Response to the Editor:

Editor Decision: Reconsider after major revisions (13 Sep 2016) by Dr Nathalie Combourieu Nebout
Comments to the Author:
Dear authors,

I have carefully read your response to reviewers and had a look on what you proposed to modify your manuscript accordingly.

Reviewer 2 asked major revisions and I agree with this decision. You propose a collection of corrections but it appears that several of them are not sufficiently discussed or not enough detailed in the text. Please see the following comments and remarks.

Response:
Dear Editor Nebout,

Thank you very much for your careful observation and comments. We revised the manuscript according to your comments and remarks. A point-by-point response to your comments and all relevant changes made in the revised manuscript are listed as follows. Please see the file "Response to the Editor" and the marked-up manuscript version for detail.

We hope we successfully complied with the comments and remarks, and we appreciate your detailed reviews and suggestions.

Kind regards,
Xiayun Xiao
In name of all the co-authors.

1- The reviewer 2 ask you to remove figure 3 and not figure 2. I would like you conserve this picture. I think that the figure 2 is informative for local climate. However, it will be better to add this "ombrothermic" diagram directly on figure 1. It will have a sense as you show a map with the location of the site and the nearby towns. In this figure localities names and elevations values on the coloured map on the right are too small or too light and then unreadable. What is the little rectangle on the right and at the base of the map at left, it is completely unreadable.
Response: Thank you very much for your detailed comment. We conserve figure 2 and add this "ombrothermic" diagram directly on figure 1. The coloured map on the right of figure 1 has been modified. The little rectangle on the right and at the base of the map at left is the nine-dash line in the South China Sea, namely the traditional maritime boundary line of China. The black dots in the nine-dash line represent the islands in the South China Sea. In the revised figure 1, we add the words "islands in the South China Sea" in the little rectangle to illustrate meaning of the little rectangle. Please see the revised figure 1 for detail.

2- Reviewer 1 ask you about the concentration compared to percentages. This have to be discussed in the method. Your choices have to be described as they are the base of discussion. Perhaps you can show the figures proposed in your response as additional data and only justify your choices in the text with reference to the additional document
Response: According to the comment, we add a paragraph about selection of percentages or concentrations of the main pollen taxa in the method. The figures (Fig. SF1 and SF2) in this paragraph are served as an additional document, and it is cited in the text. Please see lines 6-18 page 5 in the marked-up manuscript version and Fig. SF1 and SF2.

3- As the two reviewers, I think that the relation between plant and fire sensitivity is not sufficiently developed (in the

revised version too). In fact you add some words but it remains insufficient as you use largely the opposition between fire-adapted and fire non-adapted plants or groups of plants. You have to explain more which taxa are fire sensitive and which are not in your record. Perhaps it will be good to add a paragraph on that when describing the vegetation or in the methods. This discussion has to be supported by references in my opinion. It is important to reinforce your paper discussion. You begin an explanation in the response but it is not developed in the corrected manuscript in my opinion. Your sentence about the vegetation of the Hengduan Mountain is not sufficient. What is requested is a detail about which taxa are expected to be burned preferentially and which not, based on observations (present day or past data).
It will be good to use references such as Zhang et al 2015 before page 7 in this discussion.

Response: According to the comment, we add a paragraph to explain which taxa are fire sensitive and which are not in our record. Please see lines 3-20 page 4 in the marked-up manuscript version for detail.

We also add some discussion in the Discussion section according to these results of modern ecological studies on these main taxa in the record. Please see lines 20-31 page 13 and lines 19-25 page 14 in the marked-up manuscript version for detail. Accordingly, the conclusion is slightly changed. Please see lines 3-8 page 16 in the marked-up manuscript version for detail.

Some references such as Zhang et al 2015 have been cited in the Introduciton section. Please see lines 6-7 and 15-18 page 2 in the marked-up manuscript version for detail.

4- Concerning the standardization of your data, rephrase your sentence, it remains unclear. Explain more.

Response: We rephrase the sentence about the data standardization in the revised manuscript. Please see lines 4-7 page 6 in the marked-up manuscript version for detail.

5- You changed the zonation labelling. OK it was requested by reviewer 2. However the pollen zonation may be still traced on the figure I front to the charcoal one (used in the text) for a link to other papers even if it is not commented in the text (only mentioned in the figure with the reference to the published paper).

Response: Considering synthetically the comments of the editor and the reviewer 2, the pollen zonation (from TCQH-1 to TCQH-7) was added in the figure 2, which will make the link with the other published paper based on pollen data. At the same time, we add some words in the Result section to illustrate the relationship between charcoal zone and pollen zone. Please see the revised figure 2 and line 23 page 6, lines 1-3, 12, 20-23, 30 page 7, and lines 8, 16 page 8 in the marked-up manuscript version for detail.

6- As commented by the reviewer 2 there is difference in the time span of the H1 event in the studied record and the theoretical interval. The H1 has been defined in North Atlantic and you have to respect the chronology established there. If your event does not cover the whole interval or extend more or if you have differences and specificity in China, please explain more and discuss this fact.

Response: We added some discussion about the H1 in our study area. Please see lines 28-32 page 9 and lines 1-2 page 10 in the marked-up manuscript version for detail. Namely, we synthesized the results of Qinghai Lake, Tiancai Lake, and Lugu Lake located in different latitudes and altitudes in western Yunnan Province. Because of the different responses of the three study sites to global climate change and age uncertainty, the H1, B/A, and YD are considered to have occurred during the periods 17.5±0.5~15.4±0.4 ka, 14.4±0.2~12.9±0.1 ka, and 12.9±0.1~11.5 ka in western Yunnan Province, respectively. The time of the H1 is almost consistent with the date defined by Sanchez Goñi and Harrison (HS1 is between 18 to 15.6 kyr cal BP) (Sanchez Goñi and Harrison, 2010).

The sentense "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." is not very accurate. We modified it into "the frequent and intensive fire activity during the periods 18.5-15.0 ka and 13.0-11.5 ka corresponded to the relatively cold period before the H1 and the H1, and the YD, respectively." Please see lines 12-13 page 10 in the marked-up manuscript version for detail.

Sanchez Goñi, M. F. and Harrison, S. P.: Millennial-scale climate variability and vegetation changes during the Last Glacial: Concepts and terminology, Quaternary Sci. Rev., 29, 2823–2827, 2010.

7- I agree with reviewer 2 about Artemisia and Poaceae significance. If you interpret as human influence, you have to justify more. Have you Cereals pollen since 4.3kyr? if not Poaceae occurrence even in high percentage do not be explained by human influence and Artemisia is then considered as expressing climate response of the vegetation. Perhaps you have other arguments to assess human impact sinde 4.3 kyr.

Response: It is difficult to separate cereal pollen from Poaceae pollen. Based on studies of the characteristics of modern Poaceae pollen, Poaceae grains with diameters greater than 40 μm were usually classified as cereal-type (Lamb et al., 2003; Huang and O'Connell, 2000). In our study, Poaceae grains with diameters greater than 40 μm began to occur at 18.5 ka and its pollen percentages had no obvious change (Fig. SF3), which didn't reflect changes of human activity. Thus, the criterion of cereal pollen (Poaceae grains with diameters greater than 40 μm) may be not applicable in this study area. Studies on the characteristics of modern Poaceae pollen in Yunnan Province are needed for redefining the criterion of cereal pollen for this study area.

Because cereal pollen was not separated from Poaceae pollen, we can not still explicitly declare that increase of Poaceae pollen percentages is an indication of human activity. Thus, we deleted the sentence "Pollen indicative of human activities (e.g., Poaceae and *Artemisia*) unambiguously increased from 4.3 ka.". However, because cereal pollen was not separated from Poaceae pollen, we can not rule out the possibility of increase in human activity when Poaceae pollen percentages increased. At the same time, combined with the other signals in the pollen assemblage (such as the rapid degradation of the primary evergreen broadleaved forest) and the archaeological records (such as Neolithic culture began to emerge at around 4 ka or a little earlier), we speculate 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 0.8 ka.

Thus, we add these contents in the revised manuscript. Please see lines 25-32 page 10 and lines 1-6 page 11 in the marked-up manuscript version for detail.

Lamb, H., Darbyshire, I., Verschuren, D.: Vegetation response to rainfall variation and human impact in central Kenya during the past 1100 years, The Holocene, 13(2), 285-292, 2003.

Huang, C.C., and O'Connell, M.: Recent land-use and soil-erosion history within a small catchment in Connemara, western Ireland: evidence from lake sediments and documentary sources, Catena, 41, 293–335, 2000.

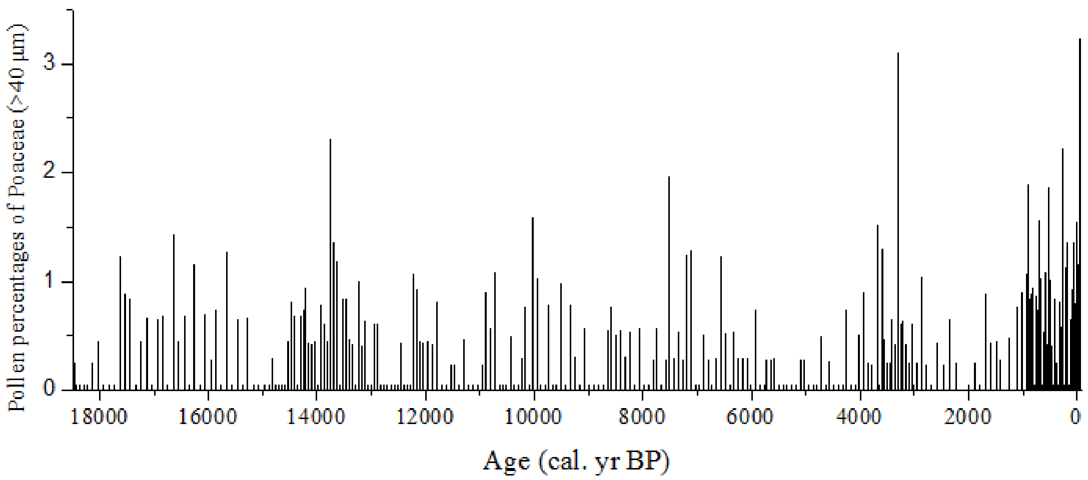

Fig. SF3 Pollen percentages of Poaceae (>40 μm) since 18.5 ka in Qinghai Lake.

8- The reference of Marlon has not been deleted in the bibliography of the manuscript I received.

Response: Thank you very much for your careful observation. We deleted the reference of Marlon in the bibliography of the revised manuscript.

This paper is certainly interesting and brings new approach of the data presented within the text and figures. However I would welcome a new version implemented accordingly to the additional comments and corrections that I request and a reply to my remarks listed above. I would probably send the paper back to other reviewers on receipt.

sincerely yours

Nathalie Combourieu-Nebout

Response: We appreciate very much your positive comments on the manuscript. According to your comments and remarks, we revised carefully the manuscript and address each comment with explanation as above. Please see the file "Response to the Editor" and the marked-up manuscript version for detail.

We hope we successfully complied with the comments and remarks, and we appreciate your detailed reviews and suggestions.

Postglacial fire history and interactions with vegetation and climate in southwestern Yunnan Province of China

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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 4.3-0.8 ka, respectively. This record was compared with major pollen taxa and pollen diversity indices 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 comparisons 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). Recently, black carbon was also gradually used as evidence of fire history reconstruction (Schmidt and Noack, 2000; Wang et al., 2013; Wolf et al., 2014). 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 (Zhao et al., 2005). 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., 2015a), and studies in southern China are relatively few (Sun et al., 2000; Luo et al., 2001; Xiao et al., 2013), especially in southwestern China, are relatively few. In southwestern China, there is only one study that reconstructed fire history by using black carbon (Zhang et al., 2015b). These 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.

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. The study about forest fire during 1982-2008 in Yunnan Province shows that forest loss rates due to forest fire in different vegetation zones are different. The highest forest loss rate occurs in zone of semi-humid evergreen broadleaved forest dominated by *Cyclobalanopsis glaucoides* and evergreen oaks and *Pinus yunnanensis* forest. Secondly, forest loss rate in zone of monsoon evergreen broadleaved forest dominated by *Castanopsis* and *Lithocarpus* is relatively low. Forest loss rate in zone of tropical rainforest and monsoon forest is lower than that in the former two vegetation zones (Chen et al., 2012). A low resolution charcoal record from Qinghai Lake in southwestern Yunnan Province of China was briefly mentioned in Xiao et al. 2015. Here, we presented a high-resolution and continuous macroscopic charcoal record spanning about 18.5 ka from the same core, and specially analyzed the fire event history and fire regime dynamics through time in southwestern Yunnan Province based on the charcoal record. Combined with the climate records and vegetation histories since 18.5 ka, reconstructed in Xiao et al. (2015), the main controlling factors of forest fire dynamics and the relationship between fire activity and vegetation were examined in this study. These results provide new evidences 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 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 (Wang et al., 2002). 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 Westerlies 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 records a mean annual temperature of 15.4°C and mean annual precipitation of 1506 mm (Fig. 1c). Most of the precipitation is concentrated in the rainy season from May to October, which is 85% of the annual precipitation (Xiao et al., 2015).

Qinghai Lake is located within zone of semi-humid evergreen broadleaved forest in Hengduan Mountains of western Yunnan Province, whose south is adjacent to zone of monsoon evergreen broadleaved forest of southwestern Yunnan Province (Wu et al., 1987). 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).

In our published pollen record from Qinghai Lake (Xiao et al., 2015), *Alnus*, evergreen oaks and *Lithocarpus/Castanopsis* are dominant tree taxa. The proportion of tropical arbors comprised mainly of *Altingia*, *Ficus*, *Pentaphylax*, *Schima*, *Symplocos*, *Camellia*, *Eurya*, and *Mallotus/Macaranga* is relatively high in the forests. And *Pinus*, *Betula* and deciduous oaks also often occur. At present, studies on combustibility of these plant species are mainly concentrated in experimental analysis. A study on fire resistance of 13 main tree species from subtropical zone in China shows that fire-resistant ability of broadleaved tree species is stronger than that of coniferous tree species (Shu et al., 2000). The trade standard for forestry in People's Republic of China (State Forestry Administration of China, 2008) suggests that *Pinus* spp. and *Quercus* spp. are identified as flammable class; *Alnus* spp., *Castanopsis* spp. and *Schima* spp. are identified as uninflammable class; and *Betula* spp., *Cryptomeria* spp. and *Cunninghamia lanceolata* fall in between these two classes. The experimental results about the combustion characteristics of 48 tree species from south China show that the fire-resistant ability of *Alnus nepalensis*, *Schima superba*, *Camellia oleifera*, *Altingia gracilipes*, *Exbucklandia populnea*, and *Myria rubra* is very strong (Tian et al., 2001). The combustion test results of 40 common tree species from Jiangxi Province suggest that *Symplocos setchuensis*, *Schima superba*, *Castanopsis sclerophylla*, and *Camellia oleifera* et al. are the strongest fire-resistant tree species (Zhen et al., 2012). *Ficus microcarpa*, *Eurya macartneyi*, and *Pentaphylax euryoides* et al. are selected as tree species of biological fire prevention belt in city because of their strong fire resistence (Lu, 2005). Combustion experiments of 25 woody plants from Kunming, Yunnan Province show that *Alnus nepalensis*, *Camellia aleifera*, and *Eurya groffii* et al. are uninflammable tree species (Li et al., 2009).

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. The core was 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 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-depth model for the core has been established in the previously published study (Xiao et al., 2015), based on the ^{210}Pb and ^{137}Cs dates and the AMS ^{14}C dates and using the recently developed Bayesian method (Blaauw and Christen, 2011). According to the 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 (Fig. 2).

3.2 Selection of percentages or concentrations of the main pollen taxa

Pollen concentration is usually used as a proxy indicator of vegetation density or biomass productivity and thus climatic condition (Grosjean et al., 2007). However, apart from biomass productivity, some other factors such as the lithology, the sedimentation rate, input of inwashed material, detritus content, within-lake sedimentary processes et al. may confuse the records of real changes in pollen concentration (Hicks and Hyvärinen, 1999). In this study, biomass productivity and climatic conditions revealed by total pollen concentration are not exactly consistent with those disclosed by pollen percentage assemblage (Fig. SF1). For example, the lowest pollen concentrations during the period 14.5-13.0 ka BP might not indicate unfavourable climatic conditions, and might be caused by the high detritus content under conditions of rising humidity and intensified surface run-off. In addition, the tendencies of the concentrations and percentages for the 6 main pollen taxa are almost consistent except for some differences during the period 14.5-13.0 ka BP (Fig. SF2). Thus, considering that the impact factors of the pollen concentration are complicated in this study, we use only pollen percentages for the main pollen taxa.

3.~~2~~ 3 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 is not 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, ~~in order to see more clearly the interrelation among the variations of the selected pollen type percentages,~~ we use min-max normalization to standardize pollen percentages, which can ~~and~~ eliminate the influence of their values and better visualize the interrelation among percentage variations of the selected pollen types in the same panel of one figure. The formula 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~~ 4 Fire event identification

Fire events were recognized by separating the macroscopic charcoal accumulation rates (CHAR; particles/cm^2/a) into CHAR background (BCHAR) and CHAR peak (PCHAR) components by using CharAnalysis software (Higuera 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/ka) is the sum of the total number of fires within a 1000-a period, smoothed with a Lowess smoother. Fire-episode magnitude (particles/cm^2/episode) is the total charcoal influx in an episode and varies with fire size, intensity, proximity, and taphonomic processes (Whitlock et al., 2006; Huerta et al., 2009; Walsh et al., 2010).

4 Results

The macroscopic charcoal and fire activity records were divided into six zones (from TCCC-1 to TCCC-6) based on their variations (Fig. 2). The characteristics of the charcoal record, fire event reconstruction and pollen diversity indices in these zones were described as follows. At the same time, they were compared to major pollen taxa and previous vegetation reconstruction for the same core (Xiao et al. 2015). In order to make the link with the published paper based on pollen data (Xiao et al. 2015), the pollen zonation (from TCQH-1 to TCQH-7) was kept in the figure 2.

Zone TCCC-1 (18.5-15.0 ka), corresponding to the pollen subzones TCQH-1a and TCQH-1b: Charcoal concentration and CHAR (including BCHAR) in this zone were relatively high. Charcoal concentration averaged 585.6 particles/cm^3. CHAR ranged from 0 to 72.4 particles/cm^2/a with an average of 16.9 particles/cm^2/a. 19 fire episodes were registered by charcoal peaks. Fire-episode magnitude varied greatly from 32.6 to 2189.2 particles/cm^2/episode with an average of 446.8 particles/cm^2/episode. Fire frequency ranged from 2.4 to 7.4 episodes/ka with an average of 4.9 episodes/ka. Palynological richness index was very low (mean of 59.6) and Simpson's index was relatively low (mean 9.1). The vegetation type during the period was semi-humid evergreen broadleaved forest dominated by evergreen oaks with relatively more dry-tolerant herbs such as *Artemisia* and Chenopodiaceae (Xiao et al., 2015).

Zone TCCC-2 (15.0-13.0 ka), corresponding to the pollen subzones TCQH-1c and TCQH-2a: Charcoal concentration and CHAR decreased markedly, averaging 114.5 (ranging from 6.7 to 412.3) particles/cm^3 and 5.2 (ranging from 0.1 to 21.4) particles/cm^2/a, respectively. Only one significant fire episode was noted in the bottom of this zone (fire-episode magnitude: 58.4 particles/cm^2/episode) and two fire episodes were registered in the top of this zone (their fire-episode magnitudes are both at 63 particles/cm^2/episode). Fire frequency declined first from 5.7 episodes/ka to 0.2 episodes/ka and then increased to 5.1 episodes/ka with an average of 2.3 episodes/ka. Palynological richness index increased markedly, averaging 67.6. Simpson's index increased first to 12.2, then decreased to an average of 8.2. In this zone, the vegetation type was still semi-humid evergreen broadleaved forest, but the dominant plant species evergreen oaks retreated first (in the pollen subzone TCQH-1c) and then expanded gradually (in the pollen subzone TCQH-2a), whereas *Alnus* expanded first (in the pollen subzone TCQH-1c) and then decreased (in the pollen subzone TCQH-2a), and dry-tolerant herbs (e.g. *Artemisia*) decreased significantly (Xiao et al., 2015).

Zone TCCC-3 (13.0-11.5 ka), corresponding to the pollen subzone TCQH-2b: This zone had the highest charcoal concentration and CHAR for the entire core, averaging 636.2 (ranging from 92.3 to 1806.2) particles/cm^3 and 25.1 (ranging from 0.4 to 67.7) particles/cm^2/a, respectively. Fire episodes occurred frequently, and their magnitudes average 426.4 particles/cm^2/episode, ranging from 0.02 to 1984.4 particles/cm^2/episode. Fire frequency was the highest for the profile, average 9.2 episodes/ka. In this zone, palynological richness and Simpson's indices were relatively low, averaging 66.6 and 7.5, respectively. The vegetation type during the period was semi-humid evergreen broadleaved forest dominated by evergreen oaks with low *Artemisia* (Xiao et al., 2015).

Zone TCCC-4 (11.5-4.3 ka), corresponding to the pollen zones TCQH-3, TCQH-4, and TCQH-5: Charcoal concentration and CHAR remained very low in this zone. Average charcoal concentration was 113.8 particles/cm^3. CHAR values ranged from 0 to 31.1 particles/cm^2/a with an average of 4.1 particles/cm^2/a. Three fire episodes were registered in the lower part of this zone (at 11.3, 10.4 and 10.2 ka, respectively) with low fire-episode magnitudes (253.5, 32.7 and 29.3 particles/cm^2/episode, respectively). In addition, three fire episodes were registered at ca. 6.7, 5.8 and 5.7 ka, respectively. Their fire-episode magnitudes were 18.3, 212.7 and 417.1 particles/cm^2/episode, respectively. Fire frequency was very low with an average of 1.1 episodes/ka. Palynological richness and Simpson's indices were relatively high, averaging 74.9 and 11.6, respectively. The vegetation type during the period changed gradually from semi-humid evergreen broadleaved forest to monsoon evergreen broadleaved forest dominated by *Lithocarpus/Castanopsis*, evergreen oaks and tropical arbors (Xiao et al., 2015).

Zone TCCC-5 (4.3-0.8 ka) (corresponding to nearly the pollen zone TCQH-6) was characterized by a marked increase in charcoal concentration and CHAR compared with Zone TCCC-4, averaging 589.7 particles/cm^3 and 23.9 (ranging from 0 to 122.2) particles/cm^2/a, respectively. Ten fire episodes were noted in the zone. Fire-episode magnitude varied from 26.3 to 939.4 particles/cm^2/episode (mean of 303.4 particles/cm^2/episode). Fire frequency averaged 2.6 episodes/ka, ranging from 0.7 to 4.8 episodes/ka. Palynological richness index had no obvious changes compared with the previous zone, while Simpson's index decreased rapidly (mean of 9.1). In this zone, the primary evergreen broadleaved forest was rapidly replaced by deciduous broadleaved forest dominated by *Alnus* (Xiao et al., 2015).

Zone TCCC-6 (after 0.8 ka), corresponding to nearly the pollen zone TCQH-7: Charcoal concentration was very low, averaging 62.3 particles/cm^3. CHAR (including BCHAR) first decreased markedly to mean of 6.8 (ranging from 0.7 to 27.1) particles/cm^2/a, then increased to mean of 58.8 particles/cm^2/a since 1940 AD. Two fire episodes were registered at 0.3 ka and 1986 AD (fire-episode magnitudes: 33.7 and 359.7 particles/cm^2/episode), respectively. Fire frequency was relatively low, averaging 1.8 (ranging from 0.7 to 3.3) episodes/ka. Palynological richness index declined slightly (mean of 70.8), and Simpson's index increased significantly (mean of 10.9). In this zone, the greater open vegetation was present in the region, the area of *Alnus* forest quickly decreased, and the proportion of tropical arboreal plants declined, whereas the secondary semi-humid evergreen broadleaved forest recovered (Xiao et al., 2015).

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 4.3-0.8 ka. Between 15.0 and 13.0 ka, fire episodes first rapidly decreased in frequency and intensity, then gradually increased.

From 11.5 to 4.3 ka, fire frequency and intensity was at a low level as a whole, and there were only six fire episodes with low intensity at 11.3, 10.4, 10.2, 6.7, 5.8 and 5.7 ka. Between 0.8 ka and 1940 AD, only one weak fire episodes were noted, and fire frequency and intensity were relatively low. Since 1940 AD, due to the high sedimentation rate (Fig.2), CHAR (including BCHAR) increased markedly although the charcoal concentration was still very low, which indicates relatively intensive fire activity. The black carbon content of the same core reveals three periods of high fire activity: 18.5-15.0 ka BP, 13.0-11.5 ka BP, and 8.0-~0.9 ka BP (Zhang et al., 2015b). Comparison of fire activity results revealed by the two proxies shows that the start and end times of the first two periods of high fire activity are consistent, whereas the start times of the last period of high fire activity are different. The pollen record reveals that vegetation type was monsoon evergreen broadleaved forest dominated by *Castanopsis/Lithocarpus*, and the climate was warm and humid during the period 8.5-4.3 ka BP (Xiao et al., 2015). The warm and humid climate resulted in high biomass productivity, which may make plant remains fallen into the lake be not completely decomposed and be partly carbonized. The carbonized plant remains can be distinguished when macroscopic charcoal particles are counted under the stereomicroscope, whereas they can not be separated when black carbon is measured. These may result in the different fire activity results during the period ~8.0-4.3 ka BP.

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. 3d, 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. 3e, 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 change from warm to cold from low scores to high scores (Fig. 3f). 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 selected as a synthetic climatic proxy (Fig. 3g, Wang, 2012). These pollen proxies from Qinghai Lake (Fig. 3d, e), Tiancai Lake (Fig. 3f), and Lugu Lake (Fig. 3g) 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. Because the different responses of the three study sites located in different latitudes and altitudes to global climate change and age uncertainty, the H1, B/A, and YD are considered to have occurred during the periods 17.5±0.5~15.4±0.4 ka, 14.4±0.2~12.9±0.1 ka, and 12.9±0.1~11.5 ka in western Yunnan Province, respectively. The time of the H1 is almost consistent with the date defined by Sanchez Goñi and Harrison (2010, HS1 is between 18 to 15.6 ka). The B/A and YD are in good agreement in timing and duration with the B/A between 14.6 and 12.8 ka given by Grootes and Stuiver (1999) and the YD between approximately 12.8 and 11.5 ka given by Muscheler et al. (2008), respectively. 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±0.3-~4.33.8±0.5 ka. After 3.8±0.54.3 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. 3h) (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. 3), 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 relatively cold period before the H1 and the H1-, and the YD, respectively. 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 rare and weak fire activity between 11.5 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 11.5-4.3 ka, six fire episodes at 11.3, 10.4, 10.2, 6.7, 5.8 and 5.7 ka may indicate six significant dry or highly seasonal rainfall periods. The five fire episodes at 11.3, 10.4, 10.2, 5.8 and 5.7 ka may correspond to the ice-rafted debris events at 11.1, 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). The pollen assemblage from Qinghai Lake shows the obvious increases in Poaceae and *Artemisia* pollen percentages and the rapid degradation of the primary evergreen broadleaved forest from 4.3 ka (Xiao et al., 2015). Poaceae grains with diameters greater than 40 μm were usually classified as cereal-type (Lamb et al., 2003). In the study, Poaceae grains (>40 μm) began to occur at 18.5 ka and its pollen percentages had no obvious change (Fig. SF3), indicating that Poaceae grains (>40 μm) didn’t reflect changes of human activity and the criterion of cereal pollen (Poaceae grains with diameters greater than 40 μm) may be not applicable in this study area. Studies on the characteristics of modern Poaceae pollen in Yunnan Province are needed for redefining the criterion of cereal pollen for this study area. Because cereal pollen was not separated from Poaceae pollen, we can not rule out the possibility of increase in human activity when Poaceae pollen percentages increased. Thus, the obvious increase in Poaceae pollen percentages, combined with the rapid degradation of the primary evergreen broadleaved forest and the archaeological records, reveal that human activity may have influenced vegetation changes from 4.3 ka in the study area. 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 0.8 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 (Editorial 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 (Editorial Board of Tengchong County Annals, 1995). The pollen record from Qinghai Lake suggests greater open vegetation presented 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 resulted in low charcoal concentration. Whereas the same low CHAR revealed the relatively low fire frequency and intensity between 0.8 ka and 1940 AD, which may be caused by human suppression of fire in an intensively managed agricultural and urbanized environment. The relatively intensive and frequent fire activity since 1940 AD corresponded to the burning and robbing during the war and subsequently rapid economic development at the expense of vegetation and raw material.

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; Daniau et al., 2010; Mooney et al., 2011). 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 subtropic, 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., 2015a). 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; Daniau et al., 2010; Mooney et al., 2011), 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

The climate exerts the dominant control on the spatial distribution of the major vegetation types on a global scale. In the study area, when the climate is warmer and more humid than today, the proportion of hygrophilous and thermophilous components in the forest increases, and even vegetation shifts gradually to a monsoon evergreen broad-leaved forest or tropical rainforest or monsoon forest. When the climate is cooler and relatively dry than the present day, the proportion of tolerant-dry components in the forest increases, and even vegetation changes gradually into a mid-montane humid evergreen broadleaved forest. In addition to the dominant control of climate on vegetation, fire was also one of important disturbance factors in vegetation changes. 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, vegetation types, 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.

2).

Among the three periods with high fire activity, the two periods with high fire activity occurred in semi-humid evergreen broadleaved forest, and the other occurred in deciduous broadleaved forest dominated by *Alnus*. Whereas fire activity was unusual or weak in the course of vegetation shift from semi-humid evergreen broadleaved forest to monsoon evergreen broadleaved forest during the period 11.5-8.5 ka and in monsoon evergreen broadleaved forest during 8.5-4.3 ka. These are consistent with the modern results on the highest forest loss rates due to forest fire in semi-humid evergreen broadleaved forest and relatively low forest loss rates in monsoon evergreen broadleaved forest (Chen et al., 2012).

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 4.3-0.8 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 0.8 ka, evergreen oak pollen percentages continued to decline, while *Alnus* pollen percentages decreased markedly.

These comparisons between fire activity and major pollen taxa illustrate that evergreen oaks and *Alnus* are flammable plants. The speculative combustibility of evergreen oaks is consistent with *Quercus* spp. identified as flammable class in the trade standard for forestry in People's Republic of China (State Forestry Administration of China, 2008). However, *Alnus* spp. is identified as uninflammable class in the trade standard, and the results of combustion experiments of *Alnus nepalensis* suggest that it is also an uninflammable tree species (Tian et al., 2001; Li et al., 2009). The observation after an intensive fire on 17 April, 1995 in Anning County of Yunnan Province finds that a patch of *Alnus nepalensis* natural forest was not burned after undergoing this fire, which indicates that the fire resistant ability of *Alnus nepalensis* natural forest is very strong (Liu et al., 1996). The further observation shows that low-density *Alnus nepalensis* forest was completely burned. These observation results indicate that density of *Alnus* forest is a key factor to decide its fire resistant ability (Liu et al., 1996), even if the results of combustion experiments suggest that it is an uninflammable tree species. In our study, the comparison between past fire activity and *Alnus* pollen percentages suggests that *Alnus* is a flammable plant, which may be because *Alnus* forest during the period 4.3-0.8 ka was low density or it was not pure *Alnus* forest. 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 0.8 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 11.5 and 4.3 ka corresponded to the gradual increase in *Lithocarpus/Castanopsis* and tropical arboreal pollen percentages, and 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, which is in good agreement with the results of combustion experiments suggesting that *Castanopsis* spp., *Schima superba*, *Camellia oleifera*, *Altingia gracilipes*, *Symplocos setchuensis*, *Ficus microcarpa*, *Eurya macartneyi*, and *Pentaphylax euryoides* et al. are uninflammable tree species. ~~but are sensitive to frequent and intensive fire activity. Namely, *Lithocarpus/Castanopsis* and tropical arbors are fire-sensitive taxa in the study area,~~ However, ~~and~~ frequent and intensive fire leaded to rapid decreases in ~~their~~ abundance of *Lithocarpus/Castanopsis* and tropical arbors. Referring to Tinner et al. (2000)' definition of fire-sensitive taxa, we consider that *Lithocarpus/Castanopsis* and tropical arbors are fire-sensitive taxa in the study area.

Our results show~~s~~ 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 no obvious change and then kept relatively low level. 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 11.5-4.3 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 4.3-0.8 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 0.8 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.

CombustibilityFlammability 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, semi-humid evergreen broadleaved forest dominated by evergreen oaks and deciduous broadleaved forest dominated by *Alnus* are flammable. 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 is not cleared by human activity. Evergreen oak forest needs a longer time to restore after fires even if it is not influenced by human activity. The forests dominated by *Lithocarpus/Castanopsis* and/or tropical arbors are not easy to ignite because of their relative uninflammability. 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 comparisons 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. The combustibility of evergreen oaks, *Lithocarpus/Castanopsis* and tropical arbors is in good agreement with the results of combustion experiments of these plants. However, the combustibility of *Alnus* in here is not consistent with the observation result and the results of combustion experiments of *Alnus*, which may be because density of *Alnus* forest is a more important factor to decide its fire resistant ability. 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~~ after 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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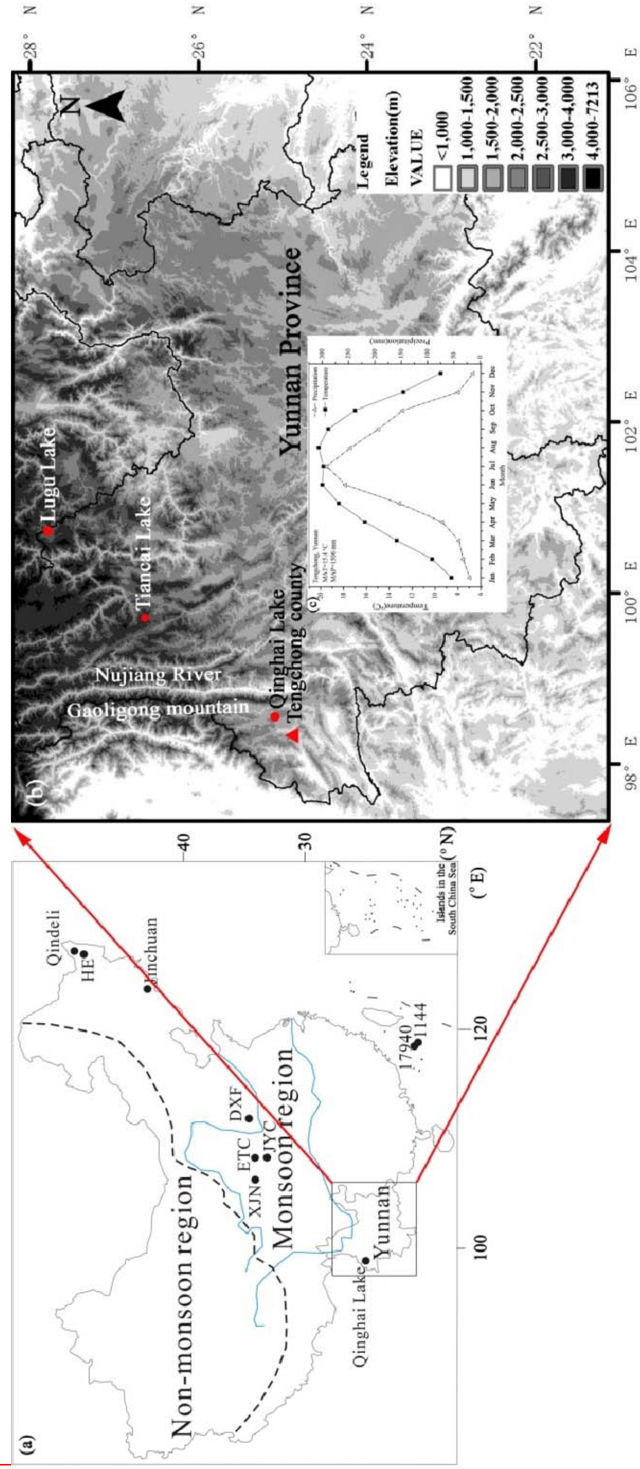
Figures


(a)
Non-monsoon region
Monsoon region
Qindeli
HE
Jinchuan
DXF
ETC
JYC
XJN
17940
1144
Yunnan
Qinghai Lake
Islands in the South China Sea
(°E)
(°N)
(b)
Yunnan Province
Lugu Lake
Tiancai Lake
Nujiang River
Gaoligong mountain
Qinghai Lake
Tengchong county
Legend
Elevation(m)
VALUE
<1,000
1,000-1,500
1,500-2,000
2,000-2,500
2,500-3,000
3,000-4,000
4,000-7213
N
(c)

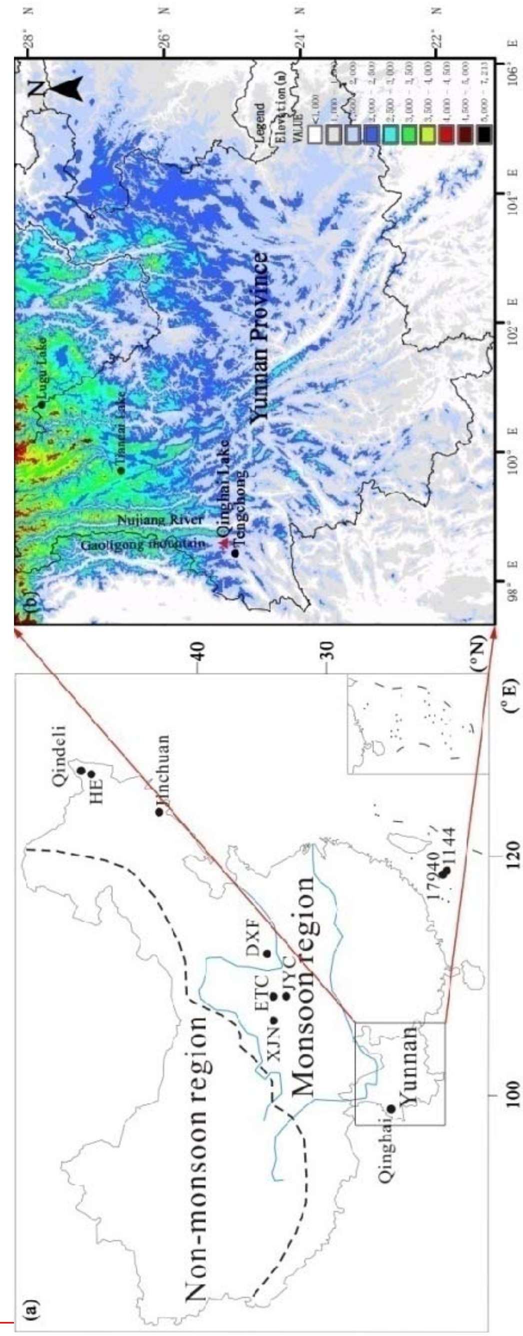
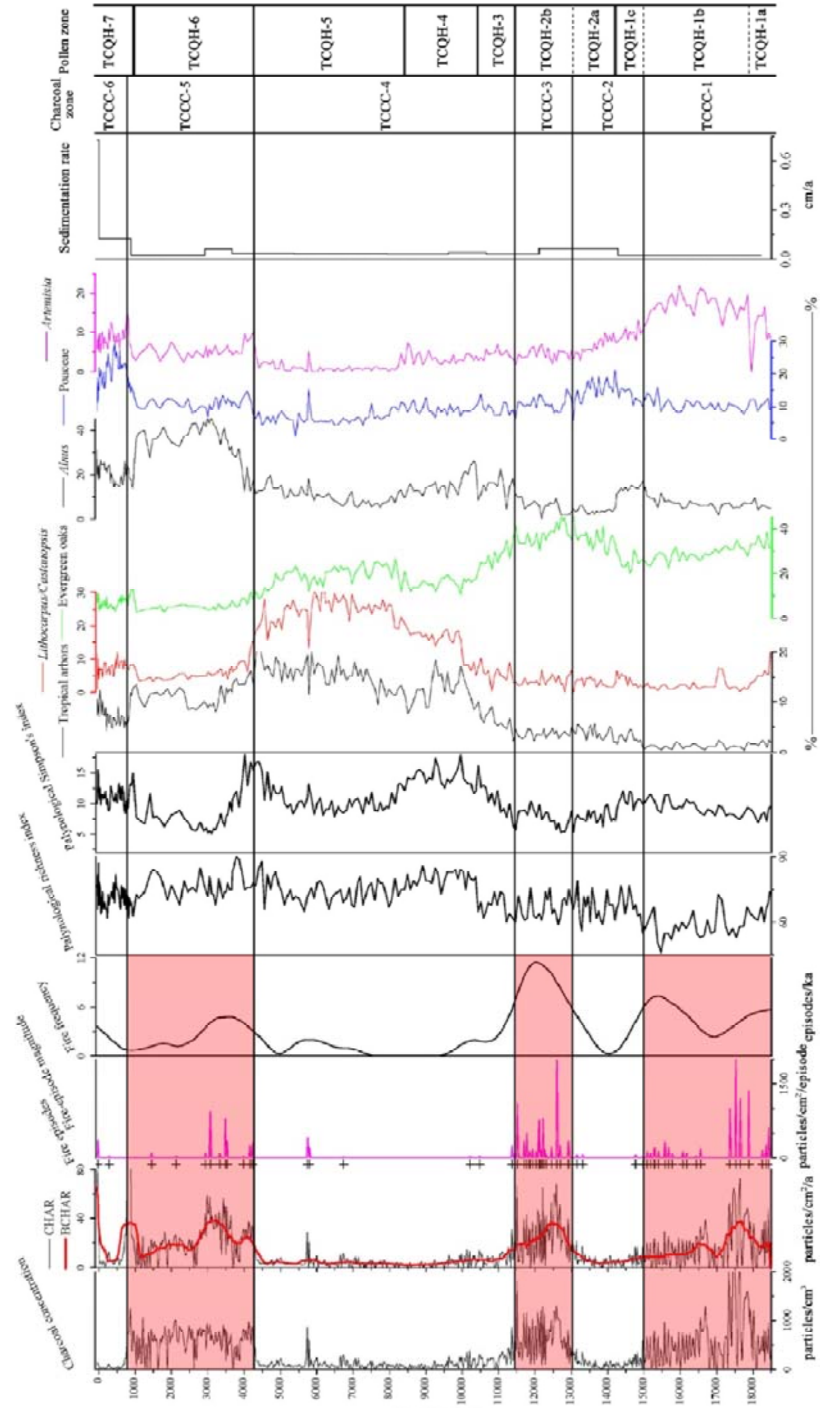


Figure 1. (a) The sketch map of monsoon and non-monsoon regions in China and other sites mentioned in text (XJN: Xujianian; ETC: Ertangcun; JYC: Jiangyangcun; DXF: Dongxiafeng). (b) Topographic map of southwestern China and the location of Qinghai Lake. (c) Climate diagram from Tengchong meteorological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


Pollen zone
TCQH-7
TCQH-6
TCQH-5
TCQH-4
TCQH-3
TCQH-2b
TCQH-2a
TCQH-1c
TCQH-1b
TCQH-1a
Charcoal zone
TCCC-6
TCCC-5
TCCC-4
TCCC-3
TCCC-2
TCCC-1
Sedimentation rate
cm/a
Artemisia
Poaceae
Alnus
Lithocarpus/Castanopsis
Evergreen oaks
Tropical arbors
%
Palynological Simpson's index
Palynological richness index
Fire frequency
episodes/ka
Fire-episode magnitude
particles/cm²/episode
CHAR
BCHAR
particles/cm²/a
Charcoal concentration
particles/cm³
Age (cal. yr BP)

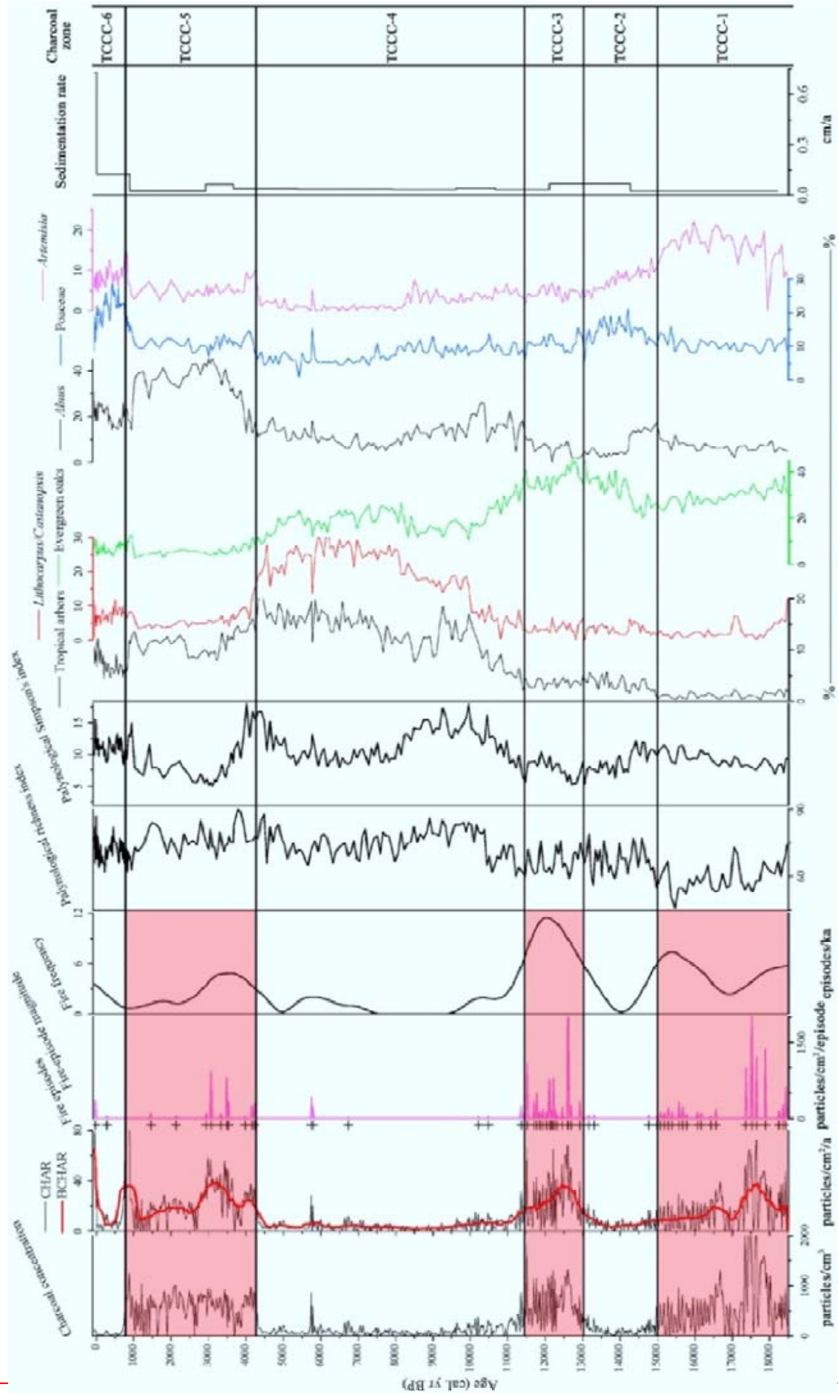


Figure 2. Results from charcoal analyses, pollen diversity indices, percentages of six main pollen taxa, and sedimentation rate from Qinghai Lake. The red shadings indicate the three periods with high fire activity.

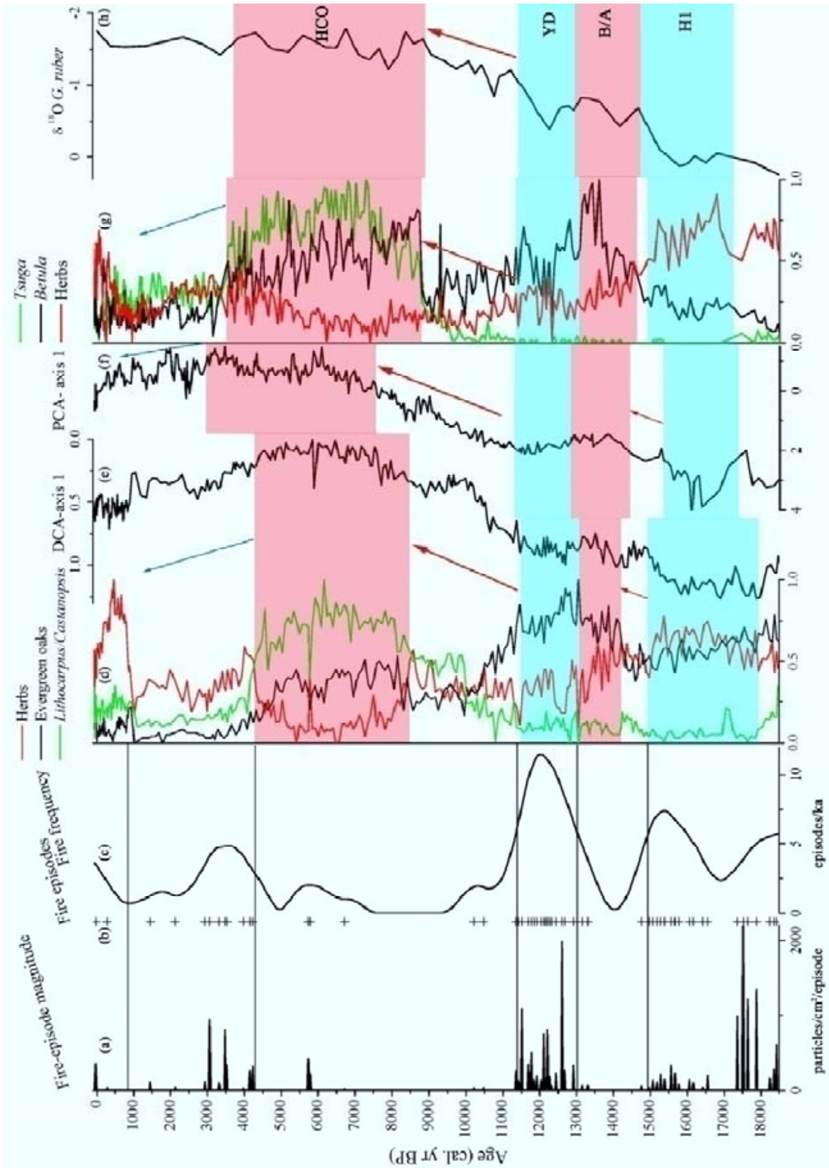


Figure 3. A comparison of fire activity from Qinghai Lake and climate proxies from the southwest monsoon regions. (a) Fire-episode magnitude. (b) Fire episodes. (c) Fire frequency. (d) Standardized data of pollen percentages of *Castonopsis/Lithocarpinus* (green line), evergreen oaks (black line), and 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 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.