Biogeosciences Discuss., 12, 13793–13817, 2015
www.biogeosciences-discuss.net/12/13793/2015/
doi:10.5194/bgd-12-13793-2015

Biogeosciences Discussions
Open Access

Spatial distribution and sources of organic carbon in the surface sediment of the Bosten Lake, China

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Received: 9 July 2015 – Accepted: 3 August 2015 – Published: 25 August 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Lake sediment is an important carbon reservoir. However, little is known on the dynamics and sources of sediment organic carbon in the Bosten Lake. We collected 13 surface (0–2 cm) sediment samples in the Bosten Lake and analyzed total organic carbon (TOC), total nitrogen (TN), stable carbon isotopic composition in TOC ($\delta^{13}C_{org}$) and grain size. We found a large spatial variability in TOC content (1.8–4.4 %) and $\delta^{13}C_{org}$ value (−26.77 to −23.98 ‰). Using a three end member mixing model with measured TOC : TN ratio and $\delta^{13}C_{org}$, we estimated that 54–90 % of TOC was from autochthonous sources. Higher TOC content (> 3.7 %) was found in the east and central-north sections and near the mouth of the Kaidu River, which was attributable to allochthonous, autochthonous plus allochthonous, and autochthonous sources, respectively. The lowest TOC content was found in the mid-west section, which might be a result of high kinetic energy levels. Our study indicated that the spatial distribution of sediment TOC in the Bosten Lake was influenced by multiple and complex processes.

1 Introduction

Inland water bodies such as rivers and lakes are unique components on the Earth. In spite of their relatively small coverage (Downing et al., 2006), lakes often receive a large amount of terrestrial materials from the watersheds (Battin et al., 2009; Anderson et al., 2013), and store a significant amount of carbon in the sediments (Ferland et al., 2012; Tranvik et al., 2009). Thus, inland lakes may play an important role in the terrestrial carbon cycle. Compared to the oceans, lakes have actively biogeochemical processes with stronger "biological pump", which often leads to higher sedimentation rates and a large amount of organic carbon (OC) burial at the bottom of lakes (Dean and Gorham, 1998).

There have been a number of studies from the North America (Dean and Gorham, 1998), West Europe (Bechtel and Schubert, 2009; Woszczyk et al., 2011), East Asia

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(Khim et al., 2005; Wang et al., 2012) and other regions (Dunn et al., 2008), showing large spatial variability in total organic carbon (TOC) of lake sediment. The magnitude of TOC in surface sediment may depend on many factors, including column water productivity, terrestrial inputs of organic materials, properties of sediment, and rate of microbial activity (Burone et al., 2003; Gireeshkumar et al., 2013). Among them, contributions of autochthonous and allochthonous sources have direct impacts on the spatial distribution, which vary largely accross regions (Bechtel and Schubert, 2009; Anderson et al., 2009), partly due to differences in lake productivity and morphology (Barnes and Barnes, 1978). In general, lakes with high productivity have more autochthonous TOC, but lakes with low productivity mainly allochthonous TOC (Dean and Gorham, 1998). There is evidence of littoral sources of TOC in small and shallow lakes, but autochthonous sources, derived from planktonic organisms, in larger and deeper lakes, especially fjord lakes (Shanahan et al., 2013; Sifeddine et al., 2011; Barnes and Barnes, 1978).

A number of techniques have been applied to quantify different sources of sediment TOC (Fang et al., 2014; Hanson et al., 2014; Meyers and Ishiwatari, 1993; Bechtel and Schubert, 2009). One of the common approaches is to use two or three end-member mixing models with combined use of TOC to total nitrogen (TN) ratio (C : N) and stable carbon isotope in organic material ($\delta^{13}C_{org}$) (Rumolo et al., 2011; Yu et al., 2010; Liu and Kao, 2007). It is well known that there are large differences in C : N ratio and $^{13}C_{org}$ value between exogenous and endogenous organic materials (Brodie et al., 2011; Kaushal and Binford, 1999). For example, aqueous organic matters have low C : N ratios (4–10) (Meyers, 2003) whereas vascular land plants have much higher C : N ratios (> 20) (Rumolo et al., 2011; Lamb et al., 2004; Sifeddine et al., 2011). On the other hand, due to the difference in isotopic fractionation during photosynthesis, $\delta^{13}C_{org}$ value is more negative (ranging from −33 to −22 ‰) in terrestrial C_3 plants (Pancost and Boot, 2004; Wang et al., 2013) and lake plankton (Bertrand et al., 2010; Vuorio et al., 2006) than in C_4 plants (ranging from −16 to −9 ‰) (Pancost and Boot, 2004; Wang et al., 2013).

Bosten Lake, as the largest lake in Xinjiang of China, is a typical place for studying lake carbon cycle. Previous studies have provided evaluations on water quality (Wu et al., 2013), changes in lake level (Guo et al., 2015), and the controlling factors of carbon and oxygen isotopic composition of surface sediment carbonate (Zhang et al., 2009). A recent study indicated that particulate organic carbon (POC) variability in the water column was affected by allochthonous sources in the Bosten Lake (Wang et al., 2014). However, little has been done to assess the dynamics and sources of sediment TOC in the Bosten Lake. Therefore, this study was designed to evaluate the spatial distributions of major physical and biogeochemical parameters in the surface sediment, and to quantify the contributions of various sources to the sediment TOC in the Bosten Lake.

2 Materials and methods

2.1 Site description

Bosten Lake (41°32′ ∼ 42°14′ N, 86°19′ ∼ 87°26′ E) is located in the lowest part of the intermontane Yanqi Basin between the Taklimakan Desert and Tienshan Mountains, Northwest China (Fig. 1). It is the largest inland lake in Xinjiang, which is about 55 km long from east to west and about 25 km wide from south to north, comprising a total lake surface area of approximately 1005 km^2, with a maximum depth of 14 m (Wu et al., 2013). The lake level was 1045 m in 2012 when sampling was carried out. The lake lies in the center of the Eurasian Continent and is influenced by a temperate continental climate. The mean annual air temperature is approximately 8.3 °C, the mean annual precipitation approximately 65 mm and the mean annual evaporation approximately 1881 mm (Zhang et al., 2009). Winds come mainly from the southwest, indicating dominant influence by the westerly throughout the summer season. Lake water input mainly comes from the Kaidu River that is supplied by melting ice, precipitation and groundwater, whereas water output includes outflow (57 %) via the Peacock River

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and evaporation (43 %) (Guo et al., 2015). There are also small seasonal rivers (mainly during flood seasons), e.g., the Huangshui River and Qinhshui River near the northwest of the lake.

2.2 Field sampling and analyses

For the present study, a Kajak gravity corer was used to collect surface sediments from 13 sites in the main section of the Bosten Lake in August 2012 (Fig. 1). The sampling sites covered most parts of the lake, with water depths ranging from 3 to 14 m. The sediment cores were carefully extruded and the top 2 cm sections were sliced into 1 cm and placed in polyethylene bags that were kept on ice in a cooler during transport and before analyses.

Following Liu et al. (2014), each sediment sample (~ 0.5 g) was pretreated, in a water bath (between 60 and 80 °C), with 10–20 mL of 30 % H_2O_2 to remove organic matter, then with 10–15 mL of 10 % HCl to remove carbonates. The samples were then mixed with 2000 mL of deionized water, and centrifuged after 24 h of standing. The solids were dispersed with 10 mL of 0.05 M $(NaPO_3)_6$, then analyzed for grain size, using a Malvern Mastersizer 2000 laser grain size analyzer at the State Key Laboratory of Lake Science and Environment (SKLLSE), Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (CAS). The Malvern Mastersizer 2000 automatically outputs the median diameter $d(0.5)$ (µm), the diameter at the 50th percentile of the distribution, and the percentages of clay (< 2 µm), silt (2–64 µm) and sand (> 64 µm) fractions.

Sediment C and N contents were measured using an Elemental Analyzer 3000 (Euro Vector, Italy) at the SKLLSE, Nanjing Institute of Geography and Limnology, CAS. All samples were freeze-dried and ground into a fine powder, then placed in tin capsules, weighed and packed carefully, according to Eksperiandova et al. (2011). For the analysis of TOC, each sample (~ 0.3 g) was pretreated with 5–10 mL 2 M HCl for 24 h at room temperature to remove carbonate, dried overnight at 40–50 °C, then analyzed for C content using the Elemental Analyzer.

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For the analyses of $\delta^{13}C_{org}$, approximately 0.2 g of the freeze-dried sediment sample was pretreated with 5–10 mL 2 M HCl for 24 h at room temperature to remove carbonate, and then rinsed to a pH of approximately 7 with deionized water and dried at 40–50 °C (Liu et al., 2013). The pre-treated samples were combusted in a Thermo elemental analyzer integrated with an isotope ratio mass spectrometer (Delta Plus XP, Thermo Finnigan MAT, Germany). Isotopic data were reported in delta notation relative to the Vienna Pee Dee Belemnite (VPDB).

2.3 Calculations of TOC sources

We applied a three end-member mixing model (Liu and Kao, 2007) to quantify the contributions (f) of three sources (i.e., soil, high plant and lake plankton, denoted by 1, 2 and 3, respectively):

$$\delta = f_1\delta_1 + f_2\delta_2 + f_3\delta_3 \quad (1)$$

$$r = f_1 r_1 + f_2 r_2 + f_3 r_3 \quad (2)$$

$$1 = f_1 + f_2 + f_3 \quad (3)$$

where δ and r were $\delta^{13}C_{org}$ value and C : N ratio, respectively.

Given that there were limited crops around the lake and most crops' growing season was less than five months each year, we assumed that native plants, mainly reed (*Phragmites australis (Cav.) Trin. ex Steud*), Manaplant Alhagi (*Alhagi sparsifolia Shap*) and Achnatherum splendens (*Achnatherum splendens (Trin.) Nevski*), were responsible for high plant's contribution. Based on a recent study conducted in the Yanqi Basin (Zhang, 2013), average C : N ratio was 22.1 and 10, and mean $\delta^{13}C_{org}$ value was −26.4 and −23.6 ‰ for the native plants and surface soils around the lake, respectively. We used these values as the end-members for the mixing model.

We measured POC, particulate organic nitrogen (PON) and $\delta^{13}C_{org}$ in POC in the water column of the Bosten Lake (Wang et al., 2014). Lake average POC and PON increased from 0.61 mg C L^{-1} and 0.072 mg N L^{-1} in spring to 0.70 mg C L^{-1} and

0.088 mg N L^{-1} in summer, and $\delta^{13}C_{org}$ value in POC was −22.9 ‰ in spring and −23.5 ‰ in summer. It is reasonable to assume that the seasonal changes were resulted from the production of lake plankton. Accordingly, we estimated that lake plankton (including phytoplankton and zooplankton) would have a C : N ratio of 5.3 and $\delta^{13}C_{org}$ value of −27.7 ‰, and used these values as the end-members for the mixing model.

2.4 Statistical methods and mapping

Correlation analyses were performed using the SPSS Statistics 19 for Windows. Spatial distribution maps were produced using Surfer 9.0 (Golden Software Inc.) and the Kriging method of gridding was used for data interpolation.

3 Results

3.1 Physical characteristics

Figure 2 showed the spatial distributions of the main granulometric variables of the surface sediment. In general, clay content was low (6–17 %), showing relatively higher values in the southern part than in the northern part. The highest clay content was found in the southwest, and the lowest in the northwest section. On the other hand, silt content was much high (greater than 80 %) with clearly higher values near the mouths of the Kaidu River (southwest) and Huangshui River (northwest). The lowest content of silt was found in the mid-west, between the rivers' mouths, where sand content was highest (Fig. 2c). As expected, the spatial distribution of $d(0.5)$ was similar to that of sand, showing the highest values in the mid-west section, indicating strong hydrodynamic effect in this area.

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3.2 Spatial distribution of TOC, TN, C : N and $\delta^{13}C_{org}$

Concentration of TOC was highly variable, with higher values (4.3–4.4 %) found in the northern and eastern sections of the lake (Fig. 3a). There was also high concentration of TOC (4.1–4.2 %) near the mouth of the Kaidu River (southwest). On the other hand, lower TOC concentration (1.8–2.4 %) was observed in the mid-west section. Similarly, TN concentration (ranging from 0.28 to 0.68 %) was lowest concentration in the mid-west and highest in the northwest and east sections (Fig. 3b). Overall, the spatial distribution of TN was similar to that of TOC. The exception was in the northwest area that had high TN value, but low TOC concentration.

Figure 4a showed a large spatial variability in the C : N ratio with a range from 4.6 to 8.6. In general, C : N ratio was higher in the central part relative to other parts. The highest C : N ratio was found in the mid-west, and the lowest found in the northwest area. The $\delta^{13}C_{org}$ values ranged from −26.77 to −23.98 ‰ (Fig. 4b). The most negative value was observed in the area of 41.9–42° N and 86.9–87° E, and the least negative value near the mouth of the Huangshui River (northwest). Overall, values of $\delta^{13}C_{org}$ were more negative in the eastern and central parts than in the northwestern and southwestern parts.

3.3 Contributions of different sources

Using the three end member mixing model, we calculated the contributions of autochthonous and allochthonous sources to the surface sediment TOC. As shown in Fig. 5a, the contribution of lake plankton ranged from 54 to 90 %, with the highest in the western shallow lake area, and the lowest in the southern and eastern deep lake area. The contribution of soils varied between 10 and 40 %, with the highest in the southeast and central south area (Fig. 5b). Apparently, the contribution from native plants was extremely low (< 4 %), with only a few sites showing values of 10–12 % (Fig. 5c). On average, the contributions from lake plankton, soils and native plants were 66, 30 and 4 %, respectively.

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There were large differences in the spatial distributions of TOC between the autochthonous and allochthonous sources. Autochthonous TOC revealed highest value (∼ 3.5 %) near the mouth of the Kaidu River and lowest (∼ 1.5 %) in the mid-west of the lake (Fig. 6a). For the area east of 87° E, autochthonous TOC showed a clear increase from south to north. On the other hand, there was an apparent elevation in the allochthonous TOC, from 0.5 % in the west to 1.9 % in the east (Fig. 6b).

4 Discussion

The concentration of TOC in the surface sediment of the Bosten Lake ranged from 1.8–4.4 %, which was relatively higher than those (0.2–2 %) in the Tibetan Plateau (Lami et al., 2010; Wang et al., 2012) and Yangtze floodplain (Wu et al., 2007; Dong et al., 2012), but much lower than those (5–13 %) in the lakes of the Yunnan–Guizhou Plateau (Zhu et al., 2013; Wu et al., 2012). Low TOC contents in the Tibetan Plateau lakes were a consequence of low biological productivity owing to the high altitude and low temperature (Lami et al., 2010). Although lakes in the Yangtze floodplain had higher productivity in the water column due to eutrophication (Qin and Zhu, 2006), most of them were shallow lakes that were subject to frequent turbulence and resuspension of sediments (Qin et al., 2006). In addition, warm-humid climate in the Yangtze floodplain could promote decomposition of POC in the water column and TOC in the sediments (Gudasz et al., 2010), which led to less TOC storage in the surface sediments. On the other hand, lakes in the Yunnan–Guizhou Plateau were deep with higher lake productivity, which had favorable TOC burial conditions (Jiang and Huang, 2004).

Sediment organic compounds are either of terrestrial origins or derived from phytoplankton and zooplankton remains and feces (Meyers, 2003; Meyers and Ishiwatari, 1993; Barnes and Barnes, 1978). A number of studies have demonstrated that TOC in small and shallow lakes are attributable to allochthonous sources, but TOC in larger and deeper lakes to autochthonous sources that are derived from planktonic organisms (Shanahan et al., 2013; Sifeddine et al., 2011; Barnes and Barnes, 1978). Our

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analyses showed that the majority of TOC was autochthonous in the surface sediment of the Bosten Lake. We also found a significant negative relationship between TOC and dry bulk density (Table 1), confirming that higher TOC (with lighter weight) would be a result of sedimentation of non-terrestrial organic materials.

Our study demonstrated large spatial variability in the TOC of the surface sediment in the Bosten Lake, with higher values in the central north and east sections and near the mouth of the Kaidu River, but lower values in the west section and mid-south section (Fig. 3a). Further analyses showed that the highest autochthonous TOC was found near the mouth of the Kaidu River and the highest allochthonous TOC in the east section (Fig. 6). There is evidence of high productivity near the sources of nutrients, such as estuaries owing to extra nutrient input from riverine (Deng et al., 2006; Lin et al., 2002). Nutrient conditions in the Bosten Lake may be largely affected by the transportation of the Kaidu River, which has a significant decline from the mouth to the east section. Similar finding was also observed in the Nam Co Lake (Wang et al., 2012).

As known, TOC burial in sediments is a result of sedimentation of POC. Here, we compared the spatial pattern of autochthonous TOC in the 0–1 cm sediment with the summer POC reported by Wang et al. (2014), which showed the highest values of both variables near the mouth of the Kaidu River (Fig. 7). Statistical analysis indicated that the correlation was not significant ($r = 0.14$, $P > 0.1$, Table 1) between these two variables, which might be due to the mismatch in the locations of the lowest values. As shown in Figs. 2 and 3, coarse particle components were dominant in the mid-west section where TOC was the lowest. Table 1 also illustrated that TOC had a negative relationship with sand content and $d(0.5)$. Usually, in a relatively close hydraulic equivalence, coarser sediment particles indicated a stronger water energy environment (Jin et al., 2006; Molinaroli et al., 2009). These analyses indicated that the relative lower TOC values in the mid-west section of the Bosten Lake were attributable to both the lower POC in the water column and higher kinetic energy level.

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The magnitudes and spatial distribution of TOC in lake sediment may reflect multiple, complex processes (Sifeddine et al., 2011; Woszczyk et al., 2011; Dunn et al., 2008; Wang et al., 2012). Our analyses showed a significant negative relationship between the $\delta^{13}C_{org}$ value and water depth (Table 1), implying that the shallow sections in the Bosten Lake accumulated more allochthonous TOC (with less negative $\delta^{13}C$). Apart from the lake own characteristics (such as lake current and depth), other factors may have influences on the dynamics of TOC. For example, land use changes such as agricultural development and fertilization would enhance the riverine input of nutrients, leading to changes in lake productivity and subsequently altering TOC burial in the sediment (Rumolo et al., 2011; Lami et al., 2010; Lamb et al., 2006). There has been evidence of climate change and human activities over the past decades in the surrounding region, which has caused remarkable lake level changes in the Bosten Lake (Guo et al., 2015). All these changes would have impacts on the production of POC and TOC burial. Further studies are needed to assess the spatial and temporal variations in the water column biological production to better understand the dynamics of OC in the Bosten Lake and the impacts of human activity and climate change.

Acknowledgements. This study is financially supported by the National Key Basic Research Program (2013CB956602), and the Special Environmental Research Funds for Public Welfare of the State Environmental Protection Administration (grant 201309041).

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Table 1. Correlation coefficient (r) between various variables for the sediments.

Variables	WD	DBD	$d(0.5)$	Clay	Silt	Sand	TOC	$\delta^{13}C_{org}$
TOC	0.50	−0.58[a]	−0.71[b]	0.18	0.77[b]	−0.76[b]		−0.15
TN	0.07	−0.83[b]	−0.60[a]	−0.05	0.79[b]	−0.72[b]	0.71[b]	0.45
C : N	0.50	0.50	0.01	0.25	−0.19	0.11	0.14	−0.82[b]
$\delta^{13}C_{org}$	−0.66[a]	−0.46	−0.13	0.03	0.21	−0.20	−0.15	
POC	−0.42	−0.41	0.11	−0.29	0.11	−0.02	0.14	0.22

WD = water depth (m), DBD = dry bulk density ($g\,cm^{-3}$), $d(0.5)$ = median diameter (µm) from the 0–2 cm sediments. Significance of Pearson correlation is marked with [a] ($p < 0.05$) and [b] ($p < 0.01$).

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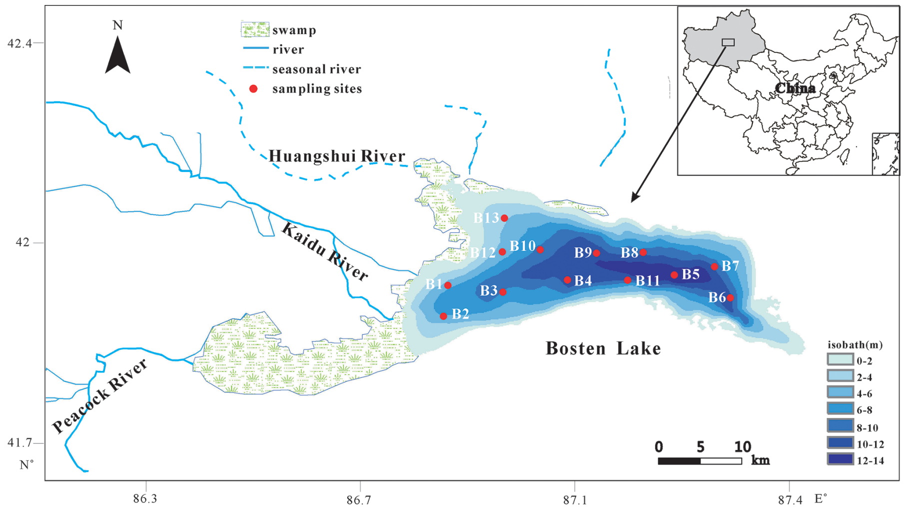

Figure 1. Map of the Bosten Lake with the water depth and the 13 sampling stations (red dotes). Bathymetric was measured in 2008 by Wu et al. (2013) and bathymetric contours were plotted by using software ArcGIS 9.3 and Corel DRAW X3.

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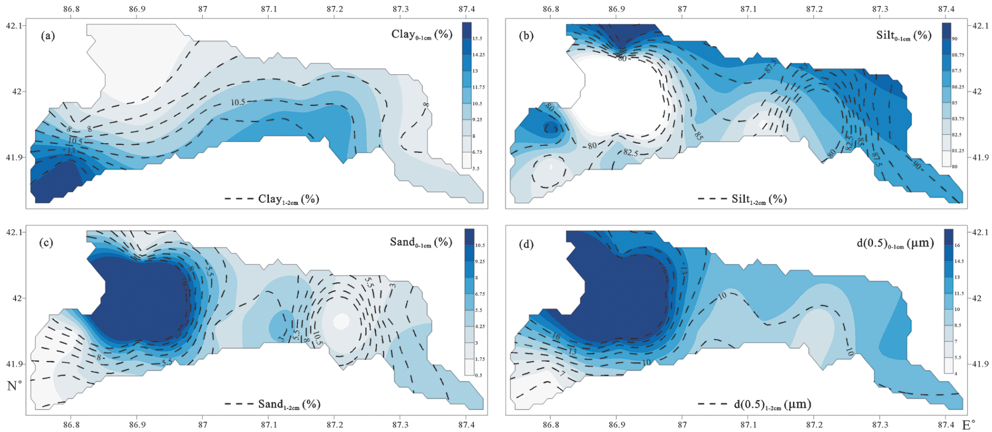

Figure 2. Distributions of **(a)** clay, **(b)** silt, **(c)** sand and **(d)** the median diameter (d(0.5), µm) in the 0–1 cm (color map) and 1–2 cm (dashed lines). The spatial distribution maps (Figs. 2–7) were produced using Surfer 9.0 (Golden Software Inc.) and the interpolated data in the maps was made using the Kriging method of gridding.

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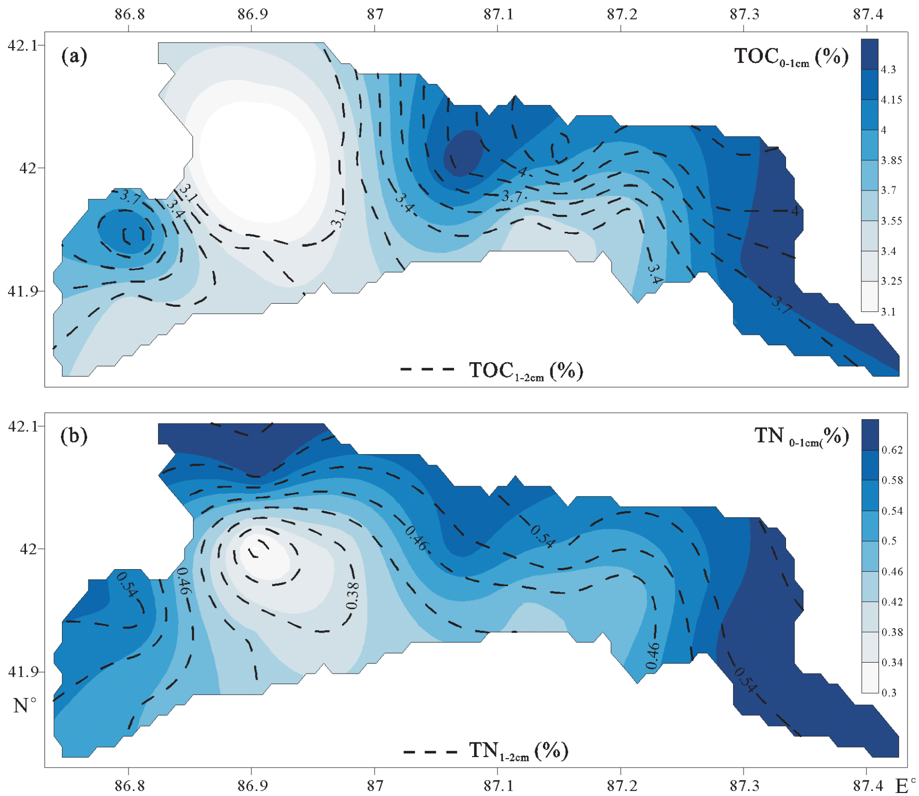

Figure 3. Spatial distributions of **(a)** total organic carbon (TOC) and **(b)** total nitrogen (TN) in the 0–1 cm (color map) and 1–2 cm (dashed lines).

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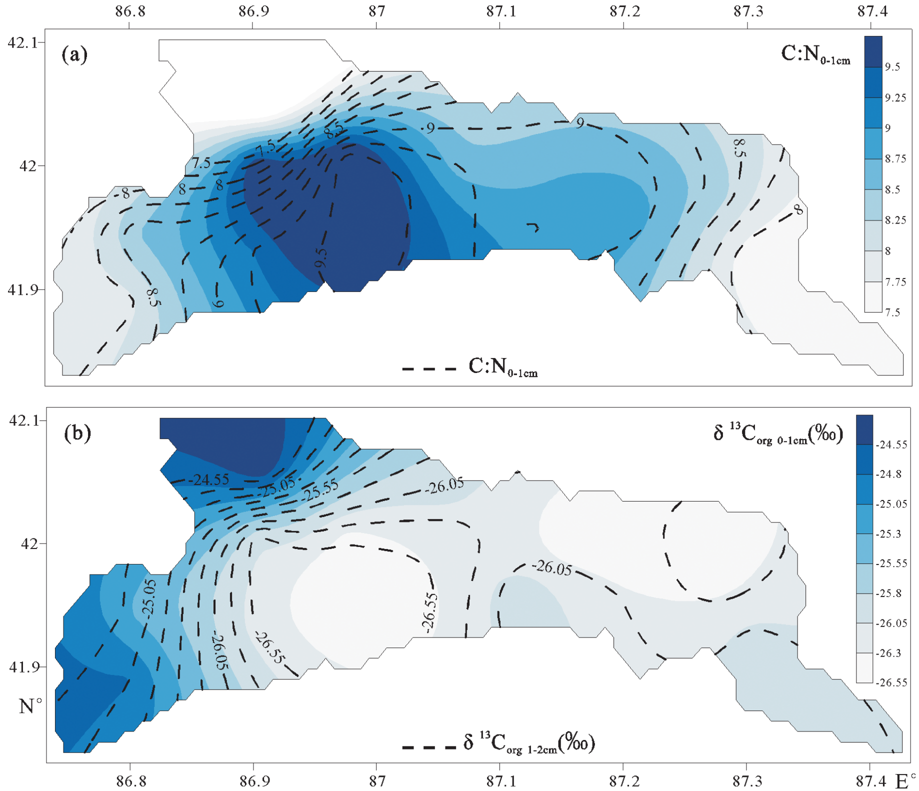

Figure 4. Spatial distribution of **(a)** C : N ratio and **(b)** carbon stable isotope ($\delta^{13}C_{org}$) of TOC in the 0–1 cm (color map) and 1–2 cm (dashed lines).

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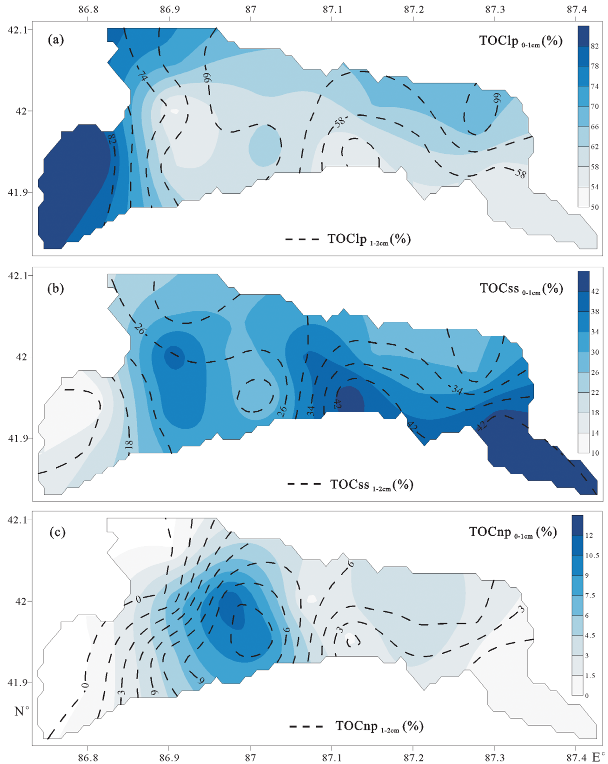

Figure 5. Spatial patterns of the relative contributions for TOC in the 0–1 cm (color map) and 1–2 cm (dashed lines) sediments. **(a)** TOC from lake plankton (TOC_{lp}), **(b)** TOC from surface soils (TOC_{ss}), and **(c)** TOC from native plants (TOC_{np}).

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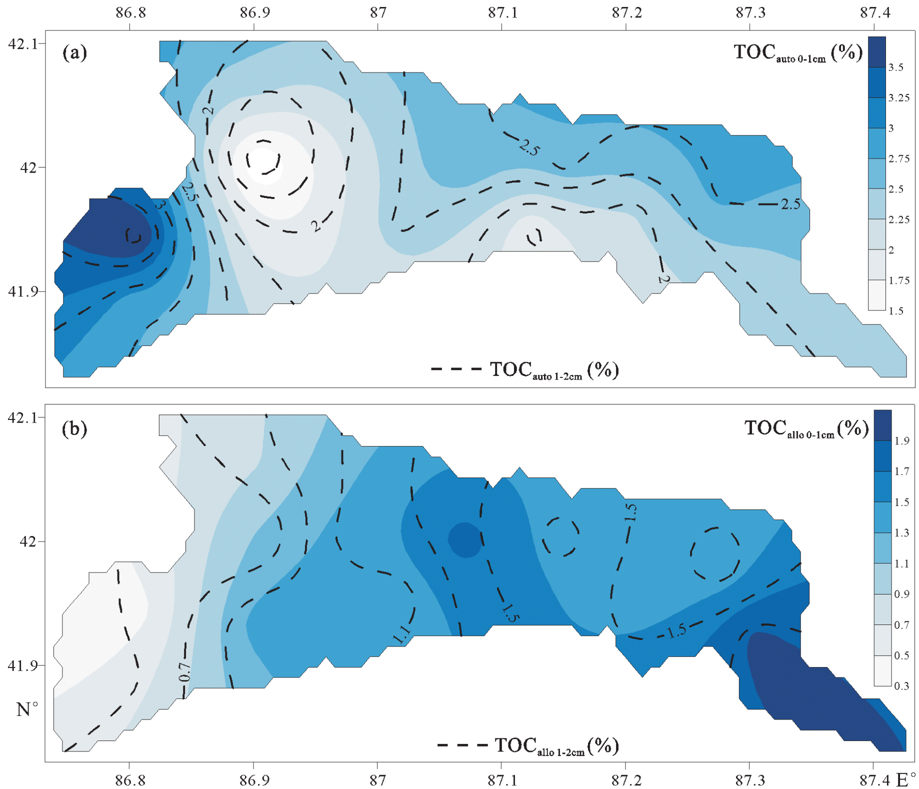

Figure 6. Spatial distributions of **(a)** autochthonous TOC (TOC_{auto}) and **(b)** allochthonous sources TOC (TOC_{allo}) in the 0–1 cm (color map) and 1–2 cm (dashed lines) sediments.

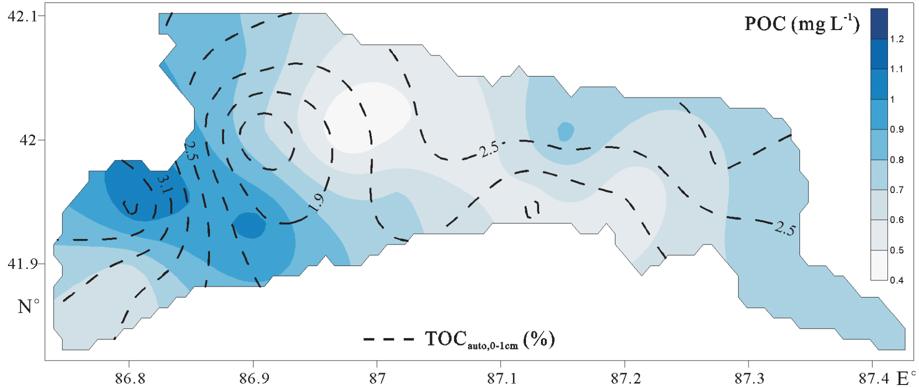

Figure 7. Spatial distributions of POC concentrations in summer (color map) and autochthonous TOC in the 0–1 cm sediment ($TOC_{auto\ 0-1\ cm}$, dashed lines). POC data were from Wang et al. (2014).

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