Vegetation History and Archaeobotany (2019) 28:365–377
https://doi.org/10.1007/s00334-018-0699-2

ORIGINAL ARTICLE

Distribution and vegetation representation of pollen assemblages from surface sediments of Nam Co, a large alpine lake in the central Tibetan Plateau

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Received: 29 July 2017 / Accepted: 10 September 2018 / Published online: 17 September 2018

Abstract

Lacustrine fossil pollen records have been widely used to reconstruct palaeovegetation and palaeoclimate changes on the Tibetan Plateau (TP). However, little is known about the vegetation representation of modern lacustrine pollen assemblages there. This paper presents the results of modern pollen investigation on 63 surface sediments from the lake basin and 37 topsoil samples from the drainage area of a large lake, Nam Co, located in the central TP. It aims to assess quantitatively the influences on lacustrine pollen assemblages of the pollen sources and sedimentary processes, and to establish vegetation representations for modern lacustrine pollen assemblages. Modern pollen assemblages from topsoils of different vegetation had diagnostic features in terms of their composition and pollen percentage. The spatial variabilities and results of principal component analysis suggested that lacustrine pollen assemblages were influenced by both the regional/local source vegetation and sedimentary processes. The lacustrine pollen assemblages were mainly homogeneous due to in-lake sedimentary processes (mixing and redistribution). An accumulation zone for lacustrine pollen assemblages was found in the deep lake basin (depth > 60 m) due to sediment focusing. The results of boosted regression tree analysis further confirmed that source vegetation was the predominant factor (85.8%) responsible for the vegetation representation of lacustrine pollen assemblages, while sedimentary processes accounted for only 14.2%. The results of discriminant analysis indicated that most lacustrine pollen assemblages (90.5%) were representative for the regional vegetation of alpine steppe in the Nam Co catchment and central TP, while only 9.5% were representative for the local meadow vegetation. Therefore, it is recommended that lacustrine pollen assemblages from deep lake basin of accumulation zone in large lakes of the TP can be used to retrieve efficiently the signals from regional vegetation and climate changes.

Keywords Modern pollen assemblage · Surface lake sediment · Nam Co · Tibetan Plateau

Introduction

Lacustrine fossil pollen records from the Tibetan Plateau (TP) are widely utilized to reconstruct past vegetation and climate changes (e.g. Gasse et al. 1991; van Campo et al. 1996; Shen et al. 2005, 2008; Tang et al. 2009; Herzschuh et al. 2010; Kramer et al. 2010; Lu et al. 2011; Li et al. 2016), the advance and retreat history of the Asian Summer Monsoon and Westerlies (e.g. Jarvis 1993; Shen 2003; Kramer et al. 2010; Li et al. 2011; Zhu et al. 2015) and the history of the TP uplift on different time scales (e.g. Lu et al. 2001, 2011; Dupont-Nivet et al. 2008; Sun et al. 2014). Many studies have investigated the relationships between modern pollen assemblages, contemporary vegetation and the climate conditions on the TP (Cour et al. 1999; Yu et al. 2001; Shen et al. 2006; Herzschuh 2007; Lu et al. 2008, 2011; Zhao and Herzschuh 2009). These studies have played a crucial role in the quantitative interpretations of fossil pollen spectra in terms of the palaeovegetation (Shen 2003; Li et al. 2011), palaeoclimate (Shen et al. 2008; Tang et al. 2009; Herzschuh et al. 2010; Lu et al. 2011; Wang et al. 2014) and palaeo-elevation of the TP (Lu et al. 2011; Sun

Communicated by J. Kitagawa.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00334-018-0699-2) contains supplementary material, which is available to authorized users.

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et al. 2014). However, previous investigations were mostly conducted at a regional scale and covered a large vegetation-climate gradient (Yu et al. 2001; Shen et al. 2006; Herzschuh 2007; Lu et al. 2011). To date, there is little known about in-lake sedimentary processes and vegetation representation of modern pollen assemblages from the surface lake sediments on the TP.

Lake sediments usually receive a mixture of pollen and spore grains from a broader source region than topsoil samples (Wilmshurst and McGlone 2005). Various factors, including lake size (Davis and Brubaker 1973; Sugita 1994), pollen source area (Sugita 1993; Wang et al. 2014), transport paths either by inflow/outflow river or wind (Luly 1997) and in-lake sedimentary processes and preservation condition (Davis 1968; Davis et al. 1984), influence the distribution and composition of pollen assemblages preserved in lake sediments. Due to a lack of detailed investigation on modern pollen assemblages from surface lake sediments, questions remain as to what extent sedimentary processes affect the in-lake distribution of pollen assemblages and how well the lacustrine pollen assemblages from a large lake represent the contemporary regional and/or local vegetation of the TP.

Nam Co, the second largest lake on the TP, is located in the transitional region of alpine meadow and alpine steppe in the central TP. Previous palaeoenvironmental studies have reconstructed the long-term history of environmental changes in the catchment of Nam Co in terms of palaeoclimate changes (Lin et al. 2008; Zhu et al. 2008), lake level fluctuations (Daut et al. 2010; Kasper et al. 2012), vegetation shifts of local altitudinal belts (Li et al. 2011), atmospheric circulation changes (Herrmann et al. 2009; Zhu et al. 2015) and so on. Some investigations have been conducted on the lake bathymetry and water physicochemistry (Wang et al. 2009) and on the spatial distribution of minerals and elements, organic matter and grain sizes of the surface lake sediments from the lake basin of Nam Co (Li et al. 2012a; Wang et al. 2012, 2015).

In this paper, a systematic investigation of modern pollen assemblages from 63 surface lake sediments and 37 topsoil samples was conducted in the catchment of Nam Co. Based on several quantitative approaches, this paper aims to assess the possible influences on lacustrine pollen assemblages from in-lake sedimentary processes and source vegetation and to establish the vegetation representation of the lacustrine pollen assemblages from a large alpine lake. This work provides a basis for quantitative reconstructions of the palaeovegetation and palaeoclimate of the TP.

Study area and vegetation

Nam Co (30°30′–30°56′N, 90°16′–91°03′E, lake surface 4,718 m a.s.l.) is situated toward the northern slope of the Nyainqentanglha Mountains (with a strike N 60° E,maximum elevation 7,162 m a.s.l.) in the central TP (Fig. 1a). Nam Co is a large, closed lake that has a water area of 1,982 km^2 and a catchment area of 10,610 km^2. Bathymetric investigations revealed that nearly half of the lake basin area is deeper than 90 m. The mean annual temperature in the lake catchment is approximately 0 °C, and the mean annual precipitation is approximately 280 mm (Zhu et al. 2008).

There are three alpine vegetation zones that dominate the landscape of the central TP, including an alpine steppe zone to the west and northwest of the Nyainqentanglha Mountains, an alpine meadow zone to the east and northeast, and a temperate subalpine steppe to the south (Hou 2001). Nam Co is located in the alpine steppe zone. As the regional vegetation type in our study region, an alpine steppe dominates most of the lake catchment (< 4,800 m a.s.l.) and mainly consists of *Artemisia* spp., *Stipa* spp., *Poa* spp. and *Carex moorcroftii* (Fig. 1b).

An altitudinal vegetation belt covers the northern slope of the Nyainqentanglha Mountains. This belt is composed of an alpine steppe, which is distributed on the lake shore, alpine meadow (4,800–5,200 m a.s.l.), and sparse alpine vegetation (5,200–5,900 m a.s.l.) above (Fig. 1b). The alpine meadow extends over an elevation range of 400 m. As one of the local vegetation types in the Nam Co catchment, the alpine meadow is mainly composed of *Kobresia* spp. and associated with *Festuca* spp., *Poa* spp., *Polygonum* spp. and so on. Sparse alpine vegetation is mainly composed of *Saussurea* spp., *Rhodiola* spp., *Waldheimia glabra, Saxifraga* spp. and cushion plants such as *Androsace* spp. and *Arenaria* spp. Some marsh meadow occurs in the wetland around the lake and is composed of *Kobresia tibetica* and *Blysmus* spp. (Hou 2001; Editorial Committee of Vegetation Map of China 2007).

Materials and methods

Field sampling

A total of 63 surface sediment samples (top 2–3 cm) from the lake bottom of Nam Co were collected during August 2007 and September 2008 by using an Ekman-style grab sampler. The water depths at the sampling locations varied from 7 to 98 m. Meanwhile, 37 topsoil samples (top 2 cm) were collected from representative vegetation types around the lake (Fig. 1b, Table S1).

Pollen analysis

All of the samples for pollen analysis were treated with a standard acetolysis method, including HCl, KOH, HF and

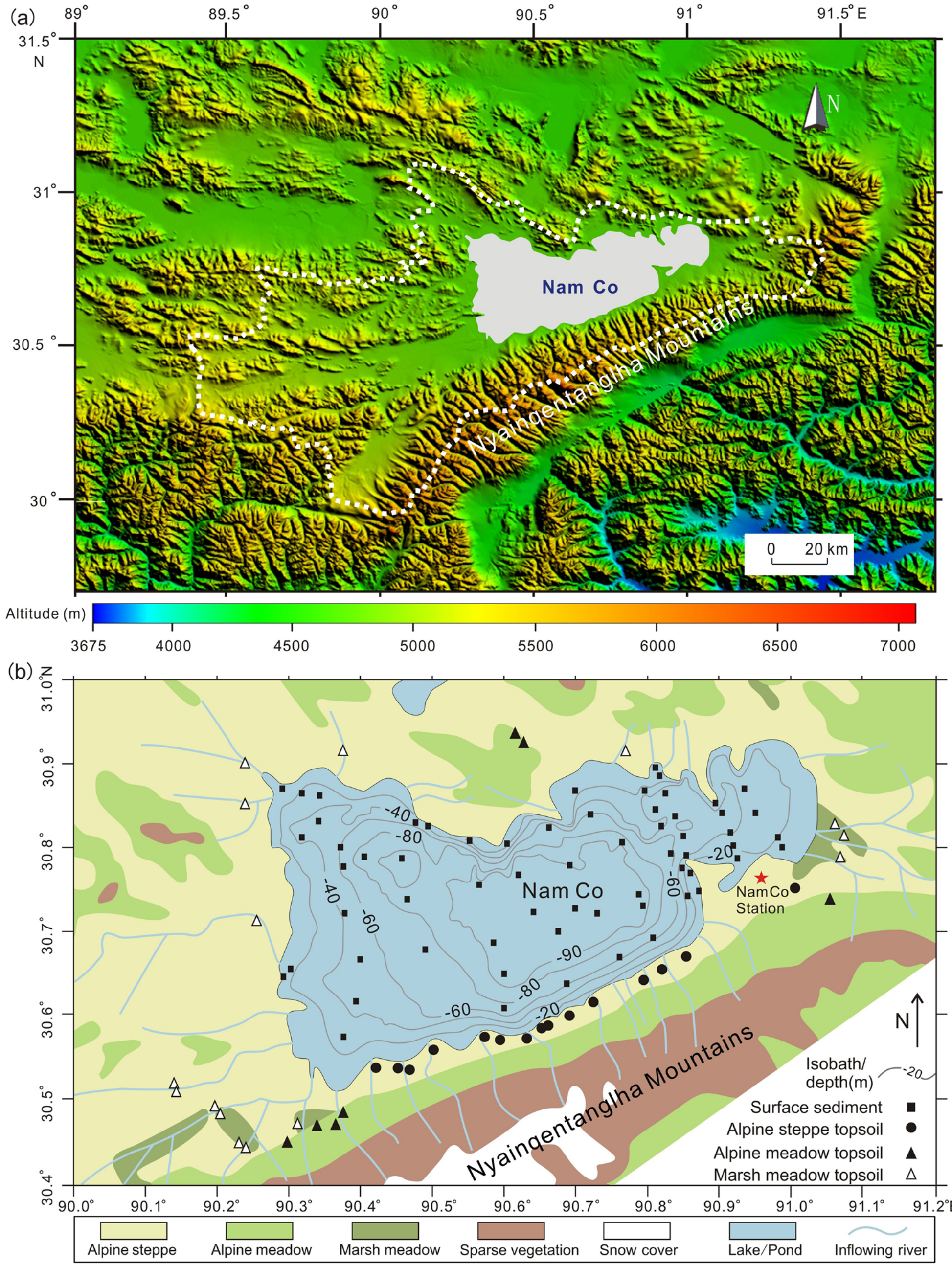

Fig. 1 **a** Location of the Nam Co catchment in the central Tibetan Plateau; **b** modern vegetation and locations of the samples (Editorial Committee of Vegetation Map of China 2007). The terrain elevation data set for **a** was provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn)

acetolysis treatments, and were sieved through a 7-µm screen (Fægri and Iversen 1989). The pollen percentages were calculated based on the sum of pollen and spores. One tablet of *Lycopodium* spores with a known concentration of 27,637 grains/tablet was added to each sample to estimate the pollen concentration, which was based on the dry weight of each sample. The pollen zonation of topsoil samples was determined according to the similarity of pollen assemblages calculated by constrained clustering analysis (constrained by the ascending sample code within each vegetation group) in the software PAST3 (Hammer et al. 2001).

Numerical analyses

Principal component analysis and discriminant analysis

Principal component analysis (PCA) and detrended correspondence analysis (DCA) were conducted using the pollen percentages of 16 major taxa (greater than 2% in at least one sample and of ecological importance), including *Artemisia*, Poaceae, Cyperaceae, *Thalictrum*, Polygonaceae, Amaranthaceae, *Saussurea, Aster*, Ranunculaceae, Caryophyllaceae, Rosaceae, Fabaceae, Brassicaceae, *Gentiana, Pinus* and *Alnus*. The software used was CANOCO 4.5 (Ter Braak and Smilauer 2002). First, DCA was used to estimate the gradient length. The gradient lengths of the first four DCA ordination axes were less than 2.5 standard deviations. Then, PCA was applied to the raw percentage data of 16 major pollen taxa to ordinate their pollen and all samples in terms of the vegetation types and composition differences. The PCA was based on the variance–covariance matrix and displayed with the biplot in distance (Marquer et al. 2014).

Discriminant analysis (DA) was employed to assess whether the lacustrine pollen assemblages from large-lake sediments could quantitatively represent the regional/local vegetation. DA has been used to reconstruct palaeovegetation (Liu and Lam 1985; Lynch 1996; Shen et al. 2008; Li et al. 2011), and to investigate the relationship between modern pollen assemblages and contemporary vegetation (Li et al. 2012b). Here, topsoil samples were classified into three a priori groups according to the actual vegetation types at each sampling locations (i.e. alpine steppe, alpine meadow and marsh meadow, Fig. 1b). The percentages of the major pollen types in topsoil samples were used to build the discriminant functions, which were subsequently applied to the pollen assemblages in surface lake sediments to generate their representative vegetation types (predicted source vegetation types). Two indices, the probability of a modern analog (PMA) and vegetation zonal index (VZI), were introduced to interpret the DA results. PMA expressed the similarity between modern pollen assemblages and predicted vegetation types, while the VZI could quantitatively describe the predicted vegetation type. The software used here was SPSS 17.0 (SPSS Inc. 2005). The detailed processes and interpretations of pollen-based DA followed the procedures of Liu and Lam (1985) and Shen et al. (2008).

Boosted regression tree analysis

To evaluate quantitatively to what extent terrestrial source vegetation and in-lake sedimentary processes influence the distribution and composition of modern lacustrine pollen assemblages, boosted regression tree analysis (BRT) was employed to explore the best explanations for the variations of the modern pollen assemblages from the surface lake sediments. BRT is able to use data with different units of measurement without prior transformation, as well as the non-linear responses of pollen assemblages and complex interactions between different external variables (Elith et al. 2008).

Here, scores from the first PCA axis (PC1) were used to represent in-group internal variations among lacustrine pollen assemblages. Meanwhile, a proxy of the mean grain size of surface lake sediment was used as an integrated variable for sedimentary processes within the lake Nam Co (Wang et al. 2015), while the water depth was used as an integrated variable for the in-lake transport distance. Furthermore, the VZI value of lacustrine pollen assemblage, calculated using the possibilities of DA predicted group memberships, was employed as an independent variable that represented the influence from terrestrial source vegetation.

Software R version 2.9.1 with the bgm package was used to conduct BRT analysis (Elith et al. 2008). A default bag fraction of 0.5, Gaussian error distribution, very slow learning rate (0.0005) and tree complexity of 3 were established to model PC1 variations along variable gradients. Finally, the model of each lacustrine pollen assemblage was fitted with a total number of 6,970 trees.

Results

Modern pollen assemblages

In modern pollen assemblages from the Nam Co catchment, a total of 96 pollen and spore taxa belonging to 53 families were identified. The numbers of counted pollen and spores for each sample varied between 104 and 652 grains (mean 318 grains/sample). In general, herbaceous pollen taxa accounted for the majority in all samples (pollen percentage > 70%), including *Artemisia* and Cyperaceae (dominant), Poaceae, other Asteraceae (*Saussurea, Aster, Chrysanthemum, Taraxacum*), Rosaceae (*Potentilla, Filipendula, Neillia, Sibiraea*), Lamiaceae, Polygonaceae (*Rumex, Polygonum, Fagopyrum, Oxyria*) and Ranunculaceae (*Thalictrum, Ranunculus, Aconitum, Aquilegia, Trollius*). Arboreal pollen taxa (< 20%) were mainly composed of *Pinus, Tsuga* and *Alnus*. Shrub pollen taxa (< 8%) mainly included *Caragana, Spiraea* and *Hippophaë*. Fern spores (< 5%) were mainly from Polypodiaceae and *Selaginella*. Aquatic pollen types from the lake sediments were *Myriophyllum* (mean 0.6%), *Nymphoides* and *Typha* with very low contents (Fig. 2).

Pollen assemblages from the topsoil samples showed marked differences between various vegetation types, implying the great potential to build discriminant functions using the pollen-based DA (Figs. 2a, 3a) (Li et al. 2011). Pollen assemblages from the alpine steppe zone were mainly composed of *Artemisia* (mean 25.1%), Cyperaceae (13.6%) and Poaceae (11.5%), accompanied by Fabaceae (3.3%), *Thalictrum* (2.8%), Amaranthaceae (2.7%) and some arboreal types, such as *Pinus* pollen (4.1%). The pollen assemblages from the meadow samples (alpine meadow and marsh meadow) were dominated by Cyperaceae pollen (mean

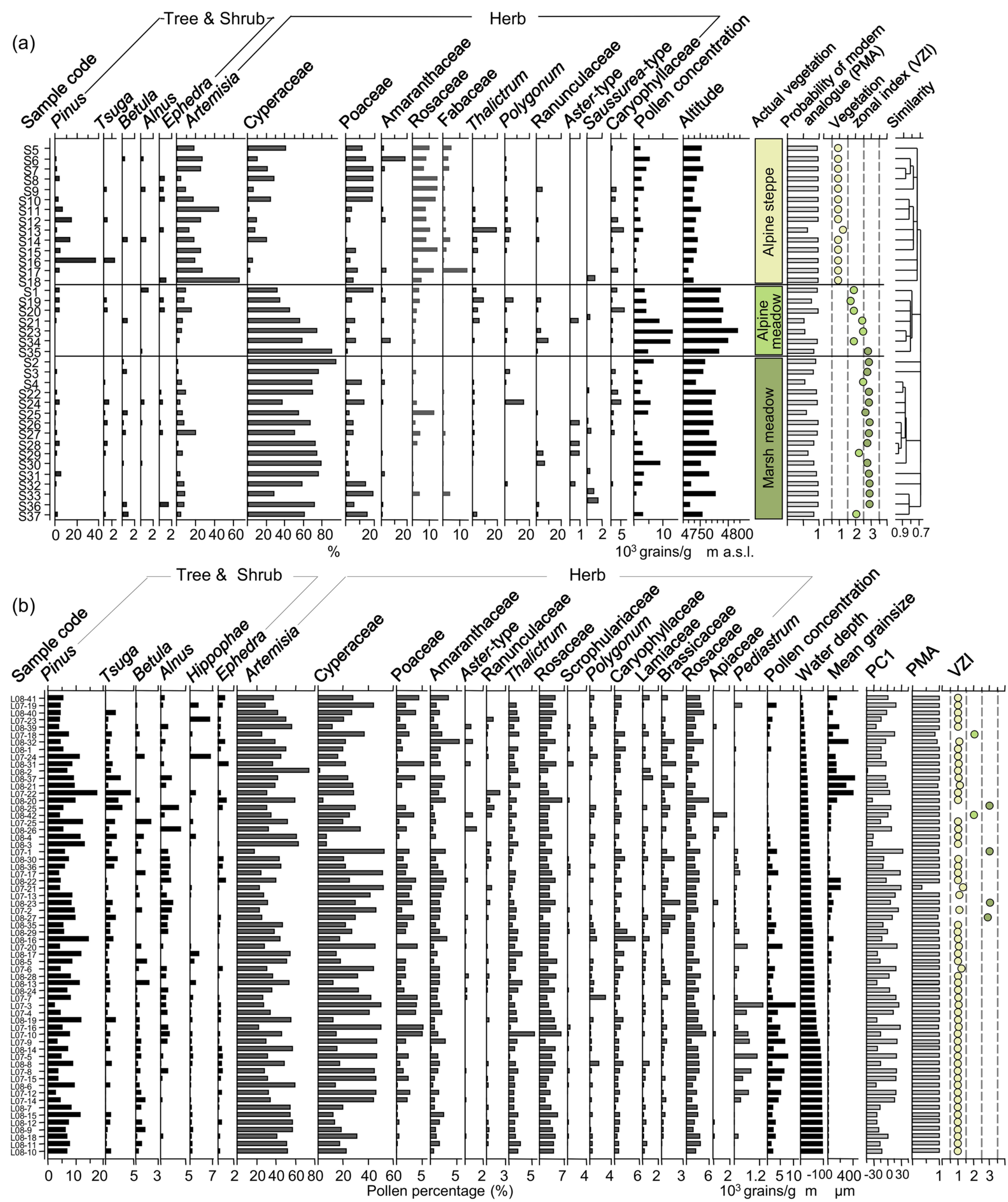

Fig. 2 Pollen percentage diagrams of the topsoil samples (**a**) and surface lake sediments (**b**) from the Nam Co catchment, with the results of pollen-based principal component analysis and discriminant analysis

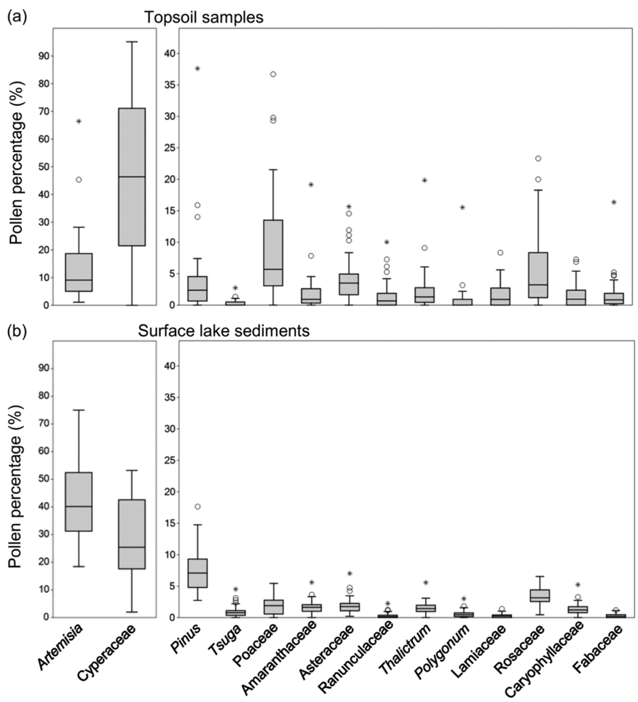

Fig. 3 Boxplots of the pollen percentages for the major taxa from 37 topsoil samples and 63 surface lake sediments from the Nam Co catchment, central Tibetan Plateau, showing the medians (horizontal lines within the boxes) and 25–75% quartiles (as the boxes). The short horizontal lines outside are drawn from the top of the box up to the largest data point less than 1.5 times the box height from the box, and similarly below the box. Outliers of extreme values are shown as circles, while values greater than 3 times the box height from the box are shown as stars

63.1%), accompanied by some Poaceae (7.6%), *Artemisia* (7%), Ranunculaceae (> 2%), *Polygonum* (1.9%) and *Thalictrum* (1.9%).

The pollen assemblages from the surface lake sediments were mainly characterized by abundant arboreal pollen (mean 10.2%, mainly *Pinus*) and *Artemisia* (41.8%), and less so by Cyperaceae (28.5%), Poaceae (1.9%), Ranunculaceae (1.8%), Rosaceae (3.4%) and Polygonaceae (0.9%), compared to those from the topsoil samples (Fig. 2). In addition, they were more homogeneous in composition than those from the topsoil samples, as indicated by the narrow percentage ranges for major pollen taxa shown in Fig. 3b.

Distribution of modern pollen assemblages

The spatial distribution of the major pollen taxa and pollen concentrations in the Nam Co catchment are presented as contours in Fig. 4. High concentrations of total pollen and spore grains (> 5,000 grains/g) were located in the central region of the lake basin below 50 m water depth, and in the altitudinal belt of the alpine meadow along the northern slope of the Nyainqentanglha Mountains (Fig. 4a).

Within the lake basin, the percentages of *Pinus* increased from 2 to 15% with increasing water depth (Fig. 4b). High percentages of *Artemisia* appeared in the central and eastern deep bottom of the lake basin at a depth of greater than 60 m (> 40%), and in estuarine regions in the northwest and southwest parts of the lake (> 30%) (Fig. 4c).

High percentages of Cyperaceae were limited to the western lakeshore (> 60%) and to the shallow lake basin at a depth of less than 80 m (Fig. 4d). The percentages of Poaceae and Polygonaceae were higher on the southern and northern lakeshore (> 10% and > 2%, respectively) (Fig. 4e, f), while that of Ranunculaceae reached high values (> 6%) on the western and southern lakeshores (Fig. 4g). Other Asteraceae (> 5%), Rosaceae (> 10%) and Lamiaceae (> 4%) were abundant in the alpine meadow belt on the southeastern lakeshore, and distinctly decreased from the lakeshore to the central lake basin (Fig. 4h–j).

Results of principal component analysis

The PCA biplots of the pollen taxa and all samples are shown in Fig. 5. The first two principal components, axis 1 and axis 2, account for 78.5 and 14.4% of the total variance of pollen data respectively.

According to the PCA biplot of the pollen taxa (Fig. 5a), Cyperaceae had the highest positive score on axis 1, while *Artemisia* had the highest negative score on axis 1. Poaceae had the highest positive scores on axis 2, followed by Rosaceae, Fabaceae, Amaranthaceae, Caryophyllaceae and so on.

In the PCA biplot of all samples (Fig. 5b), samples from the alpine meadow and swampy meadow had high positive scores on axis 1, which corresponded well to the ordination of Cyperaceae. Conversely, most samples from the alpine steppe obtained negative scores on axis 1, which corresponded well to the ordination of *Artemisia* (Fig. 5a). Therefore, the first principal component (PC1) primarily distinguished alpine steppe samples from meadow samples. Additionally, all of the surface lake sediments were strongly distributed along PCA axis 1, indicating homogeneous compositions in lacustrine pollen assemblages (Fig. 5b).

The PCA results indicated that the pollen assemblages from the topsoil samples are markedly different between the alpine steppe and meadows. Thus, they can be used for the pollen-based discriminant functions. In addition, the first principal component (PC1) efficiently reflects in-group variations of the pollen assemblages from surface lake sediments from the Nam Co basin (Figs. 2b, 5b).

Results of discriminant analysis

The results of DA for the topsoil samples and surface lake sediments are shown in Figs. 2 and 6. Three major vegetation

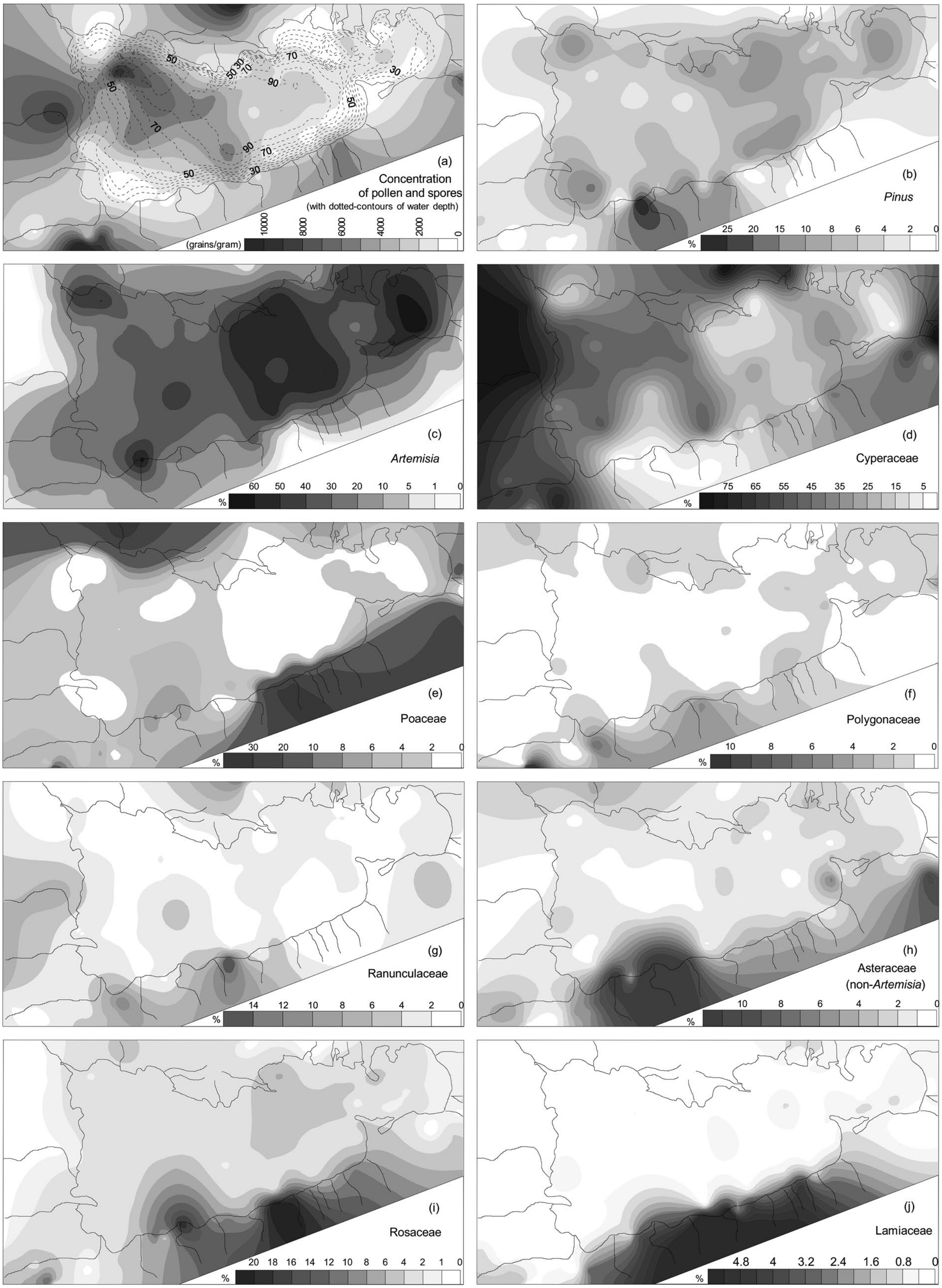

Fig. 4 Spatial distributions of the pollen concentration (**a**) and typical pollen taxa (**b**–**j**) of modern pollen assemblages in the Nam Co catchment

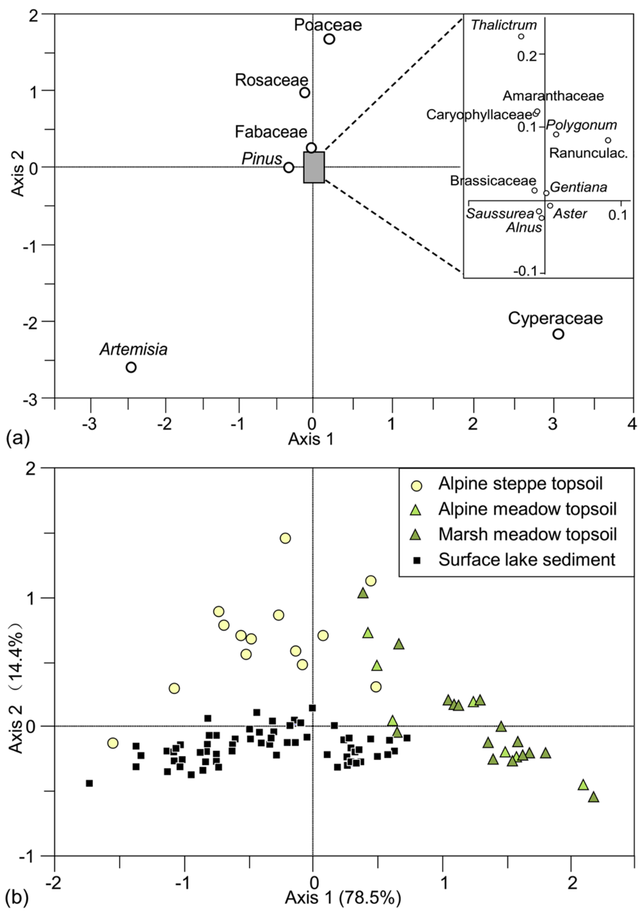

Fig. 5 Results of principal components analysis of the modern pollen assemblages in the Nam Co catchment. **a** Biplot of the major pollen taxa. **b** Biplot of the surface lake sediments and topsoil samples

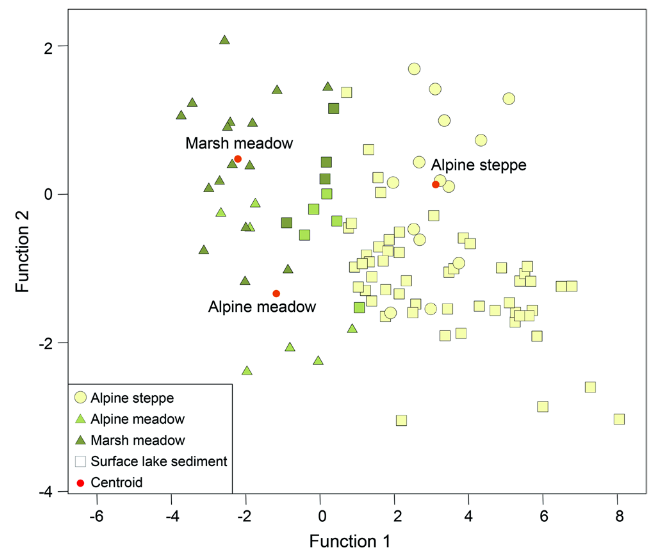

Fig. 6 Results of primary discriminant analysis of the 63 surface lake sediments and 37 topsoil samples from the Nam Co catchment

types in the Nam Co catchment were originally assigned numbers as the standard VZI values (a value of 0.5–1.5 for alpine steppe as the regional vegetation, 1.5–2.5 for alpine meadow and 2.5–3.5 for marsh meadow as local vegetation types).

After the primary DA, a total of 32 topsoil samples (86.5%) were correctly classified into the groups corresponding to their actual vegetation types (Table 1). All of the topsoil samples from the alpine steppe were correctly predicted into one group, while only a few samples of the alpine meadow (S21, S23, S35) and marsh meadow (S29, S37) were misclassified due to the compositional similarities of their vegetation and pollen assemblages. The high PMA values (mean 0.9) for the topsoil samples suggest that the regional vegetation of alpine steppe and local vegetation of the meadows can be clearly differentiated according to the topsoil pollen assemblages (Fig. 2a) (Li et al. 2011). Then, the results of leave-one-out cross-validation further verified that 30 topsoil samples (81.1%) were correctly classified into the actual vegetation groups (Table 1). Therefore, discriminant functions, which were obtained from pollen assemblages of 30 topsoil samples, were subsequently applied to the pollen assemblages from Nam Co surface lake sediments for an unbiased evaluation.

The unbiased DA results of the pollen assemblages from surface lake sediments showed that 90.5% were classified as alpine steppe from the regional vegetation zone (57 samples, mean VZI = 1.0, mean PMA as high as 0.98). The others (6 samples, accounting for 9.5%) were classified to the group of meadow vegetation, among which 2 samples were possibly predicted as alpine meadow from the local altitudinal vegetation belt (mean VZI = 1.9, mean PMA = 0.92), and 4 samples as marsh meadow which is patchily distributed in the lake catchment (mean VZI = 2.9, mean PMA = 0.98) (Table 1; Fig. 6).

Results of boosted regression tree analysis

BRT analyses were conducted on the PC1 scores and the VZI values for the modern lacustrine pollen assemblages, as well as the variables of water depth and mean grain size for the surface lake sediments (Figs. 2b, 7).

The results of BRT analysis showed that the VZI values contributed 85.8% to the developed model, but the water depth and mean grain size only contributed 10.5 and 3.7%, respectively. The modelled interactions between these three variables highlighted that regional/local pollen sources (i.e. VZI values) were the most important factor that influenced the pollen assemblages from the surface lake sediments, compared with the in-lake transport distances and sedimentary processes (i.e. variables of water depth and mean grain size).

Table 1 Discriminant analysis results of surface lake sediments based on the relationship between topsoil pollen assemblage and source vegetation in Nam Co catchment, central Tibetan Plateau

Actual group membership	Predicted group membership			No. of samples
	Alpine steppe	Alpine meadow	Marsh meadow	
Alpine steppe	14[a] (100%)[b]	0	0	14
Alpine meadow	0	4 (57.1%)	3 (42.9%)	7
Marsh meadow	0	2 (12.5%)	14 (87.5%)	16
Percentage of topsoil samples primarily correctly classified: 86.5%				
Alpine steppe	13[c] (92.9%)[d]	1 (7.1%)	0	14
Alpine meadow	1 (14.3%)	4 (57.1%)	2 (28.6%)	7
Marsh meadow	0	3 (18.7%)	13 (81.3%)	16
Percentage of topsoil samples correctly classified after cross-validation: 81.1%				
Unbiased group membership for surface lake sediments	57 (90.5%)	2 (3.2%)	4 (6.3%)	63

Total number of topsoil samples: 37; Total number of surface lake sediment samples: 63

[a]Number of samples classified as that group after the primary DA

[b]Percentage of samples classified into that group after the primary DA

[c]Number of samples classified into that group after the cross-validation

[d]Percentage of samples classified into that group after the cross-validation

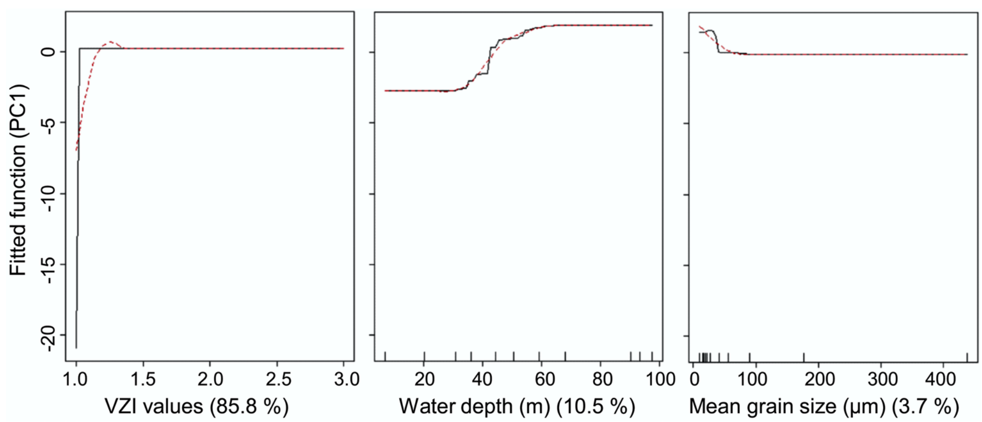

Fig. 7 Results of the boosted regression tree analysis (BRT) based on the PC1 scores and VZI values of modern lacustrine pollen assemblages, proxies of water depth and mean grain size of the 63 surface lake sediments from Nam Co

Discussion

Source analysis of modern pollen assemblages in Nam Co

Modern pollen assemblages from the 63 surface lake sediments and 37 topsoil samples consisted of various pollen types with different pollen sources. Arboreal pollen taxa, such as *Pinus, Tsuga* and *Alnus*, are the dominant exotic airborne pollen types in the Nam Co catchment and central TP (Lu et al. 2010; Li et al. 2016). They only account for less than 10% in most modern pollen assemblages in the Nam Co catchment (Fig. 2).

The larger lake basin and more open landscape could have led to higher proportions of long-distance transported pollen and more regional pollen, such as *Pinus* in the lake sediments (Punning and Koff 1997). According to an investigation of airborne pollen and a backward trajectory analysis in the Nam Co catchment, arboreal pollen could be transported via wind from the southern TP to the central TP, covering long distances of several hundred kilometres (Lu et al. 2010). Another investigation of modern pollen rain in Zabuye Salt Lake in the central TP reported a transportation distance of at least 400 km for *Pinus* pollen carried by atmospheric circulations (Wu and Xiao 1995).

Artemisia and Cyperaceae are the two dominant taxa for both vegetation and modern pollen assemblages of the Nam Co area and central TP (Shen et al. 2008; Li et al. 2011). In the topsoil samples from the Nam Co catchment, modern pollen assemblages from the alpine steppe had high percentages of *Artemisia* (25.1%), while those from the alpine meadow mainly consisted of Cyperaceae (63.1%) (Fig. 2a). In the surface lake sediments, the combined percentages of *Artemisia* and Cyperaceae accounted for more than 70% of the lacustrine pollen assemblages (Fig. 2b). The presence of other herb pollen taxa, including Amaranthaceae, non-*Artemisia* Asteraceae, Rosaceae, Ranunculaceae, Caryophyllaceae, *Polygonum* and Fabaceae, were consistent with alpine steppe and meadow vegetation in Nam Co and the central TP (Fig. 2). Therefore, the regional vegetation of the alpine steppe in the lake catchment and an alpine meadow belt on the northern slope of the Nyainqentanglha Mountains are the major vegetation sources and provide the majority of pollen input to the surface lake sediments of Nam Co.

Spatial variability of modern pollen assemblages in Nam Co

In the Nam Co catchment, the spatial variabilities of modern pollen assemblages and various pollen types have been influenced by regional/local pollen sources and in-lake sedimentary processes (Figs. 2, 3, 4, 5, 6).

Pollen assemblages from the topsoil samples exhibited marked spatial consistency with the vegetation types. Modern pollen assemblages from the topsoil samples of different vegetation types had diagnostic features in terms of their composition and pollen percentages (Fig. 2a) (Li et al. 2011). As confirmed by DA, the major vegetation types in the lake catchment, including the regional vegetation of alpine steppe, local vegetation of the alpine meadow from an altitudinal belt and azonal vegetation of the marsh meadow, could be distinguished by their pollen assemblages (Table 1; Figs. 2a, 6).

In general, the pollen assemblages from the surface lake sediments of Nam Co showed two major patterns of spatial variability for different pollen types, which resulted from different source areas and sedimentary processes (Fig. 4).

1. The percentages of some pollen taxa (e.g. *Pinus* and *Artemisia*) and total pollen concentrations gradually increased towards the central lake basin, and maintained high values in a deep central region at a depth of over 60 m (Fig. 4), possibly resulting from in-lake sediment focusing (Wang et al. 2015). Pollen grains carried by water currents across the lake were preferentially deposited into the deep lake centre with finer sediments due to repeated floatation, sorting and redeposition, i.e. an effect of sediment focusing (Davis and Brubaker 1973). In addition, smaller pollen grains such as *Artemisia* tended to accumulate in the lake centre (Luly 1997). Consequently, sediment focusing could have led to high pollen concentrations and high percentages of pollen taxa with regional sources and smaller sizes in the deep lake bottom (Davis 1968; Xu et al. 2005).
2. Conversely, the pollen percentages for Cyperaceae, Poaceae, Polygonaceae, Ranunculaceae, non-*Artemisia* Asteraceae, Rosaceae and Lamiaceae appeared to be high in the topsoil samples on the lakeshore and the submerged estuaries close to their source vegetation, and gradually decreased towards the central lake basin (Fig. 4). This result could reflect the local vegetation sources of these pollen types, and a relative short transport distance due to surface runoff from the northern slope of the Nyainqentanglha Mountains and inflow rivers (Wang et al. 2015).

Furthermore, according to the PCA results, surface lake sediments of Nam Co had homogeneous pollen assemblages compared to the topsoil samples (Fig. 5b). In the surface lake sediments, the pollen percentages of most of the taxa had narrow ranges, compared to the topsoil samples (Fig. 3). The homogenization of pollen assemblages within a large lake could reduce variations in lacustrine pollen assemblages, which can be attributed to the mixing effect during in-lake re-suspension and redeposition processes (Sugita 1993). These processes are caused by water circulation driven by wind, river inflow or seasonal salinity/temperature gradients at different depths of the lake (Davis 1968; Davis et al. 1984; Wang et al. 2015).

Vegetation representation of modern pollen assemblages from surface lake sediments of Nam Co

Based on DA and the transfer functions established by the modern pollen assemblages from the topsoil samples in the Nam Co catchment (Fig. 2a), most of the predicted vegetation types for the pollen assemblages from surface lake sediments were the alpine steppe (90.5%), while only 9.5% were classified as meadow vegetation (Figs. 2b, 6, 8; Table 1).

The spatial variability of the lacustrine pollen assemblages is influenced by sediment focusing and homogenization during in-lake sedimentary processes (Figs. 2, 3). However, the results of BRT analysis on the PC1 scores, VZI values, water depth and mean grain size suggest that sedimentary processes in Nam Co only account for a minor proportion (14.2%) of the various lacustrine pollen assemblages. Conversely, contributions from the regional and local source vegetation played a dominant role (85.8%) in lacustrine pollen assemblages (Fig. 7). Therefore, the results of the predicted vegetation types for surface lake sediments can efficiently indicate the vegetation representation of lacustrine pollen assemblages in Nam Co.

According to the spatial distribution of the predicted vegetation for surface lake sediments (Fig. 8), pollen assemblages from the central lake basin (water depth > 60 m) solidly represented the regional vegetation of alpine steppe. Some of the modern pollen assemblages from the shallow area (< 60 m) contained the representation of the local meadow vegetation (alpine meadow from the altitudinal belts and marsh meadow patch). Thus, the deep area of the central lake basin of Nam Co appeared to be an accumulation

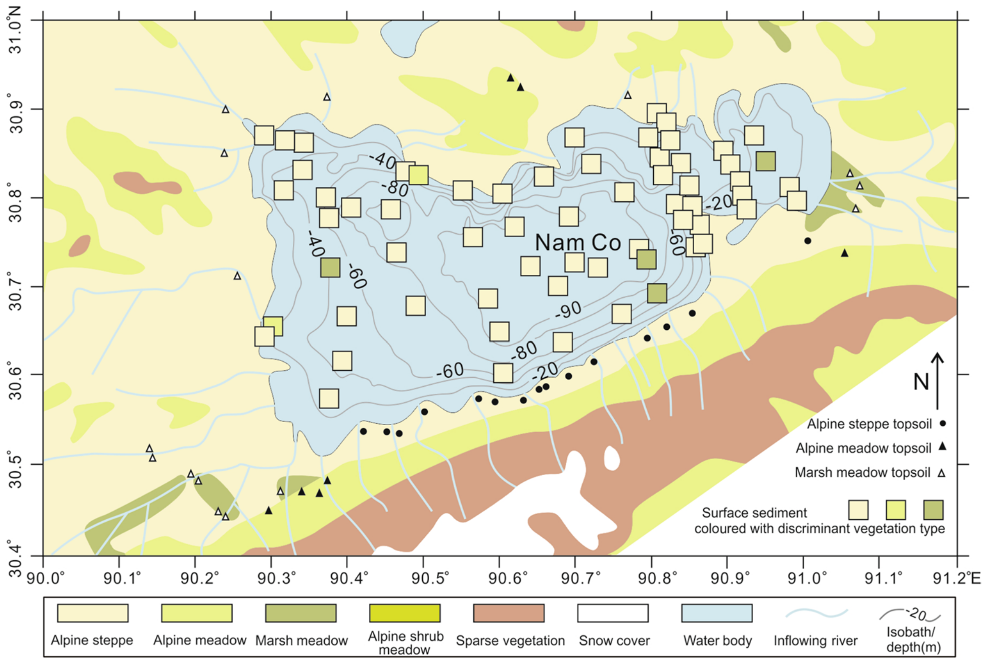

Fig. 8 Spatial distribution of the predicted vegetation representation for the surface lake sediments in Nam Co, central Tibetan Plateau

zone for both lacustrine pollen assemblages and pollen from regional alpine steppe (Figs. 2b, 8).

As a whole, this study presented a quantitative result of predicted vegetation representation for modern lacustrine pollen assemblages from the large lake Nam Co in the central TP. Most modern pollen assemblages from the deep lake basin represented the regional vegetation of alpine steppe in the central TP, while those from shallow areas were more influenced by the local meadow vegetation. In the future, palaeoenvironmental studies in large lakes such as Nam Co should conduct a detailed investigation on the modern pollen assemblages from the lake catchment, which is of great importance to the pollen-based interpretations of palaeovegetation and palaeoclimate at the local scale (Li et al. 2011) or the regional scale (Zhu et al. 2015).

Conclusions

Modern pollen assemblages from surface lake sediments and topsoil samples from Nam Co in the central TP were investigated in this study. The influences on lacustrine pollen assemblages from source vegetation and sedimentary processes were quantitatively assessed. In addition, vegetation representations of modern lacustrine pollen assemblages were established based on statistical analyses. The main conclusions are summarized below.

1. The spatial variability of lacustrine pollen assemblages was influenced by both the regional/local vegetation and in-lake sedimentary processes. Compared with topsoil samples, surface lake sediments contained homogeneous pollen assemblages, possibly resulting from in-lake mixing and redistribution. In addition, an accumulation zone for lacustrine pollen assemblages was found in the deep lake basin at a depth of over 60 m due to sediment focusing.
2. Although in-lake sedimentary processes had some influence on the distribution of lacustrine pollen assemblages, the results of BRT analysis confirmed that the source vegetation was the dominant factor for the vegetation representation of lacustrine pollen assemblages, which may explain 85.8% variation of the pollen assemblages from surface lake sediments.
3. The results of DA revealed that most of the modern lacustrine pollen assemblages (90.5%) were representative of the regional vegetation of the alpine steppe in the Nam Co catchment and central TP. The local vegetation of the alpine meadow and marsh meadow were only represented by a few surface lake sediments (9.5%) in the shallow region of the lake basin. Therefore, lacustrine pollen assemblages from the deep lake basin as an accumulation zone of large lakes can efficiently document signals from the regional vegetation and climate change.

Acknowledgements This research was supported by the Strategic Priority Research Program of Chinese Academy of Sciences (Grant no. XDA20070101) and the National Natural Science Foundation of China (Grant nos. 41471169, 41330105, 41571189, 41690113 and 41271226). The author is grateful to Houyuan Lu, Junbo Wang and Liping Zhu for their helpful discussion and to Yong Wang and Jianting Ju for their assistance in the field investigation, as well as the two anonymous reviewers for valuable comments and suggestions.

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