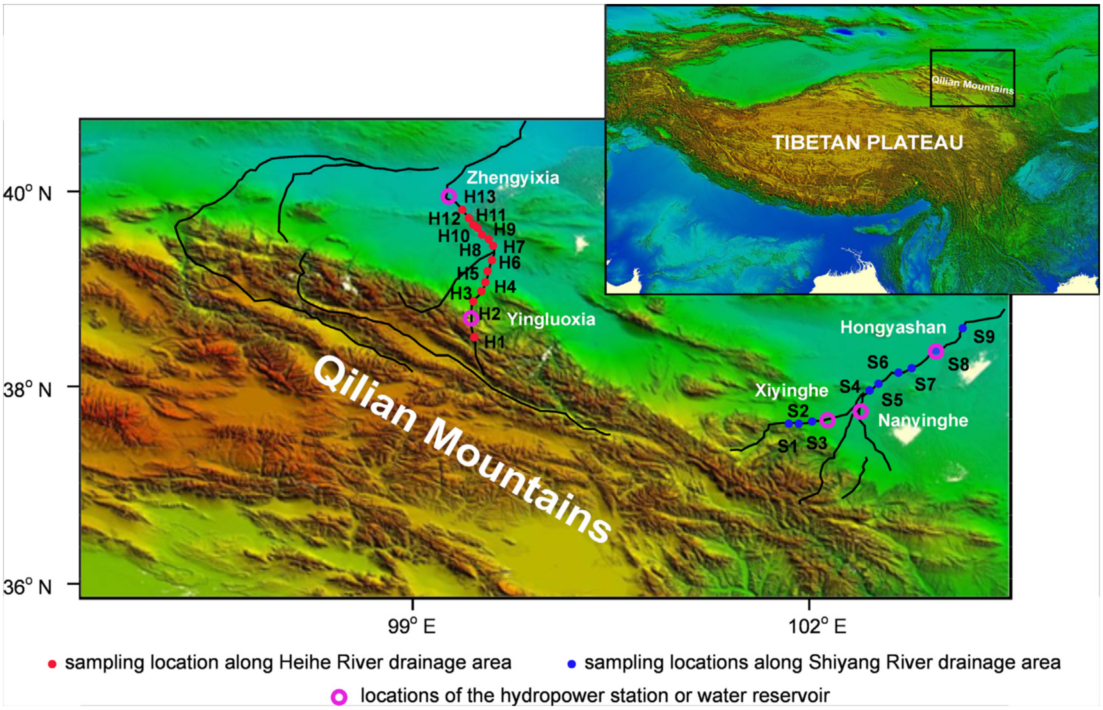

Fig. 1. Location map of the northern Qilian Mountains, showing the Heihe and Shiyang Rivers, as well as the sampling sites.

the elevation (Fig. 2). The perennial snow and ice zone (>4500 m) shows no vegetation. A zone of cushion-like vegetation lies between 4500 and 3800 m and contains mostly ting-shaped *Arenaria serpyllifolia L.*, *Androsace brachystegia*, *Saussurea medusa Maxim*, *Saussurea involucrata*, and *Lagotis brevituba Maxim*. The meadow zone (3800–3500 m) harbors mainly *Artemisia*. The alpine shrub zone (3500–3100 m) shows plants like *Salix cupularis*, *Caragana jubata*, *Dasiphora davurica*, *Rhododendron capitatum*, and *Saussurea japonica*. *Picea crassifolia* and *Sabina przewalskii* cover the shady slopes of the mountain forest grassland zone (3100–2800 m), and *Thalictrum L.*, *Epilobium angustifolium Linn.*, and *Hedrysarum multijugum* lie on the sunny slopes. Grasses, dotted with *Populus davidiana*, *Lycium chinense*, and the like dominate the mountainous grassland zone (2800–2300 m). The desert steppe zone (2300–2000 m) and the gobi-sand desert zone (<2000 m) contain some scattered xerophytic plants, such as *Nitraria spp.* (Editorial Board of Chinese Vegetation, 1980; Wu, 1995; Huang, 1997).

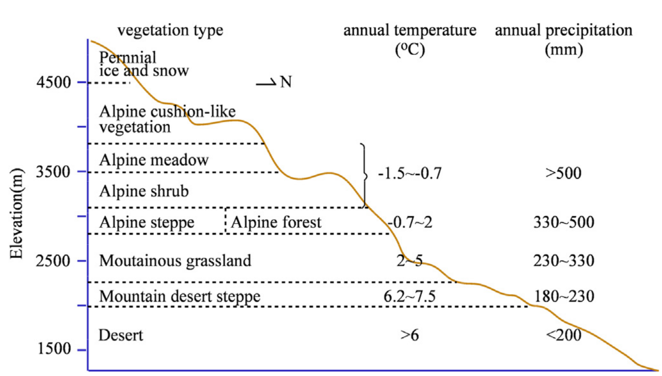

Fig. 2. The sampling zones and their dominant vegetation types. Annual temperature averages and precipitation shown where available.

3. Materials and methods

This study collected two sets of samples, synchronously, along the main streams of the Heihe and Shiyang Rivers. The first set consists of fine-grained mud deposited by the rivers, "surface river sediments". The second set consists of modern surface soils taken from open terrain near the river. The uppermost surface litter was scraped and removed before sampling. Each sample analyzed consists of a mix of five field samples, taken in the shape of a five-pointed star within an area of 5 m by 5 m. Fig. 1 shows the sampling locations. The samples were taken at elevations between 1290 m and 2312 m, mainly out of the desert grass areas and the desert areas. The 13 samples taken from the Heihe River drainage area are numbered from sample H1 to H13, and the 9 samples taken from the Shiyang River drainage area are numbered from sample S1 to S9 (Fig. 1).

For preparation, each surface river sediment sample consisted of 20 g of material and each soil sample consisted of 10 g. Sample preparation followed standard palynological methods (e.g., Kaiser and Ashraf, 1974) with use of the ultrasonic vibration screening method. This includes treatment with HCl, HF and other chemicals to isolate the palynomorphs from the sample materials. *Lycopodium* sporelets were added to determine pollen concentrations of each sample during pollen analysis. A microscope with ×400 magnification was routinely used for identification and counting of sporopollen. For small and difficult types, ×1000 magnification was preferred.

4. Sporopollen results

All samples yielded abundant pollen grains. The average content often exceeded 630 grains/g in the surface river sediment samples, but regularly exceeded 4600 grains/g in the surface soil samples. At least 100 pollen grains were identified within the river sediment samples, whereas about 300 pollen grains were identified from the soil samples. Fifty-nine taxa were distinguished

(Table 1), including some arboreal tree taxa and many scrubby and herbaceous taxa (as well as a few pteridophyte and algal spores, which were excluded from the total pollen sum in the calculation the pollen percentages).

and *Betula* (0–2.2%) contribute various lower percentages. Conifer pollen are only marginally represented: *Pinus* ranges between 0 and 11% and *Picea* appears sporadically in most samples (0–2.8%), except in sample S1 (8.8%: Fig. 4).

Table 1
Main taxa identified in the Heihe and Shiyang River drainage area samples.

Coniferous pollen	Broadleaf trees pollen	Shrubs and herbs pollen	Shrubs and herbs pollen	Shrubs and herbs pollen
Picea	*Juglans*	Chenopodiaceae	*Stellera*	*Rosa*
Pinus	*Quercus*	*Tamarix*	Caryophyllaceae	Oleaceae
Cedrus	Shrubs and herbs pollen	*Ephedra*	Ericaceae	*Urtric*
Sabina	Gramineae	*Nitraria*	Zygophyllaceae	Malvaceae
Juniperus	Cruciferae	Polemoniaceae	*Typha*	*Typhera*
Broadleaf trees pollen	*Ranunculus*	*Elaeagnus*	*Calligonum*	*Cypera*
Betula	*Amthemis* type	*Polygonum*	Leguminosae	spores
Ulmus	*Taraxacum* type	*Corylus*	Plumbaginaceae	*Polypodium*
Populus	*Aster* type	Solanceae	Rhamnaceae	*Selaginella*
Salix	*Artemisia*	Umbelliferae	Caprifoliaceae	Lycopodium

Figs. 3 and 4 display pollen diagrams arranged according to the percentages of the main species. The bars on the left in each pair show the results reached from the counting of river sediment samples, and the bars to the right in each pair show the results reached from the nearby surface soil samples.

In the surface river sediments from the Heihe River, pollen of herbs and shrubs mirror the current dominant vegetation types. The main taxa are: *Artemisia*, Chenopodiaceae, Gramineae, and other Compositae, among which the percentages of *Artemisia* reach more than 30% (24.2%–48.6%) in all of the samples except H12 (10.7%). The percentages of Chenopodiaceae range from 15.8% to 52.6%, whereas the portion of Gramineae reaches percentages between 1.2% and 9.8%. Pollen from broad-leaved trees like *Betula* (0–1.6%) and *Salix* (0–0.5%) are occasionally present. Percentages of *Populus* are also low (0–1.2%), except in sample H12 (12.5%). Pollen from conifers including *Picea* are abundant, with percentages reaching 18.6% in sample H1, and 4%–15.9% in samples between H7 and H13. *Pinus* pollen plays a minor role (0.4%–8.1%: Fig. 3).

The pollen from herbs and shrubs also dominate in the modern surface soils from the Heihe River drainage area. *Artemisia* and Chenopodiaceae taxa pollen are the most prominent. The percentages of Chenopodiaceae exceed 30% (32.8%–90.7%) in all of the samples except H12 (24.6%). The pollen of *Artemisia* reaches high percentages, ranging from 23.1% to 63.5%, except in samples H2 (15.6%), H3 (4.1%), and H6 (7%). The pollen of Gramineae (0.1%–9.2%) and *Nitraria* (0.8%–11.8%) also have notable percentages. The pollen of the broad-leaved trees indicates small amounts of *Betula* (0–1.4%) and *Populus* (0–1%). The percentages of conifer pollen remain low. The highest percentage of *Pinus* is 2%, and *Picea* reaches a relatively high percentage in sample H2 (6.5%), but does not exceed 5% (0–4.4%) in the rest of the samples (Fig. 3).

In the sporopollen assemblages of the surface river sediments from the Shiyang River, *Artemisia* (19.5%–61.8%) and Chenopodiaceae (9.1%–30.1%) exhibit a wide range in their percentages. Analyses also showed a few pollen of broad-leaved trees, such as *Betula* (0–5.4%) and *Populus* (0–1.7%). Of coniferous trees, *Picea* pollen is abundant in sample S1–S3 (7%–20%) and sample S8 (11.3%), and appears sporadically in the other samples (0.1%–1.7%). *Pinus* contributes up to 11.6% in sample S1, but makes up only low percentages in the other samples (0–6%: Fig. 4).

In the modern surface soils from the Shiyang River drainage area, pollen of *Artemisia* (19.8%–78.1%) and Chenopodiaceae (13.7%–40.4%) dominate. Gramineae (0.1%–8.2%), *Populus* (0–7.1%),

5. Discussion

Many studies regarding the representation of common plant pollen in modern surface soils have already been reported. The results indicate that *Artemisia* and Chenopodiaceae are over-represented. If the percentages of *Artemisia* and Chenopodiaceae in sporopollen assemblages exceed 30%, studies indicate that those pollen may have been emitted by autochthon *Artemisia* and Chenopodiaceae plants growing in the vicinity of the sampling location (Li and Yan, 1990; Yan, 1991; Huang, 1993). These and other studies also observe *Pinus* pollen as being over-represented. The percentages of *Pinus* in regions without pine forests usually fall below 30% (Li and Yao, 1990). Other pollen types are often under-represented. For example the pollen exine of *Populus* is thin (Xu et al., 2005), and thus almost impossible to preserve during the process of analysis. *Populus* pollen also tends to be damaged in strata (Campbell, 1999), resulting in its under-representation in sporopollen assemblages. Due to its thin-walled exine, average measured percentages of Gramineae pollen rarely exceed 3.0%–6.0% (Li and Yan, 1990; Yan, 1991; Huang, 1993), even though they are commonly dominant taxa.

The sporopollen results in the surface soils from the drainage areas along the Heihe and Shiyang Rivers show high percentages of *Artemisia* and Chenopodiaceae, which exceed 30% in most of the samples. These findings characterize *Artemisia* and Chenopodiaceae as dominant species within these sporopollen assemblages. Pollen of Gramineae is rare, whereas *Populus* pollen occurs occasionally. The percentages of *Pinus* (11% maximum) suggest that there were no pine forests around the sampling location. Based on the sporopollen records (Figs. 3 and 4), the vegetation elements of the geographical surrounding are as follows. In the desert-steppe, drought-tolerant *Artemisia* and Chenopodiaceae provide the main vegetation elements, with some mesophilous herbs including Graminae, *Ranunculus*, and some Compositae plants growing in between. Broad-leaved *Populus*, *Betula* and *Salix* populate the vicinity of the river. This corresponds relatively well to the current vegetation distribution.

However, certain differences exist between the results of sporopollen analysis from surface river sediments and those from surface soils of the Heihe and Shiyang River drainage areas. High percentages of *Picea* occur in the surface river sediments compared to the soil samples. In the surface river sediments from the Heihe River, the percentage of *Picea* in sample H1 reaches 18.6%, whereas

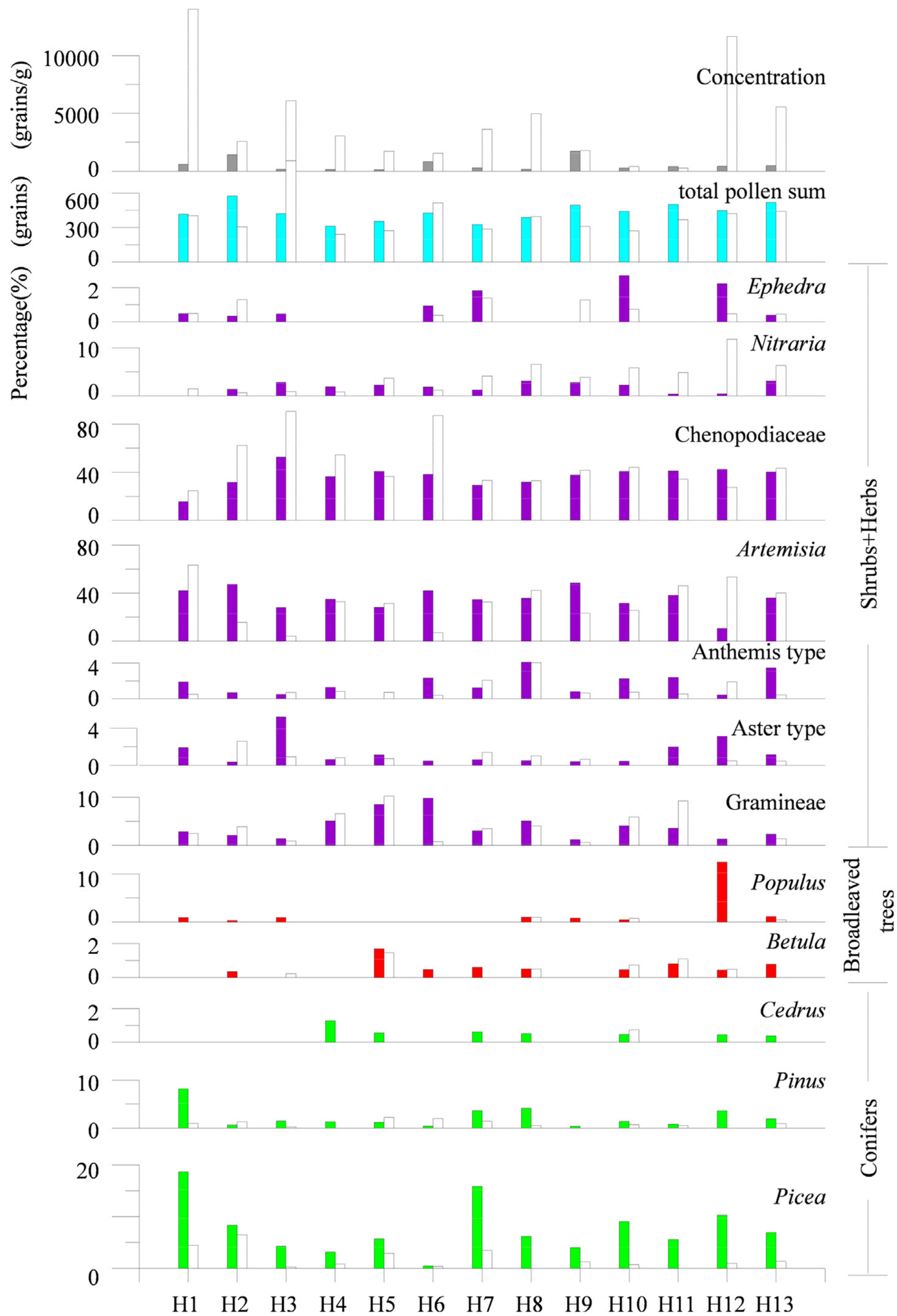

Fig. 3. Pollen diagram of the Heihe River drainage area, colored bars (on the left in each pair) show the results of the surface river sediments, colorless bars (to the right in each pair) show the results of the surface soils. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in samples H2–H6 its percentages only reach 0.5%–8.3%. Starting with sample H7, the *Picea* percentages increase (4%–15.9%). In the surface river sediment samples from the Shiyang River (Fig. 4), percentages of *Picea* reach their highest values between sample S1 and S3 (7%–20%), and in sample S8 (11.3%). Almost no *Picea* was found in any of the other Shiyang River surface sediment samples.

Erdtman (1969) discovered that *Picea abies* pollen grains are much heavier than most of the other seed plant pollen, and suggested that its sinking speed therefore was much faster. Furthermore, *Picea* pollen grains are large, and when airborne in the forests after being pollinated, they more likely collide with obstacles such as tree trunks, branches, and leaves, and fall to the ground. This could help explain the low concentrations of *Picea* pollen grains in sediments compared to *Pinus* pollen, although both are bisaccate pollen types. Therefore, *Picea* is generally acknowledged to be very representative (Li, 1991; Xiao et al., 2011) of autochthonous vegetation, although some researchers suggest that various factors such as violent air motions and geography affect the amount of *Picea* dispersal to some extent. The percentages of *Picea* pollen in regions far away from *Picea* forests are generally not very high. For instance, the analysis of surface soil pollen in the Chaiwopu basin of Xinjiang revealed that the percentages of *Picea* can reach 2%–5% in desert samples taken 3 km away from *Picea* forests (Li and Yao, 1990).

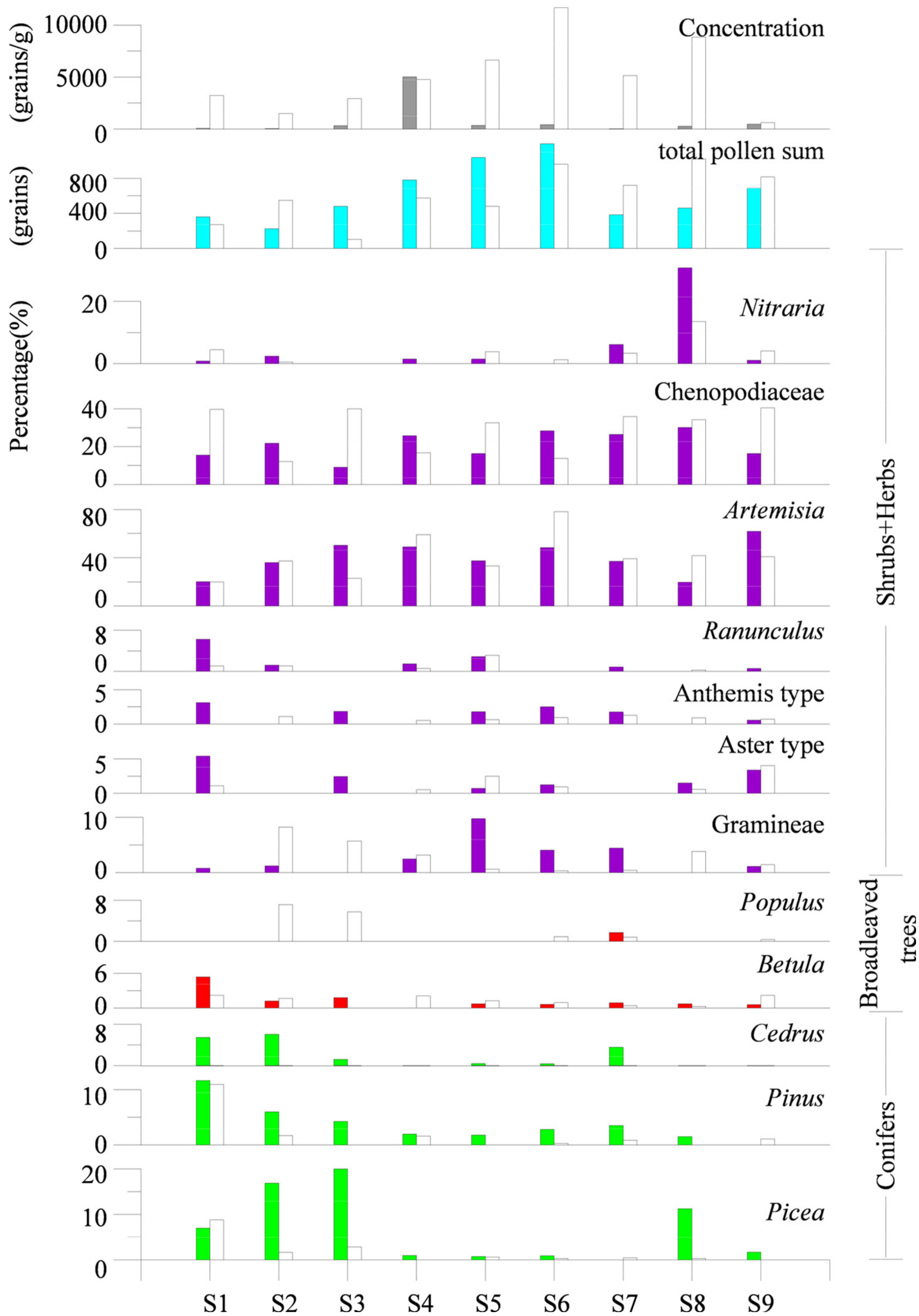

Fig. 4. Pollen diagram of the Shiyang River drainage area, colored bars (on the left in each pair) show the results of the surface river sediments, colorless bars (to the right in each pair) show the results of the surface soils. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

High percentages of the *Picea* pollen in the results means that it was carried a very long distance by the water flow in the rivers. The distance between the sampling location H7 and the lower spruce forest line is about 120 km, and the percentage of *Picea* in this sample reaches a high value of 15.9%. The elevation of sampling location of sample H13 is 1290 m, indicating about 1500 m height difference between this sampling location and the lowest spruce forest line (as well as a distance of about 180 km). However, the percentage of *Picea* in sample H13 reaches 6.9%. This demonstrates that the stream water's capacity in carrying detectable *Picea* pollen exceeds the capacity of air transport.

The conclusion above raises another question — which dominates: the impact of *Picea* pollen deposition in dammed reservoirs (of hydropower stations) or the deposition of *Picea* pollen in still water areas of rivers? The Yingluoxia hydropower station (Fig. 1) located between sample H1 and sample H2 in Heihe River area provides a favorable still water environment for the settling of *Picea*. It is assumed that this is the main reason for the sharp decrease in *Picea* pollen percentages between sample H2 and H6. The other branches of the Heihe River may be responsible for the further increased percentages of *Picea* pollen after sample H6.

Xiying hydropower station (Fig. 1) lies along the Shiyang River, between sample sites S3 and S4. Its reservoir also provides a stable environment for the settling of *Picea* pollen. As a result, the percentages of *Picea* pollen decrease sharply between samples S4 and S7. Sample S8 comes from the Hongyashan reservoir (Fig. 1) located downstream from the Shiyang River, 140 km away from the lowest spruce forest line. The percentage of *Picea* pollen reaches 11.3% in sample S8, showing that the reservoir plays an important role in catching the pollen.

The influence that fluvial transport may have on pollen representation requires further understanding. Some researchers think that fluvial transport of pollen grains faithfully reflects nearby plant communities (Hall, 1989; Chmura and Liu, 1990; Campbell and Chmura, 1994; Smirnov et al., 1996). These findings were mainly obtained from investigations on the Mississippi and Atchafalya Rivers and have been supported by other studies conducted in North America (Brush and Defries, 1981; Mudie, 1982). Other researchers believe that the fluvial pollen have been sorted by size (Brown, 1985; Catto, 1985; Fall, 1987). The Heihe and Shiyang River get their water from melting ice and snow during the spring and from precipitation in the summer. This rainfall often occurs in form of torrential rain, and the maximum rainfall takes place at elevations above 4000 m (Wang et al., 2009). *P. crassifolia*, as a major constructive species, grows at elevations between 3100 and 2800 m, and blooms in May. Thus, sudden floods during the late spring may be the main force carrying and depositing *Picea* pollen along the streams to places far away or into reservoirs. Dynamic factors, such as velocity, discharge, size of drainage basin, etc. of the different river system may impact the spread of *Picea* pollen. More detailed work is needed to provide accurate explanations.

In the northwest arid areas of China, no broad-leaved forest zone exists in the vertical vegetation distribution (Wu, 1995). Thus, coniferous components (such as *Picea*) transported by water, occupy prominent roles in the pollen assemblages of surface river sediments. Therefore, the content of *Picea* pollen in the fossil records obtained from fluvial-lacustrine strata must be carefully analyzed, along with thorough consideration of their possible pollen sources.

6. Conclusions

Sporopollen from surface soils and surface river sediments of the Heihe and Shiyang River drainage area have been sampled and analyzed. These rivers originate in the Qilian Mountains, located along the northeast margin of the Tibetan Plateau. This study found significant differences between pollen types found in the surface river sediments compared to nearby surface soils. Notably, the percentages of *Picea* in surface soils are relatively low, while in surface river sediments, even 120 km away from spruce forests, percentages exceed 15%. Even 180 km away from spruce forests, their pollen percentages still reach almost 7%. Furthermore, in a water reservoir about 140 km away from any spruce forests, the percentages of *Picea* pollen can exceed 11%. This shows that *Picea* can be over-represented in fluvial-lacustrine deposits. Future work should therefore develop an instrument to quantify the capacity of flowing water to carry *Picea* pollen. Quantification of such results could improve the accuracy of pollen based vegetation reconstructions based on lake and alluvial sediments deposited under substantial fluvial conditions.

Acknowledgments

This work was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDB03020103), the National Natural Science Foundation of China (41021001, 41272184, 41172153). Many thanks to Jinbo Zan, Weilin Zhang, Yi Chen and Yan Bai for their field assistance and to Hongxia Yu for her laboratory assistance. Special thanks to Editor Norm Catto and reviewers for their positive response to this paper and Prof. Bill Isherwood for help with improvement of the English.

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