Response to the editor and the reviewers:

Major Revision
Editor Decision: Reconsider after major revisions (06 Dec 2016) by Dr Nathalie Combourieu Nebout
Comments to the Author:
Dear authors,

We have now received new reports from two reviews concerning your paper. Both reviewers (especially two of them) made important comments about your manuscript that need to be absolutely taken into consideration in a new version. Particularly one of the reviewers would like to have more details about your hypothesis about diversity and to develop what you want to demonstrate with this curve, the dynamic of diversity in the studied area and the comparison with the other data. Precision and adjustments are also needed about fire effect on the different component of the vegetation and it is necessary to amend the discussion on fire too.

I am strongly recommending you to reply quickly to both reviews, justify your response to all comments and follow the reviewers suggestions and remarks.

Please prepare a revised version of your paper accordingly. In the revised version, I would like to see your corrections in track change mode. Please, don't forget to send, with your revised version, a replies to all the comments explaining how you have modified your manuscript. With the new manuscript and your response, I will decide if your paper will need again other reviews.

Waiting after your new version
Best regards
Nathalie Combourieu-Nebout

Response:
Dear Editor Nebout,

Thank you very much for your comments and your help. We revised carefully the manuscript according to the reviewers' comments. Especially, we proposed a hypothesis that effects of fire on biodiversity in different regions may be different in the introduction. The discussion section was reorganized, and more discussion about the dynamic of diversity was added in the discussion. Fire effect on the different component of the vegetation was more precisely illustrated. A point-by-point response to the reviewers' comments and all relevant changes made in the revised manuscript are listed as follows. Please see the file "Response to the editor and the reviewers" and the marked-up manuscript version for detail.

We hope that we successfully complied with the comments, and this revised manuscript can meet the requirements. We appreciate your help again.

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

Report #1

Comments on "Postglacial fire history and interactions with vegetation and climate in southwestern Yunnan Province of China" by Xiayun Xiao et al.

This paper utilizes a traditional method, charcoal analysis, to study the linkage among wildfires, vegetation, and climate change. Although this topic is not new, considering the sparseness of fire history in Southwestern China, a region prone to drought, such study is still welcome. This paper is well-organized, and it presents information on the flammable, fire-adapted, and fire-tolerant plants. It should be published with more audiences. But some statements seems imprecise. I point out some of, but not limited to, them listed below. I recommend the paper to being published with minor revisions.

Response: We appreciate very much your positive comments on the manuscript. According to your comments, we revised carefully the imprecise statements in the manuscript and address each comment with explanation as follows. Please see the following response and the marked-up manuscript version for detail.

1. Abstract. "Vegetation responses to fire before 4.3 ka are not consistent with that after 4.3 ka" I suggest changing it to" Vegetation responses to fire aftere 4.3 ka are not consistent with that before 4.3 ka".

Response: Done. Please see lines 18 page 1 in the marked-up manuscript version for detail.

2. Lines 11-12, Page 2, "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)." I think that this statement maybe not precise. Now there is a Global Charcoal Database (https://www.ncdc.noaa.gov/paleo/impd/gcd.html), which summarized the wildfire data worldwide. You can check the database.

Response: We check the database, and find that most sites on paleofire concentrate in North and South America. Thus, we change "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)." into "At present, studies on fire history and the interactions between long-term vegetation, fire, and climate are mainly concentrated in North and South America (https://gis.ncdc.noaa.gov/map/viewer/#app=cdo&cfg=paleo&theme=paleo&layers=000000000001)."

3. Lines 6-7, Page 2. "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)." I would like to suggest adding "black carbon was also gradually used as evidence of fire history reconstruction (Schmidt and Noack, 2000; Wang et al., 2013; Wolf et al., 2014) and its subtypes of char and soot (Han et al., 2012, Global Biogeochemical Cycles; Han et al., 2016, Sci. Rep.) have potential to differentiate between smoldering and flaming fires."

Response: Done. Please see lines 17-18 page 2 in the marked-up manuscript version for detail.

4. Page 2, "In southwestern China, there is only one study that reconstructed fire history by using black carbon (Zhang et al., 2015b)." I would like to suggest adding "to the best of our knowledge".

Response: Done. Please see lines 26 page 2 in the marked-up manuscript version for detail.

5. Page 2 " 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." References are needed. Also, I don't think that this statement is precise. I agree with you that there are limited data on historical wildfire reconstruction. But I think that there are still some studies on " past fire frequency and magnitude and its relationship to climate, human activity and vegetation dynamics".

Response: We further searched studies on fire history in China, and found an important reference which analyzes the interaction between climate, fire, and vegetation history over the last 2000 years in southwestern China. Thus, we changed "whereas studies of past fire frequency and magnitude and its relationship to climate, human activity and vegetation dynamics have rarely been attempted in China." into "Studies of past fire frequency and magnitude and its relationship to climate, human activity and vegetation dynamics are however, uncommon for China." At the same time, some references are added. Please see lines 30-31 page 2 in the marked-up manuscript version for detail.

6. Line 23, Page 2. " The study about forest fire during 1982-2008 in Yunnan Province" Please give a ref.
Response: A reference was cited. Please see lines 4 page 3 in the marked-up manuscript version for detail.

7. Lines 20-23, Pages 10. Regarding to the 8.2 event with no corresponding wildfire event, I would like to suggest considering the temperature influence. General speaking, low temperature would inhibit wildfire occurrence, and this can also be reflected from the low wildfire intensity in Daihai, China (Han et al., 2012, GBC), where there has a far lower temperature due to its location in north China. In Asian monsoon-influenced area, the dryness and temperature are two competition factors influencing wildfire activities. In my opinion, dryness is very likely to be the key factor influencing fire occurrences, but the temperature factor cannot be ignored. Or else, it seems that cold climate facilitates fire occurrences. But this apparently is not the case from modern observations. This point should be clarified in this paper.
Response: Yes, dryness is the key factor influencing fire occurrences in southwestern China, but the temperature factor cannot be ignored. Thus, we add influence of the temperature on fire occurrences when explain the reasons for the abrupt cold event at 8.2 ka not marked in the charcoal record. Please see lines 6-9 page 11 in the marked-up manuscript version for detail.

Report #2

The study by Xiao et al. deals with fire dynamics in comparison with vegetation proxies since the LGM. Fire regime is reconstructed from a high resolution macrocharcoal record while vegetation is reconstructed from the same core using pollen percentages and diversity indices calculated from the pollen record. The data are then compared and discussed based on visual observation of those tendencies. Those comparisons are then discussed and compared to pollen from other lakes and a d18O record. This record is cited only once in the text in the discussion section, and I wonder if it is really useful in the manuscript. The text is well written but will require copyediting from a native English speaker, for example multiple occurrences of the word 'arbor' thorough the text is confusing, do the authors mean trees? That being said the manuscript in its present form lacks some concepts that will be useful to strengthen its message and to clearly demonstrate the novelty compared to Xiao et al. 2015 that is roughly based on the same data.
Response: Though the δ^{18}O record was cited only once in the manuscript, it represents a regional climate in the Indian Ocean. So we consider it is useful in this manuscript. In our manuscript, the word 'arbor' means trees and shrubs. We added an explanation of 'arbor' following the word in the revised manuscript, please see lines 14 page 4 in the marked-up manuscript version for detail. The revised manuscript was copyedited by Ph. D Mark Burrows (a native English speaker), because Professor Simon G. Haberle (the second author) is still on holiday.

The use of diversity indices is interesting and I more than agree that diversity from a paleo-perspective is capital for understanding past ecosystem dynamics. However, those indices are underexploited in the manuscript, removing them from the analyses and figures will not significantly change the manuscript and its message. What are the hypotheses about diversity that the authors are testing? Those hypotheses are lacking in the introduction; for example, do the authors expect diversity to increase or decrease after fires, do they expect intermediate disturbance promoting higher diversity? What relationship between evenness and richness is expected? The discussion about diversity dynamics could be interesting but is limited in the discussion and few conclusions are drawn for diversity.
Response: Thank the reviewer's positive comment on the significance of our manuscript. At present, there is still argument about effects of fire upon biodiversity. Namely, some ecologists have discovered that fire suppression (or the

exclusion of fire-catalyzed practices) is a powerful destroyer of biodiversity (Pyne, 1998). On the other hand, some studies suggest that plant diversity increased after fires (Trabaud and Lepart, 1980; Stocker, 1981; Nasi et al., 2002). Thus, we put forward the opinion that effects of fire on biodiversity in different regions may be different. In order to make a reasonable strategy for forest fire management for a region, we need to better understand effects of fire upon biodiversity and driving mechanism of forest fires in this region. These may be achieved through long-term fire history research (Tinner et al., 1999; McWethy et al., 2013; Morales-Molino et al., 2013; Kloster et al., 2015). We add these contents in the introduction. Please see lines 29-31 page 1 and lines 1-5 page 2 in the marked-up manuscript version for detail.

In the discussion, we added some relatively discussion about diversity and drew a conclusion about effects of fire upon palnt diversity. Namely, plant diversity increased after fires. Based on this conclusion, we consider that fire suppression and control is reasonable in our study area. please see section 5.6 in the marked-up manuscript version for detail.

We illustrated notions of evenness and richness in the section 3.3 of the origin manuscript. Following this illustration, the relationship between evenness and richness is explained in the revised manuscript. Please see lines 3-6 page 6 in the marked-up manuscript version for detail.

The discussion about diversity dynamics are added, please see section 5.6 (lines 9-31 page 15 and lines 1-13 page 16) in the marked-up manuscript version for detail.

The manuscript in its present form is thus too descriptive and lack hypotheses. This is also apparent in the treatment and the discussion about fire effect on the vegetation. The discussion about Alnus is particularly confusing. The authors seem to get lost in conjectures for explaining the abundance of Alnus concomitantly with fires. Clearer hypotheses on fire effect on vegetation will make the discussion more objective. Fire can act by promoting fire adapted species (serotinous trees for examples) or fire resistant species (resprouting trees and shrubs) and early successioners. Alnus are not flammable and the results of the analysis do not support Alnus flammability: trying to demonstrate that Alnus patch can burn under various fire regime cannot prove that they are flammable.

Response: We deleted some descriptive contents (such as P13 l7-16 and P15 l15-9) in the discussion. In the revised manuscript, we confirmed that *Alnus* are nonflammable taxa and revised the discussion about the abundance of *Alnus* concomitantly with fires. Please see lines 16-20 page 14 in the marked-up manuscript version for detail.

The authors indicate at numerous occasions that they are measuring fire intensity, this is not possible using sedimentary charcoal records. Fire intensity is in W.m2 and the relationship between charcoal number and fire intensity has to be demonstrated. Likewise fire episode magnitude should be avoided because a single charcoal peak can encompass multiple fire episodes, also it is unclear what this measure is referring to: intensity, severity, burned area, burned biomass. Most of the studies are agreeing that peak magnitude and raw charcoal values are indicative of burned biomass.

Response: Thank you very much. This is a very professional comment. We looked up some references (Keeley, 2009; Ali et al., 2012) and understood that fire intensity describes the physical combustion process of energy release from organic matter, thus it is justifiably restricted to measures of energy output and it has the units of W m^{-2}. However, fire intensity is sometimes used incorrectly to describe fire effects. Fire severity has generally emphasized degrees of organic matter loss or decomposition both aboveground and belowground, which is positively correlated with fire intensity. Thus, we changed “intensity” to “severity” in the revised manuscript.

Considering that a single charcoal peak encompasses multiple fire episodes, we change “fire episode magnitude” to “peak magnitude". The magnitude of CHAR peaks can be used as a proxy for fire severity (Ali et al., 2012), indicating further degrees of organic matter loss or burned biomass.

Keeley JE (2009) Fire intensity, fire severity and burn severity: A brief review and suggested usage. Int J Wildland Fire 18(1):116–126.
Ali AA, Blarquez O, Girardin MP et al. Control of the multimillennial wildfire size in boreal North America by spring climatic conditions. PNAS, 2012, 109(51): 20966-20970.

I carefully read the author response to the two first reviewers, if most of the previous comments are very well addressed, I still question what is the marker of human influence. For example, p10 line 4 the authors argue that the climate is accompanied by signs of slash and burn and cite Xiao 2015. What are those signs? In Xiao 2015 the slash and burn is emitted as a hypothesis in the discussion, and here this hypothesis appears as a certitude. How can the authors prove that?

Response: We changed this certain opinion in the origin revised manuscript into a hypothesis. Namely, we changed the sentence "After 3.8±0.5 ka the climate became cooler and drier, accompanied by signals of human activity such as slash and burn (Xiao et al., 2015)." to "After 3.8±0.5 ka the climate became cooler and drier, which may be accompanied by signals of human activity such as slash and burn (Xiao et al., 2015)." Except for this sentence, human influence was deduced as a hypothesis in the other places in the origin revised manuscript. The reasons for possible human influence from 4.3 ka were listed in lines 1-4 page 11 in the origin revised manuscript (lines 9-23 page 12 in the marked-up manuscript version).

The discussion could by shortened significantly without losing information, large parts of the discussion are actually results and should be moved in the appropriate section. The discussion could also be reorganized to become clearer and less descriptive, for example the 5.1 paragraph deal with too numerous topics such as fire climate and human and is difficult to follow.

Response: The discussion was reorganized. Some descriptive contents (such as P13 l7-16 and P15 l15-9) are deleted. Please see the discussion in the revised manuscript for detail.

I hope that those comments will help the authors to strengthen the message and hypotheses of their study.

Response: Thank you very much for your constructive comments. After the manuscript was revised according to these comments, we considered that the quality of the revised manuscript has been evidently improved.

Specific comments:

P1 l13 'correlated' imply that the authors did some sort of correlation analysis, replace with related for example

Response: Done.

P1 l11 intensity is not well measured from charcoal records, authors can have a look at Ali et al. 2012 PNAS for size/biomass burning/frequency reconstruction

Response: We read carefully Ali et al's (2012) and Keeley (2009)'s studies, and understood difference of the terminology of fire intensity and fire severity. Namely, fire intensity is justifiably restricted to measures of energy output, whereas fire severity has generally emphasized degrees of organic matter loss or decomposition both aboveground and belowground, which is positively correlated with fire intensity. Thus, we change "intensity" to "severity" in the revised manuscript.

P1 l20 Alnus are not flammable plants

Response: We revised it in the revised manuscript.

P1 l22 and elsewhere specify 'abor' meaning

Response: The word 'arbor' means 'trees and shrubs'. We added an explanation of 'arbor' following the word when it first appeared.

P2 l8 Ali et al. 2009 is not clearly about management, but the authors may have a look at Oris et al 2014 Ecol Applications.

Response: We read carefully the paper (Oris et al., 2014), and put forward some corresponding suggestions for management strategy for forest fires to our study area. Please see lines 14-30 page 16 in the marked-up manuscript version for detail.

P2 l12 Zhao et al citation is not about boreal forest. Numerous examples from the boreal forest exist

Response: According to the first reviewer's comment, we revised the sentence and its citation. Please see lines 20-21 page 2 in the marked-up manuscript version for detail.

P3 l16 '1990', did the catchment area changed since 1990, why does using a date here be useful?

Response: No, the catchment area didn't change since 1990, but the surface area of the lake changed because of the change of water level. We changed this sentence into 'Qinghai Lake is a volcanic dammed lake with a catchment area of 1.5 km^2 and a surface area of c. 0.25 km^2 (in 1990), respectively (Wang et al., 2002).'

P5 and 6 it is not clear how palynological richness was calculated, in the result section richness is given with decimals, if the raw number of taxa is used where those decimals are coming from? If raw number of taxa is used from pollen counts, those results are not reliable because of species area type relationship. The richness need to be rarefied to the same pollen count, authors should have a look at Birks and Line 1992 The Holocene. It is also unclear if data is transformed before or after evenness calculus.

Response: Palynological richness index is the number of different pollen types in every pollen sample, which was illustrated in the section 3.3 of the origin manuscript. The reason for richness given with decimals in the result section is that it is an average of palynological richness for every zone. Considering palynological richness index is an integer, we rounded average of palynological richness index in the revised manuscript.

We read carefully the reference (Birks and Line 1992 The Holocene). In the revised manuscript, rarefaction analysis was used to estimate palynological richness, which was computed using the vegan package in the R programming environment (http://CRAN.R-project.org/package=vegan) (Oksanen et al, 2016). Fortunately, their results and tendencies of rarefied richness and pollen taxa sum are very similar (Fig. S1).

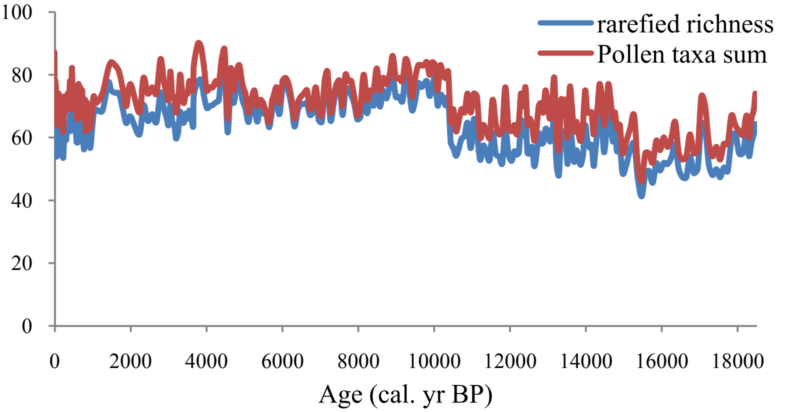

Fig. S1 Comparison of the rarefied richness and the pollen taxa sum.

Data isn't transformed before and after evenness calculus. Simpson's reciprocal index (1/D) is calculated according to the formula ($\frac{1}{D}=\frac{N(N-1)}{\sum_{i=1}^{S} n_i(n_i-1)}$).

Oksanen J., Blanchet F.G., Friendly M., Kindt R., Legendre P., McGlinn D., Minchin P.R., O'Hara, R.B. Simpson G.L., Solymos P., Stevens M.H.H., Szoecs E., Wagner H. (2016) vegan: Community Ecology Package. R package version 2.4-1.

P6 It is unclear how the zonation was done, if based on fire frequency or fire events, why zone 2 has only 1 fire at the beginning and two at the end, it would have been more logical to define a zone without fires. If the zonation is based

on a calculus (distance metric?) or on visual estimation or any method the procedure used must appear in the method section.
Response: In order to facilitate a comparison between fire activity and major pollen taxa and previous vegetation reconstruction for the same core (Xiao et al. 2015), the zonation was done based on the visual inspection of the macroscopic charcoal and fire activity records and referring to palynological zonation boundaries. We added an illustration about the zonation in lines 9-10 page 7.

P8 l20 and elsewere "increased significantly" what test did the author used for assessing the significance of the change?
Response: Here, meaning of "significantly" is "evidently" or "markedly". It is replaced by "evidently" or "markedly" in the revised manuscript.

Result and discussion section: how do the authors interpret the concomitant increase in richness and decrease in diversity?
Response: The explanation about the concomitant increase in richness and decrease in diversity is listed in lines 4-11 page 16 in the marked-up manuscript version.

P10 l16-17 is seems to me that this is an over interpretation of the results.
Response: This sentence was deleted.

P10 l20 'was'
Response: Done.

P10 l4 circular reasoning see above
Response: Done.

P12 l3-6 What are those fires #1 and #2? How do those results relate to the present study?
Response: The fires #1 and #2? are two fire events inferred from the two charcoal peaks, occurred at 5120±66 cal. yr B.P. (fire event 1) and 1288±8 cal. yr B.P. (fire event 2) (Jiang et al., 2008). Jiang et al. (2008) consider that fire event 1 was a natural origin and probably facilitated by drying environmental conditions, whereas fire event 2 was caused by clearing and may be related to the spread of the Han farming culture. The relationship between these results and our study is that fires are all controlled by dry climatic conditions in the two regions under the background of natural factor' control.

P12 l19-24 Citations are missing
Response: A reference is cited.

P13 l7-16 and P15 l5-9 Move to results
Response: These sentences are deleted.

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 (1 ka=1000 cal yr BP) macroscopic charcoal record from Qinghai Lake in southwestern Yunnan Province, China reveals postglacial fire frequency and variability history. The results show that three periods with high-frequency and high-severity fires 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 related 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 after 4.3 ka are not consistent with those before 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 are flammable plants and fire-tolerant taxa. *Alnus* is a fire-adapted taxon and a nonflammable plant, but density of *Alnus* forest is a key factor to decide its fire resistant ability. 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. Fire is unfavourable to plant diversity in the study area.

1 Introduction

Fire is a natural, recurring episodic event in almost all types of vegetation and 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 cause serious harm and huge losses to the forest, environment and human livelihoods. In order to decrease the harm and losses, it seems necessary to prevent the occurrence of fires and suppress fires. However, some ecologists have discovered that fire suppression (or the exclusion of fire-catalyzed practices) is a powerful destroyer of biodiversity (Pyne, 1998). On the other hand, some studies suggest that plant diversity increases after fires (Trabaud and Lepart, 1980; Stocker, 1981; Nasi et al., 2002). Thus, there is still argument about the effects of fire upon biodiversity, which may illustrate different effects of fire on biodiversity in different regions. In order to make a reasonable strategy for forest fire management for a region, we need to better understand effects of fire upon biodiversity in this region. At the same time, a better understanding of the driving mechanisms of forest fires is also imperative. Knowledge of 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 (Tinner et al., 1999; McWethy et al., 2013; Morales-Molino et al., 2013; Kloster et al., 2015). Fire histories can be reconstructed by using the 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) and its subtypes of char and soot have potential to differentiate between smoldering and flaming fires (Han et al., 2012, 2016).

At present, studies on fire history and the interactions between long-term vegetation, fire, and climate are mainly concentrated in North and South America (https://gis.ncdc.noaa.gov/map/viewer/#app=cdo&cfg=paleo&theme=paleo&layers =000000000001). Based on these studies, the 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 studies on fire history are concentrated in northern China (Li et al., 2005; Huang et al., 2006; Jiang et al., 2008; Han et al., 2012; Li et al., 2013; Wang et al., 2013; Zhang et al., 2015a), while studies in southern China are relatively few (Sun et al., 2000; Luo et al., 2001; Gu et al., 2008; Xiao et al., 2013; Zhang et al., 2015b). In southwestern China, to the best of our knowledge, only Gu et al. (2008) reconstructed fire history for the past 2.0 ka using microcharcoal and Zhang et al. (2015b) reconstructed fire history for the past 18.5 ka using black carbon. These studies on fire history in China have mostly concentrated on the relationship between fire activity and climatic change on orbital to suborbital timescales (Sun et al., 2000; Luo et al., 2001; Li et al., 2005; Huang et al., 2006; Jiang et al., 2008; Zhang et al., 2015a, b). Studies of past fire frequency and magnitude and its relationship to climate, human activity and vegetation dynamics are however, uncommon for China (Gu et al., 2008; Wang et al., 2013).

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, conditions typically conducive to frequent forest fires (Xu, 1991). Consequently, Yunnan Province is a zone of high fire frequency in China. The study of forest fire events for the peroid 1982-2008 in Yunnan Province shows that forest loss rates due to forest fire in different vegetation zones are different (Chen et al., 2012). The highest forest loss rate occurs in semi-humid evergreen broadleaved forest dominated by *Cyclobalanopsis glaucoides* and evergreen oaks and *Pinus yunnanensis* forest. The forest loss rate in monsoon evergreen broadleaved forest dominated by *Castanopsis* and *Lithocarpus* is relatively low. Forest loss rate in tropical rainforest and monsoon forest zones is however, 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 (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). Gaoligong 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 below 2500 m a.s.l. Qinghai Lake is a volcanic dammed lake with a catchment area of 1.5 km^2 and a surface area of c. 0.25 km^2 (in 1990) (Wang et al., 2002). The average and maximum water depths were 5.2 m and 8.1 m in 2010, respectively. Currently fed by precipitation, groundwater and surface runoff, the lake is without a natural outlet.

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 (trees and shrubs, the same below) 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. 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 a flammable class; *Alnus* spp., *Castanopsis* spp. and *Schima* spp. are identified as a nonflammable 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* are the strongest fire-resistant tree species (Zhen et al., 2012). *Ficus microcarpa*, *Eurya macartneyi*, and *Pentaphylax euryoides* 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* are nonflammable 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) was extracted in waters 6.3 m deep near the centre of Qinghai Lake, 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 evidently 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, sedimentation rate, input of inwashed material, detritus content and within-lake sedimentary processes 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, but rather high detritus content under conditions of rising humidity and intensified surface run-off. In addition, the tendencies of the concentrations and percentages for the six 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.

3.3 Pollen diversity indices and standardized method

Richness and evenness 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). Analytic arguments, mathematical models, and simulations indicate that relationship between richness and evenness is simple, positive, and strong (Stirling and Wilsey, 2001). However, other studies indicate that richness and evenness may be independent measures in diversity (Smith and Wilson, 1996; Wilsey and Potvin, 2000), and their relationships may vary with ecological effects. In order to evaluate the plant diversity and explore the relationship between richness and evenness around the study area, palynological richness index and Simpson's reciprocal index were adopted in this study.

Palynological richness index is the number of different pollen types in every pollen sample. Because pollen counts in samples may differ, rarefaction analysis was used to estimate palynological richness (Birk and Line, 1992), which was computed using the vegan package for R (http://CRAN.R-project.org/package=vegan) (Oksanen et al., 2016). Simpson's reciprocal index (1/D) was calculated as

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

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). The higher values of this index indicate the greater sample evenness.

In this study, we use min-max normalization to standardize pollen percentages, which can 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.

3.4 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 represent 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. Peak magnitude (particles/cm^2/peak) is the total charcoal influx in a CHAR peak and varies with fire size, severity, proximity, and taphonomic processes (Whitlock et al., 2006; Huerta et al., 2009; Walsh et al., 2010). The magnitude of CHAR peaks can be used as a proxy for fire severity (Ali et al., 2012), indicating further degrees of organic matter loss or burned biomass.

4 Results

The macroscopic charcoal and fire activity records were divided into six zones (from TCCC-1 to TCCC-6) (Fig. 2) based on their visual inspection and referring to palynological zonation boundaries, in order to facilitate the comparison with major pollen taxa and previous vegetation reconstruction for the same core (Xiao et al., 2015). The characteristics of the charcoal record, fire event reconstruction and pollen diversity indices in these zones were described as follows. 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 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. Peak magnitude varied greatly from 32.6 to 2189.2 particles/cm^2/peak with an average of 446.8 particles/cm^2/peak. 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 53) and Simpson's reciprocal 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 (peak magnitude: 58.4 particles/cm^2/ peak) and two fire episodes were registered in the top of this zone (peak 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 59. Simpson's reciprocal 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 evidently (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 the magnitudes of CHAR peaks average 426.4 particles/cm^2/peak, ranging from 0.02 to 1984.4 particles/cm^2/peak. Fire frequency was the highest for the profile, average 9.2 episodes/ka. In this zone, palynological richness and Simpson's reciprocal indices were relatively low, averaging 57 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 peak magnitudes (253.5, 32.7 and 29.3 particles/cm^2/peak, respectively). In addition, three fire episodes were registered at ca. 6.7, 5.8 and 5.7 ka with peak magnitudes of 18.3, 212.7 and 417.1 particles/cm^2/peak, respectively. Fire frequency was very low with an average of 1.1 episodes/ka. Palynological richness and Simpson's reciprocal indices were relatively high as a whole (averaging 70 and 11.6, respectively), and their highest values occurred during the period 10.4-8.5 ka. 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. Peak magnitude varied from 26.3 to 939.4 particles/cm^2/peak (mean of 303.4 particles/cm^2/peak). Fire frequency averaged 2.6 episodes/ka, ranging from 0.7 to 4.8 episodes/ka. Palynological richness index had no obvious changes (mean of 68) compared with the previous zone, while Simpson's reciprocal 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 (peak magnitudes: 33.7 and 359.7 particles/cm^2/peak), respectively. Fire frequency was relatively low, averaging 1.8 (ranging from 0.7 to 3.3) episodes/ka. Palynological richness index declined markedly (mean of 62), whereas Simpson's reciprocal index increased (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).

Palynological richness and Simpson's reciprocal indices indicate that relationship of plant richness and evenness is roughly positive before 4.3 ka, except that the increase of richness at 10.4 ka is slightly later than the increase of evenness at 11.5 ka. However, plant richness and evenness show an approximately inverse correlation after 4.3 ka.

5 Discussion

5.1 Fire activity history from Qinghai Lake

The results of fire event reconstruction based on the macroscopic charcoal record from Qinghai Lake reveals that fire frequency and peak 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 severity, then gradually increased. From 11.5 to 4.3 ka, fire frequency and severity was at a low level as a whole, and there were only six fire episodes with low severity 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 severity 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 severe 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 cannot 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.

5.2 Regional climate changes in the southwest monsoon region

From the pollen record in Qinghai Lake, standardized data of *Lithocarpus/Castanopsis* (taxa indicating a warm and humid environment), evergreen oak (indicating relatively temperate environment), and herb (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 condition to cold condition 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* (indicating humid environment), *Betula* (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±0.3~3.8±0.5 ka. After 3.8±0.5 ka the climate became cooler and drier, which may be 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).

5.3 Climate forcing on fire occurrences

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 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. 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) was not marked in the charcoal record. The reason may be that on one the hand, the relatively low temperature was unfavourable to fuel desiccation, but it is more important that the climate was not too dry or rainfall seasonality was relatively low in the study area, because drought is the key factor influencing fire occurrences in southwestern China (Gu et al., 2008).

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. As the study area is located in the southern subtropics, 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, which is consistent with Gu et al. (2008)'s conclusion. 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 severity 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 evidently 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 a 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.

5.4 Possible influence of human activity on fire activity

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 cannot 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. The same low CHAR revealed the relatively low fire frequency and severity 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 corresponds to burning and plundering events during World War Ⅱ and subsequently rapid economic development at the expense of vegetation.

5.5 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 drier 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 (Wu et al., 1987). 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*. 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).

Frequent and severe fire activity during the periods 18.5-15.0 ka and 13.0-11.5 ka was linked to high pollen percentages of evergreen oaks, indicating that evergreen oaks are flammable plants, which 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). When the high fire activity began at 18.5 and 13.0 ka, evergreen oak pollen percentages declined gradually; whereas 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, indicating that 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.

In this trade standard (State Forestry Administration of China, 2008), *Alnus* spp. is identified as nonflammable class, and the results of combustion experiments of *Alnus nepalensis* suggest that it is also a nonflammable 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 a nonflammable tree species. In our study, high *Alnus* pollen percentages correspond to high fire activity during the period 4.3-0.8 ka, which may be because *Alnus* forest around Qinghai Lake during the period 4.3-0.8 ka was relatively low density or it was not pure *Alnus* forest. Modern pollen rain results in southwestern China approved it, which shows that *Alnus* pollen percentages are more than 70% in a patch of *Alnus* forest (unpublished result). The abundance of *Alnus* promptly 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 (at 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* at ~1.0 ka is probably caused by selective felling of human (Xiao et al., 2015).

The very low fire frequency and severity 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* are nonflammable tree species. However, frequent and intensive fire leaded to rapid decreases in 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 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).

5.6 Dynamics of plant diversity

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 evidently different. Before 4.3 ka, the high fire activity corresponded to relatively low plant diversity (including two aspects of richness and evenness), whereas the very low fire activity corresponded to relatively high plant diversity. After high fire activity ended at 15.0 ka, plant richness and evenness increased. The reason may be that some fire-sensitive species and some thermophilous elements responding to the obvious increase of temperature at this time occurred, resulting in the increase of richness. At the same time, proportion of a few dominant fire-adapted or fire-tolerant species declined, resulting in the decline of concentricity and the increase of evenness. When high fire activity ended at 11.5 ka, plant evenness increased and plant richness had no obvious change. The possible reason why plant richness did not increase at this time is that the number of new types for fire-sensitive species and the number of disappearing types for fire-adapted species may be roughly equal, while a slight increase in temperature at this time is not sufficient to promote the emergence of warmer species. All these indicate that fire is unfavourable to plant diversity, and may be a destroyer of plant diversity in the study area. 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).

For the entire profile, the highest plant richness and evenness synchronously occurred during the period 10.4-8.5 ka when the temperature and precipitation increased evidently. And then, plant richness and evenness declined slightly when the climate is optimum during the period 8.5-4.3 ka. These indicate that an evident ameliorating climate was more favorable to plant diversity. Because different plant species (including trees and herbs) were competing for habitat space and dominant species was not obvious during the course of the gradual increases in the temperature and humidity. The optimum climate conditions made the forest ecosystem be in a steady state. During the period, the forest was dominated by a few warm and moist species such as *Lithocarpus/Castanopsis*.

After 4.3 ka, the high fire activity (during the period 4.3-0.8 ka) was linked to relatively high plant richness and relatively low plant evenness, the possible reason is that the fire-adapted pioneer plants (such as *Alnus*) responded promptly to disturbance of human activity from 4.3 ka and became the dominant species before the end of high fire activity. However, the intensity of human activity at this period, as well as the frequency and severity of fire, is not enough to promote disappearance of fire-sensitive or disturbance-sensitive plant species. The low fire activity corresponded to the decrease of richness and the increase of evenness, which may be caused by a stronger disturbance of human activity such as deforestation and selective clearance, resulting in some disturbance-sensitive plant species disappearing and proportion of a few dominant species declining.

The possible reason for the different post-fire reactions of plant diversity and different relationship between richness and evenness before 4.3 ka and after 4.3 ka is that vegetation was influenced by human activity after 4.3 ka.

5.7 Implications for management strategy for forest fires

Combustibility 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 is flammable. In order to prevent potentially destructive fires, there is a need to pay greater attention to the origins and control of fire events to this forest. Once semi-humid evergreen broadleaved forest dominated by evergreen oaks is burned out, this forest needs a longer time to restore after fires even if it is not influenced by human activity. *Alnus* is a nonflammable tree species. However, if *Alnus* is used to prevent fires, it is necessary to plant pure *Alnus* forest, because fire resistant ability of low-density *Alnus* forest or mixed-*Alnus* forest is relatively weak. In addition, *Alnus* forest is easy to restore after fires if it is not cleared by human activity. Thus, *Alnus* is an ideal fire-resistant plant. 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.

In our study area, fire is unfavourable to plant diversity, and may be a destroyer of plant diversity. Thus, fire control and suppression is a necessary management strategy for forest fires in the study area, which will reduce the risk of large forest fires and even keep relatively high biodiversity in the future.

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 a 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 are flammable plants. 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. Although *Alnus* is a nonflammable tree species, high *Alnus* pollen percentages corresponded to high fire activity during the period 4.3-0.8 ka, 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 after 4.3 ka are not consistent with that before 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. Fire control and suppression is a necessary management strategy for forest fires in the study area. Since vegetation was influenced by a mixture of natural processes and anthropogenic activity (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

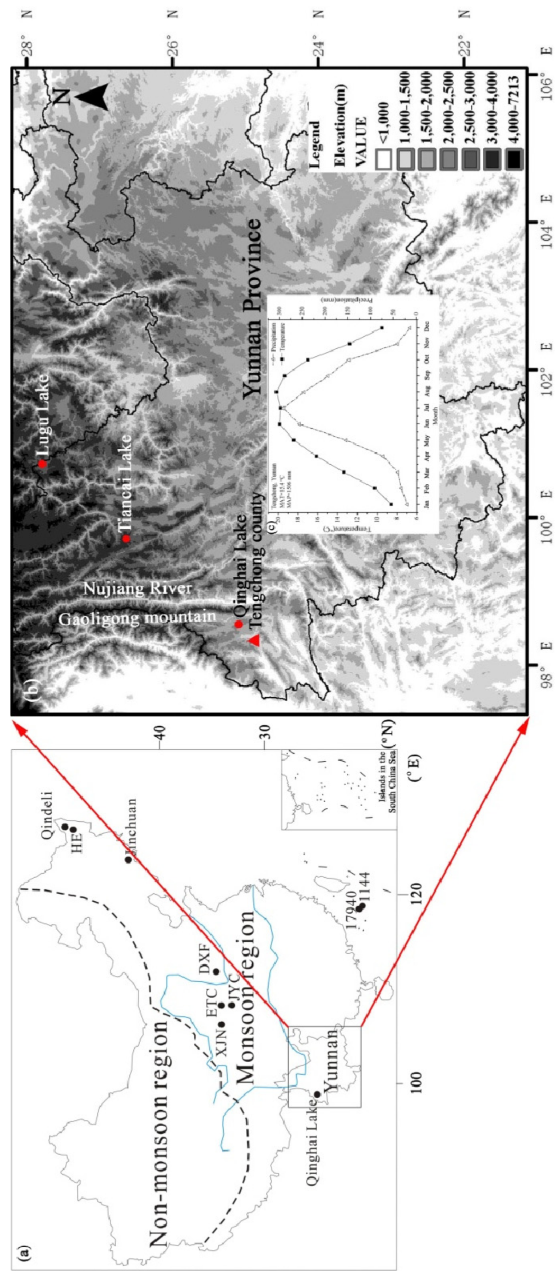

Figure 1. (a) The sketch map of monsoon and non-monsoon regions in China and other sites mentioned in text (XJN: Xujianian; ETC: Ertangcun; JYC: Jiangyangcun; DXF: Dongxiafeng). (b) Topographic map of southwestern China and the location of Qinghai Lake. (c) Climate diagram from Tengchong meteorological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

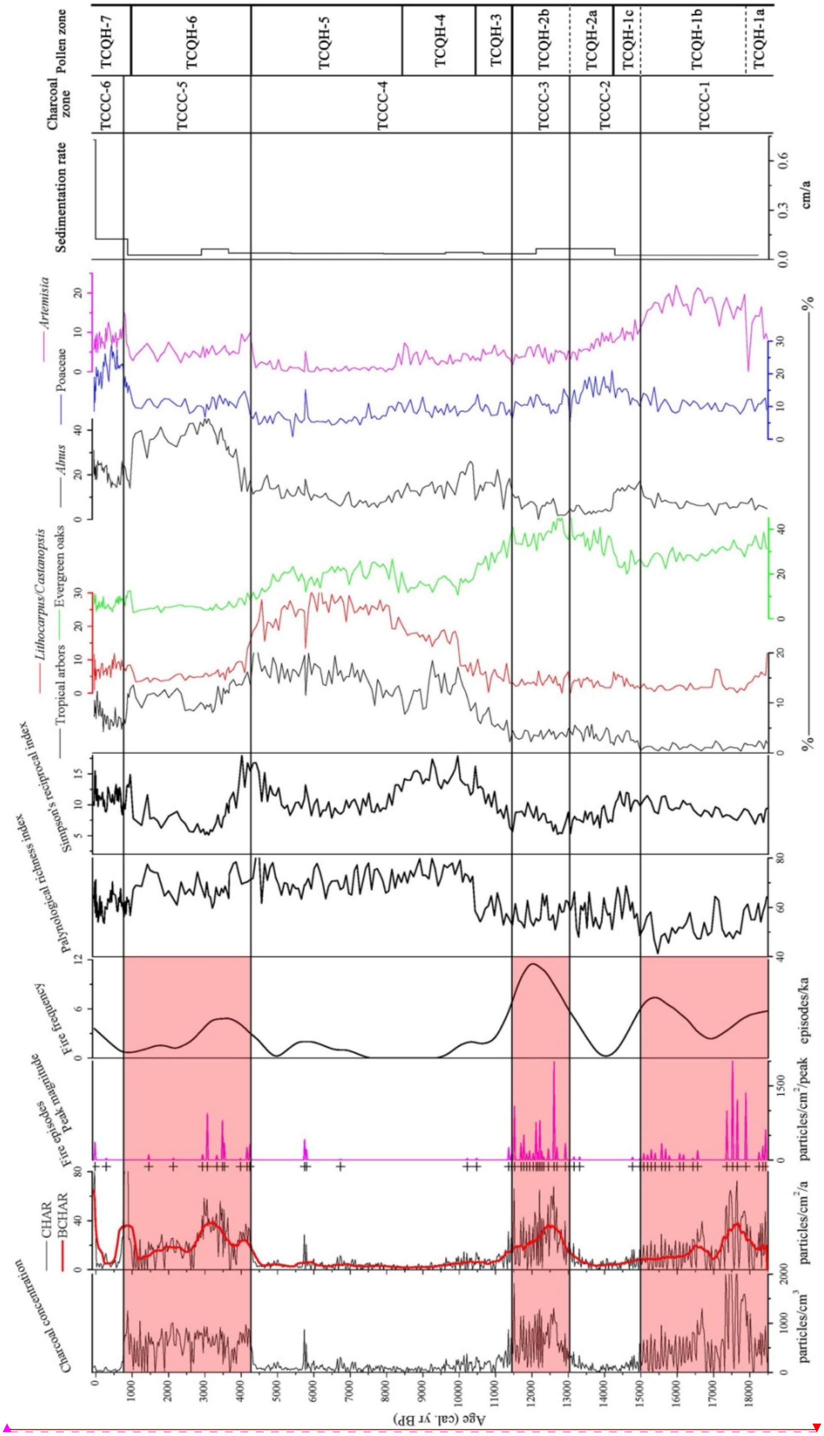

Figure 2. Results from charcoal analyses, pollen diversity indices, percentages of six main pollen taxa, and sedimentation rate for Qinghai Lake. The red shadings indicate the three periods with high fire activity.

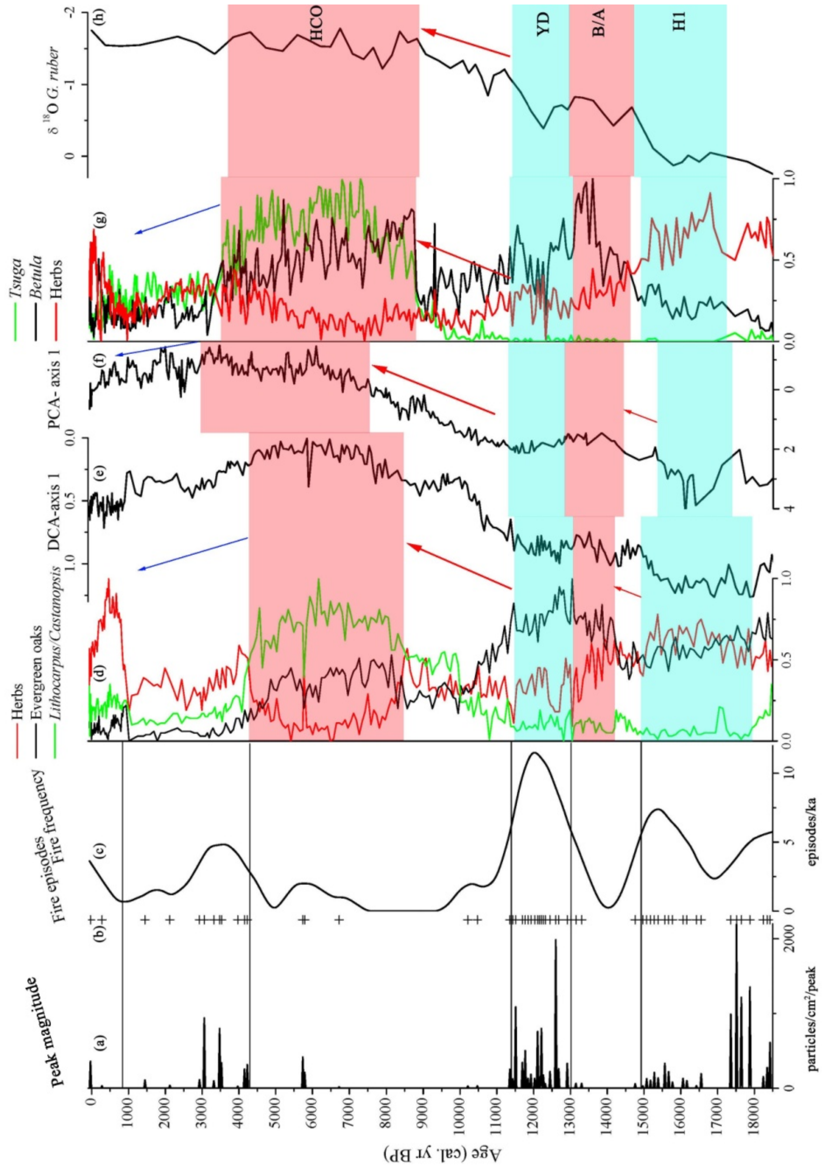

Figure 3. A comparison of fire activity from Qinghai Lake and climate proxies from the southwest monsoon regions. (a) Peak magnitude. (b) Fire episodes. (c) Fire frequency. (d) Standardized data of pollen percentages of *Castonopsis/Lithocarpinus* (green line), evergreen oaks (black line), and herbs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

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.