Journal of Soils and Sediments (2022) 22:1597–1608
https://doi.org/10.1007/s11368-022-03191-2

SEDIMENTS, SEC 2 • PHYSICAL AND BIOGEOCHEMICAL PROCESSES • RESEARCH ARTICLE

Isotopic constraints on sources of organic matter in surface sediments from two north–south oriented lakes of the Yunnan Plateau, Southwest China

Lizeng Duan[1] · **Hucai Zhang**[1] · **Fengqin Chang**[1] · **Donglin Li**[2] · **Qi Liu**[1] · **Xiaonan Zhang**[1] · **Fengwen Liu**[1] · **Yang Zhang**[1]

Received: 27 October 2021 / Accepted: 10 March 2022 / Published online: 17 March 2022

Abstract

Purpose Lake sediment is an important carbon reservoir, and knowledge of organic carbon distribution and its controlling factors can provide insights into the effects of natural processes and anthropogenic pressures on carbon dynamics in drainage basin.

Materials and methods Here, we combined total organic carbon (TOC), total nitrogen (TN), and their stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) with a Bayesian isotope mixing model to identify the origin of organic matter (OM) and the key factors influencing OM accumulation in surface sediments from Lake Yangzong (YZ) and Lake Chenghai (CH), located on the Yunnan Plateau, SW China.

Results and discussion The $\delta^{13}C$ values in surface sediments from YZ showed a gradual increase from south to north, with an asynchronous decrease in $\delta^{15}N$, suggesting an increasing contribution of pollutants originating from the Yangzong River. In contrast, CH was characterized by a rapid decrease in $\delta^{13}C$ and an increase in $\delta^{15}N$ values occurring in the deepest part of the lake, indicating that water depth may play an important role in OM accumulation in the lake. Allochthonous OM (C3 plant and soil OM) was the dominant sediment OM source for surface sediments in YZ, while substantial contributions of OM originated from plankton, soil OM, and sewage in CH.

Conclusions These findings suggest that trophic state and terrestrial input may exert large impact on OM accumulation in deep lakes, which results in different distribution patterns of OM sources.

Keywords Carbon isotope · Nitrogen isotope · Organic carbon accumulation · Trophic level · Deep lakes

1 Introduction

Lake sediments represent an important terrestrial carbon reservoir, which can accumulate large amounts of terrestrial material from watersheds and store a significant amount of carbon in sediments (Anderson et al. 2009; Battin et al. 2009; Tranvik et al. 2009; Ferland et al. 2012). Although the carbon (hereafter "C") burial flux in lakes is often small compared to C emissions, it represents a significant long-term C sink, with an estimated 0.09 Pg C per year of organic carbon (OC) burial (Mendona et al. 2017). Therefore, lakes may play an important role in the global and regional carbon cycle. Previous studies have proven that there is strong spatial variability in the total organic carbon (TOC) of lake sediment (Dean and Gorham 1998; Khim et al. 2005; Bechtel and Schubert 2009; Woszczyk et al. 2011; Wang et al. 2012). The distribution pattern of TOC in surface sediment is closely linked with water column productivity, terrestrial inputs of organic materials, rates of microbial activity, and properties of the sediment (Burone et al. 2003; Gireeshkumar et al. 2013). In particular, the contributions of autochthonous and allochthonous sources have direct impacts on the spatial distribution

---

Responsible editor: Nives Ogrinc

✉ Hucai Zhang
zhanghc@ynu.edu.cn

[1] Institute for Ecological Research and Pollution Control of Plateau Lakes, School of Ecology and Environmental Science, Yunnan University, Yunnan 650500, China

[2] Institute for International Rivers and Eco-Security, Yunnan University, Kunming 650500, China

of TOC in surface sediments (Anderson et al. 2009; Bechtel and Schubert 2009). In general, lakes with high productivity have more autochthonous TOC, while lakes with low productivity are derived mainly from allochthonous TOC (Dean and Gorham 1998). Therefore, the knowledge of sedimentary organic matter (OM) sources, their distribution, and controlling factors in a lake can provide insights into the effects of anthropogenic pressures and natural processes on the aquatic ecosystem in the drainage basin.

Quantitative analysis techniques, e.g., two- or three-end-member mixing models and the Bayesian isotope mixing model (MixSIAR model), have been broadly applied to quantify different sources of OM (Liu and Kao 2007; Yu et al. 2010; Rumolo et al. 2011; Chen et al. 2018; Guo et al. 2020; Wu et al. 2021). The application of these mixing models is based on the hypothesis that different OM sources (e.g., autochthonous and allochthonous sources) show significantly distinguishable stable isotope values and C/N ratios (Liu et al. 2006). Terrestrial OM has a C/N ratio of > 20 (Meyers 1994), while freshwater OM is characterized by less variable C/N ratios (ca. 4–10; (Meyers 1994)). Furthermore, terrigenous OM has depleted $\delta^{13}C$ and $\delta^{15}N$ values compared to freshwater OM (Cifuentes and Eldridge 1998; Harmelin-Vivien et al. 2008). Typical $\delta^{13}C$ and $\delta^{15}N$ values of terrestrial OM range from −32 to −22‰ (Kendall et al. 2007) and from −6 to 5‰ (Fry 1991), respectively. Marine OM such as plankton ranges from −22 to −18‰ (Kendall et al. 2007) and from 5 to 8‰ (Thornton and McManus 1994) for typical $\delta^{13}C$ and $\delta^{15}N$ values, respectively. $\delta^{15}N$ signatures have been proven to be an effective approach to track anthropogenic inputs, although nitrogen transformation is susceptible to isotope fractionation at different magnitudes (Ke et al. 2017). Fortunately, the combination of $\delta^{13}C$ and the C/N ratio of OM has been widely applied to evaluate the sources of OM in aquatic ecosystems (Chen et al. 2018; Guo et al. 2020; Wu et al. 2021).

Most lakes in the Yunnan-Guizhou Plateau are characterized by a small catchment area, steep lakeshore, a north–south orientation and have widespread bare bedrock lake bottoms and are controlled by the surrounding terrain (Yang and Huang 2002). Specifically, the flat terrain surrounding these lakes is mainly located on the northern or southern shores, where a large number of contaminants and soil loss may affect the accessibility of these lakes due to the high intensity of human activities. Correspondingly, increasing anthropogenic pressure and pollutant discharge may exert large impacts on the accumulation and burial of OM in these lakes. Lake Yangzong (YZ) and Lake Chenghai (CH) are N-S orientated lakes in Yunnan Province and are ideal places for studying surface sediment lake carbon burial due to their similar lake geomorphologies. Previous studies have shown that the two lakes have experiences threatening water deterioration in recent decades, such as the decline in water level, eutrophication, and heavy metal contamination (Wang and Dou 1998; Wu et al. 2004; Wang 2011; Zhang et al. 2012; Liu et al. 2015). Recently, a sedimentary core study indicated that sedimentary organic carbon variability in the YZ was affected by allochthonous sources (Wu et al. 2021). However, little research has been carried out to assess the dynamics and sources of surface sediment OM in the YZ and CH, N-S oriented lakes. Therefore, this study aimed to evaluate the spatial distributions of TOC, TN, C/N ratios, $\delta^{13}C$, and $\delta^{15}N$ in the surface sediment of YZ and CH, and to quantify the contributions of various OM sources to the sediment.

2 Materials and methods

2.1 Study area

Lake Yangzong (24°51′-24°58′ N, 102°5′-103°2′ E) is located in the eastern part of Kunming city, Yunnan Province, Southwest China, and belongs to the upper part of the Pear River. The lake is approximately 12 km long from north to south and 3 km wide from east to west, with a surface area of ~ 29 km^2 (at an altitude of 1770 m a.s.l.) and has a maximum water depth of 30 m, and a catchment area of 171 km^2 (Fig. 1). The climate in the region is dominated by the southwest monsoon in summer and by westerlies in winter, with an average annual air temperature of ~ 14.5 °C, a mean annual precipitation of ~ 963.5 mm, and the mean annual evaporation of ~ 1377 mm. The lake is mainly controlled by south and southwest winds, and the lake currents flow from south to north. The main water inputs include river discharge from the Yangzong, Qixing, and Luxichong rivers. The outflow from YZ is manually controlled by Tangchi River at the northeast end of the lake, which drains into Nanpan River (Wang and Dou 1998). The main pollution sources in the watershed are non-point agricultural source pollution and domestic sewage, which are located in the southern part of the catchment area (Wang 2003; Zhang et al. 2017). The basin has also suffered from severe soil erosion, with an average annual soil loss of 29.32×10^4 t (Zhu 2008).

Lake Chenghai (26°27′-26°38′ N, 100°38′-100°41′ E) is a relatively deep lake (average depth of 25.7 m, maximum depth of 35.1 m) located in the southeastern part of Lijiang city, Yunnan Province, Southwest China. The lake has a surface area of 75.97 km^2 and a catchment area of 259 km^2, with a maximum water volume of 19.79×10^8 m^3 at a level of 1502 m (Fig. 1). The region is dominated by a warm-temperate mountain monsoon climate, which is one of the typical hot-dry river valley areas along the Jinsha River (Xiao et al. 2018). The average annual temperature in the region is 13.5 °C, with an average precipitation of 738.6 mm and annual evaporation of 2040.3 mm. More than 90% of the

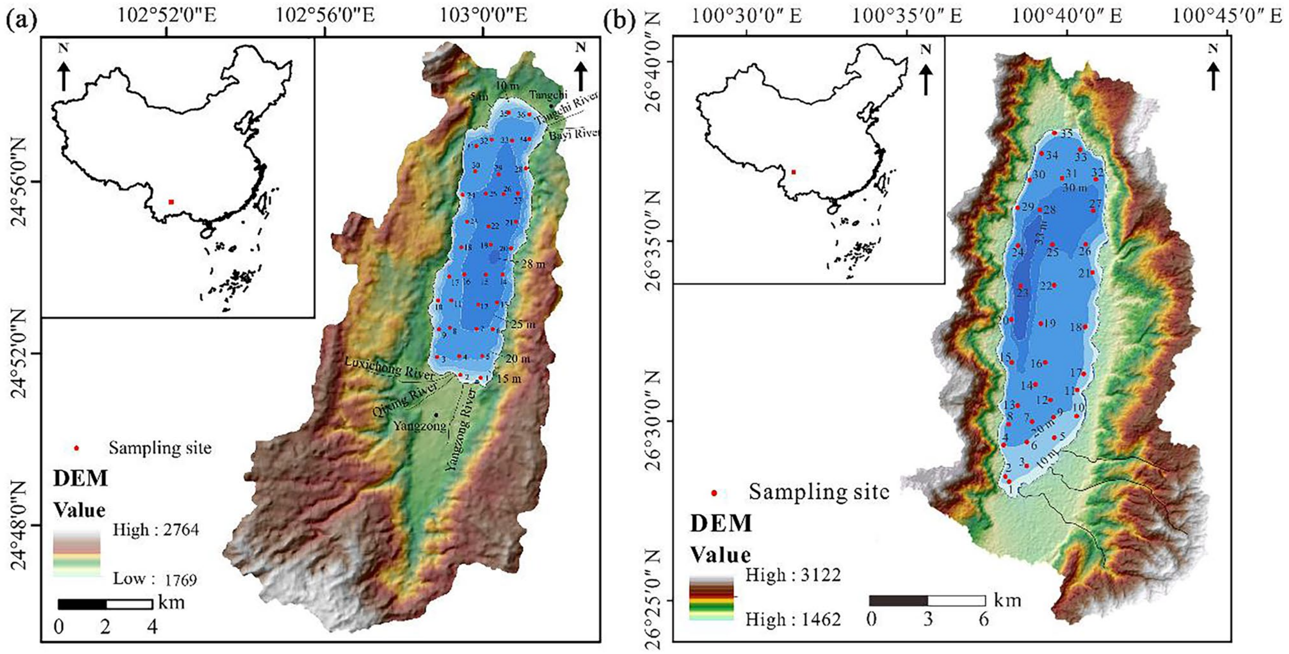


Fig. 1 Map showing the site location, catchment morphology, and lake bathymetry, with the sampling sites (red dots) in YZ (left) and CH (right), their positions were marked in red dots in the inserted maps of China

total annual rainfall occurs from June to September. Since the mid-1980s, the lake watershed has experienced greater usage by humans and increased pollution due to the increasing application of agricultural fertilizers to enhance farm production (Wu et al. 2004).

2.2 Sample collection

In November 2015 and March 2018, surface sediment samples were collected at 36 sites in YZ and 35 sites in CH using a UWITEC gravity sampler (Fig. 1). The sampling sites covered most of the two lakes, with water depths ranging from 9.5 to 26.2 m in YZ and 4.6 to 29.1 m in CH. The sediment cores were carefully extruded, and the top 2 cm was sliced into 1 cm section and placed in polyethylene bags that were kept on ice in a cooler during transport and before analysis.

2.3 Laboratory methods

An elemental analyzer (Vario Micro Cube, Elementar) was used to determine the TOC and TN concentrations in the surface sediment samples at the laboratory of Yunnan Normal University. In general, all samples were first freeze-dried and ground to 500 mesh size then placed in a beaker and weighed. A total of 0.5 mol/L HCl was added to each sample and stirred until the reaction stopped to remove inorganic carbonates. Then each sample was washed with deionized water until the supernatant liquid was neutral (pH≈7). All the samples were dried for 3 h at 60 °C in a type 101 electric heating blast dryer and then cooled to room temperature. The C/N ratios of the OM were determined based on the TOC and TN data.

The $\delta^{13}C_{org}$ and $\delta^{15}N$ values were measured using a gas isotope ratio mass spectrometer (Finnigan MAT 253, Thermo Fisher Scientific, Waltham, MA, USA) with analytical errors of 0.2% at Yunnan Normal University. Before the analysis, each sample was processed according to the TOC processing method and purified using liquid nitrogen. For the $\delta^{13}C_{org}$ and $\delta^{15}N$ analysis, δ notation was used to represent the isotopic ratio differences between the measured samples and standard. The formulas are expressed as follows:

$$\delta^{13}C_{org}\ (\%_0) = [(R_{sample} - R_{standard})/R_{standard}] \times 1000, R = {}^{13}C/{}^{12}C \tag{1}$$

$$\delta^{15}N\ (\%_0) = [(R_{sample} - R_{standard})/R_{standard}] \times 1000, R = {}^{15}N/{}^{14}N \tag{2}$$

where ${}^{13}C/{}^{12}C$ and ${}^{15}N/{}^{14}N$ refer to international standards Vienna PDB and atmospheric nitrogen standard, respectively. R_{sample} and $R_{reference}$ are the isotopic ratios of the sample and reference, respectively.

2.4 Bayesian mixing model

The MixSIAR model was used to calculate the contributions of each potential OM source (e.g., macrophytes, sewage, C3 plants, plankton, and soil OM) in the surface sediments. In this study, we prove that the scatter plot of $\delta^{13}C_{org}$ vs. C/N is reliable to qualitatively assess the OM sources, suggesting that the combination of $\delta^{13}C_{org}$ and C/N can be used to calculate the proportional contributions of OM sources in the surface sediments from YZ and CH. First, the OC and N data, typical isotope values, and C/N ratios were input into the MixSIAR model programmed in R package (version 3.1.11), and the proportional contributions of different OM source types were identified. The Markov chain Monte Carlo algorithm was set as "very long" and the Gelman–Rubin and Geweke diagnostic tests were applied to assess the reliability of the output data (Stock and Semmens 2013). In general, a Gelman–Rubin diagnosis of < 1.05 suggests that the output data are reliable. The error structure and specified prior were set as "residual error" and "uninformative" respectively. The median values (50% quartiles) of the output data indicate each OM source contribution of surface sediments.

2.5 Statistical methods and mapping

We used OriginPro 2016 software (Origin Lab, Ltd, Northampton, USA) to the data interpolation by Kriging method. Moreover, the Pearson correlation of data was also analyzed by OriginPro 2016 software.

3 Results

3.1 Spatial distribution of TOC, TN, and C/N ratios

Figure 2 shows the spatial variability of TOC, TN, and C/N ratios in the surface sediments of YZ and CH. The TOC concentrations in YZ ranged from 1.51 to 11.35% (average of 7.45%), with higher values found in the southwest sections of the lake. There were also higher values of TOC in the deepest section of the lake. On the other hand, lower TOC values were identified in the northeast section and south sections near the mouth of the Yangzong River. In general, the distribution of TN in the sediments is similar to that of TOC, with a significant linear relationship between TOC and TN ($p < 0.001$) (Fig. 3a). There is also a general gradient showing an increase in C/N ratios from south to north. The TOC and TN concentrations in CH surface sediment ranged from 2.36 to 12.17% and 0.27 to 1.95%, respectively. In contrast to YZ, there is a clear spatial gradient from the shallow water part of TOC and TN values in the deepest part of the lake. In CH, the C/N ratio was characterized by large spatial variability with a range from 2.38 to 25.62. In general, the C/N ratio was lower in the eastern part than in other parts. The highest C/N ratio was found in the southern part of the lake near the river mouth.

3.2 Spatial distribution of $\delta^{13}C_{org}$ and $\delta^{15}N$

The spatial variation in $\delta^{13}C_{org}$ and $\delta^{15}N$ values of surface sediments form YZ and CH is presented in Fig. 4. The $\delta^{13}C_{org}$ and $\delta^{15}N$ values in YZ ranged from −30.94 to −27.50‰ and from 3.27 to 8.59‰, respectively (Fig. 5). $\delta^{13}C_{org}$ showed a clear spatial gradient with higher values towards the north, while there was a decreasing trend in $\delta^{15}N$ values from south to the north. The exception was in the southwest area, which had a high $\delta^{13}C$ value but a low $\delta^{15}N$ value. The $\delta^{13}C_{org}$ values in CH vary from −23.78 to −29.40‰, with the most depleted values generally occurring in the deepest part of the lake. The $\delta^{15}N$ value in the sediments ranged from 2.33 to 4.82‰, with the most depleted $\delta^{15}N$ values occurring at or close to the lakeshore (Fig. 4).

3.3 Source of sedimentary organic matter

According to field surveys and possible OM sources published in previous studies (Machiwa 2010; Shao et al. 2019), five OM sources (plankton, macrophytes, C3 plants, sewage, and soil OM) were chosen to evaluate the OM sources in YZ and CH. The typical stable composition of each potential OM source is presented in Table 1. As is shown in scatter plots of $\delta^{13}C_{org}$ vs. C/N, OM in YZ is within the ranges of C3 plants, soil OM, sewage, plankton, and macrophytes (Fig. 5a), while OM in CH mainly came from soil OM, sewage, plankton, and macrophytes. Scatterplots of the $\delta^{15}N$ vs. C/N (Fig. 5b) in YZ show that the sedimentary OM was mainly separated into three sources, namely, C3 plants, macrophytes, and soil OM, while the sedimentary OM in CH originated from soil OM. In addition, scatterplots of $\delta^{13}C_{org}$ vs. $\delta^{15}N$ (Fig. 5c) show that OM in YZ sediments was primarily dominated by C3 plants, soil OM, plankton, and macrophytes, whereas sedimentary OM in CH was only derived from C3 plants, soil OM, and macrophytes.

The MixSIAR model is effective in assessing the relative proportions of terrestrial and lake organic carbon in lake sediments (Guang et al. 2010; Guo et al. 2020). We used −23.5‰, −24.8‰, −27.0‰, −27.5‰, and −27.5‰ as the $\delta^{13}C_{org}$ values of macrophytes, sewage, C3 plants, plankton, and soil OM, respectively, based on the typical stable composition of OM sources (Table 1). Similarly, the C/N ratios of macrophytes, sewage, C3 plants, plankton, and soil OM were 20.0, 9.8, 22.5, 6.5, and 11.5, respectively. Among the variables analyzed in this study, none was higher than the lowest estimated factor of 1.05 for the Gelman–Rubin test, thereby suggesting that our output data were reliable. The results shown in Fig. 6a indicate that the contribution of C3 plants in YZ sedimentary OM was 72.3 to 76.0% (average of 74.6%), soil OM was 7.3 to 9.3% (average of 8.1%), macrophytes was

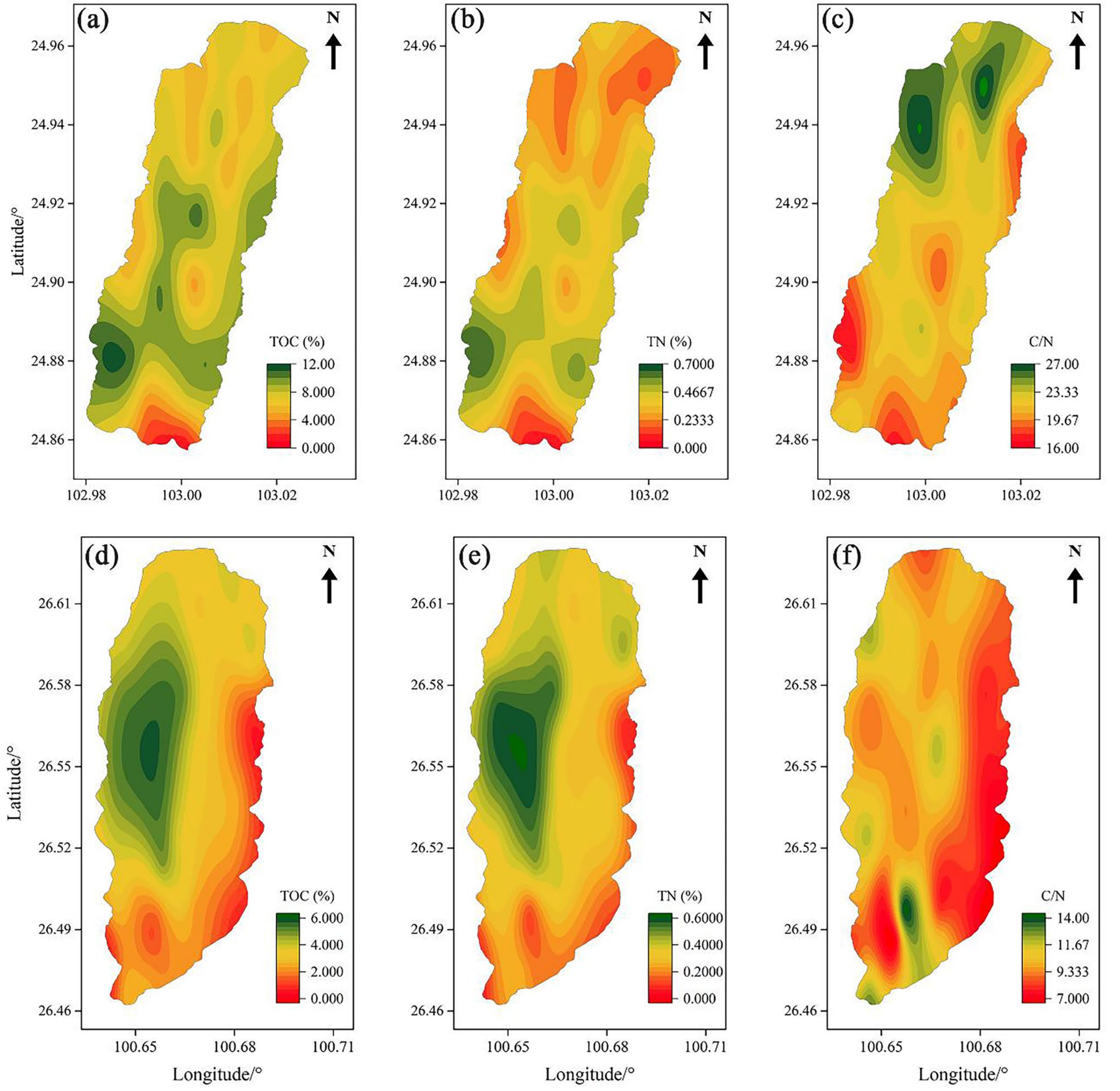


Fig. 2 Spatial distributions of TOC (**a** and **d**), TN (**b** and **e**), and C/N ratios (**c** and **f**) in surface sediments of YZ and CH, respectively

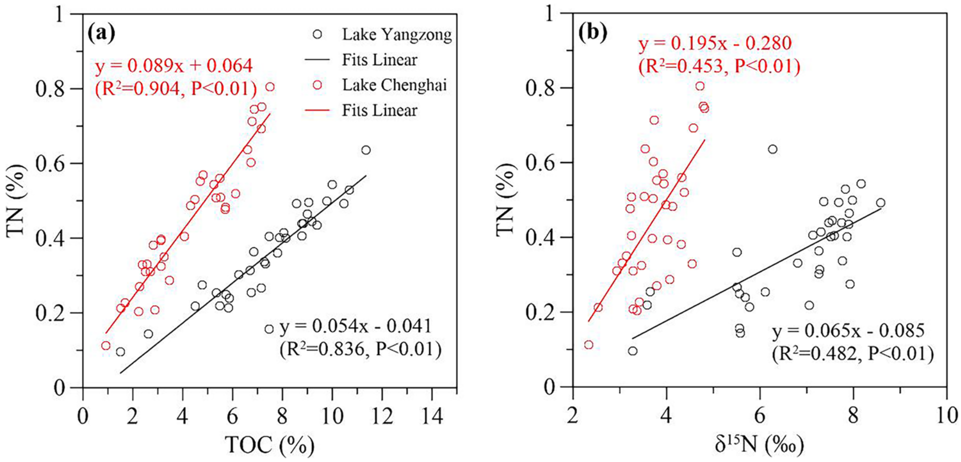
5.3 to 7.1% (average of 5.9%), sewage was 4.7 to 5.3% (average of 5.0%), and plankton was 5.8 to 7.3% (average of 6.5%). Compared with YZ, CH was characterized by a significantly lower contribution of C3 plants (4.1 to 5.6%; average of 4.5%) and larger contributions of soil OM (2.1 to 2.4%; average of 2.2%), plankton (36.2 to 43.0%; average of 40.5%), sewage (23.3 to 28.4%; average of 26.1%), and macrophytes (5.9 to 8.0%; average of 6.5%) (Fig. 6b).

4 Discussion

4.1 Variation in sedimentary TOC, TN, C/N, $\delta^{13}C_{org}$, and $\delta^{15}N$ and driving factors

The concentrations of TOC in the surface sediment of YZ and CH ranged from 1.51 to 11.35% (average of 7.45%) and 2.36 to 12.17% (average of 8.23%), respectively, which

Fig. 3 Correlations of TN with TOC and δ^{15}N values for surface sediments of YZ and CH, respectively



were significantly higher than those in Lake Fuxian (2.02 to 3.40% from Song et al. 2016). In addition, the mean TN contents of YZ and CH also showed significantly higher values than those in Lake Fuxian (Song et al. 2016). Low TOC contents in Lake Fuxian may indicate a low biological productive as a result of lower trophic state (Song et al. 2016). YZ and CH were more productive in the water column due to eutrophication, which may lead to more TOC storage in the surface sediments. In addition to nutrient levels, other factors, such as soil erosion, also increased the TOC contents. In YZ, the well-developed river system surrounding the lake may increase TOC contents and be more severely impacted by soil erosion (Zhang et al. 2012). Specifically, the TOC and TN contents in CH ($R^2 = 0.904$) have a more significant linear correlation than those in YZ ($R^2 = 0.836$) (Fig. 4a), suggesting that more organic nitrogen is stored in CH than in YZ.

As described above, there is a general decrease in both TOC and TN from south to north in the YZ (Fig. 2), with relatively low values occurring in the northern part of the lake. The distribution pattern is related to the terrestrial inputs, which control the nutrient conditions in the lake. A growing body of evidence shows that high productivity occurs near river mouths, such as in estuaries, due to the extra nutrient input supplied by the rivers (Lin et al. 2002; Deng et al. 2006). Nutrient conditions in the YZ depend largely on the material transported in the Yangzong River, and the nutrients show a significant decline from the southeast section to the northern part of lake. Similar findings have also been observed in Lake Bosten and Lake Nam Co (Wang et al. 2012; Yu et al. 2015). Although the lake morphology of YZ is similar to that of CH, TOC and TN showed different spatial distribution patterns. The TOC and TN in CH were characterized by concentric circles, with higher values in

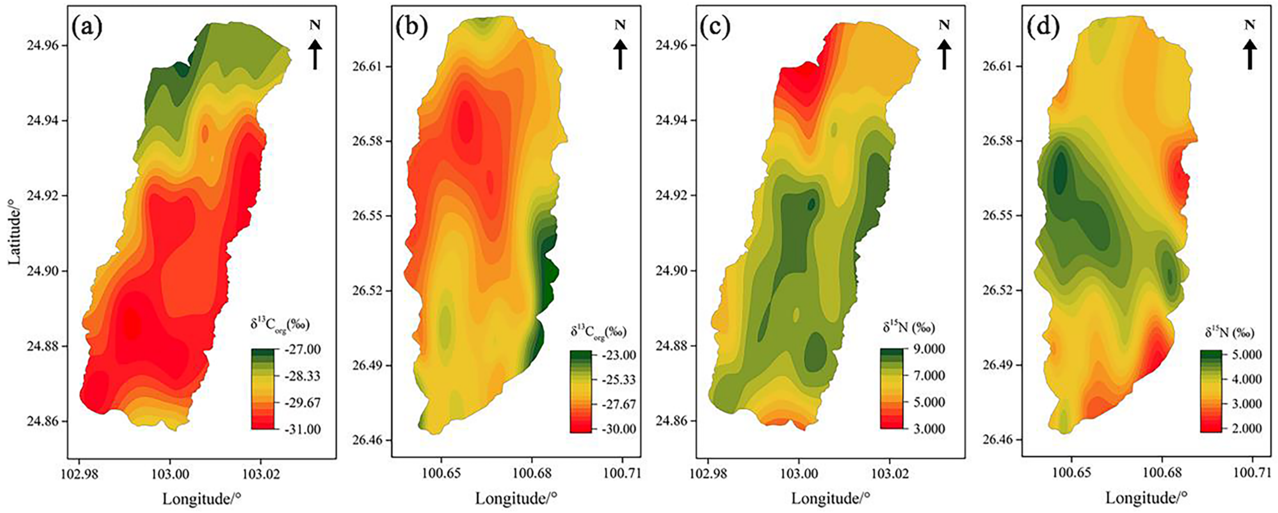


Fig. 4 Spatial distributions of $\delta^{13}C_{org}$ (**a** and **c**) and δ^{15}N (**b** and **d**) in surface sediments of YZ and CH, respectively

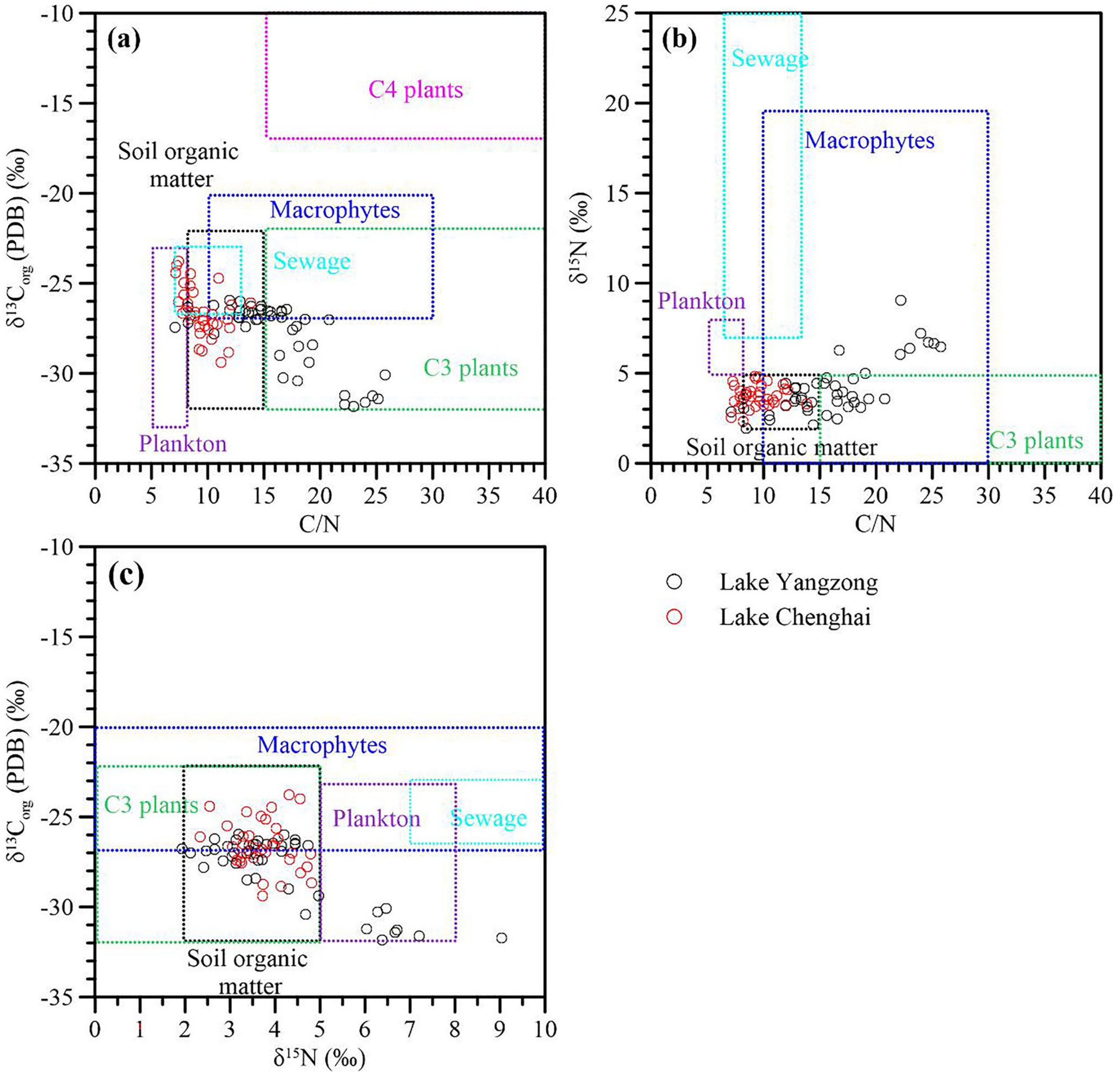


Fig. 5 Scatterplots of $\delta^{13}C_{org}$ vs. C/N ratios, and $\delta^{15}N$ vs. C/N ratios for surface sediments in YZ and CH

Table 1 Typical compositions of the main sources of sedimentary organic matter[a]

Sources of organic matter	C/N	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Plankton	5 ~ 8	−32 ~ −23	+5 ~ +8
Macrophytes	10 ~ 30	−27 ~ −20	−15 ~ +20
Soil organic matter	8 ~ 15	C3: −32 ~ −22 C4: −16 ~ −9	+2 ~ +5
Terrestrial plant	> 15	C3: −32 ~ −22 C4: −16 ~ −9	−6 ~ +5
Sewage	6.6 ~ 13	−26.7 ~ 22.9	+7 ~ +25

[a] Li et al. (2016)

the deepest part of the lake. A good correlation was found between the TOC and TN contents and water depth (Fig. 7). A simple explanation for this distributional pattern is associated with TOC mineralization. In general, in the shallow areas of a lake, the oscillating redox conditions in the surface sediment probably result in frequent sediment mixing, promoting TOC mineralization (Hulthe et al. 1998). On the other hand, the TOC content in the deepest part of a lake is comparatively high, implying that the main OC source was autochthonous material (Sobek et al. 2009; Ostrovsky and Yacobi 2010). Our analysis showed a significant negative relationship between the TOC (or TN) and the proportion of

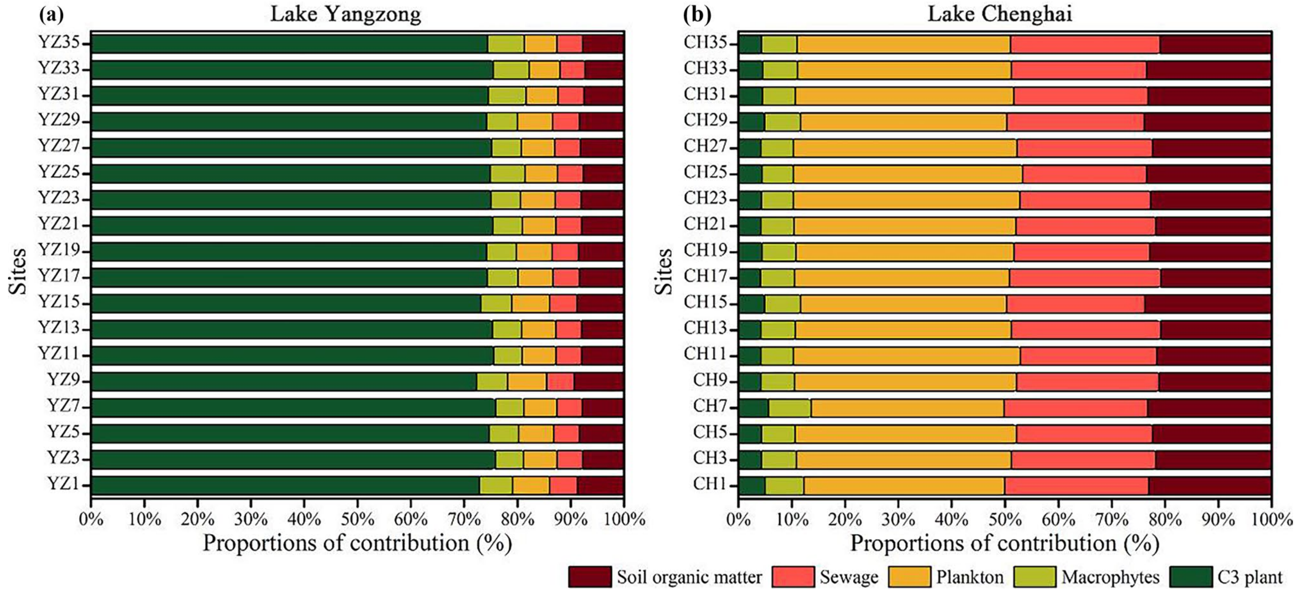


Fig. 6 The proportional contributions of OM from different endmembers for surface sediments in YZ and CH

clay (unpublished data) (Fig. 7). OM is known to be associated with fine-grained sediments because they have a large surface area and good OM binding abilities (Keil et al. 1994; Meyers 1994). With a decrease in the hydraulic transport competence towards the deepest area, more fine-grained sediment and lighter OM will be deposited lakeward of the

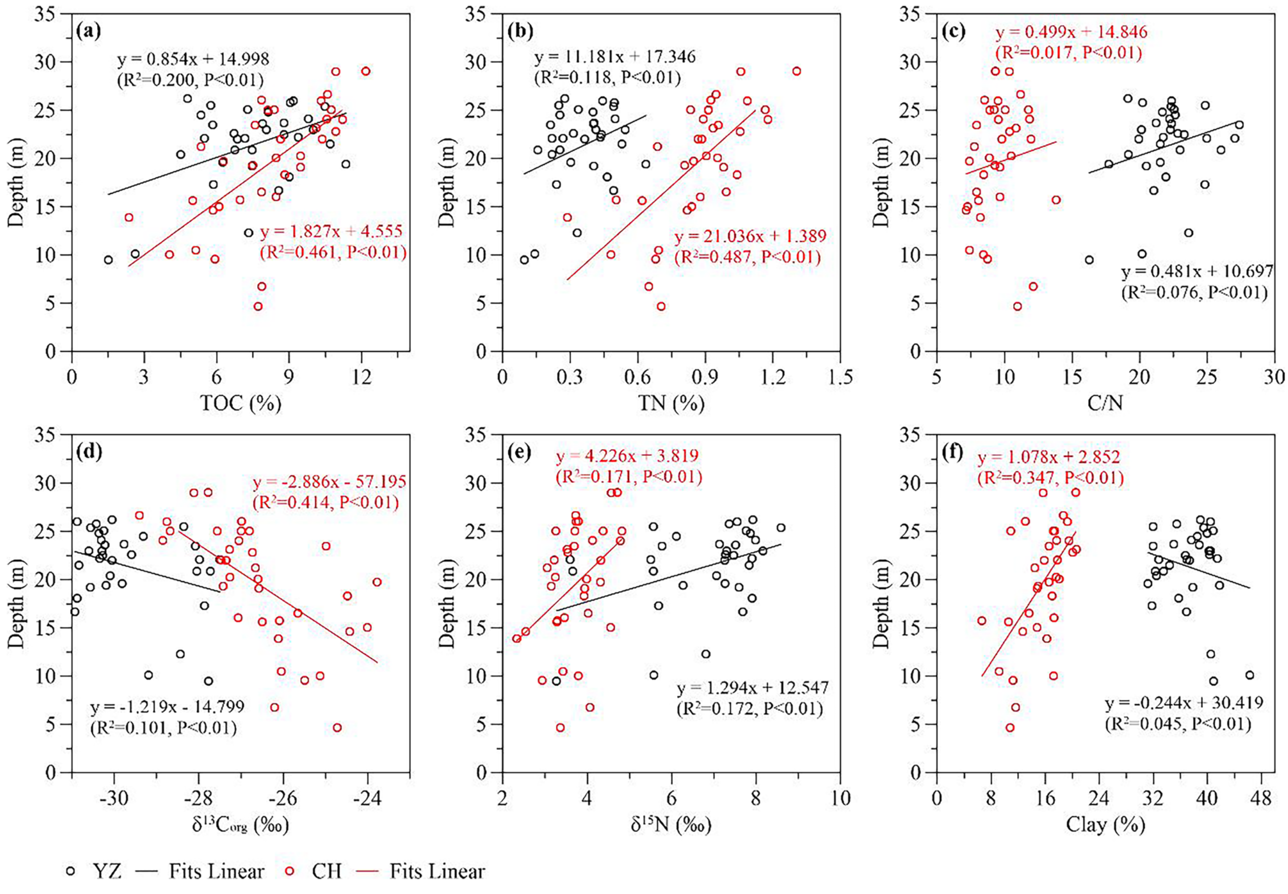


Fig. 7 Correlations of TOC, TN, C/N, $\delta^{13}C$, $\delta^{15}N$ (‰), and clay contents with water depth in the surface sediments of YZ and CH

river mouth. It is, therefore, not surprising that TOC and TN (both of which are tied with OM) and fine-grained sediment contents have similar distribution patterns in CH.

C/N ratios, and $\delta^{13}C_{org}$, and $\delta^{15}N$ values have been widely used as effective markers to estimate OM sources in lake sediments. In general, allochthonous and autochthonous OM have different C/N ratios: terrestrial plants have higher C/N ratios (> 15), whereas autochthonous materials have lower C/N ratios (< 6). Compared with CH, the C/N ratios in YZ (16.26 to 27.37, average of 22.13) were significantly higher than those in CH (7.15 to 13.82, average of 9.51), suggesting that allochthonous inputs were the main source of OM. Previous studies have shown that increasing allochthonous inputs relate to intense human activities in the catchment area and may be the main source of OM in the YZ (Yuan et al. 2010; Zhang et al. 2012; Liu et al. 2017; Wu et al. 2021). Wu et al. (2004) suggested that autochthonous phytoplankton is the main source of OM in CH. Furthermore, the increasing trend in C/N ratios from south to north in the YZ (Fig. 2c) is attributed to a progressive increase in the deposition of terrigenous OM. Comparatively, higher C/N ratios in CH were only observed at one southern site, with lower values located on the eastern shore of the lake. This may indicate that human-made pollutants have been discharging into the lake, increasing the eutrophication of the water column on the eastern shore of CH, which contributes to phytoplankton blooms and results in a decline in the C/N ratios in surface sediments.

Apart from the trophic state, terrestrial inputs may influence the dynamics of $\delta^{13}C$. In YZ, $\delta^{13}C$ showed a clear spatial gradient with higher values located in the northern part of the lake, suggesting that the contribution of allochthonous TOC decreases significantly from south to north. Furthermore, YZ was characterized by higher $\delta^{15}N$ values in the middle and southern sections of the lake, with lower $\delta^{15}N$ values in the northern section of the YZ. This indicates that the N source is derived from the southern part of the catchment basin. First, the southern catchment area is significantly larger than that of the northern catchment. Furthermore, Yangzong River located in the southern part of the basin is the main terrestrial input pathway in YZ and whose flow rate is the greatest area of concern due to major construction works and farmlands in the Yangzong basin. Plentiful sediment erosion caused by human activity contributed to the increasing terrestrial input in the southern part of the lake (Liu et al. 2017). In contrast, the intensity of anthropogenic activities in the northern basin is less, resulting in a limited amount of terrestrial materials being brought into the lake. A study by Wu et al. (2021) has shown that the contribution of sewage to sediment OM decreased northward as a result of a decrease in pollutant sources and a corresponding increase in transport distance for terrestrial materials. The nutrient conditions in Lake Yangzong are largely controlled by the Yangzong River, which results in a significant decrease in nutrient concentrations from the mouth of the river to the middle of the lake. In contrast, the most depleted δ13C values in CH were generally in the deepest area of the lake than in the shallow areas. Our analyses showed a significant negative relationship between δ13C and water depth (Fig. 7d), which indicates depleted δ13C in the deepest surface sediments. A straightforward explanation for this trend is a progressive decrease in the proportion of phytoplankton relative to the amount of terrigenous OM. Furthermore, higher δ15N values in CH are observed in the deepest part of the lake. Statistical analysis indicated that the correlation was significant ($R^2 = 0.171$, $P < 0.01$, Fig. 7e) between δ15N values and water depth, which may reflect a higher trophic state, as deeper lakes are likely to sustain more complex food webs. These observations are related to the combined influence of microbial degradation and anoxia in the water column and at the sediment–water interface. First, the elevated δ15N values may further suggest progressive enrichment of 15 N in the water column related to microbial degradation of the OM (Lehmann et al. 2002) and it may also reflect a higher trophic state, as deeper lakes are likely to sustain more complex food webs. In deeper lakes, bottom waters are also more prone to anoxia, which may induce strongly positive δ15N values related to denitrification processes (Finlay and Kendall 2008).

4.2 Sources of OM in sediments

C/N ratios (atomic) and $\delta^{13}C$ and $\delta^{15}N$ values have been widely used as markers to effectively discriminate sources of OM in aquatic ecosystems (Lamb et al. 2006; Holtgrieve et al. 2011; Kikumoto et al. 2014; Li et al. 2016). Planktonic organisms typically have C/N ratios between 4 and 7 (Mathesius 1999), whereas terrestrial vascular plants have C/N ratios that are typically higher than 12 (Kao and Liu 1996; Ogrinc et al. 2005). Based on the correlations between $\delta^{13}C_{org}$ and the C/N ratio (Fig. 5a), C3 plants were the main OM source in the surface sediments of YZ, while several samples were in the range of soil OM, macrophytes, sewage, and plankton. The OM sources in CH were derived from plankton, sewage, and soil OM, and several samples were in the ranges of macrophytes and C3 plants. This may indicate that the combination of $\delta^{13}C_{org}$ values and the C/N ratio is a reliable tool for OM source identification in CH and YZ. As shown in Fig. 5b, the combination of $\delta^{15}N$ and C/N showed that most of the samples in YZ were in the range of macrophytes, C3 plants, and soil OM, while CH was characterized by soil OM and macrophytes as the main OM source. However, one sample in YZ and seven samples in CH were observed out of the range of typical OM sources, implying that the combination of $\delta^{15}N$ and the C/N ratio was unable to identify the OM sources. According to the scatterplot of $\delta^{13}C_{org}$ vs. $\delta^{15}N$ (Fig. 5c), TOC in YZ was divided into four types, namely C3 plants, soil OM, macrophytes, and plankton, and CH was mainly composed of macrophytes and C3 plants. Notably, two samples originating from YZ were beyond the range of the selected end-members. This suggests that the combination of $\delta^{13}C_{org}$ and $\delta^{15}N$ had difficulty determining OM sources in the YZ. Previous studies have identified shortcomings in the application of the scatterplots of $\delta^{15}N$ vs. $\delta^{13}C_{org}$ and C/N ratios for OM source identification (Guo et al. 2020; Wu et al. 2021). Overall, our results suggest that all samples could be estimated via the scatterplot of $\delta^{13}C_{org}$ vs. C/N and that the combination of $\delta^{13}C_{org}$ and C/N is more reliable for tracing OM sources.

The relative contributions of OM from different sources to the surface sediments of YZ and CH were evaluated using Bayesian mixing models based on the combination of $\delta^{13}C_{org}$ and the C/N ratio (Fig. 6). The results indicate that C3 plants (72.3−76.0%) were the main source of OM in surface sediments in YZ, followed by soil OM (7.3−9.3%). Furthermore, the contribution of sewage is evident in the surface sediments of CH, with a contribution of 4.7 to 5.3%. This indicates that terrigenous inputs have an important influence on the composition of OM in the surface sediments of YZ in addition to the endogenous plankton. In contrast, the model indicates that 36.2−43.0% of the OM in the surface sediments of CH originated from plankton. In addition, the contribution of sewage in CH is greater than in YZ, with a contribution of 23.3−28.4%. Macrophytes, C3 plants, and soil OM also contribute to the OM in the surface sediments of CH. Overall, the contribution of terrigenous inputs (C3 plants and soil OM) to the surface sediments of YZ was significantly higher than that of CH, while autogenous OM (plankton, sewage, and macrophytes) accounted for the main OM in CH. We preliminarily interpret these differences as being related to trophic state, water level, and soil erosion. In YZ, the main pollution sources are domestic sewage and agricultural nonpoint source pollution (Wang 2003; Zhang et al. 2017).

5 Conclusions

This study assessed the spatial distribution patterns of TOC, TN, and their isotopes ($\delta^{13}C_{org}$ and $\delta^{15}N$) and identified the main source of OM and their driving factors in the surface sediments of YZ and CH. In YZ, the TOC, TN, $\delta^{13}C_{org}$, and $\delta^{15}N$ showed a clear trend from south to north except at the several sites close to the river mouth, while in CH, the above variables showed a significant trend with water depth. For example, high TOC, TN, and $\delta^{15}N$ values in YZ were observed in the southern and middle sections of the lake, with a lower $\delta^{13}C_{org}$ in the same location, suggesting that terrigenous input controls the carbon dynamics. In contrast, higher TOC, TN, and $\delta^{15}N$ values occurred in the deepest part of CH, with lower $\delta^{13}C_{org}$ values in the shallow sections of the lake, implying that water depth may play an important role in organic matter distribution. The main OM source to the surface sediments in YZ is C3 plants, while substantial contributions from plankton, soil OM, and sewage were observed in CH. The sources of OM in deep-water lakes are affected by different trophic states and terrestrial inputs, and OM sources show different spatial patterns.

Funding This work is supported by the National Science Foundation of China (41820104008), the Yunnan Provincial government Leading Scientist Program (No.2015HA024), and the basic research program of Yunnan province (No. 202101AT070049).

Declarations

Competing interests The authors declare no competing interests.

References

Anderson NJ, D’Andrea W, Fritz SC (2009) Holocene carbon burial by lakes in SW Greenland. Global Change Biol 15(11):2590–2598. https://doi.org/10.1111/j.1365-2486.2009.01942.x

Battin TJ, Luyssaert S, Kaplan LA, Aufdenkampe AK, Richter A, Tranvik LJ (2009) The Boundless Carbon Cycle Nat Geosci 2(9):598–600. https://doi.org/10.1038/ngeo618

Bechtel A, Schubert CJ (2009) A biogeochemical study of sediments from the eutrophic Lake Lugano and the oligotrophic Lake Brienz. Switzerland Org Geochem 40(10):1100–1114. https://doi.org/10.1016/j.orggeochem.2009.06.009

Burone L, Muniz P, Pires-Vanin AMS, Rodrigues M (2003) Spatial distribution of organic matter in the surface sediments of Ubatuba Bay (Southeastern Brazil). An Acad Bras Cienc 75(1):77–90. https://doi.org/10.1590/S0001-37652003000100009

Chen J, Yang H, Zeng Y, Guo J, Song Y, Ding W (2018) Combined use of radiocarbon and stable carbon isotope to constrain the sources and cycling of particulate organic carbon in a large freshwater lake, China. Sci Total Environ 625:27–38. https://doi.org/10.1016/j.scitotenv.2017.12.275

Cifuentes LA, Eldridge PM (1998) A mass- and isotope-balance model of DOC mixing in estuaries. Limnol Oceanogr 43(8):1872–1882

Dean WE, Gorham E (1998) Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. Geology 26(6):535–538. https://doi.org/10.1130/0091-7613(1998)026

Deng B, Zhang J, Wu Y (2006) Recent sediment accumulation and carbon burial in the East China Sea. Glob Biogeochem Cycles 20(3). https://doi.org/10.1029/2005gb002559

Ferland M, Giorgio P, Teodoru CR, Prairie YT (2012) Long-term C accumulation and total C stocks in boreal lakes in northern Québec. Global Biogeochem Cy. https://doi.org/10.1029/2011GB004241

Finlay JC, Kendall C (2008) Stable isotope tracing of temporal and spatial variability in organic matter sources to freshwater ecosystems. Emerg Med J 26(3):183–186

Fry B (1991) Stable isotope diagrams of freshwater food webs. Ecology 72(6):2293–2297

Gireeshkumar TR, Deepulal PM, Chandramohanakumar N (2013) Distribution and sources of sedimentary organic matter in a tropical estuary, south west coast of India (Cochin estuary): a baseline study. Mar Pollut Bull 66(1–2):239–245. https://doi.org/10.1016/j.marpolbul.2012.10.002

Guang G, Wang Z, Hui LS, Yang Y, Feng J, Fang; J, Shu Y (2010) Distribution of biogenic elements and potential contamination assessment in surface sediments from western Guangdong coasts. J Shenzhen University (Science and Technology) 27347–353 (in Chinese with English abstract)

Guo Q, Wang C, Wei R, Zhu G, Cui M, Okolic CP (2020) Qualitative and quantitative analysis of source for organic carbon and nitrogen in sediments of rivers and lakes based on stable isotopes. Ecotoxicol Environ Saf. https://doi.org/10.1016/j.ecoenv.2020.110436

Harmelin-Vivien M, Loizeau V, Mellon C, Beker B, Arlhac D, Bodiguel X, Ferraton F, Hermand R, Philippon X, Salen-Picard C (2008) Comparison of C and N stable isotope ratios between surface particulate organic matter and microphytoplankton in the Gulf of Lions (NW Mediterranean). Cont Shelf Res 28(15):1911–1919. https://doi.org/10.1016/j.csr.2008.03.002

Holtgrieve GW, Schindler DE, Hobbs WO, Leavitt PR, Ward EJ, Bunting L, Chen G, Finney BP, Gregory-Eaves I, Holmgren S, Lisac MJ, Lisi PJ, Nydick K, Rogers LA, Saros JE, Selbie DT, Shapley MD, Walsh PB, Wolfe AP (2011) A coherent signature of anthropogenic nitrogen deposition to remote watersheds of the Northern Hemisphere. Science 334(6062):1545–1548. https://doi.org/10.1126/science.1212267

Hulthe G, Hulth S, Hall POJ (1998) Effect of oxygen on degradation rate of refractory and labile organic matter in continental margin sediments. Geochim Cosmochim Ac 62(8):1319–1328. https://doi.org/10.1016/S0016-7037(98)00044-1

Kao SJ, Liu KK (1996) Particulate organic carbon export from a subtropical mountainous river (Lanyang Hsi) in Taiwan. Limnol Oceanogr 41(8):1749–1757. https://doi.org/10.4319/lo.1996.41.8.1749

Ke Z, Tan Y, Huang L, Zhao C, Jiang X (2017) Spatial distributions of delta(13)C, delta(15)N and C/N ratios in suspended particulate organic matter of a bay under serious anthropogenic influences: Daya Bay. China Mar Pollut Bull 114(1):183–191. https://doi.org/10.1016/j.marpolbul.2016.08.078

Keil RG, Montlucon DB, Prahl FG, Hedges JI (1994) Sorptive preservation of labile organic-matter in marine-sediments. Nature 370(6490):549–552. https://doi.org/10.1038/370549a0

Kendall C, Elliott EM, Wankel SD (2007) Tracing anthropogenic inputs of nitrogen to ecosystems. Stable Isotopes in Ecology and Environmental Science pp. 375–449

Khim BK, Jung HM, Cheong D (2005) Recent variations in sediment organic carbon content in Lake Soyang (Korea). Limnology 6(1):61–66. https://doi.org/10.1007/s10201-004-0134-5

Kikumoto R, Tahata M, Nishizawa M, Sawaki Y, Maruyama S, Shu DG, Han J, Komiya T, Takai K, Ueno Y (2014) Nitrogen isotope chemostratigraphy of the Ediacaran and Early Cambrian platform sequence at Three Gorges. South China Gondwana Res 25(3):1057–1069. https://doi.org/10.1016/j.gr.2013.06.002

Lamb AL, Wilson GP, Leng MJ (2006) A review of coastal palaeoclimate and relative sea-level reconstructions using δ13C and C/N ratios in organic material. Earth-Sci Rev 75(1–4):29–57. https://doi.org/10.1016/j.earscirev.2005.10.003

Lehmann MF, Bernasconi SM, Barbieri A, McKenzie JA (2002) Preservation of organic matter and alteration of its carbon and nitrogen isotope composition during simulated and in situ early sedimentary diagenesis. Geochim Cosmochim Ac 66(20):3573–3584. https://doi.org/10.1016/S0016-7037(02)00968-7

Li Y, Zhang HB, Tu C, Fu CC, Xue Y, Luo YM (2016) Sources and fate of organic carbon and nitrogen from land to ocean: Identified by coupling stable isotopes with C/N ratio. Estuar Coast Shelf Sci. https://doi.org/10.1016/j.ecss.2016.08.024

Lin S, Hsieh IJ, Huang KM, Wang CH (2002) Influence of the Yangtze River and grain size on the spatial variations of heavy metals and organic carbon in the East China Sea continental shelf sediments. Chem Geol 182(2–4):377–394. https://doi.org/10.1016/S0009-2541(01)00331-X

Liu GM, Liu ZW, Smoak JM, Gu BH (2015) The dynamics of cladoceran assemblages in response to eutrophication and planktivorous fish introduction in Lake Chenghai, a plateau saline lake. Quatern Int 355:188–193. https://doi.org/10.1016/j.quaint.2014.07.029

Liu KK, Kao SJ (2007) A three end-member mixing model based on isotopic composition and elemental ratio. Terr Atmos Ocean Sci 18(5):1067–1075. https://doi.org/10.3319/TAO.2007.18.5.1067(Oc)

Liu M, Hou LJ, Xu SY, Ou DN, Yang Y, Yu J, Wang Q (2006) Organic carbon and nitrogen stable isotopes in the intertidal sediments from the Yangtze Estuary. China Mar Pollut Bull 52(12):1625–1633. https://doi.org/10.1016/j.marpolbul.2006.06.008

Liu YL, Zhang EL, Liu EF (2017) TOC and black carbon records in sediment of Lake Yangzong, Yunnan Province under the influence of human activities during the past century. J Lake Sci 29(4):1018–1028 (in Chinese with English abstract)

Machiwa JF (2010) Stable carbon and nitrogen isotopic signatures of organic matter sources in near-shore areas of Lake Victoria. East Africa J Great Lakes Res 36(1):1–8. https://doi.org/10.1016/j.jglr.2009.11.005

Mathesius AM (1999) The palaeoenvironments of coastal lagoons in the southern Baltic Sea, I. The application of sedimentary Corg/N ratios as source indicators of organic matter. Palaeogeogr Palaeocl 145(1):1–16. https://doi.org/10.1016/S0031-0182(98)00094-7

Mendona R, Müller R, Clow D, Verpoorter C, Sobek S (2017) Organic carbon burial in global lakes and reservoirs. Nat Commun 8(1):1694. https://doi.org/10.1038/s41467-017-01789-6

Meyers PA (1994) Preservation of elemental and isotopic source identification of sedimentary organic-matter. Chem Geol 114(3–4):289–302. https://doi.org/10.1016/0009-2541(94)90059-0

Ogrinc N, Fontolan G, Faganeli J, Covelli S (2005) Carbon and nitrogen isotope compositions of organic matter in coastal marine sediments (the Gulf of Trieste, N Adriatic Sea): indicators of sources and preservation. Mar Chem 95(3–4):163–181. https://doi.org/10.1016/j.marchem.2004.09.003

Ostrovsky I, Yacobi YZ (2010) Sedimentation flux in a large subtropical lake: spatiotemporal variations and relation to primary productivity. Limnol Oceanogr 55(5):1918–1931. https://doi.org/10.4319/lo.2010.55.5.1918

Rumolo P, Barra M, Gherardi S, Marsella E, Sprovieri M (2011) Stable isotopes and C/N ratios in marine sediments as a tool for discriminating anthropogenic impact. J Environ Monitor 13(12):3399–3408. https://doi.org/10.1039/c1em10568j

Shao L, Wu D, Zhang D, Feng T (2019) Using isotopes to identify the sources of organic carbon and nitrogen in surface sediment in shallow lakes alongside Poyang Lake. Wetlands 39S25-S33. https://doi.org/10.1007/s13157-017-0988-z

Sobek S, Durisch-Kaiser E, Zurbrugg R, Wongfun N, Wessels M, Pasche N, Wehrli B (2009) Organic carbon burial efficiency in lake sediments controlled by oxygen exposure time and sediment source. Limnol Oceanogr 54(6):2243–2254. https://doi.org/10.4319/lo.2009.54.6.2243

Song YL, Chen JA, Yang HQ, Ding W, Wang JF (2016) Distribution and source of the organic matter in the sediment of Fuxian Lake. Yunnan Province Bull Mineral Petrol Geochem 35(4):618–624. https://doi.org/10.3969/j.issn.1007-2802.2016.04.002

Stock BC, Semmens BX (2013) MixSIAR GUI user Manual. Version 3:1

Thornton SF, Mcmanus J (1994) Application of organic-carbon and nitrogen stable-isotope and C/N ratios as source indicators of organic-matter provenance in estuarine systems - evidence from the Tay Estuary. Scotland Estuar Coast Shelf S 38(3):219–233. https://doi.org/10.1006/ecss.1994.1015

Tranvik LJ et al (2009) Lakes and reservoirs as regulators of carbon cycling and climate. Limnol Oceanogr 54(6):2298–2314. https://doi.org/10.4319/lo.2009.54.6_part_2.2298

Wang H (2003) Present situation and trend analysis of water quality in Yangzonghai Lake. Yunnan Environ Sci 22(S1):170–171 (in Chinese with English abstract)

Wang SM, Dou HS (1998) Lakes in China. Science Press, Beijing (in Chinese)

Wang Y, Zhu L, Wang J, Ju J, Lin X (2012) The spatial distribution and sedimentary processes of organic matter in surface sediments of Nam Co. Central Tibetan Plateau Chinese Sci Bull 57(36):4753–4764. https://doi.org/10.1007/s11434-012-5500-9

Wang Z (2011) Levels, trends and risk assessment of arsenic pollution in Yangzonghai Lake, Yunnan Province, China. Science China Chemistry 531809−1817 (in Chinese with English abstract)

Woszczyk M, Bechtel A, Gratzer R, Kotarba MJ, Kokocinski M, Fiebig J, Cieslinski R (2011) Composition and origin of organic matter in surface sediments of Lake Sarbsko: a highly eutrophic and shallow coastal lake (northern Poland). Org Geochem 42(9):1025–1038. https://doi.org/10.1016/j.orggeochem.2011.07.002

Wu H, Zhang HC, Chang FQ, Duan LZ, Zhang XN, Peng W, Liu Q, Zhang Y, Liu FW (2021) Isotopic constraints on sources of organic matter and environmental change in Lake Yangzong. Southwest China J Asian Earth Sci. https://doi.org/10.1016/j.jseaes.2021.104845

Wu JL, Gagan MK, Jiang XH, Xia WL, Wang SM (2004) Sedimentary geochemical evidence for recent eutrophication of Lake Chenghai, Yunnan. China J Paleolimnol 32(1):85–94. https://doi.org/10.1023/B:JOPL.0000025290.09365.98

Xiao XY, Haberle SG, Li YL, Liu EF, Shen J, Zhang EL, Yin JJ, Wang SM (2018) Evidence of Holocene climatic change and human impact in northwestern Yunnan Province: high-resolution pollen and charcoal records from Chenghai Lake, southwestern China. Holocene 28(1):127–139. https://doi.org/10.1177/0959683617715692

Yang L, Huang YZ (2002) Study on comprehensive development of lake area in Yunnan Plateau. J Chongqing University (Social Sciences Edition) (in Chinese with English abstract)

Yu FL, Zong YQ, Lloyd JM, Huang GQ, Leng MJ, Kendrick C, Lamb AL, Yim WWS (2010) Bulk organic delta C-13 and C/N as indicators for sediment sources in the Pearl River delta and estuary, southern China. Estuar Coast Shelf S 87(4):618–630. https://doi.org/10.1016/j.ecss.2010.02.018

Yu ZT, Wang XJ, Zhang EL, Zhao CY, Liu XQ (2015) Spatial distribution and sources of organic carbon in the surface sediment of Bosten Lake. China Biogeosciences 12(22):6605–6615. https://doi.org/10.5194/bg-12-6605-2015

Yuan G, Ru HJ, Liu XQ (2010) Fish diversity and fishery resources in lakes of Yunnan Plateau during 2007–2008. J Lake Sci 22(6):837–841 (in Chinese with English abstract)

Zhang E, Liu E, Shen J, Cao Y, Li Y (2012) One century sedimentary record of lead and zinc pollution in Yangzong Lake, a highland lake in southwestern China. J Environ Sci (china) 24(7):1189–1196. https://doi.org/10.1016/s1001-0742(11)60896-6

Zhang HJ, Liu YG, Wang Y (2017) Spatial distribution ofheavy metals in the sediments of Yangzonghai Lake wetland. J Hydroecol 38(2):44–50. https://doi.org/10.15928/j.1674-3075.2017.02.007 (in Chinese with English abstract)

Zhu Y (2008) Study on environmental background of Yangzonghai Lake Basin. Environ Sci Survey 27(5):75–78 (in Chinese with English abstract)