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Lacustrine lignin biomarker record reveals a severe drought during the late Younger Dryas in southern Taiwan

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ABSTRACT

The Younger Dryas (YD) event, which punctuated the last glacial-Holocene transition period and had a profound impact on global climate, is the most well studied millennial-scale climate event although the triggering mechanism remains debate. Weakened Asian summer monsoon during the YD is recorded in oxygen isotopes of stalagmite from Mainland China. However, lacustrine climate record of the YD event has not been reported from the subtropical land-ocean boundary of the Asian continent near the Pacific warm pool. We provide a lignin biomarker record covering the last deglaciation and early Holocene (17–9 ka BP) from the Dongyuan Lake, southern Taiwan, located at the frontal zone of typhoon invasion. The lignin phenol ratio S/V shows that the vegetation in the catchments had shifted from gymnosperm dominant to angiosperm dominant plants since 12.2 ka BP. Significantly decreased lignin concentrations (TLP and λ_8) and elevated lignin degradation parameters ((Ad/Al)v, P/(V + S), DHBA/V) in combination with other organic proxies (TOC, δ13Corg) during the late YD suggest a severe drought had occurred in southern Taiwan during this specific period. Changes in the lignin proxies from the Dongyuan Lake lagged the climate changes registered in stalagmite records by around 500–800 years, suggesting a slow response of vegetation and soil processes to rapid climate changes.

1. Introduction

The Younger Dryas (YD, 12.9–11.7 ka BP) event is one of the most well-studied millennial-scale cold events during the last glacial period (Broecker et al., 2010). Greenland ice core records showed that the temperature over central Greenland dropped to that of full glacial conditions within a few decades (Severinghaus et al., 1998). The YD event had a profound impact on climate system across the Northern Hemisphere (Broecker et al., 2010) and even the Southern Hemisphere (Griffiths et al., 2010; Ledru et al., 2002; Maslin and Burns, 2000), and its influence increased poleward (Shakun and Carlson, 2010). Recently, cave deposits indicated a weakened Asian monsoon (Dykoski et al., 2005; Huang et al., 2016; Liu et al., 2008, 2013; Ma et al., 2012; Shakun et al., 2007; Shen et al., 2010; Sinha et al., 2005; Wang et al., 2001; Yang et al., 2010) and a strengthened Australian–Indonesian monsoon during the YD (Ayliffe et al., 2013; Griffiths et al., 2009). Other archives such as lake sediments and peat deposits also show clear dry conditions in the Asian monsoon region during the YD (Chen et al., 2015; Hong et al., 2014; Li et al., 2016; Park et al., 2014; Rao et al., 2016; Wang et al., 2016; Zhong et al., 2015; Zhou et al., 2001).

Although the YD event has drawn much attention for several decades, the triggering mechanism of this event is still controversial. The most prevailing hypothesis of the triggering mechanism of the YD is a sudden influx of freshwater into the Northern Atlantic and subsequent weakening of the Atlantic meridional overturning circulation (AMOC) (Broecker et al., 1985; Carlson et al., 2007; Clark et al., 2002; McManus et al., 2004). Alternatively, extraterrestrial impact was once considered as the trigger of the YD event (Firestone et al., 2007). The hypothesis of extraterrestrial impact, which led to enhanced atmospheric dust levels and reduced radiative forcing, possibly in combination with increased ice-sheet melt, was highly debated, and almost all of the original lines of evidence proposed for the impact hypothesis were doubted (Daulton et al., 2016; Holliday et al., 2014; Pinter et al., 2011; van Hoesel et al., 2014). Other suggestions include reduced solar minimum triggered strong cooling (Renssen et al., 2000), wind shifts associated with changes in ice-sheet configuration (Eisenman et al., 2009; Wunsch, 2006), and tropical processes (Clement et al., 2001). Recently, based on model simulations, Renssen et al. (2015) proposed that the YD event registered in proxy evidence is best stimulated using a combination of processes: a weakened AMOC,

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moderate negative radiative forcing, and an altered atmospheric circulation. Regardless of the triggering mechanism, the YD event has been proposed as an intrinsic feature of late Pleistocene climate change at millennial timescales (Sima et al., 2004) or an integral part of glacial terminations (Broecker et al., 2010). Moreover, high-resolution proxy records (stalagmite records and atmospheric methane) documented a YD-like event during glacial termination III (Carlson, 2008; Cheng et al., 2009). To better understand the global climate response to the YD event, full scale geographical coverage of high-resolution climate records is required. However, high-resolution records of climate change and vegetation evolution especially for the YD event at the subtropical land-ocean boundary of the Asian continent near the Pacific warm pool are very limited.

Taiwan is located at a hotspot of land-ocean-atmosphere interaction, and its climate is mainly influenced by the East Asian monsoon system which is crucial in regulating global atmospheric circulation through heat and moisture transport from the West Pacific warm pool across the equator to the extratropics. Thus, the lake sediments and peat deposits in Taiwan archived historical environmental changes and East Asian monsoon variability (Ding et al., 2016; Lee and Liew, 2010; Lee et al., 2010; Li et al., 2013; Liew and Huang, 1994; Liew et al., 2013, 2006a, 2014, 1998, 2006; Lou and Chen, 1997; Selvaraj et al., 2011, 2007, 2012; Wang et al., 2015, 2011, 2014; Yang et al., 2014, 2011). However, due to the frequent occurrence of typhoons and earthquakes as well as extremely high erosion rate, most of the natural archives in Taiwan are short in term of time scales only covering the Holocene, with a few exceptions (Lee and Liew, 2010; Liew et al., 2006a).

Several studies on the Dongyuan Lake in southern Taiwan have been published (Ding et al., 2016; Lee and Liew, 2010; Lee et al., 2010; Yang et al., 2011). Pollen records in the Dongyuan Lake were applied to infer vegetation changes, for which temperate conifer, broadleaved mixed forest and warm temperate evergreen forest were reported to dominate the catchment before the Holocene, while warm-temperate evergreen forest occupied the area during the early Holocene (Lee and Liew, 2010). Organic proxies, such as total organic carbon (TOC) and C/N ratio, were utilized to reconstruct the precipitation variation over the last 20 ka (Yang et al., 2011). Most recently, we have unraveled the detailed information of East Asian summer monsoon (EASM) precipitation variation in southern Taiwan specifically for the last deglaciation and early Holocene with high-resolution multi-proxies (Ding et al., 2016). During the last deglaciation, the variation of EASM precipitation generally agree with the North Atlantic climate oscillation on millennial timescales. Meanwhile, changes in sea surface temperature in the western tropical Pacific might also have an influence on the precipitation variability in Taiwan on centennial timescales during the last deglaciation (Ding et al., 2016). In addition, the high sedimentation events accompanied by significant amounts of wood fragments occurrence during the early Holocene coincided with the paleo-records of maximum mass wasting events in downstream floodplains in Taiwan, suggesting an intensification of typhoon activity during the early Holocene (Ding et al., 2016).

In our previous study, we reported a dramatic decreased allochthonous organic input as well as enriched δ^{13}Corg of organic matter in the sediments of the Dongyuan Lake, southern Taiwan during the YD event (Ding et al., 2016). For further investigation of the environmental conditions during the YD in southern Taiwan, we examined the lignin biomarker record in the same sediment core from the Dongyuan Lake during the last deglaciation and early Holocene, especially focusing on the climate change during the YD in the present study.

Lignin, an abundant biopolymer found almost exclusively in terrestrial vascular plants, contributes to a substantial portion of the total organic matter preserved in soils, peats and sediments (Jex et al., 2014). Lignin has been regarded as resistant to microbial degradation in comparison to other plant components. Thus, lignin in lake sediments and peat deposits offers considerable information in paleoclimate research, as compositions of lignin oxidation products can reveal information about vegetation source, terrestrial organic matter degradation processes, and thus climate (Bourdon et al., 2000; Filley et al., 2001; Hedges et al., 1982; Hu et al., 1999; Ishiwatari et al., 2009, 2006, 2005; Ishiwatari and Uzaki, 1987; Kuliński et al., 2007; Li et al., 2015a, 2015b; Meyers and Ishiwatari, 1993; Ohira et al., 2013; Pempkowiak et al., 2006; Philben et al., 2014; Tareq et al., 2006, 2011, 2004).

2. Samples and methods

2.1. Study site

Dongyuan Lake (22°10′N, 120°50′E; 360 m above sea level) is located on the northern edge of a hilly basin in southern Taiwan (Fig. 1). The drainage area covers around 94×10^4 m^2 and ranges from 360 to 500 m a.s.l. Southwest winds prevail during summer from May to August, while the northeast winter monsoon season runs from October to January. Annual precipitation is greater than 2000 mm. East Asian summer monsoon and typhoons bring about 90% of the precipitation. Sources of summer precipitation include plume rain, typhoons, and tropical depressions. Present-day mean monthly temperatures are 20.7 °C in winter and 28.4 °C in summer, with an annual mean temperature of 25.1 °C (http://www.cwb.gov.tw/). The drainage basin of the present-day Dongyuan Lake is largely a swampy wetland featured with species of the families *Poaceae* and *Cyperaceae*. Vegetation on the uplands surrounding the basin is of the lowland evergreen forest type. Four major families, *Lauraceae*, *Aquifoliaceae*, *Euphorbiaceae*, and *Fagaceae* occupy approximately 40% of the total vegetation type (Lee and Liew, 2010).

2.2. Core acquisition and chronology

The ~14.5 m-long core TYP-B was collected from the center of the Dongyuan Lake, southern Taiwan in 2004. The lithological composition of the core consists of alternate layers of gray-green or dark brown muds and dark gray muds containing amount of visible wood materials, which has been described previously (Ding et al., 2016).

The chronology of the entire core was established by Yang et al. (2011), with 16 AMS ^{14}C ages on plant debris. The entire core covered the last 21 ka (Yang et al., 2011). Ding et al. (2016) added 12 more radiocarbon dates specifically for the period of the last deglaciation and the early Holocene to obtain a better chronology. Due to lack of plant debris in the section between 1010 cm and 1130 cm, two dates were derived based on bulk sediment samples at 1060 cm and 1097 cm. However, these two dates represent abnormally older ages relative to nearby dates based on plant debris (Fig. 1B). The inverse ages indicate that the organic carbon associated with mineral soils might contain "old carbon" (Kao and Liu, 1996; Kao et al., 2014). Another two inverse dates based on plant debris at 1180 cm and 1219 cm might be reworked wood. The remaining 12 dates (all based on plant debris) were converted to calendar years (calibrated ages) using the INTCAL13 data set (Reimer et al., 2013). It has been demonstrated that the plant remains and wood fragments deposited in lake systems along with inorganic sediments are not subjected to the reservoir effect (MacDonald et al., 1991; Selvaraj et al., 2012; Zhou et al., 2010) and thus they can yield reliable radiocarbon dates. The chronology was established by linear interpolation between each adjacent pair of calendar ages. The 2σ errors of calendar ages are less than

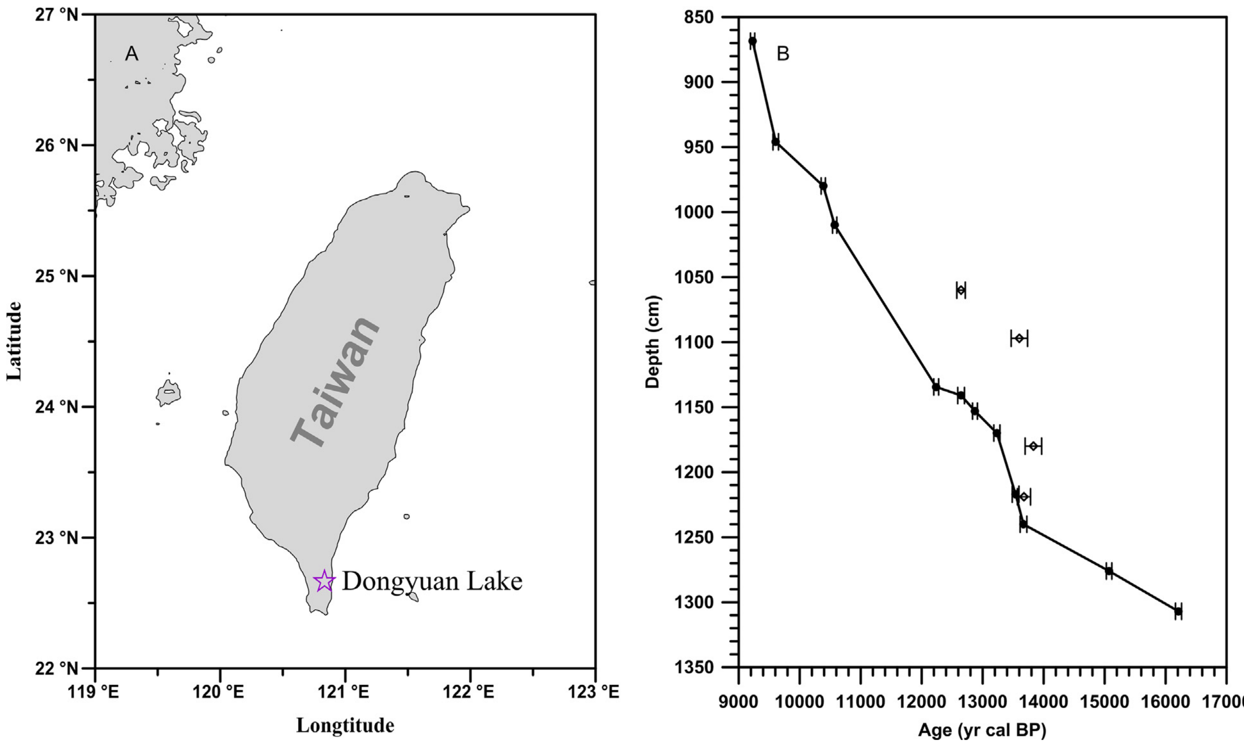

Fig. 1. Location of Dongyuan Lake (A) and the chronology of the investigated sediment core retrieved from Dongyuan Lake (B).

203 years. Especially during the YD, the 2σ errors are less than 175 years. Thus our age model is reliable for interpreting the sequence of climate events. The sedimentation rate during the investigated interval varied between ~0.2 mm/year to ~2 mm/year.

2.3. Lignin biomarker analyses

Lignin phenols analysis was carried out according to the method developed by Hedges and Ertel (1982), with slight modifications. Generally, ground dry sediment samples were placed in a PTFE mini-bomb with 10 mL of 2 M NaOH, 500 mg CuO and 100 mg $Fe(NH_4)_2(SO_4)_2$ in a nitrogen-filled glove box. The bombs were heated at 165 °C for 3 h. Ethyl vanillin was added to the samples as the recovery standard after the samples cooled down. After separating the solution from the solids, the solution was adjusted to pH < 2 with concentrated HCl, and then samples were extracted three times using ethyl acetate and dried with Na_2SO_4. Lignin oxidation products in the concentrated residual were then measured as trimethylsilyl derivatives by adding 50 μl of BSTFA + TMCS (99:1; Supelco) solution. Lignin phenols were analyzed by gas chromatography coupled with a flame ion detector (GC-FID, Agilent 6890 N). The capillary column was a DB-1 chromatography column (30 m × 0.25 mm i.d. × 0.25 μm film thickness, J&W scientific). The temperature increased from 100 to 270 °C at a rate of 4 °C/min, holding for 12.5 min. The whole run time for one sample was 55 min. The analytical precision for the total concentration of lignin phenols was <5% for replicates of the sediment samples.

3. Results and discussion

3.1. Vertical distributions of lignin phenols

Fifty-seven discrete subsamples were selected for lignin phenol analysis on the basis of the organic carbon and δ^{13}Corg. Because lignin is a large complex molecule, it is analyzed as its constituent individual phenols in four groups: the vanillyl group (V; vanillin, acetovanillone, and vanillic acid), syringyl group (S; syringaldehyde, acetosyringone, and syringic acid) and the cinnamyl group (C; p-coumaric acid and ferulic acid), with a fouth, the p-hydroxyl group (P; p-hydroxybenzaldehyde, p-hydroxyacetophenone, and p-hydroxybenzoic acid) being of lignin and non-lignin origin (Jex et al., 2014). The total lignin phenol (TLP) is the content of total lignin oxidation products in the sediments. The lignin parameters (V, S, C and P) are defined as the total concentrations of three V-phenols, three S-phenols, two C-phenols and three P-phenols, respectively, normalized to 100 mg OC. The λ_8 is the sum of V, S, and C groups normalized to 100 mg OC. TLP, λ_8 and individual lignin phenols (V, S, C and P) are compiled in Fig. 2.

The TLP values are highly variable fluctuating between 0.002 and 1.21 mg/100 mg sediments, with an average value of 0.18 mg/100 mg sediments. The TLP strongly correlate with the TOC content (r^2 = 0.91, n = 57, p < 0.01), suggesting that a relatively constant proportion of deposited organic matter was derived from vascular plants. The λ_8 values ranged from 0.55 to 8.09 mg/100 mg OC, with an average value of 2.83 mg/100 mg OC (Fig. 2). Variation of individual lignin phenols indicates that influxes of lignin to the lake sediments varied with depths because of changes in catchment vegetation through time. V-phenols were the most abundant CuO-oxidation products of lignin ranging between 0.22 and 5.55 mg/100 mg OC, followed by S-phenols (0.22–2.78 mg/100 mg OC). C-phenols and P-phenols were relatively less abundant (0.10–0.95 mg/100 mg OC and 0.22–1.55 mg/100 mg OC, respectively). Higher concentrations of V- and S-phenols indicated that woody rather than non-woody plants dominated the catchment vegetation.

3.2. Lignin phenol ratios

The relative contribution of individual lignin phenols in soils and sediments can be related to major plant groups such as

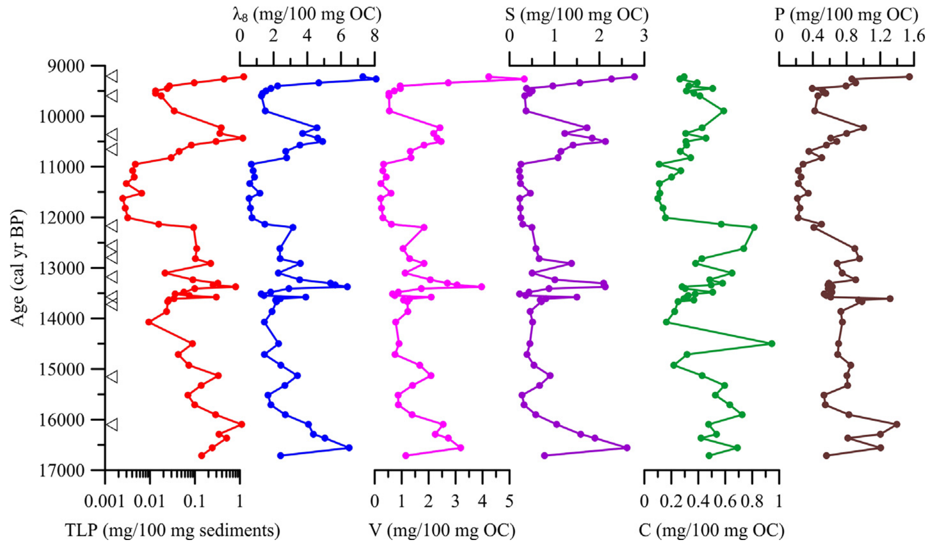

Fig. 2. Chronology variation of total lignin oxidation production contents in sediments (TLP, mg/100 mg sediments), TOC normalized sum of V, S, and C group lignin phenols (λ8: mg/100 mg OC) and individual lignin phenols (V, S, C and P: mg/100 mg OC). V: total vanillyl phenols, S: total syringyl phenols, C: total cinnamyl phenols, P: total p-hydroxyl group. Triangles at the Y-axis represent the radiocarbon dates.

angiosperms and gymnosperms (Thevenot et al., 2010). V-phenols are found in woody and non-woody tissues of both angiosperms and gymnosperms. S-phenols are produced by angiosperms and are found in both woody and non-woody tissue (Goñi et al., 1993; Hedges and Mann, 1979). C-phenols are only found in non-woody plant tissues (Hedges and Mann, 1979). Thus, the relative concentrations of S and C with respect to V can provide further details, such as the proportion of angiosperm (S/V > 0) and gymnosperm (S/V = 0) and the relative composition of woody (C/V = 0) to non-woody (C/V > 0) tissues (Hedges and Mann, 1979). Vertical distributions of lignin phenol ratios in the Dongyuan Lake are illustrated in Fig. 3. The S/V values ranged from 0.27 to 1.08, with an average value of 0.62 for the investigated interval. The S/V had shifted to higher values since 12.2 ka BP, suggesting an increased contribution of angiosperm vegetation. The C/V values fluctuated between 0.05 and 1.07, with an average value of 0.38, and no obvious down-core trend was observed.

The ratio of the acidic functional group to the aldehyde group within the vanillyl ((Ad/Al)v) has been applied in numerous studies to indicate lignin degradation that through propyl side-chain oxidation or aromatic ring cleavage (e.g., by white-rot fungi and bacteria) (Goñi and Hedges, 1992; Hedges et al., 1988; Opsahl and Benner, 1995; Otto and Simpson, 2006). (Ad/Al)v of fresh plant tissues generally varies within 0.1–0.3, while that of highly degraded terrestrial organic matter is >0.6 (Dittmar and Lara, 2001). Demethylation/demethoxylation of lignin (e.g., by brown-rot

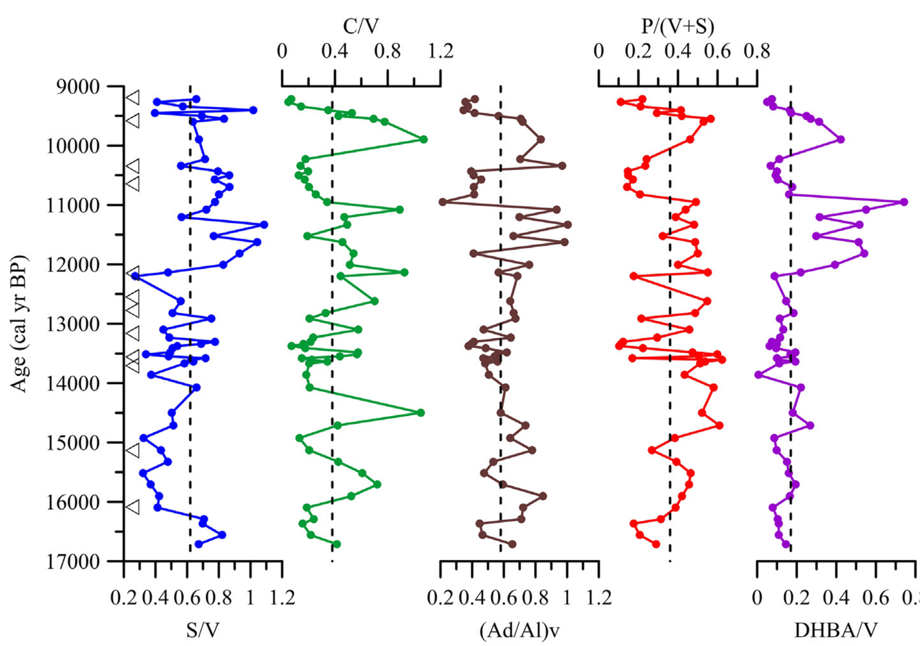

Fig. 3. Chronology variation of lignin phenol ratios in Dongyuan Lake sediment core. S/V: ratios of total syringyl to total vanillyl phenols; C/V: ratios of total cinnamyl phenols to total vanillyl phenols; (Ad/Al)v: acid to aldehyde ratio of vanillyl; P/(V + S): ratio of total p-hydroxyl to sum of vanillyl and syringyl phenols; DHBA/V: ratio of 3,5-hydroxy benzoic acid to total vanillyl phenols. The dashed lines indicate the mean values of the corresponding parameters. Triangles at the Y-axis represent the radiocarbon dates.

decay) may lead to selective loss of methoxylated phenols (Ertel et al., 1986) with nonmethoxylated phenols (such as P-phenols) unaffected. Thus, the ratio of P/(V + S) may reflect the diagenetic state of lignin when the other sources of P phenols (such as protein) are relatively constant (Dittmar and Lara, 2001; Zaccone et al., 2008). The (Ad/Al)v and P/(V + S) ranged from 0.21 to 1.00 with an average value of 0.58 and from 0.10 to 0.62 with an average value of 0.36, respectively, suggesting a moderately degraded state of the lignin in Dongyuan Lake sediments through most period of the investigated interval (Fig. 3).

On the other hand, 3, 5-hydroxy benzoic acid (DHBA), a CuO oxidation product, is sourced from soil degradation processes and tends to accumulate in soils as a degradation by-product of fresh vascular plant macromolecules (Farella et al., 2001; Goñi and Hedges, 1995; Goñi et al., 2000; Prahl et al., 1994). Hence, the ratio of DHBA/V is also considered as a degradation index for the organic matter in rivers and soils (Prahl et al., 1994). The DHBA/V values in the sediments of the Dongyuan Lake ranged from 0.01 to 0.74, with an average value of 0.17. The DHBA/V values were generally low throughout the investigated interval except for the period of 12.2–10.7 ka BP (Fig. 3, up to 0.74). The substantially elevated DHBA/V values during 12.2–10.7 ka BP indicate that the lignin in the sediments of the Dongyuan Lake is highly degraded during this period.

No lignin degradation parameter displayed a consistent downward increasing pattern, suggesting that the diagenetic alteration during burial was not influential. Therefore, the lignin degradation parameters may mainly reflect the environmental conditions before burial. Fig. 4 shows the relationships between λ_8 and lignin degradation parameters. Both P/(V + S) and DHBA/V better correlate with λ_8 than (Ad/Al)v, suggesting that demethylation/demethoxylation play a more important role in lignin degradation (Yang et al., 2009). Although the lignin degradation parameters are influenced by different processes and demethylation/demethoxylation dominate the lignin degradation through investigated interval, elevated (Ad/Al)v and DHBA/V ratios in combination with relatively higher values P/(V + S) from 12.2 to 10.7 ka BP (Fig. 3) suggest an apparent environment change during this period.

3.3. Severe drought during the late YD in southern Taiwan

Highly fluctuating lignin phenols and lignin phenol ratios in the Dongyuan Lake might indicate drastic climate oscillation in southern Taiwan during the last deglaciation. In combination with previous published proxies in the Dongyuan Lake, we found that the most evident climate event during the investigated period

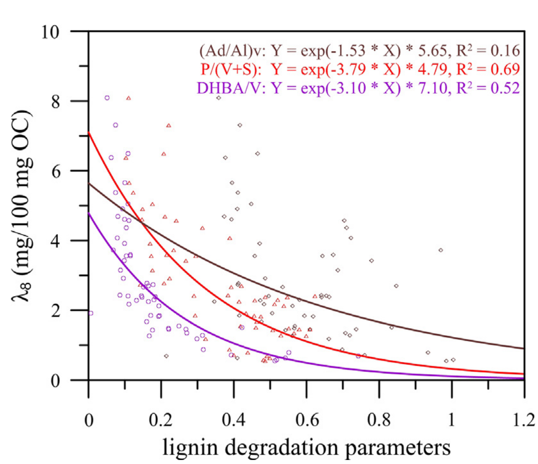

Fig. 4. Scatter plots of λ_8 against lignin degradation parameters.

appeared between 12.2 and 10.7 ka BP (Fig. 5). This climatic reversal corresponds to the YD period, with time lag of about 500–800 years. All proxies from the Dongyuan Lake suggest a severe dry condition during this period with significantly decreased TOC, C/N ratio and TLP, enriched δ^{13}Corg and increased lignin degradation parameters ((Ad/Al)v, P/(V + S), DHBA/V) (Fig. 5). The extremely low TOC content (less than 1%), TLP, and λ_8 suggest substantially decreased allochthonous organics due to lower rainfall intensity. Enriched δ^{13}Corg (up to −15‰) indicates increased C_4 plant contribution. During the same interval, the pollen records from Dongyuan Lake exhibit a greater abundance of *Artemisia* (Lee et al., 2010) which mainly uses the C_4 photosynthesis pathway and usually flourishes in arid or semiarid habitats (Jia et al., 2015). Thus, the pollen records also support a dry condition during the late YD in southern Taiwan. It is interesting to see that the S/V ratio had also increased since 12.2 ka BP (Fig. 5), suggesting an increased proportion of angiosperm plants on the landscape. This may have been caused by development of angiosperms due to a warm climate in southern Taiwan at that time which resulted from persistent increased summer solar insolation and sea surface temperature in the western tropical Pacific during the late deglaciation (Stott et al., 2004). An alternative explanation might be a significant decrease in gymnosperm contributions from high altitudes (gymnosperm dominant) due to extremely dry conditions. The elevated lignin degradation parameters during the late YD seem contradictory to a previous study (Otto and Simpson, 2006) that suggests warmer and drier climates may limit lignin degradation. It is worthwhile to note that their study was conducted in deep north high latitude regions, and little information is available on lignin degradation state in tropical regions. We propose that groundwater flow routes switch to deeper, organic-poor, and lignin depleted soils during the late YD. The deepened flow pathways, caused by significantly decreased precipitation during the warm dry summers, may leach the older carbon pool with higher degradation state in the upper catchment. This hypothesis can also be supported by a recent study in the Mekong River (Ellis et al., 2012). It has been reported that the lignin content decreases with depth in soils (Otto and Simpson, 2006; Thevenot et al., 2010), while lignin degradation state is much higher in deeper soils than that in surface soils (Bao et al., 2015; Goñi et al., 2014; Hedges et al., 1988; Houel et al., 2006; Kögel, 1986; Opsahl and Benner, 1995; Otto and Simpson, 2006).

Fresh plant materials produce extremely low DHBA content and DHBA/V ratios (Houel et al., 2006). In our record, the DHBA/V peak during the late YD period makes DHBA/V the most prominent degradation parameter. DHBA is mainly derived from proteins and "tannin-like" compounds or from the demethylation of lignin (Goñi and Hedges, 1995; Goñi et al., 2000; Prahl et al., 1994). The tannin-like materials tend to accumulate with the degradation and humification of fresh vascular plant tissues in deep soils (Houel et al., 2006). Moreover, in dry periods, lignin has a longer residence time in soil before it is transported and buried in sediments and is thus subject to increased degradation by fungus (Li et al., 2015b). Additionally, two AMS ^{14}C dates based on TOC-poor sediments during this interval displayed older ages relative to the dates based on plant debris beyond this interval in the same core (Ding et al., 2016). It is very likely that the older ^{14}C ages of the organic matter delivered to the lake during this period was sourced from deeper soils. However, a critical issue is that if the organic matter in the lake sediments during the YD was solely from deep soils and its age was older than the YD, then the lignin proxies would not be able to reflect the vegetation and environment in the time frame based on plant debris ^{14}C analysis. But, the organic matter was not necessarily older than the YD. For instance, we can see a clear increase of S/V values during the late YD. If the organic matter came from materials older than YD, then the S/V record

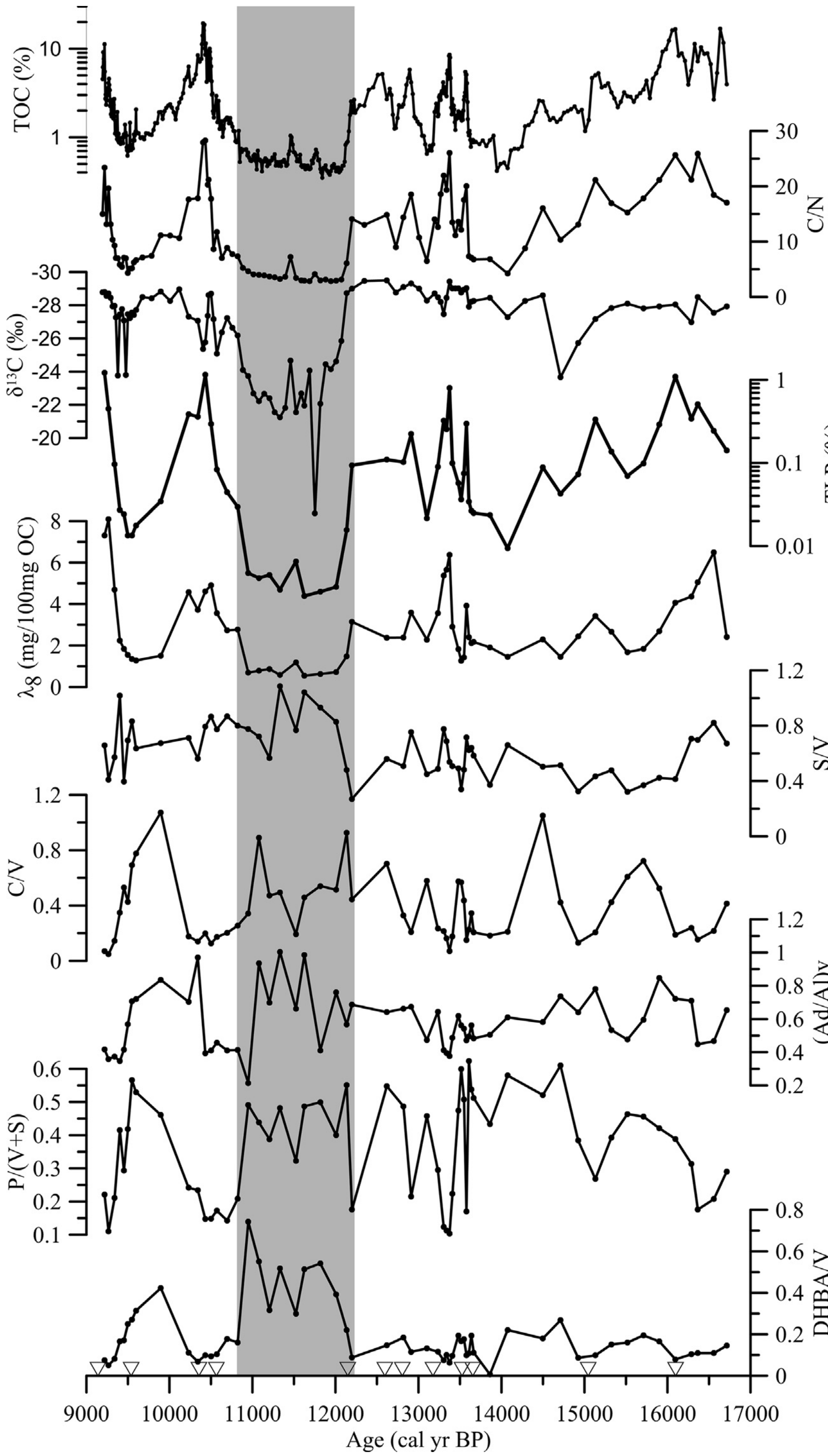

Fig. 5. Chronology variation of TOC, C/N, δ^{13}Corg and lignin proxies. TOC, C/N and δ^{13}Corg have been reported in Ding et al. (2016). The gray bar highlights the dry interval. Triangles at the Y-axis represent the radiocarbon dates.

should remain low, similar to those prior to the YD or even lower since the degradation process normally cause a decrease of S/V values because the syringyl phenols decay much faster than vanillyl phenols (Feng et al., 2013; Hedges et al., 1988; Opsahl and Benner, 1995; Otto and Simpson, 2005). Based on the information mentioned above, we suggest that the organic matter in our lake record during the YD was relatively older but still within the YD event. Thus, the lignin proxies from the Dongyuan Lake can be used to trace the vegetation and environmental change during the YD.

3.4. Time lag between lignin proxies and climate change

Changes in the proxies from the Dongyuan Lake lagged by about 500–800 years for both the onset and the termination of the YD event registered in the stalagmite records (Fig. 6). Furthermore, the Asian monsoon records are characterized by gradual onset when compared to the northern high latitude temperature records during the early YD (Liu et al., 2013; Ma et al., 2012; Park et al., 2014; Shakun et al., 2007; Sinha et al., 2005; Wang et al., 2001;

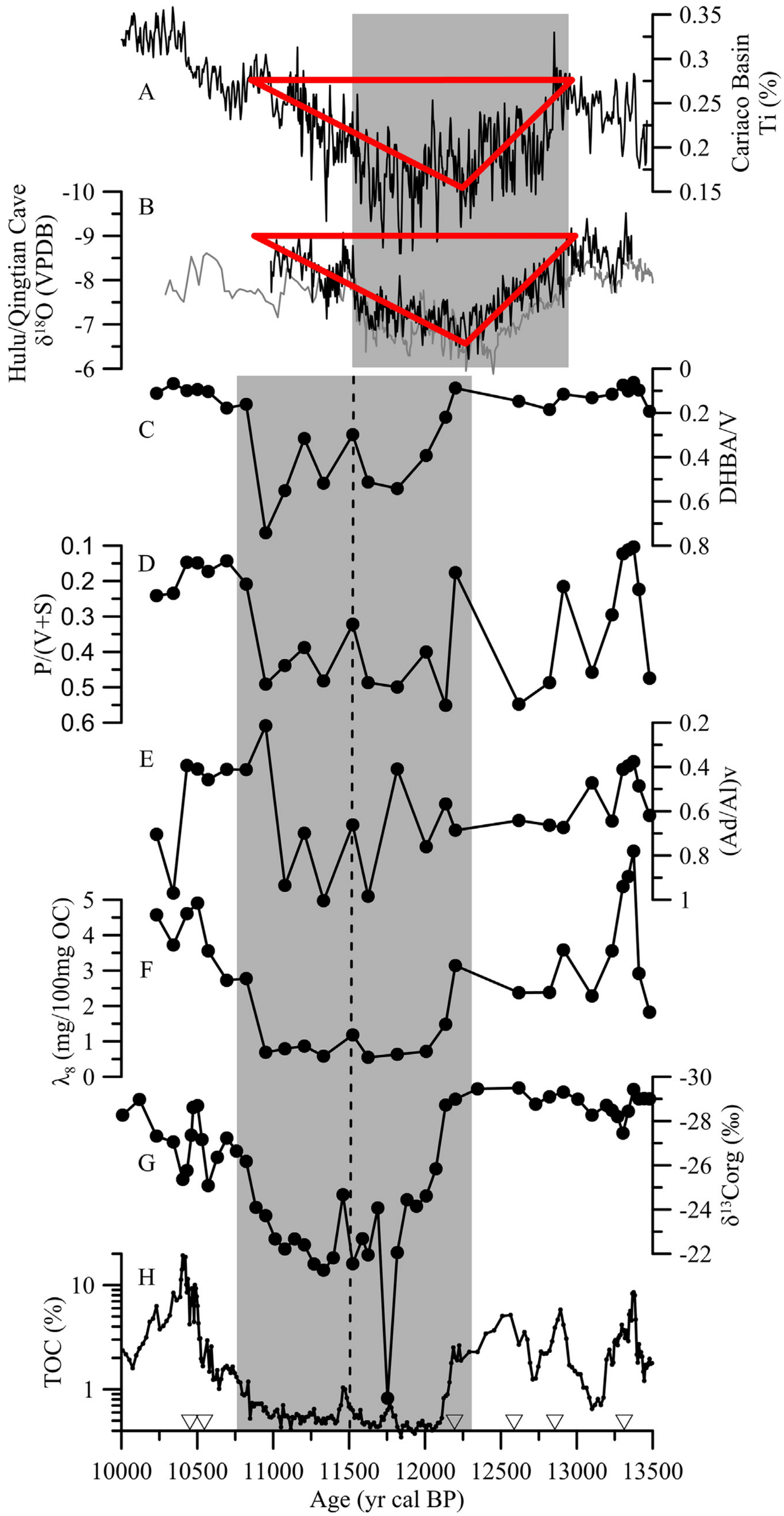

Fig. 6. Comparison of proxies in Dongyuan Lake with low latitude hydrology proxies. A: Titanium record from Cariaco Basin; B: stalagmite $\delta^{18}O$ record from Qingtian Cave (black, Liu et al., 2013) and Hulu Cave (gray, Wang et al., 2001); and C-H: proxies from Dongyuan Lake. The gray shading mark the time duration of the Younger Dryas event recorded in Greenland ice cores and the dry interval in southern Taiwan respectively. The triangles at the top represent generally weakened Asian monsoon period and decreased rainfall period in the Cariaco basin. Triangles at the X-axis represent the radiocarbon dates.

Yang et al., 2010). Recently, Partin et al. (2015) compiled high resolution hydrology and temperature records from low to high latitudes to highlight the difference between hydroclimate and temperature responses to the YD event. They suggest that although the onset and termination are synchronous across the records, tropical hydroclimate changes are more gradual than the abrupt temperature changes in the northern Atlantic Ocean (Fig. 6; Partin et al., 2015). Generally, the tropical hydroclimate records required 300–500 years to reach and recover from the full YD conditions. Differences in YD transitions between temperature records in northern Atlantic and hydroclimate records in northern tropical region were also evident based on simulations (Partin et al., 2015). The authors suggest that tropical hydrology is likely primarily influenced by changes in the mean Northern Hemisphere temperature (Deplazes et al., 2013), which requires a longer adjustment time than regional sea ice changes in Greenland. In addition to an increase in the strength of Atlantic meridional ocean circulation during the recovery, increasing summer insolation and atmospheric CO_2 concentration might also contribute to the slow recovery from the YD in the northern tropics (Partin et al., 2015).

On the other hand, we note that the changes in proxies from Dongyuan Lake occurred at the time of the minimum $\delta^{18}O$ values of stalagmites during the YD (Fig. 6). A recent study based on $\delta^{13}C$org on $\delta^{18}O$ of a stalagmite record in southwestern China also revealed that changes in $\delta^{13}C$org lagged the $\delta^{18}O$ record by about 300–500 years on the millennial scale climate events during the last deglaciation (Huang et al., 2016). Indeed, both $\delta^{13}C$org and lignin degradation parameters are related to vegetation evolution and microbial processes in soils. It has been pointed out that the responses of vegetation and microbial processes would produce a delayed effect by lagging behind climate changes regardless of whether the environment deteriorated or ameliorated (Genty et al., 2003; Ryan et al., 2012).

4. Conclusions

Based on a sediment core in the Dongyuan Lake from southern Taiwan, we present the lignin biomarker record and reconstruct the paleovegetation evolution and environment variation during the interval from the last deglaciation to early Holocene. Our records show a clear shift in vascular plants in the lake catchment from gymnosperm-dominant to angiosperm-dominant since 12.2 ka BP, which probably resulted from persistent increase in solar insolation and sea surface temperature in the western tropical Pacific. Dramatically decreased TOC, TLP, λ_8, enriched $\delta^{13}C$org and increased lignin degradation from 12.2 ka BP to 10.7 ka BP, which corresponds to the YD event, suggest a severe drought in southern Taiwan. Changes in the lignin proxies from the Dongyuan Lake lagged the stalagmite $\delta^{18}O$ records by about 500–800 years for both the onset and the termination of the YD event, suggesting a slow response of vegetation and soil processes to rapid climate change.

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