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Lake ecosystem dynamics and links to climate change inferred from a stable isotope and organic palaeorecord from a mountain lake in southwestern China (ca. 22.6–10.5 cal ka BP)

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ABSTRACT

A detailed understanding of long-term climatic and environmental change in southwestern China is hampered by a lack of long-term regional palaeorecords. Organic analysis (%TOC, %TN, C/N ratios and $\delta^{13}C$ values) of a sediment sequence from Lake Shudu, Yunnan Province (ca. 22.6–10.5 cal ka BP) indicates generally low aquatic palaeoproductivity rates over millennial timescales in response to cold, dry climatic conditions. However, the record is punctuated by two marked phases of increased aquatic productivity from ca. 17.7 to 17.1 cal ka BP and from ca. 11.9 to 10.5 cal ka BP. We hypothesise that these shifts reflect a marked, stepwise lacustrine response to Asian summer monsoon strengthening during the last deglaciation.

Introduction

China is likely to be one of the most seriously impacted regions under future climate change projections (Zeng et al., 2008). Impacts are likely to be particularly marked in extreme environments, including the high mountains of southwestern China. Within this zone, many plants are growing at the limit of ecological tolerance. Consequently, even small climatic shifts may significantly alter nutrient cycling and organic matter (OM) supply within ecosystems, changing organic productivity rates and/or vegetation assemblages (Boyle, 2007; Watson et al., 2007; Reuss et al., 2010). Gaining a deeper understanding of the long-term impacts of climate change upon the ecosystems located within this zone and the wider biosphere is therefore essential (Watson et al., 2007; Reuss et al., 2010). However, progress is hindered by a lack of palaeoenvironmental records, particularly in southwestern China and the Tibetan Plateau (Hodell et al., 1999; Zhang and Mischke, 2009).

Here we present a new organic palaeorecord from Lake Shudu, northwestern Yunnan Province, which provides insights into lake ecosystem dynamics and Asian Summer Monsoon (ASM) strengthening from ca. 22.6–10.5 cal ka BP. The data described here compliments previously published palaeoenvironmental datasets (e.g., Cook et al., 2011), focusing on terrestrial vegetation, sedimentary and fluvial responses to climate change at Lake Shudu.

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Geographic setting

Lake Shudu (27°54.616'N; 99°56.974'E) is a medium-sized open lake located ~3630 m asl in Zhongdian County, northwestern Yunnan Province (Figure 1) on the southeastern edge of the Tibetan Plateau. The catchment is ~14.2 km^2, the lake surface area is ~1.7 km^2 and maximum water depth is ~7.8 m, with a Secchi depth of ~1.4 m. Catchment geology is varied and includes quartzite, mica schist, limestone and sandstone. Located within the alpine/subalpine ecotone (Korner and Paulsen, 2004), catchment vegetation primarily consists of montane conifers such as Spruce (e.g., *Picea georgii*), sclerophyllous Oak (e.g., species of *Quercus*/*Cyclobalanopsis*) and grassland able to tolerate a monsoonal climate defined by cold, dry winters and warm summers (Peel et al., 2007; Cook et al., 2011).

Methods

A ~6.35 m long core (06SD) was extracted from the center of Lake Shudu at a depth of 7.8 m using a Uwitech Coring Platform System (Figure 1), subsampled at 0.5-cm intervals and freeze-dried. This study focuses on the sediments spanning 635–144 cm. AMS ^{14}C radiocarbon dating was performed on bulk sediment and pollen concentration samples (0.5-cm slices) by the NERC Radiocarbon Laboratory and the Oxford Radiocarbon Accelerator Unit, using published methods

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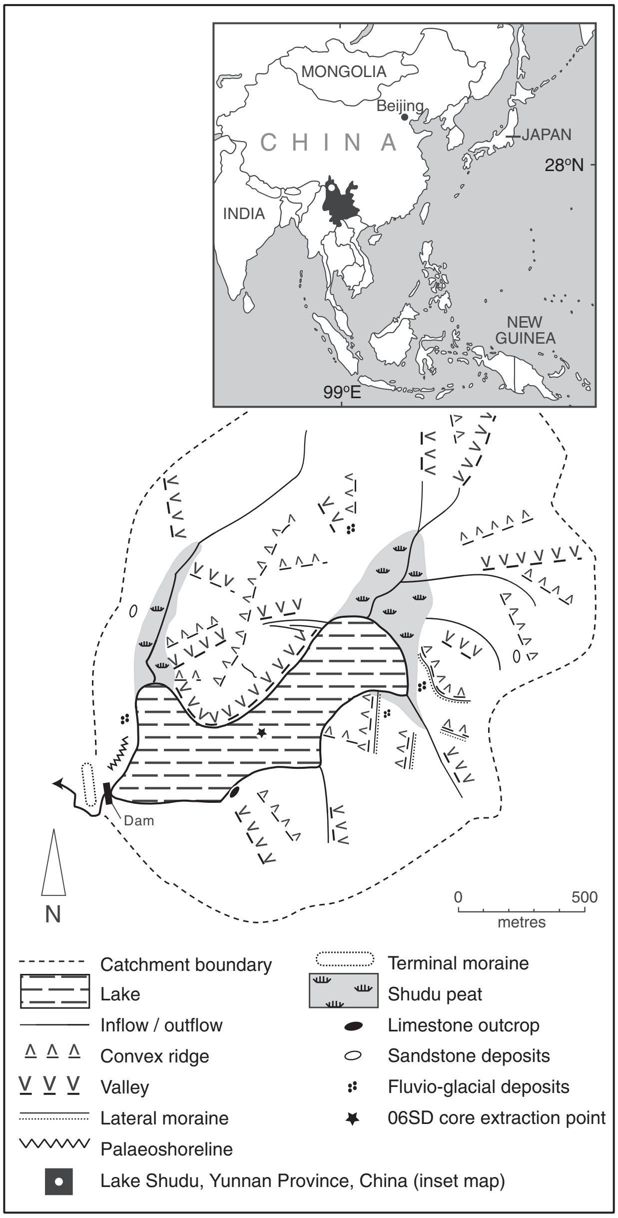

Figure 1. Map of Lake Shudu, Yunnan Province, China, with an inset map indicating its location within China.

and instrumentation (Bronk Ramsey et al., 2004). Dates were calibrated and modelled using Oxcal v. 4.17 and IntCal09 (Bronk Ramsey, 1995, 2001, 2008, 2009; Reimer, et al., 2009). For further details of the dating method / modelling approach used see Cook et al. (2011). Unless stated otherwise, 06SD dates are quoted in cal ka BP. The extrapolated basal age of the core is ca. 22.6 cal ka BP and the mean core resolution is ~30 years/cm.

Total Organic Carbon (%TOC), Total Nitrogen (%TN) (from which Carbon/Nitrogen (C/N) ratios were inferred) and $\delta^{13}C$ analyses were undertaken at 2-cm intervals using standard techniques (Leng et al., 2006). %TOC, %TN and $^{13}C/^{12}C$ analyses were performed at the NERC Isotope Geoscience Laboratories, Keyworth by combustion in a Costech Elemental Analyser (EA) on-line to a VG TripleTrap and Optima dual-inlet mass spectrometer. $\delta^{13}C$ values were calculated to the VPDB scale using a within-run laboratory standards calibrated against NBS-18, NBS-19 and NBS-22. Replicate analysis of well-mixed samples indicated a precision of $\pm$<0.1‰ (1 SD). %TOC and %TN content were calibrated against an Acetanilide standard. Replicate analysis of well-mixed samples indicates a precision of $\pm$<0.1%.

Results

AMS ^{14}C radiocarbon dating results for 06SD are presented in Table 1. Of particular note are the relatively young dates obtained from sediments at 335.25 cm and 339.25 cm (Table 1, Figure 2), most likely due to the percolation of humic acids and/or other organic residues through fine-grained sediment, resulting in the production of pre-aged dates (Bol et al., 1996; Mollenhauer et al., 2008).

The organic datasets are shown in Figure 2, alongside the core stratigraphy and primary regional terrestrial vegetation types inferred from the 06SD pollen record (Cook et al., 2011). In summary, %TOC is low, ranging from ~1% to 10%, %TN is also low at ~0.1% to 0.6%, C/N ratios are mostly <10 and $\delta^{13}C$ values are to −28‰ to −24‰. Notably, the palaeorecord is punctuated by marked increases in %TOC, %TN, C/N ratios and low $\delta^{13}C$ values from ca. 17.7 to 17.1 cal ka BP and ca. 11.9 to 10.5 cal ka BP.

Discussion

%TOC and %TN are likely to reflect organic palaeoproductivity rates. However, %TOC and %TN may be influenced by other factors such as post-depositional processes (e.g., diagenesis, oxidation of OM in the lake waters or in oxic pore waters in the upper sediments and burial; Vreca and Muri, 2010). These effects are usually small in lake sediments containing little OM (Wolfe et al., 1999), so this is unlikely to be a significant influence upon 06SD %TOC and %TN. Consequently, the %TOC and %TN records are used as proxies for organic palaeoproductivity rates. Generally low %TOC and %TN (<10% and <0.6% respectively) in the Lake Shudu record therefore suggests generally low organic productivity rates during the late Pleistocene–early Holocene.

C/N ratios provide insight into the source of sedimentary OM (i.e., whether primarily derived from terrestrial or aquatic sources). C/N ratios within 06SD are predominantly <10 (Figure 3a) and aligned to non-vascular, aquatic plants (e.g., phytoplankton) that contain little or no carbon-rich cellulose or lignin (Meyers, 1997; Meyers and Lallier-Verges, 1999; Leng et al., 2006). C/N ratios are ~6 up until 18 cal ka BP. This is low but not unheard of, as aquatic plants (including diatoms) tend to have low C/N ratios (Meyers and Teranes, 2001).

Because the C/N record indicates that OM is primarily derived from aquatic sources, the $\delta^{13}C$ record is interpreted in relation to within-lake processes (i.e., aquatic plant types and / or abundances). Other factors could also influence the $\delta^{13}C$ record. For example, there is a shift to slightly lower $\delta^{13}C$ values within 06SD (Figures 2 and 3), which may be linked to temporal changes in atmospheric CO_2 composition, rather than to changes in plant type / abundances (Mackie et al., 2007). Nevertheless, there are no major changes in plant type (i.e. from aquatic to terrestrial sources) inferred from the C/N record, so we assume that this does not significantly alter our interpretation of the $\delta^{13}C$ record.

Cross-referencing of the 06SD C/N and $\delta^{13}C$ records with the relevant modern global fields for C/N ratios and $\delta^{13}C$ values (Figure 3a) confirms a strong alignment to aquatic sources of OM. $\delta^{13}C$ values range from −28‰ to −24‰ (Figure 2) and are therefore likely to be derived from either phytoplankton (−47‰ to −26‰) or submerged or floating macrophytes (−50‰ to −11‰) (Meyers, 1997; Meyers and Lallier-Verges, 1999; Leng et al., 2006; Reuss et al., 2010). However, due to the overlap in 06SD $\delta^{13}C$ values of these groups, it is not possible to distinguish them.

In addition, the lack of terrestrial OM inferred from the C/N and $\delta^{13}C$ records, coupled with tundra or steppe and patches of boreal or cold–cool mixed forest vegetation inferred from the pollen record (Cook et al., 2011) implies thin soils and sparse regional terrestrial vegetation cover defined the landscape (Figure 2). During phases when soil-generated CO_2 is severely restricted, atmospheric CO_2 becomes an important contributor to mineral weathering processes

(Wolfe et al., 1999). Lacustrine plants subsequently utilise bicarbonate, reducing the fractionation against ^{13}C between the Dissolved Inorganic Carbon (DIC) and OM, and resulting in the production of lacustrine OM with relatively high $\delta^{13}C$ values (Turney, 1999). $\delta^{13}C$ values in the palaeorecord are high compared to typical $\delta^{13}C$ values for phytoplankton (−47‰ to −26‰) and macrophytes (−50‰ to −11‰) (Leng et al., 2006), suggesting that atmospheric processes were an important influence upon aquatic palaeoproductivity. Previous studies have indicated that atmospheric sources of CO_2 processes are more influential during cold, dry climatic phases (Wolfe et al., 1999).

Low long-term aquatic productivity rates coupled with relatively high $\delta^{13}C$ values implying reliance upon atmospheric sources of CO_2 may be related to prevailing cold, dry climatic conditions during the late Pleistocene, as reported in other published studies. For example, two lake records (14-X-94 and 16-X-94) from Xingyun Hu (24°20′N; 102°47′E, 1723 m asl) and Qilu Hu (24°10′N; 102°45′E, 1797 m asl), Yunnan Province indicate broadly low levels of $CaCO_3$, OM and high $\delta^{18}O$ values in sediments spanning ~25 to 12 cal ka BP. These shifts were attributed to a weakened ASM at the end of the last ice age (Hodell et al., 1999).

A palaeorecord (Erhai-99) from Lake Erhai, Yunnan Province (25°50′ N; 100°10′E, 1974 m asl), spanning ca. 18.5–10.5 cal ka BP, captures levels of %TOC, %TN, C/N ratios and $\delta^{13}C$ comparable to 06SD, which are attributed to low levels of aquatic organic productivity broadly linked to Asian Monsoon variability (Tareq et al., 2011). In a pollen record from Xi Hu, Yunnan Province (26°N; 100°E, 1980 m asl), abundances of montane conifers and *Pinus* evergreen sclerophyllous *Quercus* from ~17 to 15 cal ka BP are attributed to cold, semi-humid climatic conditions (Lin et al., 1986). At Lake Naleng (31.10°N; 99.75°E, 4200 m), the presence of pollen aligned to alpine steppe was attributed to low effective moisture from 17.7 to 14.8 cal ka BP (Kramer et al., 2010). High $\delta^{18}O$ values in a speleothem record (SJ3) from Songjia Cave, Sichuan Province (32°24′46″N; 107°10′45″E, ~680 m asl) spanning ~20–10 ka (Zhou et al., 2008) indicate cold climatic conditions relative to the present. $\delta^{18}O$ values are high from ca. 17.6 to 14.5 cal ka BP.

In addition to the long-term trends identified in the Lake Shudu palaeorecord, there are also marked shifts the organic variables over shorter timescales. From ca. 20.3 to 17.7 cal ka BP, %TOC, %TN and C/N ratios reduce to minimal levels. However, $\delta^{13}C$ values become lower. In other sections of the core, a shift to lower %TOC is accompanied by higher $\delta^{13}C$ and vice versa. %TOC is largely controlled by preservation, remineralisation, and sedimentary rate processes (Leng et al., 2006), which may explain why changes in %TOC is independent of $\delta^{13}C$ in this section of the record.

From ca. 17.7 to 17.1 cal ka BP, peaks in %TOC and %TN (Figure 2) suggest enhanced rates of organic palaeoproductivity. C/N ratios exceed 10, perhaps indicating the presence of more mixed sources of OM (Leng et al., 2006). $\delta^{13}C$ values are also much lighter, which when coupled with higher C/N ratios may correlate with a shift in sediment composition to include increased levels of OM derived from terrestrial sources.

A sharp influx of OM may be caused by an inwash event. However, we assume that this is not the cause of the observed shifts in the Shudu record because there is clear evidence for successional vegetation changes in the pollen record leading up to this event (Cook et al., 2011). In addition, it is likely that an inwash event would result in an influx of large quantities of old carbon into the lake. We would therefore expect the sediments in this section of the core to return correspondingly old ages. However, the ages obtained for the sediments at 335.25 cm and 339.25 cm were younger, which provides support for the theory that the shifts captured in the Lake Shudu record were not caused by an inwash event.

Alternatively increased levels of OM can occur when there is a greater influx of soil-derived CO_2 (Leng et al., 2006), for example when terrestrial organic productivity increases and vegetation cover becomes denser in response to warmer, wetter climatic conditions. The Lake Shudu pollen record provides support for this view, capturing a shift from largely sparse tundra vegetation (dominated by Poaceae) to denser steppe vegetation (including *Artemisia*, Gentianaceae, Ranunculaceae and Rosaceae) and an expansion in regional boreal *Pinus* forest cover (Figure 2 and Cook et al., 2011).

From ~23 ka, solar insolation levels (June, 30°N) began to rise (Berger and Loutre, 1991). The marked environmental shifts at Lake Shudu from ~17.7 cal ka BP therefore perhaps represent the initial response to warming, which accords well with the findings of other studies (e.g., Herzschuh, 2006). Notwithstanding this, it should be noted that the 06SD C/N and $\delta^{13}C$ records collectively indicate that OM was still *primarily* derived from aquatic sources and the pollen record is dominated by cold and / or drought tolerant taxa. This suggests that climatic conditions remained cold and dry relative to the present, which supports other regional palaeorecords (e.g., Kramer et al., 2010).

The nature and magnitude of the shifts suggest a stepwise lacustrine response to wider climatic change. Our findings also suggest that there was a delay between the initial rise in solar insolation and marked environmental change, as has been observed in other studies (e.g., Herzschuh, 2006). This possibly due to the influence of glacial–interglacial boundary conditions on the relationship between solar forcing and the Asian monsoon (Overpeck et al., 1996; Hodell et al., 1999; Herzschuh, 2006).

Whether shifts in palaeoproductivity observed at Lake Shudu were of a comparable magnitude at other sites in southwestern China is difficult to assess because of a lack of high-resolution regional organic palaeorecords spanning this period. However, pronounced environmental changes have been recorded elsewhere in China. For example, from ca. 18.5 to 17 cal ka BP, higher C/N ratios and a shift

Table 1
Conventional and calibrated AMS ^{14}C radiocarbon dates obtained from bulk sediments and pollen concentrations from the 06SD core, Lake Shudu, southwestern China.

Laboratory code	Mean core depth (cm)	Type	$\delta^{13}C$ (VPDB‰ ±0.1)	Conventional radiocarbon age (^{14}C yr BP)	Error (±)	Modelled age (BP; 1σ)[a]		Mean age[b] (cal ka BP)
ORL 22,358.00	220.25	Pollen	−24.9	11,880	80	13,617.5	13,357	13.5
SUERC 17151	220.75	Bulk	−27	12,256	54	–	–	–
SUERC 17154	250.75	Bulk	−27.7	13,071	54	15,218	14,906.5	15.1
SUERC 17155	305.75	Bulk	−26	14,063	59	16,931	16,755	16.8
SUERC 14156	335.25	Bulk	−28.6	10,045	45	–	–	–
ORL 22,359.00	339.25	Pollen	−24.8	9240	70	–	–	–
SUERC 17156	359.75	Bulk	−26	14,690	63	17,870.5	17,607.5	17.7
SUERC 17157	441.75	Bulk	−26.5	16,516	78	19,460	19,285	19.4
SUERC 17158	498.75	Bulk	−25.9	17,773	91	20,563	20,356	20.5
SUERC 17159	579.75	Bulk	−24.8	17,781	89	21,339.5	21,105	21.2
SUERC 14157	621.25	Bulk	−25	18,887	103	22,391	22,064	22.2

[a] Rejected dates that were not included in the final (modelled) chronology are denoted by a '–' symbol in the modelled and mean age columns. The chronology was produced using Oxcal 4.1.7 and IntCal09 (Bronk Ramsey, 1995, 2001, 2008, 2009; Reimer, et al., 2009).
[b] Mean ages are rounded to the nearest century.

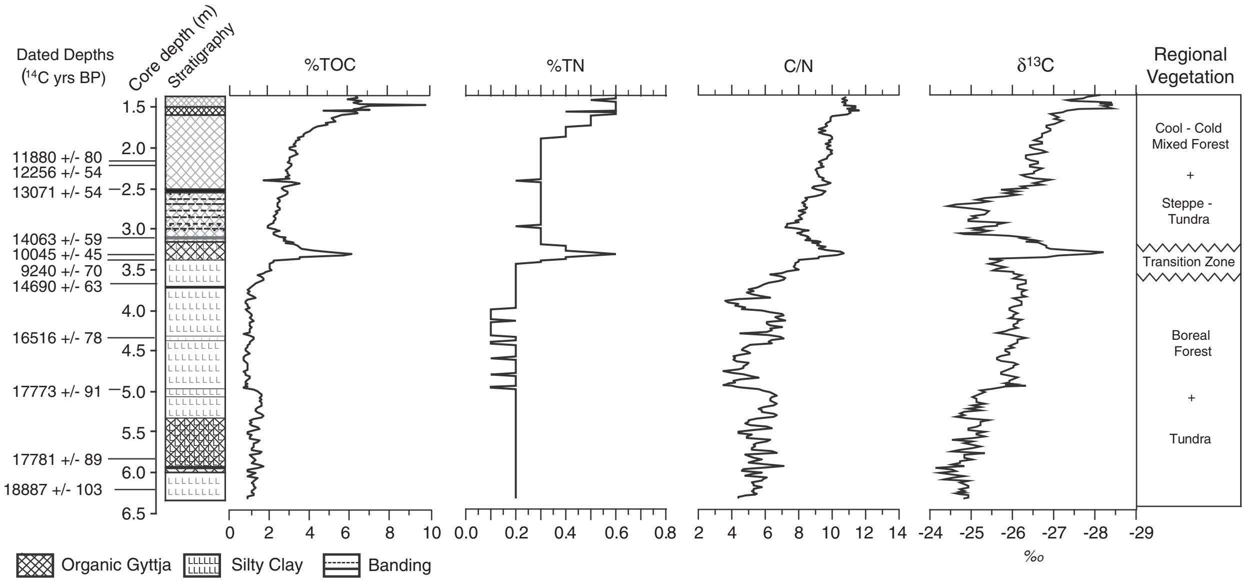

Figure 2. Stable isotope and organic data, 06SD core, Lake Shudu. From left to right: uncalibrated ^{14}C dates, core stratigraphy; primary regional vegetation biomes inferred from the 06SD pollen record (published in Cook et al., 2011), showing a marked vegetation transition from ca. 17.7 to 17.1 cal ka BP (zigzag lines); Total Organic Carbon (%TOC); Total Nitrogen (%TN); Carbon to Nitrogen ratios (C/N); carbon isotope values (δ^{13}C, quoted in ‰ per mil).

from charophytes to vascular macrophytes in a palaeolimnological record from Lake Luanhaizi in the Qilian Mountains, northwestern China (Herzschuh et al., 2005) were attributed to higher temperatures and increased moisture availability associated with significant climate amelioration. At the same time, increased continental runoff in the South China Sea (Wang et al., 1999) was ascribed to ASM strengthening following the last glacial maximum (LGM) (Herzschuh et al., 2005).

High δ^{13}C values coupled with relatively high %TOC from ca. 17.1 to 15.1 k cal ka BP may be attributable to the exhaustion of available light δ^{13}C within the lake carbon pool, forcing aquatic plants to utilise ^{13}C-enriched dissolved carbon within the lake. This may be attributed to a swifter aquatic response to climatic warming (than in terrestrial vegetation), preventing the establishment of a supply of terrestrial OM to the lake (Turney, 1999).

From ca. 15.1 to 11.9 cal ka BP, the organic variables indicate a marked increase in aquatic productivity (Figures 2 and 3). Within the catchment, the Lake Shudu pollen record indicates a shift to pollen types aligned to steppe and cool–cold mixed forest (e.g., *Pinus, Abies, Betula, Salix*) (Figure 2; Yu et al., 2000; Cook et al., 2011). An increase in mesophilous (e.g., *Picea*) and thermophilous pollen (e.g., *Ulmus*) is also evident. The changes broadly coincide with environmental changes in other regional lake palaeorecords spanning this time period, which are attributed to ASM strengthening and deglaciation during the transition from Pleistocene to Holocene conditions. For example, at Xi Hu, Yunnan Province, changes in vegetation composition from ~15 to 10.5 cal ka BP inferred from the pollen record include an increase in deciduous arboreal taxa, indicating enhanced seasonality (Lin et al., 1986). At Lake Erhai, Yunnan Province, an increase in angiosperms from ~14.2 cal ka BP inferred from lignin biomarkers is attributed to deglaciation and ASM strengthening (Tareq et al., 2011). Lower δ^{18}O values in the Songjia Cave record from Sichuan Province for the period ca. 14.5 to 12 ka are attributed to warm, humid conditions (Zhou et al., 2008). At Lake Naleng, the expansion of alpine meadows and treeline advancement from 14.8 to 12.5 cal ka BP is interpreted as a sign of a warmer, wetter climate (Kramer et al., 2010).

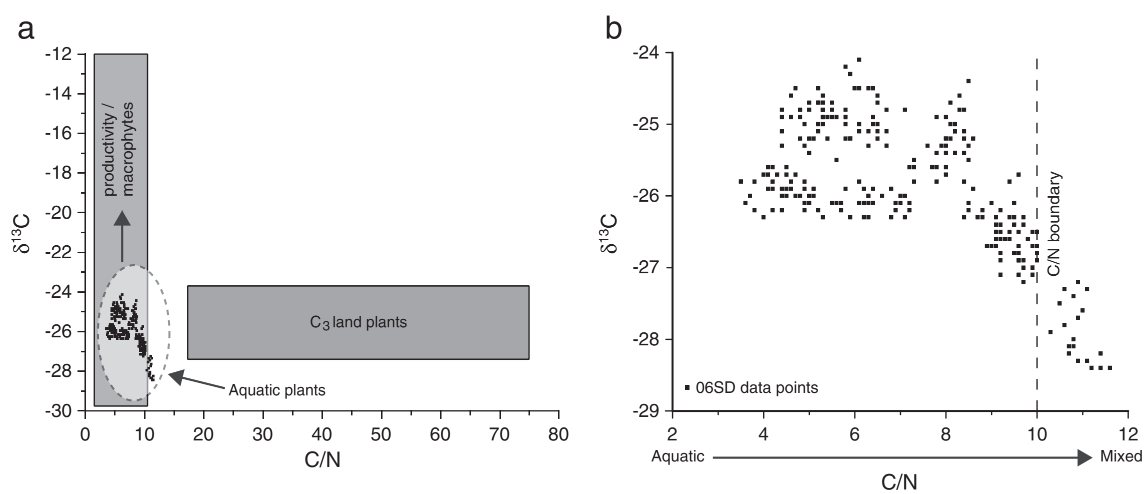

Figure 3. C/N ratios plotted against δ^{13}C values, 06SD core, Lake Shudu. (a) 06SD C/N and δ^{13}C data points plotted against modern global fields (dark grey boxes) for aquatic and C_3 plants (Meyers, 1997; Meyers and Lallier-Verges, 1999). The global field for C_4 plants is not shown because there are no values in this range in the Lake Shudu record. The OM in the 06SD core is primarily derived from aquatic plants (delineated by the ellipse with dashed lines). (b) Detailed view of the 06SD C/N and δ^{13}C data points. C/N ratios of >10 (the 'C/N boundary', dashed line) may indicate the presence of mixed sources of organic matter (OM). δ^{13}C values are quoted in ‰.

Notably, marked shifts captured in other regional palaeorecords spanning the deglacial period (e.g., Hodell et al., 1999; Wang et al., 2001; Zhou et al., 2008; Kramer et al., 2010) possibly correlated with intervals in the Greenland ice core records (e.g., Heinrich 1, Bølling/Allerød, Younger Dryas etc.) (Stuiver et al., 1995) are not clearly captured at Lake Shudu. Further research is required to determine the reasons for this and to examine whether these events are truly correlated or not.

Marked shifts in %TOC, %TN, C/N ratios and $\delta^{13}C$ from ca. 11.9 to 10.5 cal ka BP (Figure 2) reflect a phase of enhanced within-lake palaeoproductivity and increased recycling of aquatic OM within the water column/bottom sediments (Wolfe et al., 1999). C/N ratios suggest that OM in the core sediments perhaps indicate a change in the types and/or abundances of aquatic biota present in the lake (Figure 3b and Leng et al., 2006). Within the catchment, the pollen record indicates an increase in shrubs including *Salix* and *Corylus* a shift to pollen types aligned to steppe (e.g., Gentianaceae, Violaceae, Saxifragaceae) increase and diversify, pointing to more dense terrestrial vegetation cover (Figure 2; Yu et al., 2000; Cook et al., 2011). These environmental changes are likely to be linked to the onset of Holocene climatic conditions. At Qilu Hu and Xingyun Hu, Yunnan Province, an increase in OM and a decrease in calcite $\delta^{18}O$ values from ca. 12 cal ka BP is likely to reflect a decrease in the $\delta^{18}O$ of lake water and warmer temperatures (Hodell et al., 1999). A strong intensification of the ASM at ~11.5 cal ka BP inferred from Central Asian palaeorecords has been linked to the Pleistocene–Holocene (P–H) Transition (Herzschuh, 2006). Changes in the abundances of deciduous and coniferous pollen types (including increases in mesic deciduous taxa) from ~11 cal ka BP is evident in a pollen record from Lake Shayema, Sichuan Province and is attributed to ASM strengthening during the early Holocene (Jarvis, 1993).

Conclusions

The Lake Shudu palaeorecord suggests that from ca. 22.6 to 10.5 cal ka BP, palaeoproductivity rates were low and primarily driven by within-lake processes. Other studies indicate that cold, dry climatic conditions prevailed, which restricted palaeoproductivity at Lake Shudu. However, the Lake Shudu record is punctuated by two phases of enhanced aquatic productivity, from ca. 17.7 to 17.1 cal ka BP and from ca. 11.9 to 10.5 cal ka BP. We hypothesise that these shifts reflect a marked, stepwise lacustrine response to ASM strengthening during the last deglaciation. However, known events within this period (such as the Heinrich 1, the Younger Dryas etc.) captured in other regional palaeorecords (e.g., Hulu and Songjia Cave $\delta^{18}O$ records; Wang et al., 2001; Zhou et al., 2008) are not clearly captured at Lake Shudu. Further work is required to establish the reasons for this, and to develop new highly resolved, well-constrained palaeorecords from sites across southwestern China.

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