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Carbon and nitrogen signatures of sedimentary organic matter from Dali Lake in Inner Mongolia: Implications for Holocene hydrological and ecological variations in the East Asian summer monsoon margin

Jiawei Fan [a, b, *], Jule Xiao [a, c], Ruilin Wen [a], Shengrui Zhang [a, b], Xu Wang [a], Linlin Cui [a], Hideki Yamagata [d]

[a] Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] College of Earth Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
[d] Paleo Labo Co., Ltd., Saitama 335–0016, Japan

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A B S T R A C T

Environmental changes in the East Asian summer monsoon (EASM) margin have an important impact on the global climate system. This study presents the results of high-resolution analyses of TOC/TN (C/N) ratio, $\delta^{13}C$ and $\delta^{15}N$ of sedimentary organic matter extracted from a sediment core from Dali Lake, Inner Mongolia, in order to monitor Holocene hydrological and ecological variations in the EASM margin. Concurrent increases in the values of these proxies are generally interpreted to reflect intensified surface runoff and vegetation development in the lake catchment, elevated lake levels and enhanced lake productivity; however, changes in $\delta^{13}C$ and $\delta^{15}N$ may also result from within-lake processes due to changes in lake level. These data indicate that Dali Lake experienced gradual rises in water level and primary productivity from 11,500 to 9800 cal yr BP, as documented by increases in TOC and TN concentrations, C/N ratios and $\delta^{13}C$ and $\delta^{15}N$ values. From 9800 to 7700 cal yr BP, high, stable TOC and TN concentrations and C/N ratios together with low $\delta^{13}C$ and $\delta^{15}N$ values suggest a status of high stands and high productivity for the lake and a development of terrestrial vegetation in the catchment. Between 7700 and 5900 cal yr BP, TOC and TN were fluctuating at higher concentrations and C/N maintained high ratios, while $\delta^{13}C$ increased in its value and $\delta^{15}N$ remained at low values, denoting a further rise in lake level and a notable improvement of aquatic and terrestrial ecosystems. Around 5900 cal yr BP, TOC and TN concentrations, C/N ratios and $\delta^{13}C$ values decreased abruptly, while $\delta^{15}N$ value increased rapidly, implying dramatic drops in lake level and water temperature and drastic declines of aquatic and terrestrial ecosystems. Subsequently all geochemical proxies increased in their values until 4850 cal yr BP, indicating a gradual hydrological and ecological recovery. From 4850 to 750 cal yr BP, decreasing trends of TOC and TN concentrations and C/N ratios and increasing trends of $\delta^{13}C$ and $\delta^{15}N$ values denote a general decline in the hydrological and ecological conditions. The last 750 cal yrs witnessed the pattern of hydrological and ecological changes occurring from 5900 to 4850 cal yr BP. We suggest that hydrological and ecological changes in the EASM margin during the Holocene were closely related to the combined effects of regional precipitation and temperature which were ultimately controlled by the Northern Hemisphere summer insolation, the boundary conditions and the physical environment of ocean current.

1. Introduction

The environment of the East Asian summer monsoon (EASM) margin, defined as the semi-arid zone in northern China with mean annual precipitation ranging from 400 to 200 mm, is highly vulnerable to climate change due to the high degree of rainfall

* Corresponding author. Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China.
E-mail address: jwfan@mail.iggcas.ac.cn (J. Fan).

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variability in summer and the frequent occurrence of cold waves in winter (Chinese Academy of Sciences, 1984; Zhang and Lin, 1985). In the geological past, when the climate became dry, the EASM marginal zone acted as a major source of mineral dust production (An, 2000; Zhang et al., 2003) which potentially affected the global climate via regulation of the atmospheric radiation balance (Kinne and Pueschel, 2001; Sokolik et al., 2001) and oceanic plankton productivity (Ridgwell, 2002; Jickells et al., 2005). Recent climate model results suggest that by the end of this century, global warming may have severe environmental consequences in mid-latitude semi-arid regions, including the EASM margin (IPCC, 2013). However, in view of the inherent uncertainties of numerical models, it is important to examine proxy evidence from geological archives in order to characterize the environmental variability of the EASM margin during the current interglacial, the Holocene warm period.

The organic matter accumulated in lake sediments has long been considered to reflect changes in terrestrial vegetation in the lake catchment, aquatic plant productivity within the lake, and hydrological conditions in the lake basin; thus constitutes a source of information about variations in the regional environment through time (Prokopenko et al., 1999; Meyers and Teranes, 2001; Lamb et al., 2004; Lücke and Brauer, 2004; Wischnewski et al., 2011; Aichner et al., 2012). Total organic carbon (TOC) and total nitrogen (TN) concentrations, TOC/TN (C/N) ratio, and the $\delta^{13}C$ and $\delta^{15}N$ values of lacustrine organic matter have been widely used to reconstruct changes in the hydrology and ecology of various lake–catchment systems (Narantsetseg et al., 2013; Wang et al., 2013; Ghosh et al., 2014; Kigoshi et al., 2014; Wang et al., 2014; Sun et al., 2016). For example, in Qinghai Lake, northeastern Tibetan Plateau, C/N ratios of the sedimentary organic matter decreased, while $\delta^{13}C$ values increased, during the past 18,000 yr, indicating an increasing trend of lake primary productivity that was related to climatic warming and increasing humidity in the region (Shen et al., 2005). In Cuoe Lake, central Tibetan Plateau, high TOC concentrations and increased $\delta^{13}C$ values from 8500 to 5700 cal yr BP were inferred to reflect a high level and high primary productivity of the lake under a warm and humid climate (Wu et al., 2006). The organic matter extracted from the varved sediments of Sihailongwan Lake, northeastern China, exhibits increases in TOC and TN concentrations and $\delta^{15}N$ values during the late glacial, suggesting an increase in the productivity of planktonic algae within the lake related to increased inputs of dissolved nutrients under a warm climate (Parplies et al., 2008). Recent studies of sedimentary organic matter from Emerald Peak Lake, Taiwan, located at the core of the EASM region, suggest that high TOC concentrations and C/N ratios, together with low $\delta^{13}C$ values, during the last 2000 cal yr BP denote a high lake stand and dense development of terrestrial C_3 plants resulting from strengthened monsoonal precipitation (Selvaraj et al., 2012).

However, there are discrepancies in interpreting the above proxies with respect to the hydrology and ecology of different lakes, which can vary greatly in terms of sensitivity to factors such as basin structure and climate regime. For example, increased C/N ratios and $\delta^{13}C$ values at Luanhaizi Lake, northeastern Tibetan Plateau, were considered to reflect the presence of submerged macrophytes (Herzschuh et al., 2005). Decreased C/N ratios and $\delta^{13}C$ values at Cuoe Lake were interpreted to reflect the degradation of deposited organic matter due to lowered lake levels (Wu et al., 2006). Increased $\delta^{15}N$ values in Bosumtwi Lake, west Africa, were inferred to result from ammonia volatilization caused by increased lake water alkalinity (Talbot and Johannessen, 1992); while decreased $\delta^{15}N$ values in Tanganyika Lake, east Africa, were interpreted as resulting from nitrogen fixation by the aquatic phytoplankton community (McManus et al., 2015). Therefore, it is important to carefully examine the factors driving variations in organic matter proxies of different lakes in order fully to explore the potential of lakes as reliable sources of information on environmental changes.

Several lakes are located in the EASM margin (see Fig. 1) and are considered as ideal natural archives of past changes in EASM intensity (Li et al., 1992; Xiao et al., 2004, 2006, 2008, 2009; Zhang et al., 2012; Fan et al., 2016). Previous analyses of the TOC concentration and C/N ratio of a sediment core from Dali Lake in the EASM margin revealed the significant impact of monsoon-precipitation-induced soil erosion in the lake catchment on lacustrine processes (Xiao et al., 2008). Nevertheless, hydrological and ecological variations of lake–catchment systems in the EASM margin, and their response to climate change, remain unclear. In the present study, we present high-resolution (~50 yr) records of TN concentration, C/N ratio, $\delta^{13}C$ and $\delta^{15}N$ values of sedimentary organic matter in a Holocene sediment core from the EASM margin. The main aim of the study is to use the dataset to improve our understanding of the environmental variability in mid-latitude semi-arid regions during geological warm periods and the possible response of these fragile environments to future global warming.

2. Regional setting

Dali Lake (43°13'–43°23' N, 116°29'–116°45' E) is located in the northern margin of the E–W-extending Hulandaga Desert Land, 70 km west of Hexigten Banner, Inner Mongolia (Fig. 1), in an inland fault-depression basin that was formed in the Pliocene to Pleistocene (Li, 1993). The lake has an area of 238 km^2, a maximum water depth of 11 m, an elevation of 1226 m above sea level (Fig. 1), and is hydrologically closed. Hills surround the lake to the north and west, and lacustrine plains are present along the eastern shore. Two permanent rivers, the Gongger and Salin Rivers, enter the lake from the northeast; and two intermittent streams, the Holai and Liangzi Rivers, enter from the southwest (Fig. 1); however, there are no outflowing rivers. The Gongger River, the major inflow, rises in the southern terminal part of the Great Hinggan Mountains, where the elevation reaches 2029 m, and has a drainage area of 783 km^2 and a total channel length of 120 km (Li, 1993). Hydrological observations indicate that the discharge of the Gongger River is as large during spring floods in April as during summer floods in July, because of significant melt water runoff from the snow/ice packs covering the mountains (Li, 1993).

Dali Lake is located at the transition from semi-humid to semi-arid areas of the middle temperate zone. The climate of the region is controlled by the East Asian monsoon (Chinese Academy of Sciences, 1984; Zhang and Lin, 1985). In region, mean annual temperature is 3.2 °C with a July average of 20.4 °C and a January average of −16.6 °C (Fig. 2). Mean annual precipitation is 383 mm, and ~70% of the annual precipitation falls from June–August (Fig. 2). Mean annual evaporation reaches 1632 mm, which is more than 4 times the annual precipitation (Fig. 2). Dali Lake has a pH of 9.5, a salinity of 7.4 g/L and an alkalinity of 4.9 $CaCO_3$ g/L (measurements made in June 2010). The $\delta^{13}C$ of the lake's dissolved inorganic carbon ($\delta^{13}C_{DIC}$) averages −0.3‰ (PDB), the $\delta^{13}C_{DIC}$ of Gongger River is −7.8‰ (PDB) and the average $\delta^{13}C_{DIC}$ of the four inflowing rivers is −6.1‰ (PDB) (measurements made in June 2010).

The modern natural vegetation of the Dali Lake basin is categorized as middle temperate steppe and is dominated by grasses (Compilatory Commission of Vegetation of China, 1980; Li, 1993). In the Hulandaga Desert Land, low-growing xerophilous plants including *Polygonum divaricatum*, *Agriophyllum squarrosum* and *Artemisia desterorum* are present, together with the shrubs *Salix*

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