Modern pollen assemblages in topsoil and surface sediments of the Xingyun lake catchment, central Yunnan Plateau, China, and their implications for interpretation of the fossil pollen record

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Abstract: Modern pollen data from topsoils and surface lake sediments are commonly used as modern analogues and as climate calibration data for reconstructing vegetation and climate history from fossil pollen profiles. However, the potential differences and biases in pollen assemblages from these two sample types, as well as the processes of pollen sedimentation in lake basins, have received relatively little attention. Here we present the results of the analysis of modern pollen assemblages in 10 surface sediment samples and 25 topsoil samples from Xingyun Lake and its catchment, a shallow alpine lake site in the central Yunnan Plateau,

southwest China. The modern pollen assemblages from both types of samples are mainly composed of *Pinus*, evergreen and deciduous oaks, *Alnus*, Poaceae, *Artemisia*, Brassicaceae and Amaranthaceae, and are consistent with the modern vegetation. Although the pollen assemblages of topsoil samples vary with the type of modern local vegetation, in general they are representative in term of the composition of the main pollen taxa, with some significant differences in the case of some vegetation types. With regard to the surface lake sediment samples, the pollen assemblages are relatively constant with no significant changes with sample location and water depth. The main pollen taxa are *Pinus* (around 40%), *Alnus* (around 18%) and Poaceae (around 11%), with relatively high percentages of evergreen and deciduous oaks, *Betula* (2-4%), and low percentages of *Ulmus*, Rosaceae, *Corylus*, Cupressaceae, Euphorbiaceae, *Myrica* and Elaeagnaceae. This composition is a good representation of the main types of catchment vegetation. The relative uniformity of the pollen assemblages from the lake surface samples may partly result from the effect of currents in redistributing the pollen input to the lake by rivers and wind. Therefore, we suggest that it is better to use pollen data from surface lake sediments, rather than from topsoils from the lake catchment, for interpreting fossil pollen assemblages of lake sediment cores. Our results indicate that the pollen assemblages in a sediment core from any part of Xingyun Lake are likely to provide a reliable record of the regional vegetation history and thus climatic change. Our modern pollen results, together with modern pollen data from other surface lake sediment samples along a large altitudinal gradient from Yunnan to southwest Sichuan Province, were used to

reanalyze fossil pollen assemblages during the Last Glaciation period at Xingyun Lake. The results show that the vertical vegetation belts decreased in altitude from late Marine Isotope Stage 3 (late MIS3) to the Last Glacial Maximum (LGM) and then increased during the Last Deglaciation.

Keywords: Modern pollen assemblages, surface lake sediment, topsoil, Xingyun Lake

1. Introduction

The analysis of modern pollen assemblages is widely used to help interpret fossil pollen records. In order to better explain fossil pollen data, and to improve the quality of vegetation and the resulting climatic reconstructions, it is essential to understand the relationship between modern pollen assemblages and the modern source vegetation. There are many examples where the relationship between modern pollen assemblages and present-day vegetation has been established (e.g., Sugita, 1994; Cour et al., 1999; Davis, 2000; Ma et al., 2008; Zhao and Herzschuh, 2009; Wei et al., 2011; Zhao et al., 2012; Zhao and Li, 2013; Zheng et al., 2013; Li et al., 2015). In addition, researchers have used transfer functions to quantitatively reconstruct palaeoclimate based on modern pollen data (Shen et al., 2006; Li et al., 2007; Herzschuh et al., 2009, 2010, 2014; Xu et al., 2010; Lu et al., 2011; Chen et al., 2014a, 2015; Wang et al., 2014). Generally, modern pollen samples are collected from topsoil or moss polsters and surface lake sediments. The pollen assemblages of the respective samples have

been shown to differ, owing to differences in pollen source area and differential preservation conditions (Fall, 1992; Jackson et al., 1994; Minckley et al., 2000; Wilmshurst and McGlone, 2005; Zhao et al., 2009; Qin et al., 2015). Thus it is argued that there will be some bias for quantitative climate reconstructions when different types of sample are used in calibration data sets (Seppä et al., 2004; Zhao et al., 2009; Birks et al., 2010; Qin et al., 2015). Consequently, several researchers have focused on the differences between the pollen assemblages from topsoil and surface lake sediments in order to clarify the potential bias (DeBusk, 1997; Wilmshurst and McGlone, 2005; Zhao and Herzschuh, 2009; Zhao et al., 2009; Qin et al., 2015). However, topsoil pollen samples may not be representative of the vegetation of an entire lake catchment. For example, in the study of Zhao et al. (2009) in arid and semi-arid China only one topsoil sample was collected from each of several lake catchments. In addition, in a recent study which compared the pollen assemblages of topsoil and surface lake sediments from northwestern China, many of the topsoil samples were not collected from the lake catchment (Qin et al., 2015). Therefore, so far comparisons of the pollen composition of surface lake sediments and topsoil samples in lake catchment have not been conducted in depth (cf. the study of Lake Malaŵi by DeBusk (1997)).

It is often assumed that the pollen content of surface lake sediments is related to water depth (Su and Wu, 1987; Huang, et al., 2004, 2010; Zhao et al., 2007), and that the highest pollen concentration will be from the samples from the centre or the deepest

part of the lake. Therefore, it is often recommended that a sediment core should be taken from the lake centre when reconstructing the regional vegetation history using fossil pollen (Sun and Wu, 1987; Huang et al., 2004, 2010). However, research on Daihai Lake by Xu et al. (2005) suggested that the highest pollen percentages and concentrations of the main pollen taxa occur in the marginal sediments because of the pollen supply from inflowing rivers. Thus the variation of pollen assemblages in different parts of the lake may reflect differences in local vegetation close to the lakeshore. However, pollen assemblages of surface lake sediments are influenced by various factors, such as pollen production, pollen dispersal and transportation processes, lake basin shape and size, the presence of inflows and outflows, and other geographical conditions of the lake catchment. Thus, it should be noted that the discrepancies between the former studies may be the result of differences in the characteristics of the study sites.

Xingyun Lake is located on the central Yunnan Plateau, a region in China where the climate is controlled by the Indian summer monsoon (An et al., 2011; Liu et al., 2015) and the vegetation has a high diversity (Li and Walker, 1986; Walker, 1986). This region, therefore, is ideal for reconstructing palaeovegetation and hence Indian summer monsoon variability (An et al., 2011; Song et al., 2012; Cook et al., 2013; Chen et al., 2014a, 2014b; Xiao et al., 2014, 2015; Yang et al., 2016). Many investigations of modern pollen assemblages have been carried out in the region; for example, Sun and Wu (1987), in the earliest modern pollen study in Yunnan,

investigated pollen assemblages and the relationship between pollen content and water depth in 59 surface lake samples from Dianchi Lake. Subsequently, additional studies of the relationship between modern pollen and vegetation based on topsoil samples have been carried out: e.g., in the Yulong Snow Mountain region (Tong et al., 2003; Xiao et al., 2009; Shen et al., 2013), the Lijiang and Dali area (Li et al., 2008), Kunming (Wu and Sun, 1987; Wu and Xiao, 1989) and in southern Yunnan (Pan et al., 2008, 2009). Recently, Xiao et al. (2011) studied the spatial variation of pollen assemblages from palynological data from various lakes in Yunnan and southwest Sichuan Province, and these pollen data have great potential to be used as a reference for reconstructing the palaeovegetation and palaeoclimate of the region. However, there have been few studies of modern pollen assemblages in central Yunnan, especially those in surface lake sediments, as well as of the contrasts with pollen assemblages those from topsoils.

Here we present the results of the analysis of modern pollen assemblages in 25 topsoil samples from different local vegetation types in the Xingyun Lake catchment and in 10 surface lake sediment samples from different water depths in the lake. Our aims are as follows: 1) to investigate the relationships between modern pollen assemblages and the contemporary vegetation; 2) to explore the pollen source and pollen distribution of the lake sediments; 3) to produce guidelines for the application of different types of modern pollen surface sample to the interpretation of fossil data; and 4) to apply our findings to the interpretation of fossil pollen data.

2. Regional setting

Xingyun Lake (24°17'-24°24'N, 102°45'-102°49'E) is located in central Yunnan Province in southwest China (Fig. 1a). It is climatically controlled by the Indian monsoon and has historically been impacted by human activity, therefore, the lake is well-suited for documenting Indian monsoon variability and the history of human activity (Hodell et al., 1999; Chen et al., 2014a, 2014b; Hillman et al., 2014; Wu et al., 2015a, 2015b; Zhou et al., 2015; Chen et al., 2016). It is a shallow alpine lake surrounded by mountains, and the topography of the catchment is dominated by hilly plateaus with a small range of elevation. The lake has a surface area of c. 34.7 km² and a catchment area of c. 386 km². The maximum water depth is 11 m, with an average depth of 7 m, and the lake floor is flat in the centre (Fig. 1b). The lake is fed by 14 small, intermittent rivers (Fig. 1b) and since 2007 from Fuxian Lake via a narrow channel.

Fig. 1

The study area experiences a subtropical semi-humid climate (Editorial Board of Yunnan Vegetation in China, 1987), driven mainly by the Indian summer monsoon (Southwest monsoon), which is characterized by wet summers and dry winters. The

average annual rainfall of the Xingyun Lake catchment is 879 mm, with 85% occurring from May to October. Mean annual temperature is 16.1°C, with a mean July temperature of 21°C and a mean January temperature of 9°C (Chen et al., 2014a, 2014b).

The natural vegetation of the catchment is controlled primarily by the monsoonal climate, and the potential vegetation type of the area is semi-humid evergreen broadleaved forest, which belongs to the subtropical evergreen broadleaved forest zones of the Yunnan Plateau (Editorial Board of Yunnan Vegetation in China, 1987). The regional vegetation in central Yunnan is also related to elevation and the following altitudinal zones are recognized: 1500-2500 m- evergreen broadleaved forest-pine forest; 2500-2800 m- mid-montane, humid evergreen broadleaved forest; 2800-3200 m- *Tsuga* forest, or mixed forest with *Tsuga* and evergreen and deciduous broadleaved trees; 3200-4200 m- sub-alpine cold-temperature coniferous forest dominated by *Abies* and *Picea*; and above 4200 m- alpine heath scrub and meadow (Editorial Board of Yunnan Vegetation in China, 1987). However, due to the high local population density and well-developed agriculture, together with the long history of cultivation, the current distribution of the main vegetation types is also significantly affected by human activity. There is a large cultivated area around Xingyun Lake, including fields of rice, corn, wheat, rapeseed and various vegetables, as well as orchards. On the surrounding mountains, drought-tolerant shrubs and grassland dominate, consisting of *Myrica nana*, *Rhamnus rosthornii*, *Rhamnus virgatus* var.

sylvestris, *Myrsine africana*, *Rosa odorata* var. *gigantea*, *Rhododendron spiciferum*, *Sophora viciifolia*, *Pyracantha fortuneana*, *Arundinella setosa*, *Eremopogon delavayi*, *Eulalia quadrinervis*, *Arundinella chenii*, *Carex baccans*, and *Zingiber striolatum*.

Human impact has significantly reduced the natural forest of the region. Among the existing areas of forest and woodland, *Pinus yunnanensis* forests dominates and there is only a very limited occurrence of broadleaved forest (including *Cyclobalanopsis delavayi*, *Castanopsis delavayi*, *Lithocarpus dealbatus*) which is partly residual and grows mainly at relatively high altitudes on the surrounding mountains. In addition, numerous secondary vegetation types are distributed on the relatively high mountains, including *Alnus nepalensis*, *Quercus acutissima*, *Q. variabilis*, *Q. aliena*, *Platycarya strobilacea* and *Crataegus scabrifolia*. (Fig. 2; Editorial Board of Yunnan Vegetation, 1987).

Fig. 2

3. Materials and methods

3.1 Field work

All of the modern pollen samples were collected in May 2013. A total of 25 topsoil pollen samples were collected from the catchment of Xingyun Lake (Fig. 1b). At each

sampling site, 4-5 samples of topsoil were randomly selected and collected and then combined into one sample. The location of each sample site was identified by GPS (Fig. 1b). The vegetation type at each sampling site was recorded in the field (Table 1). Of the 25 topsoil sampling sites, 7 were in farmland, 11 in woodland and the other 7 were in shrubland or grassland (Table 1; Fig. 1b). Ten modern pollen samples were also taken from surface sediments at different water depths in Xingyun Lake using a CRAB sampler (Fig. 1b).

Table. 1

3.2 Laboratory analyses

4-6 g of topsoil and 2 g of surface lake sediments were used for pollen analysis. The samples were processed following standard procedures (Fægri and Iversen, 1989; Moore, et al., 1991): HCl (10%), KOH (10%), HF (40%) and acetolysis treatments, followed by sieving with 7 μ m mesh (Chen et al., 2014b). A tablet containing a known amount of *Lycopodium* spores was added to each sample for estimation of pollen concentration. Pollen taxa were identified under an optical microscope at $\times 400$ magnification. At least 400 terrestrial pollen grains were counted per sample. Pollen percentages were calculated based on the sum of total terrestrial pollen, and pollen diagrams were plotted using Tilia 2.0.2 (Grimm, 2004).

3.3 Numerical methods

Detrended correspondence analysis (DCA) is an ordination method often applied to pollen data. It is used to detect and summarize the major patterns of variation and to identify and characterize trends, and the magnitude of compositional changes in large data sets (Hill and Gauch, 1980; Birks, 1998). It is also used to determine whether linear- or unimodal-based techniques should be employed in subsequent ordination analyses. The analysis was first carried out on the topsoil pollen samples from the Xingyun Lake catchment. The analyses were based on taxa that occurred in at least two samples and with a relative abundance of >1%, defined as “major taxa”. A total of 27 major pollen taxa were used for DCA ordination analysis. The length of the gradient was 1.37 standard deviation (SD) units, indicating that linear techniques were appropriate for the data (Birks, 1998). Therefore, Principal Components Analysis (PCA) was conducted on both pollen samples and pollen taxa. DCA ordination analysis was then carried out on the entire modern pollen data set, including both catchment and surface lake sediment samples. Based on the results for the two different pollen data sets, 29 pollen taxa were analyzed. All of the numerical analyses were performed using CANOCO v.4.52 software (ter Braak and Smillauer, 2003) and the pollen percentage data were normalized using a square-root transformation.

The dissimilarity coefficients (using squared chord distance) were calculated using the formula in Overpeck et al. (1985) in order to compare the fossil pollen spectra with

the modern pollen spectra, thus quantitatively to assess the degree of similarity between the fossil and modern pollen samples. The following samples were used for the calculations: 70 modern pollen samples, consisting of 35 samples from this study and 35 samples from various lakes in Yunnan and southwest Sichuan Province presented by Xiao et al. (2011), together with 62 fossil pollen samples from Xingyun Lake dating to the Last Glaciation (36400-13400 cal yr BP) obtained from Chen et al. (2014b). Eight pollen types are included: (a) *Abies+Picea*, (b) *Tsuga*, (c) *Alnus*, (d) *Quercus*, (e) *Quercus (E)*, (f) Poaceae, (g) *Artemisia* and (h) the sum of selected herbs (Ranunculaceae, Liliaceae and Cyperaceae). We calculated the dissimilarity values between each fossil spectrum and the modern spectrum, and then constructed stratigraphic plots of the lowest dissimilarity values, i.e., the dissimilarity value between each fossil sample and its most similar modern sample. In general, the lower the dissimilarity coefficients the greater the similarity between the modern and fossil pollen spectra. Usually, a critical value (v_1) was used as a criterion to decide whether a modern pollen spectrum could be regarded as a suitable analog for the fossil spectra. Modern pollen samples with dissimilarity values equal or less than the v_1 are then considered to be analogues for the given fossil sample. Numerous critical values have been used in previous studies; in this study we use 0.15 as the critical value, as described by Overpeck et al. (1985) in order to evaluate the similarity between modern and fossil pollen spectra.

4. Results

4.1 Pollen assemblages of the topsoil samples

A total of 63 pollen and spore taxa were identified from the 25 topsoil samples and a summary percentage pollen diagram with 35 selected taxa is shown in Fig. 3. The pollen assemblages are dominated by *Pinus*, with percentages ranging from 28 to >85%. Poaceae is also present in almost all of the samples with an average of 12.4%. Other major pollen types include evergreen *Quercus*, Asteraceae, Amaranthaceae, Brassicaceae and Cyperaceae. *Alnus*, Rosaceae and *Artemisia* also have relatively high frequencies, and ferns, mainly comprising Polypodiaceae, *Microlepia*, *Hicriopteris* and *Pteris*, are well represented with an average of 6.3%.

Fig. 3

As shown in Fig. 3, the abundance of each pollen taxon varies in different vegetation types. Samples S1-S7 are from farmland where rice and vegetables (including cabbages, spinach, and sonchus) are planted. These samples have relatively frequencies of *Pinus* (mean of 44.3%) and of the pollen of cultivated plants (up to 46%), mainly Brassicaceae, Poaceae, Asteraceae and Amaranthaceae. The pollen assemblages from woodland are dominated by *Pinus* (mean of 56.1%) and other tree taxa, including evergreen oaks, deciduous oaks, *Alnus*, Myrtaceae and Cupressaceae. Samples S14 and S15 are from woodland where evergreen oaks dominated, and the

pollen assemblages are characterized by extremely high evergreen *Quercus* values (15.6% and 32.3%). In the samples from shrubland/grassland the most abundant pollen type is *Pinus*, with a maximum of 88% and a mean of 74.2%, which are the highest among all the vegetation types studied. In addition, in some areas of shrubland and natural grassland, *Salix*, *Hippophae*, *Alnus*, Campanulaceae and *Artemisia* are the more common pollen types, while non-*Pinus* tree pollen and the pollen of cultivated plants are least well represented.

4.2 Pollen assemblages of the surface lake sediment samples

Sixty-eight palynomorphs were identified from the 10 surface lake sediment samples. *Pinus*, *Alnus* and Poaceae are the dominant pollen types in almost all of the samples (Fig. 4). The frequency of *Pinus* is around 40%, and that of *Alnus* about 18%. The main broadleaved components, evergreen and deciduous oaks, exhibit relatively high frequencies of 2.3% and 3.3%, respectively. *Betula* varies from 2-4% and the percentages of *Ulmus*, Rosaceae, *Corylus*, Cupressaceae, Euphobiaceae, *Myrica* and Elaeagnaceae vary from around 0.5-1%. The other tree pollen types, *Lithocarpus/Castanopsis*, *Juglans*, *Salix*, *Platycarya* and *Rhus*, have frequencies of less than 0.5%. Among the herb pollen types, Poaceae and *Artemisia* are dominant, with mean values of 10.7% and 3.6%, respectively. The mean values of Ranunculaceae, Amaranthaceae and Brassicaceae are around 1%. Cyperaceae, Moraceae and Rubiaceae have relatively high values, with maximum percentages exceeding 1%. Fern spores range from 1-4%, with an average of 2.8%. In general, the

percentages of many of the pollen types, including *Pinus*, *Quercus*, *Betula* and other types with relatively low frequencies, are relatively constant with changing water depth (Fig. 4); however, evergreen oaks and Poaceae are slightly better represented in the shallow sites.

Fig. 4

The pollen concentrations of the major pollen types are illustrated in Fig. 5. The total pollen concentration ranges from 91,800-152,000 grains/g. The concentration of most pollen types, as well as the total pollen concentration, is relatively constant, except that slightly higher values occur in samples S5 and S6. In addition, the pollen concentrations of evergreen *Quercus* and Poaceae in samples S1-S3 are relatively high.

Fig. 5

4.3 Results of numerical analysis

The PCA results of the topsoil samples show that the first two axes explain 50% (axis

1: 32.3%, axis 2: 17.7%) of the total variance (Fig. 6). The PCA results based on pollen samples (Fig. 6a) indicate that the first and second principal components primarily differentiate samples from farmland and the other two vegetation types. Sample S3 from farmland, located close to pine forest and with a high percentage of *Pinus*, is an exception. However, a group of samples from woodland overlaps with the samples from shrubland/grassland, and thus they are not reliably differentiated on the basis of the first two principal components.

Fig. 6

The PCA results for the pollen types (Fig. 6b) indicate that the samples from various vegetation types are dominated by different taxa. The pollen assemblages from farmland are dominated by cultivated plant types, such as Poaceae, Brassicaceae and Amaranthaceae; the pollen spectrum from woodland mainly consisting of oaks, is dominated by evergreen *Quercus*, deciduous oaks, *Alnus*, *Rhamnus* and Rosaceae; and the pollen samples from other types of woodland and shrubland/grassland are characterized by high frequencies of *Pinus*, Cupressaceae and *Hippophae*.

Fig. 7 illustrates the DCA results for the entire data set, including both the topsoil samples from the catchment and the surface lake sediment samples. The eigenvalues

of DCA axis 1 and axis 2 are 0.117 and 0.044, respectively. Most of the variation among both axes is defined by the catchment samples rather than by the lake samples. The lake samples are discriminated by less than 0.4 units on axis 1 and by less than 0.2 units on axis 2. The catchment topsoil samples, on the other hand, span over 1.2 units on axis 1 and 1 units on axis 2. In addition, the DCA diagram (Fig. 7) shows that the surface lake samples are grouped together, plotting to the right of the topsoil samples, suggesting that the surface lake samples can be easily differentiated from the catchment samples.

Fig. 7

4.4 Results of dissimilarity analysis between fossil and modern pollen samples

Scatter diagrams illustrating the lowest dissimilarity values between fossil and modern pollen samples are shown in Fig. 8. The modern spectra from topsoils and surface lake sediments are significantly different to the fossil pollen spectra from the Last Glaciation. In addition, the dissimilarity coefficients of all of the lake surface sediment spectra vary with altitude. As show in Fig. 8, most of the modern spectra (from both topsoils and surface lake sediments) tend to be less similar to the fossil spectra: i.e., in most cases the dissimilarity values for the modern and fossil pollen spectra exceed the critical values, indicating that they are not well matched. For

example, for the spectra from surface sediments from Xingyun Lake and other lakes at elevations from 1500-2000 m from Yunnan and Sichuan Province, the dissimilarities are much greater than the critical values (Fig. 8a, c). However, a number of the other modern pollen spectra are also not well matched with the spectra from the Last Glaciation. For the sample from the Last Deglaciation, the squared chord distances with almost all of the modern spectra are greater than the critical values. Exceptions are those from the topsoil of the Xingyun Lake catchment and from the surface sediments of lakes at elevations from 2000-3000 m, where the distances approach the critical values (Fig. 8b, d). For the spectra dating from the Last Glacial Maximum, dissimilarities values below the critical values occur only for the surface samples from lakes at elevations from 3500-4000 m (Fig. 8e); in addition, the squared chord distances between modern spectra from lakes at elevations from 4000-4500 m and the spectra from the Last Glacial Maximum approach the vertical values (Fig. 8f). For the spectra from late MIS3, there are a certain number of dissimilarity coefficients with modern samples spectra from lakes at elevations from 3500-4000 m which are below the critical values; in addition, dissimilarities much closer to the critical values are evident for the modern spectra from lakes at elevations from 2000-3000 m (Fig. 8d) and 4000-4500 m (Fig. 8f).

Fig. 8

5. Discussion

5.1 Relationship between vegetation type and topsoil pollen assemblages

Both pollen assemblages and PCA results of the topsoil samples from the Xingyun Lake catchment indicate that the pollen assemblages of different vegetation types contain different representative components (Fig. 3 and Fig. 6). Poaceae, Brassicaceae and Amaranthaceae are the dominant taxa in farmland; woodland is characterized by relatively high percentages of non-*Pinus* arboreal pollen (evergreen and deciduous oaks, *Alnus*, Cupressaceae, Myrtaceae); and a very high abundance of *Pinus* occurs in the shrubland/grassland samples. In addition, various types of farmland and woodland are dominated by different indicator taxa, although *Pinus* contributes significantly to all of these samples. For example, the pollen assemblages of samples S1 and S2 from vegetable fields are characterized by a relatively high abundance of Brassicaceae and Amaranthaceae; while samples S6 and S7 are dominated by Poaceae (Fig. 3), mainly due to the fact that they are from rice fields. Similarly, the woodland samples S14 and S15 are from sites dominated by deciduous and evergreen oaks, and the pollen assemblages, therefore, are characterized by high frequencies of evergreen and deciduous *Quercus*. The samples from woodland sites dominated by Cupressaceae and Myrtaceae are characterized by the pollen of these taxa, although the percentages are relatively low. The samples from shrubland/grassland (S19-S25) have very high frequencies of *Pinus*, but very low shrub and herb pollen frequencies (including Rosaceae, *Hippophae*, Caryophyllaceae and Campanulaceae). Therefore, it is obvious

that there can be a significant difference between the pollen assemblage of a sample and the vegetation composition-as has been observed in previous studies (Zhou et al., 1984; Wu and Xiao, 1989; Li et al., 2008; Xiao et al., 2009). This may be caused by the low pollen productivity of shrub and grass taxa and the very high pollen productivity and transportability of pine pollen, which is consequently over-represented. In addition, several pollen samples from shrubland and grassland overlap with those from woodland (excluding S14 and S15) in the PCA plot (Fig. 6a). Although the pollen assemblages from these two vegetation types have different characteristics, the results of the PCA highlight the difficulty in distinguishing them. This classification is also significantly affected by the over-presented pine pollen frequencies, which obscure the variations of several of the dominant pollen taxa in these two different vegetation types. The percentages of *Pinus* alone, therefore, cannot be used to determine whether the vegetation type is pine forest or not when applied to palaeovegetation reconstruction, and they need to be considered in the context of the entire pollen assemblage (Xiao et al., 2009). The results for the topsoil samples from the Xingyun Lake catchment suggest that the modern pollen assemblages are representative of the modern vegetation composition and the dominant taxa can be used to identify the vegetation types, even though *Pinus* dominates all of the samples.

5.2 Pollen dispersion and deposition characteristics within the Xingyun Lake basins

The pollen in the Xingyun Lake sediments may be either windblown or waterborne.

Based on the pollen assemblages of the surface lake sediments from different water depths and the modern vegetation distribution in the Xingyun Lake catchment (Fig. 2), it is obvious that most of the arboreal pollen in the surface lake sediments should originate from trees and shrubs, such as *Pinus*, deciduous and evergreen oaks and *Betula*, growing in the surrounding mountains. In contrast, the majority of the herbaceous pollen, especially that from cultivated plants, such as rice and various vegetables, is likely to originate mainly from farmlands around the lake. Xingyun Lake is recharged by several permanent rivers and streams and many intermittent streams originating from the surrounding uplands (Fig. 1b), and therefore it is likely that there is significant waterborne transport of pollen to the lake basin from plants growing on the mountains and hills. However, most of the tree taxa in the catchment flower in spring, which is the driest season and has the lowest river runoff, rather than in the summer monsoon season. Thus although some tree pollen may be transported into lake via inflows we assume that its quantity is negligible and therefore that most of the tree pollen in Xingyun Lake is likely to be mainly wind-transported and deposited on the lake surface. This inference is confirmed by our own field observations and those by local farmers. With respect to shrub and grass pollen, both the wind and fluvial dynamics are likely to play an important role in pollen transport; however, it is difficult to determine which transport process is the more important.

When either wind- or waterborne pollen grains enter a lake, the distribution of the pollen types is also influenced by internal pollen deposition and re-depositional

process (e.g., Davis et al., 1971, 1973; Davis, 1973; Sun and Wu, 1987; DeBusk, 1997; Xu et al., 2005; Huang et al., 2010). For example, wind activity can generate waves and currents which may cause differential pollen distribution by size or mass. In addition, vertical or horizontal movements of the lake water can cause the redistribution of pollen grains. A study of Frains Lake in Michigan revealed that wind-induced turbulence within the epilimnion in fall and early spring resulted in the remobilization and redeposition of pollen (Davis et al., 1973). In Xingyun Lake, the most striking characteristic of the pollen assemblages from the surface lake sediments is that both the pollen percentages and the pollen concentrations from samples from different water depths are relatively invariant in the case of most of the taxa (Fig. 4; Fig. 5). This relative homogeneity may be the result of remobilization and redeposition which could be caused by either wind-induced turbulence and fluvial processes.

It is noteworthy that both the percentages and concentration of Poaceae and evergreen oaks are higher in shallow waters (Fig. 4; Fig. 5). Poaceae pollen in Xingyun Lake is probably derived from cultivated areas and farmland around the lake, or from the shrubland/grassland on the surrounding mountains. According to the topsoil pollen results (Fig. 3), however, Poaceae appears to be mainly derived from farmland, and therefore cereal-type should be the major component. Numerous studies have shown that cereal-type Poaceae pollen is relatively poorly-transported due to its large size, and therefore that it is deposited close to the parent plants and so exhibits the highest

frequencies within or close to cultivated fields (Bunting et al., 2001; Yang et al., 2010; Huang et al., 2011; Hjelle et al., 2012). In addition, Poaceae pollen has a much higher settling velocity (0.035 m/s) (Sugita et al., 1999) than other grassland pollen types (*Artemisia*: 0.015 m/s; Amaranthaceae: 0.029 m/s) (Xu et al., 2012). Thus, it is likely that it is preferentially deposited in littoral sediments. With regard to evergreen oak pollen, much of it may come from secondary trees growing near the lake and is not transported for long distances by wind or fluvial activity due to its relatively high settling velocity (0.042 m/s, Xu et al., 2012). This inference is supported by research results from Southern Michigan (Davis et al., 1971) which suggested that the pollen from plants growing the lake shore is unevenly distributed, with highest frequencies close to the parent plants. Thus the relatively high concentrations of most of the pollen taxa in sample L6 (Fig. 5) may be caused by its location (Fig. 1b) close to an area where seasonal river input would be expected to make a significant contribution to the high pollen concentration.

An improved understanding of the pollen characteristics of surface lake sediments is essential for interpreting fossil pollen records and thus for reconstructing vegetation history and related climate changes. A number of studies have found that the pollen content of surface lake sediments is related to water depth (Davis et al., 1971, 1973; Sun and Wu, 1987; Huang et al., 2004, 2010; Zhao et al., 2007), and this relationship has been used to selected sediment core locations in order to reconstruct regional vegetation history and climate change (Sun and Wu, 1987; Huang et al., 2004, 2010).

For example, a study of the pollen distribution within the surface lake sediments of Bosten Lake in northwestern China revealed that pollen concentrations were high in the central, deepest, part of the lake basin as a result of sediment focusing. Thus it was concluded that a sediment core should be obtained from that location in order to reconstruct the regional vegetation history (Huang et al., 2004, 2010). However, our findings indicate that there is no significant relationship between pollen assemblages and water depth in Xingyun Lake (Fig. 4; Fig. 5). This may be related to differences between Xingyun Lake and other lakes in terms of lake basin size, morphology and bathymetry, inflow and outflow contributions, and topographical conditions within the catchment, all of which may have important effects on the pollen distribution (Sun and Wu, 1987). The relatively small lake catchment and the presence of numerous inflowing rivers and streams but lack of a major river inflow (Fig. 1b) may be the main reason for the relative homogeneity of the pollen assemblages in the surface lake sediment samples from different water depths. The results from Xingyun Lake suggest that almost all areas of the lake basin provide a stable pollen depositional environment. A sediment core, therefore, from any part of the lake would potentially be suitable for reconstructing the regional vegetation history and climatic changes.

5.3 Differences in the representation of the pollen assemblages from the surface lake sediment and topsoil samples

Pinus and evergreen oak forest together with cultivated fields are the main vegetation types in the Xingyun Lake catchment. As previously noted, the pollen assemblages of

both topsoil and surface lake sediments reliably reflect the vegetation in the Xingyun lake catchment (Fig. 3; Fig. 6). However, the two types of sample reflect the vegetation in different ways, which has also been noted in other studies (Wilmshurst and McGlone, 2005; Zhao et al., 2009; Lisitsyna et al., 2012). Thus, a comparison of their pollen assemblages may be useful for assessing possible sources of bias in vegetation and climatic reconstructions. Both the pollen assemblages and the PCA results of the topsoil samples from the Xingyun lake catchment show that the pollen assemblages reflect the three main vegetation types in the catchment. It is obvious, however, that the pollen assemblages of surface lake sediment samples reflect a more comprehensive pollen characteristics and thus the vegetation conditions of the lake catchment than these of the topsoil samples taken from the locations of the three main vegetation types. This conclusion is supported by the DCA results of the pollen spectra from two types of sample (Fig. 7). The frequencies of the major pollen taxa in the lake sediment samples generally exhibit smaller standard deviations than those of the topsoil samples. Our results are consistent with those of other studies (e.g., Sugita, 1994; Shen et al., 2006; Herzschuh, 2007; Zhao et al., 2009; Qin et al., 2015) in supporting the conclusion that the pollen assemblages of the lake sediments are dominated by regional pollen sources while the topsoil samples are dominated by local sources. In addition, differences in the degrees of pollen preservation in the two types of sample should also be considered, which may also potentially bias the reconstructed vegetation composition. The topsoil samples may contain more pollen types with resistant exines and simple sculpturing patterns due to the relatively poor

preservation caused by oxidation and microbial attack (Wilmschurst and McGlone, 2005; Zhao et al., 2009; Qin et al., 2015). Overall, we conclude that the modern pollen assemblages from the surface lake sediments are more representative of the regional vegetation than those from the topsoil samples.

5.4 Implications of the results for the interpretation of fossil pollen records

The modern pollen assemblages presented here can be used to re-appraise a previous interpretation of the fossil pollen data from Xingyun Lake. During the Last Glaciation (36,400-13,400 cal yr BP) it was suggested that there were several vertical migrations of vegetation in the Xingyun Lake area (Chen et al., 2014b). In practice, the correspondence found between the modern pollen data and the samples from the Xingyun Lake sediment core supports the conclusion that this vertical shift in vegetation belts was a response to climate change (Chen et al., 2014b). In order to confirm this, in addition to the modern pollen data show in this study, we combined several large modern pollen data sets from surface lake sediments along an altitudinal transect from 1500 to 4500 m spanning a large area in Yunnan and southwest Sichuan Province (Xiao et al., 2011). Only the major taxa, and those taxa reflective of altitudinal differences, were selected. They included *Abies+Picea*, *Tsuga*, *Alnus*, *Quercus*, *Quercus (E)*, *Poaceae*, *Artemisia* and the sum of *Ranunculaceae*, *Liliaceae* and *Cyperaceae*. As expected, the distributions of these pollen types are strongly related to altitude (Fig. 9a-d). In addition, the results indicate that the pollen assemblages of the Xingyun Lake surface sediments (Fig. 9f) resemble the pollen

composition of surface lake sediment samples from 1500-2000 m (Fig. 9d) more closely than those of topsoil samples from the Xingyun Lake catchment (Fig. 9e). This is also consistent with the differences between the pollen assemblages from the topsoil samples and surface lake sediments discussed above.

Fig. 9

The comparison (Fig. 8) of the modern pollen data (Fig. 9a-d) with the fossil pollen record of Xingyun Lake (Fig. 9g-i) during the Last Glaciation demonstrates that the fossil samples have modern counterparts (Fig. 8) and that the gradual changes in the fossil pollen assemblages can be interpreted as reflecting the vertical migration of vegetation belts. The fossil pollen composition in the oldest part of the Xingyun Lake core XY08A (i.e., late MIS 3) (Fig. 9i) most closely matches the pollen assemblages of surface lake sediments from 3500-4000 m (Fig. 9b), which is confirmed by the fact that the dissimilarity coefficients were below the critical values (Fig. 8e), indicating the vegetation conditions during the stage late MIS 3 were similar to those of the modern vegetation at 3500-4000 m. In particular, there is a close similarity in the frequencies of *Tsuga*, *Quercus* and herbaceous taxa. For the LGM period (Fig. 9h), as indicated by the values of the squared chord distances (Fig. 8e, f), the fossil pollen data more closely resemble the pollen composition of lake sediments from the

elevation of 3500-4000 m (Fig. 9b) than those from 4000-4500 m (Fig. 9a), mainly because of the higher percentages of *Abies+Picea* and the minor contribution of those herbaceous taxa that are good indicators of alpine shrubland-alpine meadow. However, the fossil pollen assemblages of late MIS3 and LGM are not matched very well with the modern pollen data from 3500-4000 m. From a comparison of the pollen composition and the dissimilarity coefficients of these two intervals, it is obvious that the fossil pollen of stage late MIS 3 should have modern counterparts from a lower elevation than that for the LGM, and two factors may be responsible: firstly, there are relatively higher frequencies of *Abies+Picea* during the LGM but a much higher content of *Tsuga* during stage late MIS 3; and secondly, the fossil samples during the late MIS 3 are more similar to the surface lake sediment samples at relatively low elevation (i.e., 2000-3000 m, Fig. 8d), while the samples during the LGM are matched relatively well with the surface sediment samples from lakes above 4000 m (Fig. 8f). Unfortunately, there are no modern pollen data from lake sediments from 3000-3500 m. Despite this, the vertical migration of the vegetation belts from stage late MIS 3 to LGM is clearly reflected by the fossil pollen record. In the most recent period (the Last Deglaciation) the fossil pollen composition (Fig. 9g) resembles the pollen assemblages of lake sediments from 1500-2000 m (Fig. 9c), which is consistent with the variations of the dissimilarity values (Fig. 8d). It is noteworthy that the squared chord distances between fossil pollen samples during the Last Deglaciation and the topsoil samples from Xingyun Lake catchment are also close to the critical values (Fig. 8b) but those with the surface lake sediment samples are much larger than the critical

values (Fig. 8a, c), mainly due to the fact that the vegetation compositions during the Last Deglaciation are similar to those of several specific sites in the lake catchment; while the pollen assemblages of the surface lake sediments reflect the vegetation conditions of the whole lake catchment. With respect to the difference between the fossil pollen assemblages of the Last Glaciation and modern pollen assemblages, the high pollen content of *Alnus* in the surface lake sediments can be ascribed to the intensive human activity within and around the lake catchment; while the high content of *Quercus* and *Quercus* (E) may be because the climatic conditions during the Last Glaciation were different to the present and therefore that a 'no-analogue' situation exists. For example, during the Last Deglaciation and the LGM, a much drier climate than represented in the modern dataset is indicated by the very high frequencies of *Quercus* and *Quercus* (E) (Chen et al., 2014b). Although the fossil pollen assemblages of the Last Glaciation from Xingyun Lake are not well-matched with the modern pollen assemblages from the lake sediment samples from elevations between 1500 and 4500 m in Yunnan and southwest Sichuan Province, the vertical migration of vegetation belts during the Last Glaciation is still clearly indicated.

6. Conclusions

1) The modern pollen assemblages of topsoil samples taken from different vegetation types in the Xingyun Lake catchment and surface lake sediment samples from different water depths of Xingyun Lake are characterized by high frequencies of *Pinus*, evergreen and deciduous oaks, *Alnus*, Poaceae, *Artemisia*, Brassicaceae and

Amaranthaceae, and thus are representative of the contemporary vegetation. The dominant pollen taxa in the topsoil samples are reflective of the vegetation composition of woodland and farmland; however, in contrast those from shrub and grassland areas in the catchment are not because of the over-representation of *Pinus*.

2) The modern pollen assemblages from the surface lake sediment samples from water depths within the lake are relatively homogeneous and reflect the regional vegetation; however, those from topsoil samples probably reflect local pollen sources. For vegetation and climatic reconstruction, we conclude that it is better to use calibration pollen data sets from surface lake sediment samples rather than from topsoil samples.

3) The tree pollen grains in the surface sediments of Xingyun Lake are mainly transported by wind from the surrounding mountains, while shrub and herb pollen grains are transported by both wind and water. Rivers, lake currents and wave action can affect the pollen deposition process, and as a result pollen grains are distributed evenly within Xingyun Lake. Accordingly, there is no obvious relationship between pollen content and water depth.

4) Comparison of modern and fossil pollen data reveals that the vertical vegetation belts descended from late MIS 3 stage to the LGM and then rose during the Last Deglaciation. This finding is consistent with our previous interpretation of past vegetation changes as revealed by analysis of fossil pollen assemblages from Xingyun Lake during the Last Glaciation.

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Figure and table captions

Fig. 1 Location of Xingyun Lake in Yunnan and China (a); catchment and bathymetry of Xingyun Lake and the location of modern pollen samples from Xingyun Lake and its catchment (b).

Fig. 2 Vegetation types around the Qilu Lake-Xingyun Lake-Fuxian Lake region in Yunnan Province, China (modified from Hou, 2001). The red dashed line shows the Xingyun Lake catchment.

Fig. 3 Percentage pollen diagram for the topsoil samples in Xingyun Lake catchment. Only major taxa are shown.

Fig. 4 Percentage pollen diagram for surface lake sediment samples in Xingyun Lake. Only major taxa are shown.

Fig. 5 Pollen concentration diagram for surface lake sediment samples in Xingyun Lake. Only major taxa are shown.

Fig. 6 PCA results of the modern pollen data of topsoil samples from the Xingyun Lake catchment. Biplot of PCA results based on topsoil samples (a) and pollen taxa (b).

Fig. 7 Biplot of DCA results of the modern pollen data from topsoil and surface lake sediment samples. Only results based on pollen samples are shown.

Fig. 8 Scatter diagrams of the lowest dissimilarity coefficients between fossil pollen spectra from Xingyun Lake during the Last Glaciation and all the modern pollen samples from surface lake sediments (a) and topsoil samples (b) from Xingyun lake and its catchment, together with surface lake sediments at different elevations (c-f) from Yunnan and southwest Sichuan Province (Xiao et al., 2011), using squared chord distances. The pink vertical lines show the critical values ($v_1=0.15$) for the squared chord distance. The red dashed lines indicate the three vegetation stages during the Last Glaciations as showed in Chen et al. (2014b). The dissimilarity coefficients plotted in the diagram are $100\times$ the values of squared chord distance.

Fig. 9 Box charts of modern pollen data of surface lake sediments (a-d) from Yunnan and southwest Sichuan Province (Xiao et al., 2011), in Xingyun Lake (f), and for topsoil samples from the Xingyun Lake catchment (e) and of fossil pollen data (from Xingyun Lake during the Last Glaciation (g-i, Chen et al., 2014b). Only the major pollen taxa are shown. AP is *Abies+Picea*; T is *Tsuga*; A is *Alnus*; Qe is *Quercus* (E); Q is *Quercus*; P is Poaceae; Ar is *Artemisia*; H is the sum of herbs (the sum of the pollen percentages of Ranunculaceae, Liliaceae and Cyperaceae).

Table 1 Locations and surrounding vegetation types of surface pollen samples in the Xingyun Lake catchment.

Table 1

Sample code	Latitude (°N)	Longitude (°E)	Elevation (m)	Vegetation type
S1	24.3181	102.7471	1733	farmland
S2	24.2827	102.7705	1714	farmland
S3	24.2884	102.8009	1800	farmland
S4	24.3860	102.8080	1733	farmland
S5	24.4047	102.7957	1726	farmland
S6	24.4023	102.7873	1829	farmland
S7	24.3410	102.7555	1725	farmland
S8	24.2892	102.7992	1746	woodland
S9	24.3410	102.7553	1854	woodland
S10	24.3412	102.8065	1764	woodland
S11	24.3408	102.8067	1743	woodland
S12	24.3591	102.8047	1750	woodland
S13	24.3860	102.8086	1730	woodland
S14	24.4035	102.7891	1764	woodland
S15	24.4031	102.7885	1792	woodland
S16	24.2736	102.7396	1778	woodland
S17	24.3927	102.8103	1744	woodland
S18	24.3557	102.7628	1744	woodland
S19	24.3881	102.8118	1905	shrubland/grassland
S20	24.3890	102.8122	1892	shrubland/grassland
S21	24.3903	102.8117	1868	shrubland/grassland
S22	24.3906	102.8120	1845	shrubland/grassland
S23	24.3912	102.8116	1820	shrubland/grassland
S24	24.3915	102.8114	1798	shrubland/grassland
S25	24.3921	102.8112	1760	shrubland/grassland

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9