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Postglacial fire history and interactions with vegetation and climate in southwestern Yunnan Province of China based on charcoal and pollen records

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Abstract. A high-resolution, continuous 18.5 ka-long (1 ka=1000 cal yr BP) macroscopic charcoal record from Qinghai Lake in southwestern Yunnan Province, China reveals the postglacial fire frequency and variability history. The results show that three periods with high fire frequency and intensity occurred during the periods 18.5-15.0 ka, 13.0-11.5 ka, and 4.3-~1.0 ka, respectively. This record was compared with the pollen record from the same core, and tentatively correlated with the regional climate proxy records with the aim to separate climate- from human-induced fire activity, and discuss vegetation-fire-climate interactions. The results suggest that fire was mainly controlled by climate before 4.3 ka and by combined action of climate and humans after 4.3 ka. Before 4.3 ka, high fire activity corresponded to cold and dry climatic conditions, while warm and humid climatic conditions brought infrequent and weak fires. Fire was an important disturbance factor and played an important role in forest dynamics around the study area. Vegetation responses to fire before 4.3 ka are not consistent with that after 4.3 ka, suggesting that human influence on vegetation and fire regimes may have become more prevalent after 4.3 ka. The correlations between fire activity and vegetation reveal that evergreen oaks and *Alnus* are flammable plants. Evergreen oaks are fire-tolerant taxa and *Alnus* is a fire-adapted taxon. The forests dominated by *Lithocarpus/Castanopsis* and/or tropical arbors are not easy to ignite, but *Lithocarpus/Castanopsis* and tropical arbors are fire-sensitive taxa in the study area.

1 Introduction

Fire is a natural, recurring episodic event in almost all types of vegetation and it is one of the primary natural disturbance factors in forest ecosystems (Harrison et al., 2010). It has a strong influence on the extent and diversity of forest resources, carbon cycles and global climate change. Major forest fires often caused serious harm and huge losses to the forest, environment and human livelihoods. Thus, in order to decrease the harm and losses, it is necessary to better manage forest fires. This may, in part, be achieved through a better understanding of the driving mechanism of forest fires derived from long-term fire history research (McWethy et al., 2013; Morales-Molino et al., 2013; Kloster et al., 2015). Fire histories can be reconstructed by using time series of fire atlases (Rollins et al., 2001; Le Page et al., 2008), collection and analysis of fire-scarred trees (Arno and Sneck, 1977; Bake and Dugan, 2013), and charcoal particle analysis in peat and lake sediments (Whitlock and Larsen, 2001; Holz et al., 2012; de Porras et al., 2014). However, sources of fire atlases and fire-scarred trees are limited, and their time spans are relatively short, (Brunelle and Whitlock, 2003), whereas the charcoal records from peat and lake sediments can provide long continuous fire frequency history and allow vegetation-fire-climate interactions to be examined (Gavin et al., 2007; Morales-Molino et al., 2013). Knowledge of the past fire activity is a key to understanding the present day and for making sustainable management policies for forest ecosystems (Ali et al., 2009). Thus, it is necessary to reconstruct past long-term fire frequency histories, which can inform the current conceptual models of forest recovery after fire and provide guidance for forest management strategies in areas affected by frequent fires.

At present, studies on fire history and the interactions between long-term vegetation, fire, and climate are mainly concentrated in the world's boreal forests (Power et al., 2008). Based on these studies, USA, Canada and parts of Europe have been actively advancing methods and numerical approaches to reconstruct long term fire histories. China has only started relatively late in this field. Most of studies on fire history are concentrated in northern China (Li et al., 2005; Huang et al., 2006; Jiang et al., 2008; Wang et al., 2013; Zhang et al., 2015), and studies in southern China (Sun et al., 2000; Luo et al., 2001; Xiao et al., 2013), especially in southwestern China, are relatively few. The studies on fire history in China have concentrated on the relationship between fire activity and climatic change on orbital to suborbital timescales, whereas studies of past fire frequency and magnitude and its relationship to climate, human activity and vegetation dynamics have rarely been attempted in China.

Here, we presented a high-resolution and continuous macroscopic charcoal record spanning about 18.5 ka from Qinghai Lake in southwestern Yunnan Province of southwestern China, a low altitude lake in the low latitude region. The climate in Yunnan Province is characterized by distinct wet and dry seasons with warm-wet conditions in summer and mild-dry conditions in winter, resulting in forest fire occurring frequently (Xu, 1991). Consequently, Yunnan Province is a zone of high fire frequency in China (Chen et al., 2012). The charcoal record in this study reveals the fire history and fire regime dynamics through time in southwestern Yunnan Province. Combined with the climate records and vegetation histories since 18.5 ka, reconstructed in Xiao et al. (2015), the main controlling factor of forest fire dynamics and the relationship between fire activity and vegetation were examined in this study. These results provide new evidence for studies on fire frequency variability and vegetation–fire–climate interactions in southwestern China, which is important for improving our predictions of the influence of climatic change on future fire activity and planning appropriate management policies for forest ecosystems.

2 Regional setting

Qinghai Lake (25° 7'56.75" N，98°34'19.16" E, 1885 m a.s.l.) is located in the northeastern Tengchong County of

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southwestern Yunnan Province, southwestern China (Fig. 1). Southwestern China is characterized by the alternation of high mountain ranges running roughly north to south (such as Qionglai Mountain, Daxue Mountain, Shaluli Mountain from east to west) and parallel, deep and narrowly incised river valleys (such as Dadu River, Yalong River, Jinsha River). The large spans of longitude and latitude, and altitude differences (ranging from about 1000 to above 5000 m a.s.l.) in southwestern China result in rich vegetation types and various vertical vegetation belts in the region (Xiao et al., 2011). The Gaoligong Mountain is the westernmost mountain among the mountains over 3000 m a.s.l. in southwestern China (Fig. 1). Qinghai Lake is situated to the west of the Gaoligong Mountain, and the topography of its west and south is all below 2500 m a.s.l. Qinghai Lake is a volcanic dammed lake with a surface area of c. 0.25 km^2 and a catchment area of 1.5 km^2 in 1990, respectively. The average and maximum water depths were 5.2 m and 8.1 m in 2010, respectively. It is mainly fed by precipitation, groundwater and surface runoff without natural outlet currently.

The study region is characterized by a subtropical humid monsoon climate. It is mainly affected by the warm-humid airflow from the Indian Ocean and Bengal Bay in summer and by the southern branch of the westerly in winter. Because of its southwestern location in Yunnan Province, the climate in the region is warm and very humid in summer and mild and moderately dry in winter. Tengchong meteorological station near Qinghai Lake (Fig. 2) records a mean annual temperature of 15.4°C and mean annual precipitation of 1506 mm. Most of the precipitation is concentrated in the rainy season from May to October, which is 85% of the annual precipitation.

Due to the strong influence of human activities, the catchment of Qinghai Lake is mainly covered by plantation forests such as *Taiwania cryptomerioides*, *Cunninghamia lanceolata*, and *Alnus nepalensis*. The vertical vegetation belts on the west slope of the southern Gaoligong Mountain varies gradually from a semi-humid evergreen broadleaved forest (<2200 m a.s.l.) to a mid-montane humid evergreen broadleaved forest (2200-2800 m a.s.l.), *Rhododendron* shrubland (2800-3000 m a.s.l.), a sub-alpine shrub meadow (3000-3500 m a.s.l.), and sparse vegetation in rock debris (>3500 m a.s.l.) from bottom to top (Qin et al., 1992).

3 Material and methods

3.1 Sediment sampling, laboratory analysis and dating

A 832 cm long sediment core (TCQH1) from the central part (6.3 m water depth) of Qinghai Lake was extracted in November 2010 using a UWITEC piston corer. A 44 cm long short core was collected nearby using a gravity corer for the ^{210}Pb and ^{137}Cs measurements, which recovered the sediment–water interface. These cores were sectioned at 1 cm intervals. Samples were stored at 4°C until analyzed. Macroscopic charcoal particles (>125 μm in diameter) were extracted from 1 cm^3 samples at contiguous 1-cm intervals. Charcoal samples were soaked in 20 ml of 5% sodium hexametaphosphate for >24 hours and 20 ml of 10% H_2O_2 solution for 24 hour to disaggregate the sediment (Huerta et

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al., 2009). Samples were gently washed through a 125 μm mesh sieve and the residue was transferred into gridded petri dishes and counted under a stereomicroscope at magnifications of 40×. The age model was based on the ^{210}Pb and ^{137}Cs dates and the AMS ^{14}C dates. All radiocarbon dates were converted to calendar years before present (cal yr BP) using the program CALIB 6.0 and the IntCal09 calibration curve (Reimer et al., 2009). A recently developed Bayesian method (Blaauw and Christen, 2011) was used to establish the age-depth model, which was determined using the default settings for lake sediments at 5 cm intervals.

3.2 Pollen diversity indices and standardized method

The richness and the evenness (equitability) are two important components of biodiversity. Different diversity indices reflect species richness as well as evenness but with different weight (Odgaard, 1999). Richness index only counts total number of taxonomic units, whereas the number of individuals isn't considered (Magurran, 1988), thus it is easily impacted by rare species. Simpson's index is primarily influenced by the relative frequency or representation of individuals (namely species concentricity or evenness) (Simpson, 1949), which depends mainly on dominant species and is less sensitive to species richness (Odgaard, 1999). In order to evaluate the plant diversity around the study area, palynological richness index and Simpson's index were adopted in this study.

Palynological richness index is the number of different pollen types in every pollen sample. Simpson's index was calculated as

$$D = \frac{N(N-1)}{\sum_{i=1}^{S} n_i(n_i - 1)}$$

Where n_i is the number of individuals in the i th pollen types, N the total number of individuals and S the total number of pollen types (Xiao et al., 2008).

In this study, we use min-max normalization to standardize pollen percentages. The formule is $x^* = \frac{x_i - \min}{\max - \min}$. Where x^* is the standardized data of the selected pollen type; x_i is percentage of this pollen type in the i th sample; max is the maximum value of this pollen type percentage; min is the minimum value of this pollen type percentage.

3.3 Fire event identification

Fire events were recognized by separating the macroscopic charcoal accumulation rates (CHAR; particles cm^{-2} yr^{-1}) into CHAR background (BCHAR) and CHAR peak (PCHAR) components by using CharAnalysis software (Higuera

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et al., 2008; http://charanalysis.googlepages.com/). BCHAR was determined with a 500-year lowess smoother, robust to outliers, and it is the slowly varying trend in charcoal accumulation, which may represents gradual changes in regional fire activity and/or charcoal production per fire. PCHAR was taken as residual after subtracting BCHAR from CHAR, representing local fire episodes (namely one or more fire events occurring in the duration of a peak). The threshold value for charcoal peak detection was set at the 95th percentile of a Gaussian mixture modeling noise in the CHAR peak time series (Higuera et al., 2008). Fire frequency (episodes/1000 yr) is the sum of the total number of fires within a 1000-yr period, smoothed with a Lowess smoother. Fire-episode magnitude (particles/cm^2) is the total charcoal influx in a peak and varies with fire size, intensity, proximity, and taphonomic processes (Whitlock et al., 2006; Huerta et al., 2009; Walsh et al., 2010).

4 Results

4.1 Chronology

The results of 17 AMS ^{14}C dates are presented in Table 1 and Fig. 3a. It shows that there is an offset of average 460 years between the bulk sediment samples and the plant macrofossil samples, except for one bulk sediment sample at 610 cm which is less influenced by the reservoir effect because of high organic matter content. This offset was attributed to a reservoir effect in the bulk sediment samples. Because ^{210}Pb activity was not measured up to 0 in the 44 cm long short core, we can only use the ^{137}Cs date. In the record, the depth of 1952 AD (the time for initial detection of ^{137}Cs) is at 43 cm, and the depth of the ^{137}Cs 1963 AD peak is at 33 cm. Thus, only the 10 AMS ^{14}C dates from the plant macrofossils, the surface date (2010 AD) and the ^{137}Cs dates (1963 AD at 33 cm and 1952 AD at 43 cm) were selected to establish the age-depth model using the Bayesian method (Fig. 3b). From the model, calendar ages for all depths were constructed and depicted as gray-scales, where darker gray levels indicate more likely calendar ages. According to the age-depth model, the bottom date is presumed to be 18.5 ka, and the average temporal sampling resolution is ~22 years for the macroscopic charcoal record. The sedimentation rate before ~0.9 ka is relatively low and steady, with a mean of 0.0385 cm/a. Between ~0.9 ka and 1952 AD, the rate is significantly higher at 0.124 cm/a. After 1952 AD, the rate is far higher than the earlier periods, with a mean of 0.741 cm/a.

4.2 Charcoal record, fire events and palynological diversity indices

The macroscopic charcoal record, fire event reconstruction and plant diversity were described using the pollen zonation for the same core (core TCQH1) (Xiao et al., 2015) as follows (Fig. 4). In the macroscopic charcoal record, the trends in charcoal concentration and BCHAR are similar to that of CHAR, thus we only describe the results of CHAR in the following content.

Zone TCQH-1 (18.5-14.2 ka) was divided into three subzones. In **Subzone TCQH-1a** (18.5-17.9 ka), CHAR was very high, averaging 29 (ranging from 8 to 57) particles/cm^2/yr. Three fire events were identified by significant charcoal peaks with relatively small peak magnitudes (154, 276, and 611 pieces/cm^2, respectively). Fire frequency was relatively high, averaging 5.5 episodes/1000 yr (ranging from 5.1 to 5.7 episodes/1000yr). Palynological richness and Simpson's indices were relatively low, averaging 65 and 8.3, respectively. In **Subzone TCQH-1b** (17.9-15.0 ka), CHAR was still very high with larger fluctuant amplitudes, averaging 23 (ranging from 1 to 83) particles/cm^2/yr. 15 fire events were registered by charcoal peaks. Fire-episode magnitude varied greatly from 35 to 2189 pieces/cm^2. Fire frequency ranged from 2.4 to 7.4 episodes/1000 yr with an average of 4.7 episodes/1000 yr. Palynological richness index declined (mean of 58) and Simpson's index increased slightly (mean 9.3). In **Subzone TCQH-1c** (15.0-14.2 ka), CHAR decreased markedly, averaging 8 (ranging from 1 to 19) particles/cm^2/yr. Only two fire events were noted in the lower part of the subzone, with fire-episode magnitudes of 32 and 58 particles/cm^2. Fire frequency declines rapidly from 6.3 episodes/1000 yr to 0.7 episodes/1000 yr with an average of 3.3 episodes/1000 yr. Palynological richness and Simpson's indices all increased, averaging 68 and 10.5, respectively.

Zone TCQH-2 (14.2-11.5 ka) was divided into two subzones based on fire activity. **Subzone TCQH-2a** (14.2-13.0 ka) had very low CHAR, averaging 8 (ranging from 1 to 37) particles/cm^2/yr. Only two fire events were registered in the upper part of the subzone, and these fire-episode magnitudes are both at 63 particles/cm^2. Fire frequency ranged from 0.3 to 5.6 episodes/1000 yr from the bottom to the top of the subzone with an average of 2.1 episodes/1000 yr. **Subzone TCQH-2b** (13.0-11.5 ka) had very high CHAR, averaging 39 (ranging from 6 to 113) particles/cm^2/yr. Fire events occurred frequently, and their magnitudes average 445 particles/cm^2, ranging from 0.02 to 1984 particles/cm^2. Fire frequency was the highest for the entire record, average 9.5 episodes/1000 yr. In this zone, palynological richness and Simpson's indices were relatively low, averaging 67 and 7.7, respectively.

Zone TCQH-3 (11.5-10.4 ka) was characterized by a marked decrease in CHAR, averaging 10 (ranging from 0 to 32) particles/cm^2/yr. Only two fire events were registered in the bottom of the zone and one fire event in the upper of the zone, with low fire-episode magnitudes (125, 254, and 33 particles/cm^2, respectively). Fire frequency declined rapidly from 7.3 to 1.9 episodes/1000 yr with an average of 3.3 episodes/1000 yr. Palynological richness index was similar to that in Zone TCQH-2, and Simpson's index increased markedly (mean of 10.4).

Zone TCQH-4 (10.4-8.5 ka) had very low CHAR values (mean of 5 particles/cm^2/yr). Only one fire event was detected at ca. 10.2 ka with the fire-episode magnitude of 29 particles/cm^2, and the fire frequency averaged 0.6 episodes/1000 yr. Palynological richness and Simpson's indices increased, averaging 80 and 14.3, respectively.

Zone TCQH-5 (8.5-4.3 ka) CHAR values (mean of 4 particles/cm^2/yr) remained very low. Three fire events were registered at ca. 6.7, 5.8 and 5.7 ka, respectively. Their fire-episode magnitudes were 18, 213 and 417 particles/cm^2, respectively. Fire frequency averaged 1.0 episodes/1000 yr. Palynological richness and Simpson's indices declined

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compared with that in Zone TCQH-4, but they were still relatively high, averaging 74 and 10.6, respectively.

Zone TCQH-6 (4.3-1.0 ka) was characterized by a marked increase in CHAR compared with Zone TCQH-4 and TCQH-5, averaging 28 (ranging from 6 to 72) particles/cm^2/yr. Ten fire events were noted in the zone. Fire-episode magnitude varied from 26 to 939 particles/cm^2 (mean of 303 particles/cm^2). Fire frequency averaged 2.7 episodes/1000 yr, ranging from 0.7 to 4.8 episodes/1000 yr. Palynological richness index had no obvious changes compared with the previous zone, while Simpson's index decreased rapidly (mean of 8.4).

Zone TCQH-7 (after 1.0 ka) began with very high CHAR during the period 1.0-0.8 ka, averaging 89 (ranging from 15 to 310) particles/cm^2/yr. After 0.8 ka, CHAR decreased markedly to mean of 10 (ranging from 1 to 60) particles/cm^2/yr, but, then increased to mean of 89 (ranging from 31 to 264) particles/cm^2/yr in the last 50 years. Only two fire events were registered in this zone (fire-episode magnitudes: 34 and 360 particles/cm^2). Fire frequency was relatively low, averaging 2 episodes/1000 yr. Palynological richness index declined slightly (mean of 72), and Simpson's index increased significantly (mean of 11.7).

5 Discussion

5.1 Fire activity, climatic changes and human activity

The results of fire event reconstruction based on the macroscopic charcoal record from Qinghai Lake reveals that fire frequency and fire-episode magnitude were not constant over the last 18.5 ka in southwestern Yunnan Province. There are three periods with frequent and intensive fire episodes, occurring during 18.5-15.0 ka, 13.0-11.5 ka, and 4.3-~1.0 ka. Between 15.0 and 13.0 ka, fire episodes first rapidly decreased in frequency and intensity, then gradually increased. From 11.5 to 10.4 ka, fire frequency and intensity gradually declined to low levels. Between 10.4 and 4.3 ka, fire activity was rare and weak, and there were only three fire episodes at 10.2, 6.7, and 5.8 ka indicated by four significant charcoal peaks. After ~1.0 ka, only two weak fire episodes were noted, and fire frequency and intensity were relatively low. In the last 50 years, the charcoal concentration was still very low, and the relatively high CHAR may be at least partly due to the high sedimentation rate.

From the pollen record in Qinghai Lake, standardized data of *Lithocarpus/Castanopsis* (a taxon indicating warm and humid environment), evergreen oak (a taxon indicating relatively warm environment), and herb (a taxon indicating relatively dry climate) pollen percentages are selected as a synthetic climate proxy (Fig. 5d, Xiao et al., 2015). At the same time, the DCA axis 1 sample scores of pollen data from Qinghai Lake may also act as a climate proxy indicating climate changes from relatively cool and moderately dry conditions to warm and humid conditions from high scores to low scores (Fig. 5e, Xiao et al., 2015). The recent studies (Xiao et al., 2014a, b) suggest that the PCA axis 1 sample scores of the pollen data from Tiancai Lake in northwestern Yunnan Province can be mainly interpreted as temperature

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change from warm to cold from low scores to high scores (Fig. 5f). From the pollen record of Lugu Lake located on the boundary between Yunnan and Sichuan Provinces in southwest China, standardized data of *Tsuga* (a taxon indicating humid environment), *Betula* (a taxon indicating relatively temperate environment), and herb pollen percentages are select as a synthetic climatic proxy (Fig. 5g, Wang, 2012). These pollen proxies from Qinghai Lake (Fig. 5d, e), Tiancai Lake (Fig. 5f), and Lugu Lake (Fig. 5g) reveal regional climatic changes since 18.5 ka in western Yunnan Province that included two cold events (the Heinrich Event 1 (H1) and the Younger Dryas cold event (YD)) and a warm period (the Bølling/Allerød warm period, B/A) during the last deglaciation. The Holocene was clearly identified to begin at 11.5 ka. From 10.4 ka, the temperature and precipitation increased evidently. The Holocene climatic optimum (HCO) occurred during the period 8.5-4.3 ka. After 4.3 ka the climate became cooler and drier, accompanied by signals of human activity such as slash and burn (Xiao et al., 2015). This climatic change tendency is also recorded in other regions affected by the southwest monsoon, such as the $\delta^{18}O$ records from core NIOP905 in the western Arabian Sea (Fig. 5h) (Huguet et al., 2006) and core KL126 in the Bay of Bengal (Kudrass et al., 2001), and the sediment colour record from northeastern Arabian Sea (Deplazes et al., 2013).

Comparing the fire activity record from Qinghai Lake with the regional climate records in western Yunnan Province and the southwestern monsoon region (Fig. 5), it appears that the frequent and intensive fire activity during the periods 18.5-15.0 ka and 13.0-11.5 ka corresponded roughly to the H1 and the YD. The low fire activity between 15.0 and 13.0 ka corresponded to a period of slight warming (between H1 and B/A) and the B/A warm period. The gradual decline in fire frequency and intensity from 11.5 to 10.4 ka and the rare and weak fire activity between 10.4 and 4.3 ka corresponded to the gradual increases in the temperature and precipitation from 11.5 to 8.5 ka and the Holocene climatic optimum between 8.5 and 4.3 ka. Under the background of weak fire activity as a whole during the period 10.4-4.3 ka, three fire episodes at 10.2, 6.7, and 5.8 ka may indicate three significant dry or highly seasonal rainfall periods. The two fire episodes at 10.2 and 5.8 ka may correspond to the ice-rafted debris events at ~10.3 and 5.9 ka (Bond et al., 1997). The fire episode at 6.7 ka corresponds to the short-duration and moderate decrease in pollen percentages of *Lithocarpus/Castanopsis* and tropical arbors, which might indicate a regional cold event. However, the abrupt cold event at 8.2 ka recorded in other palaeoclimate records from the southwest monsoon region (Kudrass et al., 2001; Dykoski et al., 2005) were not marked in the charcoal record. The reason may be that though precipitation was relatively low at ~8.2 ka, the distribution of rainfall throughout the year might be relatively even (namely, rainfall seasonality was relatively low).

Pollen indicative of human activities (e.g., Poaceae and *Artemisia*) unambiguously increased from 4.3 ka. Archaeological records from Yunnan Province show that Neolithic culture began to emerge at around 4 ka or a little earlier (Han, 1981; Li, 2004). This raises the possibility that superimposed influence of human activities such as forest clearance and agricultural cultivation and climatic cooling and drying may result in the frequent and strong fire activity between 4.3 and 1.0 ka.

Historical documents show that the first administrative centre (Ruanhua Fu) was established in the early stage of Dali Kingdom (1.01–0.7 ka) in Tengchong (Edirotial Board of Tengchong County Annals, 1995). Subsequently, population immigration and implement of the state collective farming system accelerated deforestation and reclaimed farmland, which prompted intensification of agriculture (Edirotial Board of Tengchong County Annals, 1995). At the same time, the pollen record from Qinghai Lake suggests greater open vegetation present in the region after 1.0 ka (Xiao et al., 2015). Due to the decrease of forest area caused by human activity, the capacity for soil and water conservation declined, resulting in significant soil erosion. The coeval rapid increase in sediment accumulation rate may be caused by loss of forest cover and increased soil erosion, which diluted the charcoal input, and further caused the relatively low fire frequency and intensity after 1.0 ka. In addition, it is possible that human suppression of fire might also depress fire frequency and intensity with the development of an intensively managed agricultural and urbanized environment.

Paleofire studies at global scales reveal that high fire activity occurred during warm interstadials or interglacials, and low fire activity occurred during cold stadials or glacials (Power et al., 2008; Mooney et al., 2011; Marlon et al., 2013). These studies consider that the overall reduction in biomass was a severe constraint on fire regimes during the glacial. Namely, cold and dry climatic conditions influence severely on plant biomass, therefore available fuel for fire is limited. In this study, because the study area is located in south sub-tropic, warm and humid climate conditions lead to rich vegetation types, which means that climate change in a certain range may only result in changes in proportion of dominant trees or vegetation types, and may not cause obvious changes in plant biomass. Thus, the fuel biomass shall not be a constraining factor for fire activity in this study area, whereas the most important control factor of fire occurrence (or fire frequency) in the region is dry climate or high rainfall seasonality, particularly in the period prior to 4.3 ka. In addition, some other paleofire studies in the monsoon region of China also suggest the same factor controlling fire activity as this study (Fig. 1a). The charcoal and pollen records from peat section at Qindeli， northeastern China disclose that the frequency and intensity of fire are high in the dry period and low in the wet period (Li et al., 2005). A well-dated peat profile with high resolution charcoal and pollen records in the profile HE from the Sanjiang Plain, northeastern China indicates that low frequency regional and local fires responded to the strong summer monsoon during the interval ~6.0–4.5 ka, and then the fire frequencies increased significantly with the decline of the summer monsoon (Zhang et al., 2015). The pollen and charcoal records from a Jinchuan peat (northeastern China) indicate that a natural origin for fire event 1 (5.1 ka) was probably facilitated by drying environmental conditions and fire event 2 (1.3 ka) was caused by clearing (Jiang et al., 2008). The charcoal records in the Holocene loess–soil sequences (XJN: Xujianian, ETC: Ertangcun, JYC: Jiangyangcun, and DXF: Dongxiafeng) over the southern Loess Plateau of China suggest that local wildfires occurred frequently during the late last glacial period and the early Holocene before 8.5 ka. During the Holocene climatic optimum between 8.5 ka and 3.1 ka, natural wildfires were largely reduced. Levels of biomass burning were very high during the late Holocene, when the climate became drier and historical land-use became more intensive (Huang et al., 2006). The charcoal and pollen records from the two deep sea cores 17940 (taken by Sino-German joint cruise "SONNE-95" in 1994) (Sun et al., 2000) and 1144 (taken by ODP Leg 184 in 1999) (Luo et al., 2001) in the northern part of the South China Sea disclose that the high strength and frequency of natural fire corresponded to the drier climate during the glacials or stadials. This relationship between climate and fire in the monsoon region of China is different from that at global scale (Power et al., 2008; Mooney et al., 2011; Marlon et al., 2013), which may reveal that regional differences in climatic conditions determine vegetation type, fuel biomass and fire weather. However, it provides regional evidence for understanding the relationship between climate and fire that may be different under different climate conditions.

5.2 The relationship between fire activity and vegetation

Past effects of fire on vegetation may be revealed by correlations between charcoal and pollen records (Tinner et al., 1999, 2005; Colombaroli et al., 2007). In this study, pollen diversity indices and four main arboreal pollen types (tropical arbors, *Lithocarpus/Castanopsis*, evergreen oaks and *Alnus*) with the highest percentages in the pollen assemblage from Qinghai Lake were selected to discuss vegetation responses to fire by comparing them with the charcoal record (Fig. 4).

During the first two periods of high fire activity (the periods 18.5-15.0 ka and 13.0-11.5 ka), frequent and intensive fire activity was linked to high pollen percentages of evergreen oaks and relatively low *Alnus* pollen percentages. From the beginning of these two periods at 18.5 and 13.0 ka, evergreen oak pollen percentages declined gradually, while *Alnus* pollen percentages had no obvious change. When the high fire activity ended at 15.0 and 11.5 ka, evergreen oak pollen percentages continued to decline for a short time after going through frequent and strong fire events, while *Alnus* pollen percentages increased.

During the last period of high fire activity (the period 4.3-~1.0 ka), evergreen oak pollen percentages were very low, and *Alnus* pollen percentages were very high. At the beginning of the last period of high fire activity (at 4.3 ka), evergreen oak pollen percentages still declined gradually as the first two periods of high fire activity, whereas *Alnus* pollen percentages increased rapidly. When the high fire activity ended at ~1.0 ka, evergreen oak pollen percentages increased slightly, while *Alnus* pollen percentages decreased markedly.

These correlations between fire activity and the pollen record illustrate that evergreen oaks and *Alnus* are flammable plants. Evergreen oaks are able to withstand a degree of burning and continue growing despite gradual damage from fires. Thus, they are relatively fire-tolerant taxa. There are some different opinions about the responses of evergreen oaks to fire events. Trabaud (1990) suggests that evergreen oak can survive fire and can even re-sprout vigorously afterwards. Conedera and Tinner (2000) show that *Quercus ilex* is highly sensitive to fire disturbance under certain circumstances based on ecological studies. Reyes and Casal (2006) consider that fire has little negative effect on evergreen oak germination. Colombaroli et al. (2007) suggest that evergreen oak declines synchronously with fire-sensitive *Abies*. The reason for different responses of evergreen oak to fire events is likely different environment and evolutionary pressures for evergreen oak. The abundance of *Alnus* rapidly increased after the ending of frequent and strong fire activity before 4.3 ka, indicating that *Alnus* is a fire-adapted taxon. The adaptability of *Alnus* to fire events has been detected in the other regions such as Mediterranean area (Lago di Massaciuccoli, Tuscany, Italy) and the Oregon Coast Range of USA (Colombaroli et al., 2007; Long et al., 2007). The responses of *Alnus* to fire before 4.3 ka and after 4.3 ka are different, which may be influenced by human activity. *Alnus*, as a pioneer plant, responded rapidly to human activity from 4.3 ka (the beginning of the last high fire phase) and increased prior to the end of the frequent and intensive fire period (at ~1.0 ka). The marked reduction of *Alnus* after the end of the high fire activity at ~1.0 ka is probably caused by selective felling of human (Xiao et al., 2015).

The very low fire frequency and intensity between 10.4 and 4.3 ka corresponded to high *Lithocarpus/Castanopsis* and tropical arboreal pollen percentages. When the frequent and intensive fire activity began at 4.3 ka, *Lithocarpus/Castanopsis* and tropical arboreal pollen percentages declined rapidly. These suggest that the forests dominated by *Lithocarpus/Castanopsis* and/or tropical arbors are not easy to ignite, but are sensitive to frequent and intensive fire activity. Namely, *Lithocarpus/Castanopsis* and tropical arbors are fire-sensitive taxa in the study area, and frequent and intensive fire leaded to rapid decreases in their abundance.

Our result shows that high fire-episode frequency occurs in conjunction with forests comprised primarily of fire-adapted taxa and lower fire-episode frequency is associated with forest dominated by fire-sensitive taxa, which is consistent with the study at the Oregon Coast Range of USA (Long et al., 2007).

A comparison of fire activity and pollen diversity indices suggests that post-fire reactions of plant diversity before 4.3 ka and after 4.3 ka are significantly different. Before 4.3 ka, the frequent and intensive fire activity corresponded to relatively low plant diversity. At the beginning of the high fire activity (at 18.5 and 13.0 ka), plant diversity had not obviously changed. At the ending of the high fire activity (at 15.0 and 11.5 ka), plant diversity increased. The very low fire activity during the period 10.4-4.3 ka corresponded to high plant diversity. A similar response of plant diversity to fires is documented in Southern France that floristic richness increased markedly after fire (Trabaud and Lepart, 1980). However, the other studies suggest that there is a significant loss of plant diversity after fires in southern Switzerland (Tinner et al., 1999) and northern Tuscany of Italy (Colombaroli et al., 2007). The reason for this apparent contradiction is that forest ecosystems are naturally fire-sensitive, because fire tends to destroy the large biomass investments of trees. In contrast, fire-adapted communities that might have originated partly as a consequence of forest disruption may be favoured or even preserved by fire incidence (Colombaroli et al., 2007).

After 4.3 ka, the high fire activity (the period 4.3-~1.0 ka) was linked to relatively high plant richness and relatively low plant evenness. At the beginning of the high fire activity (at 4.3 ka), plant richness had no obvious change, yet plant evenness declined rapidly. At the ending of the high fire activity (at ~1.0 ka), plant richness declined slightly, while plant evenness increased markedly. The possible reason for the different post-fire reactions of plant diversity before 4.3 ka and after 4.3 ka is that vegetation was influenced by human activity after 4.3 ka.

Flammability of different forest types and a fire-sensitivity ranking for main plant types are helpful for forest management and restoration after fires. In the study area, evergreen oak forest and *Alnus* forest are flammable and in order to prevent potentially destructive fires, there is a need to pay greater attention to the origins and control of fire events. Fortunately, *Alnus* forest is easy to restore after fires if it isn't cleared by human activity. Evergreen oak forest needs a longer time to restore after fires even if it isn't influenced by human activity. The forests dominated by *Lithocarpus/Castanopsis* and/or tropical arbors are not easy to ignite because of their relative inflammability. However, if frequent and intensive fire events occur in or adjacent to the forests dominated by *Lithocarpus/Castanopsis* and/or tropical arbors there is a greater risk for these forests to be impacted by major fire events. Furthermore, the forests dominated by *Lithocarpus/Castanopsis* and/or tropical arbors are difficult to restore after fires highlighting the need to prevent fires in these highly vulnerable forest types.

6 Conclusions

This study about linkages of fire history, climatic change, human activity, and vegetation demonstrates that fire was mainly controlled by climate before 4.3 ka and by combined action of climate and humans after 4.3 ka. The frequent and intensive fire activity occurred under cold and moderately dry conditions or during the periods accompanied by human activity. Unusual or weak fire activity occurred under warm and humid conditions or during the periods with the temperature and humidity increasing. This relationship between climate and fire in the study area is different from that at global scale.

Fire was an important disturbance factor in the vegetation changes and played an important role in the forest dynamics and characteristics of the flora around the study area. The correlations between fire activity and vegetation reveal that evergreen oaks and *Alnus* are flammable plants and respond positively to fire events. The forests dominated by *Lithocarpus/Castanopsis* and/or tropical arbors are not easy to ignite. A fire-sensitivity ranking for main arboreal plant types in the study area is that *Alnus* is a fire-adapted species; evergreen oaks are fire-tolerant taxa; *Lithocarpus/Castanopsis* and tropical arbors are fire-sensitive taxa. However, vegetation responses to fire before 4.3 ka are not consistent with that after 4.3 ka, which points to the possibility that vegetation and fire regimes were influenced by human activity after 4.3 ka. Before 4.3 ka, when vegetation was mainly influenced by natural controls, frequent and intensive fire activity reduced plant diversity, and plant diversity increased after fires. Since vegetation was influenced by a mixture of natural processes and anthropogenic activity (at 4.3 ka), the post-fire responses of vegetation have changed and their relationships have become complex.

Our results are important for enhancing our predictions of the influence of climatic change on future fire activity and making appropriate management policies for forest ecosystems. However, because these results came only from a single lake site, it is necessary that further lacustrine sites from southwestern China are studied to improve our understanding of vegetation-climate-fire interactions.

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Table

Table 1. AMS radiocarbon dates from Qinghai Lake (core TCQH1).

Lab code[a]	Depth (cm)	Materials	^{14}C date (yr BP)	Error (±yr)	Calibrated age (cal. yr BP, 2σ)	Mid-point (cal. yr BP)
NZA 35976	152	plant macrofossil	908	15	846-914	880
NZA 35977	208	plant macrofossil	2802	20	2860-2960	2910
BETA 308448	255	plant macrofossil	3410	30	3575-3725	3650
NZA 35979	255	bulk sediment	3590	20	3833-3927	3880
BETA 308449	322	plant macrofossil	4700	30	5320-5420	5370
NZA 35981	353	bulk sediment	5842	25	6619-6741	6680
BETA 308451	416	plant macrofossil	7080	40	7834-7986	7910
NZA 35986	453	bulk sediment	8477	30	9464-9536	9500
BETA 308452	476	plant macrofossil	8630	40	9537-9683	9610
BETA 308453	521	plant macrofossil	9410	40	10555-10745	10650
NZA 35982	560	bulk sediment	10986	40	12674-12986	12830
BETA 308454	571	plant macrofossil	10310	40	11976-12224	12100
NZA 35983	610	bulk sediment	10737	40	12563-12737	12650
NZA 35980	714	bulk sediment	12803	45	14913-15647	15280
BETA 327101	715	plant macrofossil	12290	50	13952-14588	14270
NZA 35988	813	bulk sediment	15360	110	18479-18861	18670
BETA 327102	817	plant macrofossil	15100	60	18022-18378	18200

a: Samples with BETA code are measured at the Beta Analytic Radiocarbon Laboratory; samples with NZA code are measured at Rafter Radiocarbon Laboratory.

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Figures

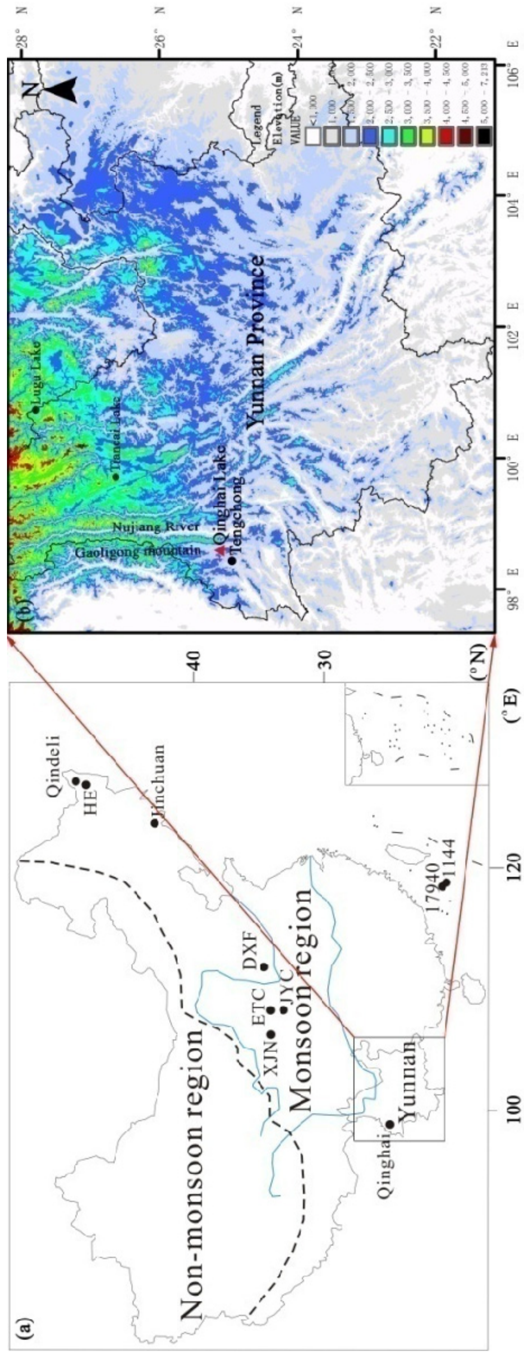

Figure 1. (a) The sketch map of monsoon and non-monsoon regions in China and other sites mentioned in text (XJN: Xujianian; ETC: Ertangcun; JYC: Jiangyangcun; DXF: Dongxiafeng). (b) Topographic map of southwestern China and the location of Qinghai Lake.

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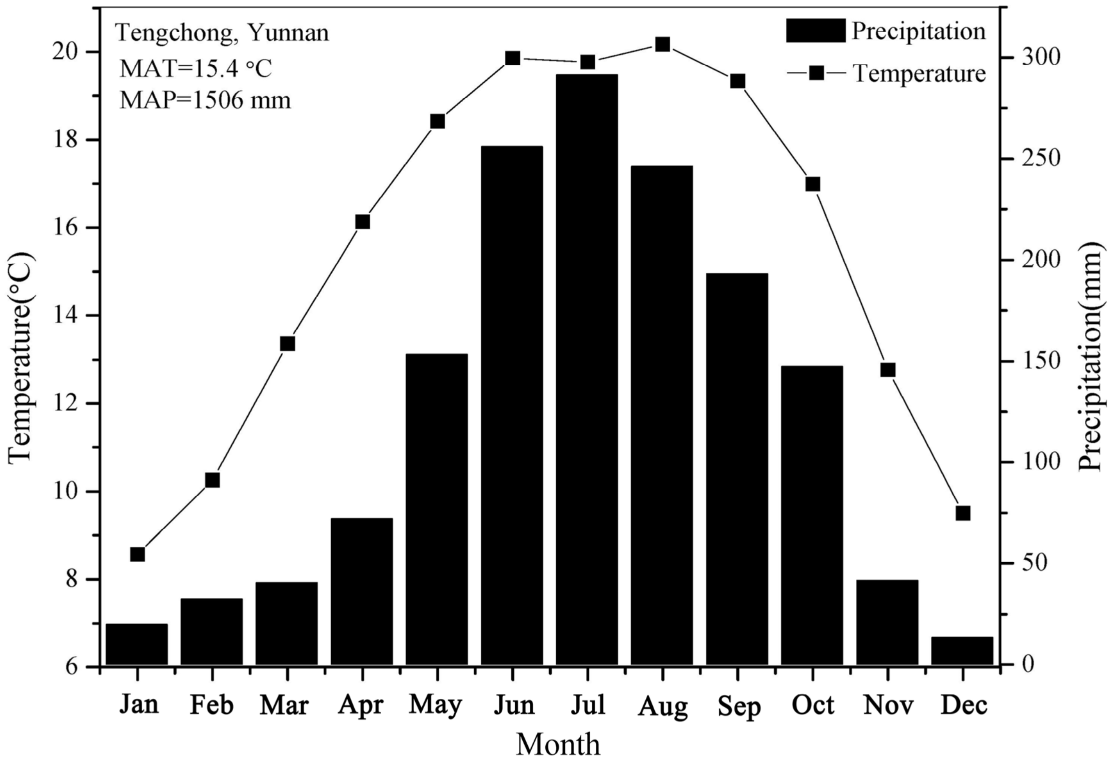

Figure 2. Climate diagram from Tengchong meteorological station near Qinghai Lake showing monthly temperature and precipitation. These data are 34-year climate averages for the period 1980-2013. MAT: mean annual temperature; MAP: mean annual precipitation.

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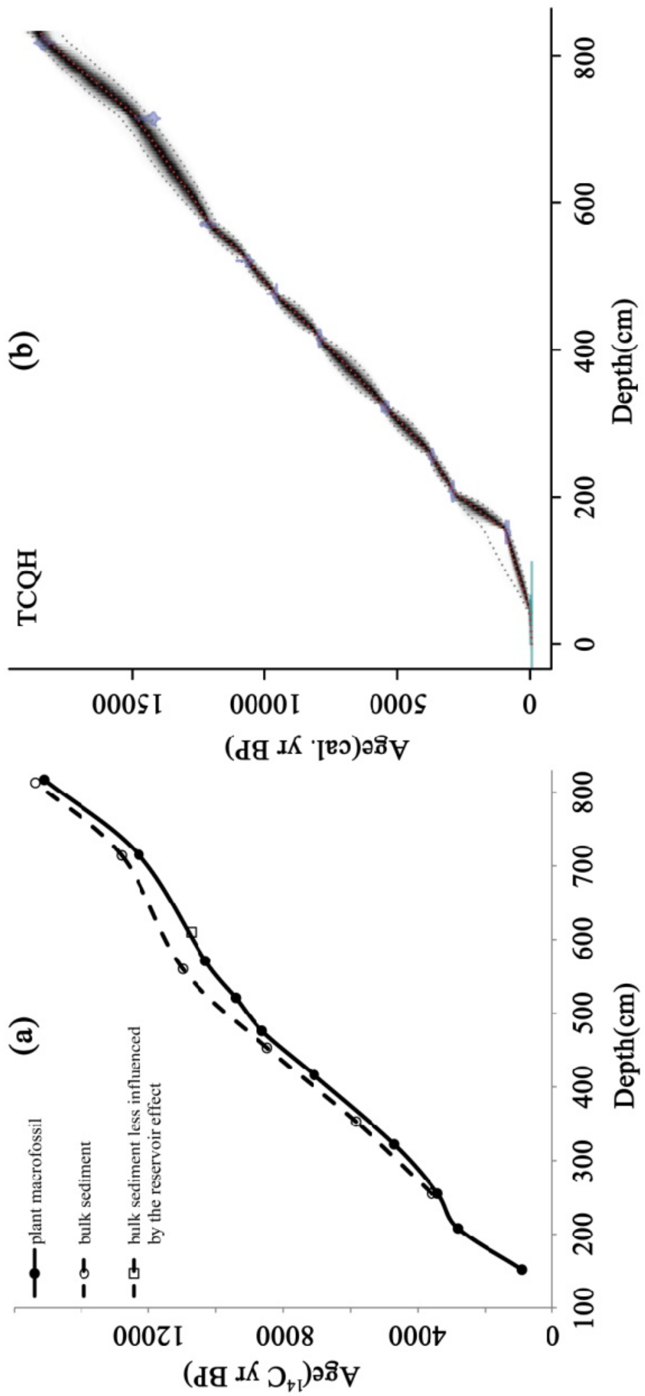

Figure 3. (a) The reservoir effect for the bulk sediment dates with the plant macrofossil dates from Qinghai Lake. (b) Age-depth model for Qinghai Lake using Bayesian method (Blaauw and Christen, 2011). Grey-scales indicate all likely age-depth models, and dotted lines indicate the 95% confidence ranges. Star shapes show 13 calendar ages.

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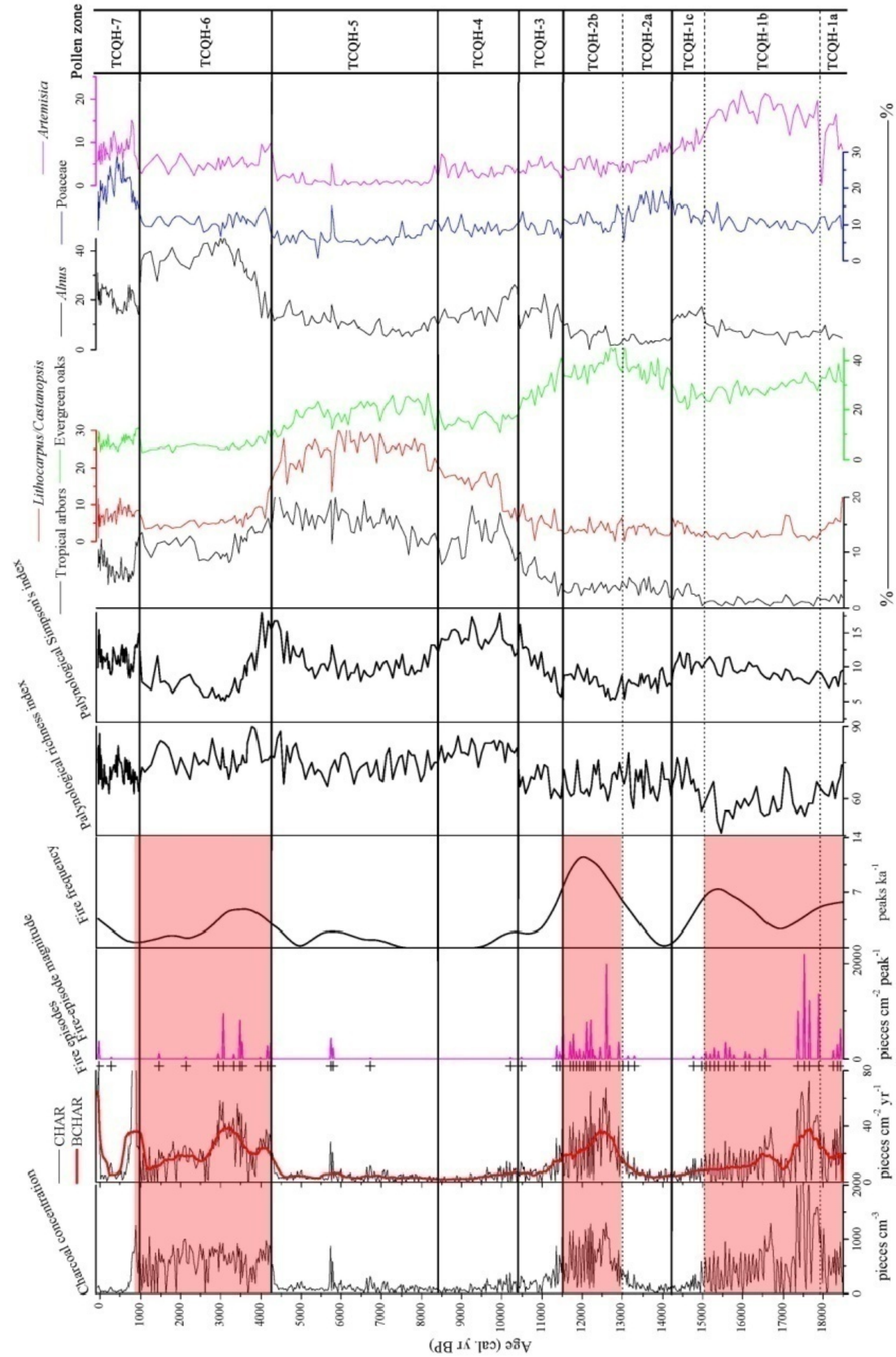

Figure 4. Results from charcoal analyses, pollen diversity indices, and percentages of six main pollen taxa from Qinghai Lake. The red shadings indicate the three periods with high fire activity.

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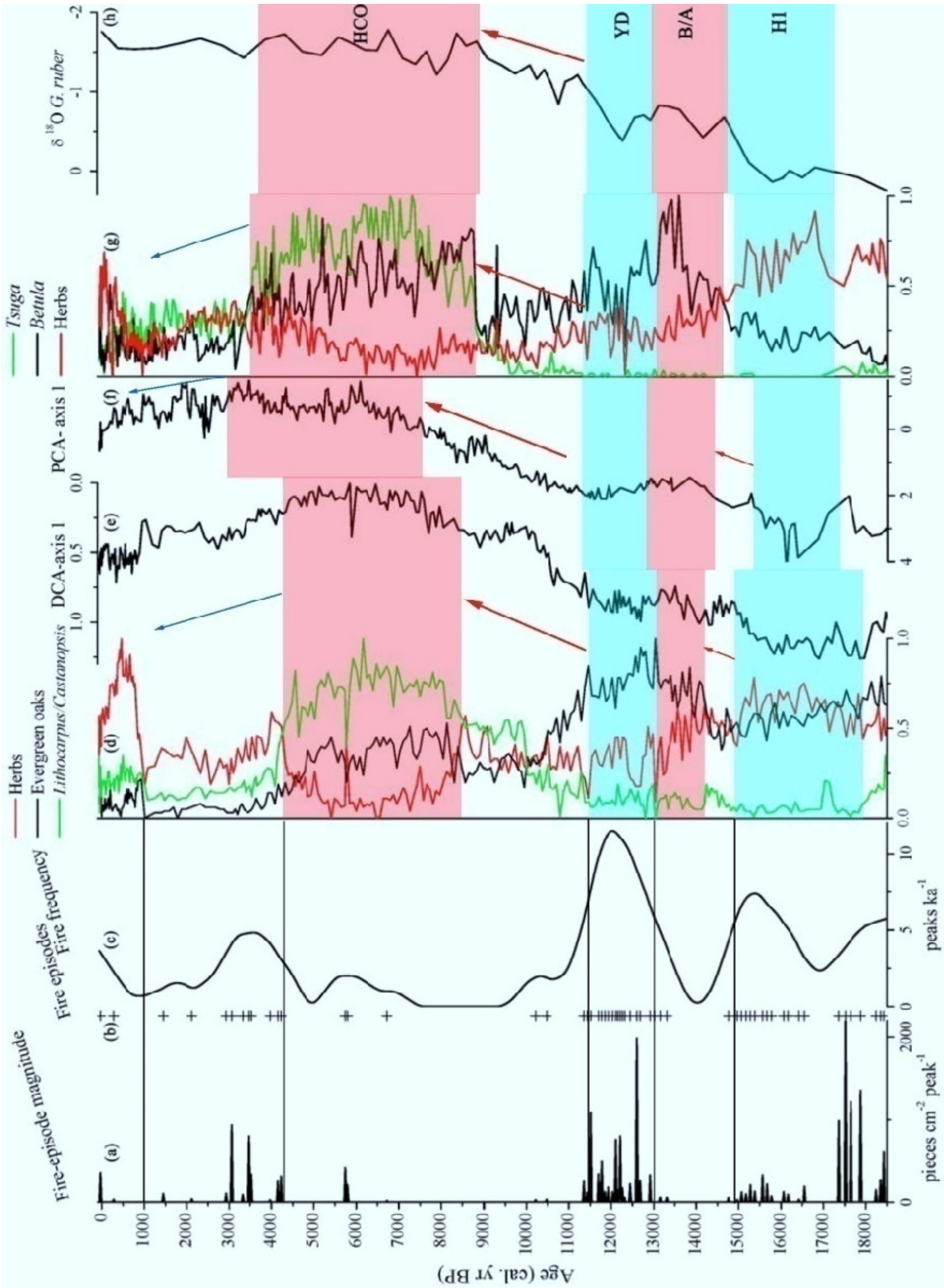

Figure 5. A comparison of fire activity from Qinghai Lake and climate proxies from the southwest monsoon regions. (a) Fire-episode magnitude. (b) Fire episodes. (c) Fire frequency. (d) Standardized data of pollen percentages of *Castonopsis/Lithocarpinus* (green line), evergreen oaks (black line), and herbs (red line) from Qinghai Lake (this study). (e) DCA axis 1 sample score of pollen data from Qinghai Lake (Xiao et al., 2015). (f) PCA axis 1 sample score of pollen data from Tiancai Lake (Xiao et al., 2014a, b). (g) Standardized data of

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pollen percentages of *Tsuga* (green line), *Betula* (black line), and herbs (red line) from Lugu Lake (Wang et al., 2012). (h) The $\delta^{18}O$ record of the planktic foraminifera *G. rubber* for core NOIP905, western Arabian Sea (Huguet et al., 2006). The light green shadings indicate relatively cold and dry periods (H1 and YD). The red shadings indicate relatively warm and humid periods (B/A and HCO). The red lines with arrows indicate increases in temperature and precipitation. The blue lines with arrows indicate climate cooling and drying.