

# Spatial Distribution of Organic Carbon in Surface Sediment of Bosten Lake



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**Abstract** Lake sediment is a vital carbon reservoir, which is affected by biogeochemical and hydrological processes in the watershed. To study the dynamics of organic carbon in surface sediment of the Bosten Lake, we analyzed total organic carbon (TOC) and its stable carbon isotopic composition ( $\delta^{13}\text{C}_{\text{org}}$ ), total nitrogen (TN), and grain size in the surface (0–2 cm) sediment. Our data showed that there was a large spatial variability in both TOC (2.1–4.2%) and  $\delta^{13}\text{C}_{\text{org}}$  (–26.65 to –24.13‰) in surface sediment of the Bosten Lake. By using a three end member mixing model, we estimated that 54–90% of TOC was from autochthonous source. We found higher TOC concentration (>3.7%) near the mouth of the Kaidu River, in the central-north section and in the east section, which was attributable to autochthonous, autochthonous plus allochthonous, and allochthonous sources, respectively. The lowest TOC was seen in the mid-west section, which might mainly be due to the high kinetic energy levels. Our analyses suggested that the magnitude and spatial distribution of TOC in the surface sediment of Bosten Lake were influenced by complex processes and regulated by multiple factors.

## 1 Introduction

Lakes, rivers and other inland water bodies, as unique components on the Earth, are strongly influenced by the watershed's biogeochemical processes. Despite of the relatively small coverage (Downing et al. 2006), lakes play a crucial role in the biogeochemical cycle of the terrestrial ecosystems because of the high sedimentation

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X. Wang et al. (eds.), *Carbon Cycle in the Changing Arid Land of China*,

Springer Earth System Sciences, [https://doi.org/10.1007/978-981-10-7022-8\\_8](https://doi.org/10.1007/978-981-10-7022-8_8)

rates and a large amount of carbon burial in the lakes's sediments (Battin et al. 2009; Dean and Gorham 1998; Tranvik et al. 2009).

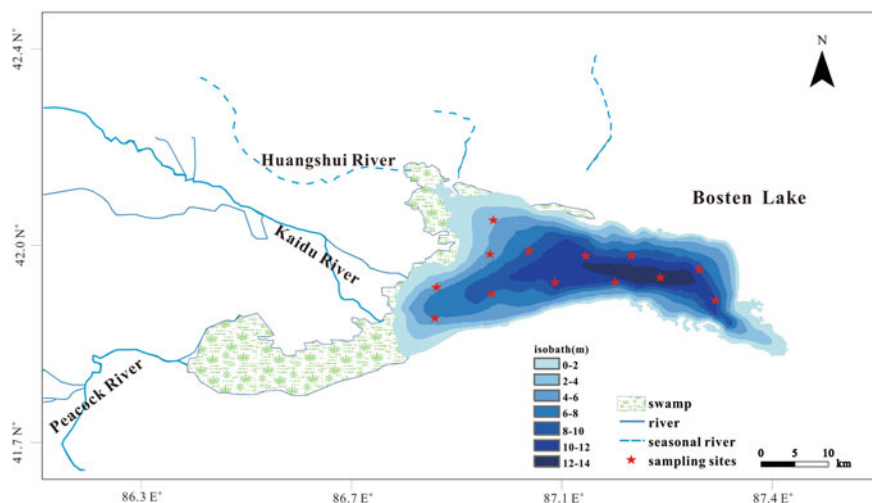
Total organic carbon (TOC) exhibits large spatial differences in lake sediment across the world, including the North America (Dean and Gorham 1998), West Europe (Bechtel and Schubert 2009; Woszczyk et al. 2011), East Asia (Khim et al. 2005; Wang et al. 2012) and other regions (Dunn et al. 2008). Many factors may affect the TOC concentration in surface sediment, including productivity and sedimentation in the water column, inputs of terrestrial materials from the watershed, microbial activity and physicochemical properties of sediment (Burone et al. 2003; Gireeshkumar et al. 2013). Apparently, spatial variability of TOC is directly related to the contributions of various sources (i.e., autochthonous and allochthonous) that may vary largely between regions, partly owing to the diverse productivity and morphology (Anderson et al. 2009; Barnes and Barnes 1978).

There are a few approaches that have been employed to quantify organic carbon sources in sediments, including the isotope method ( $\delta^{14}\text{C}$  and  $\delta^{13}\text{C}$ ), element ratio method (C:N), and biomarkers (N-alkanes and fatty acids) (Bechtel and Schubert 2009; Fang et al. 2014; Hanson et al. 2014). One common approach is to apply a two (three)-end-member mixing model with the end-members for C:N ratio and  $\delta^{13}\text{C}_{\text{org}}$  (stable carbon isotope in organic material). Such approach has been successfully used in studies of tracing biogeochemical process in various ecosystems (Liu and Kao 2007; Rumolo et al. 2011; Yu et al. 2010). Previous studies, based on such approach, have indicated that main sources of TOC are allochthonous in shallow and small lakes, but autochthonous in deep and large lakes (Barnes and Barnes 1978; Shanahan et al. 2013; Sifeddine et al. 2011).

Bosten Lake is the largest lake in Xinjiang, Northwest China, thus is a good place to study the lake carbon cycle. There have been limited studies conducted in Bosten Lake, which have focused evaluations on water quality (Wu et al. 2013), changes in lake level (Guo et al. 2014), carbon and oxygen isotopic composition of surface sediment carbonate (Zhang et al. 2009). In addition, a recent study has provided insights on the spatial and seasonal variations of particulate organic carbon (POC) for the water column of Bosten Lake (Wang et al. 2014), implying allochthonous contributions to sedimentary TOC. However, little is known about the magnitude and distribution of TOC, or the different contributions to TOC in the Bosten Lake. In addition to our previous analysis (Yu et al. 2015a), we conducted a further, comprehensive evaluation and discussion on the dynamics of TOC in surface sediment (0–2 cm) of Bosten Lake.

## 2 Sampling and Analyses

In August 2012, we used a Kajak gravity corer to collect surface (0–2 cm) sediments in the Bosten Lake's main section. There were 13 sampling locations that covered major parts of the lake, with the water depths ranging from 3 to 14 m (Fig. 1). Each



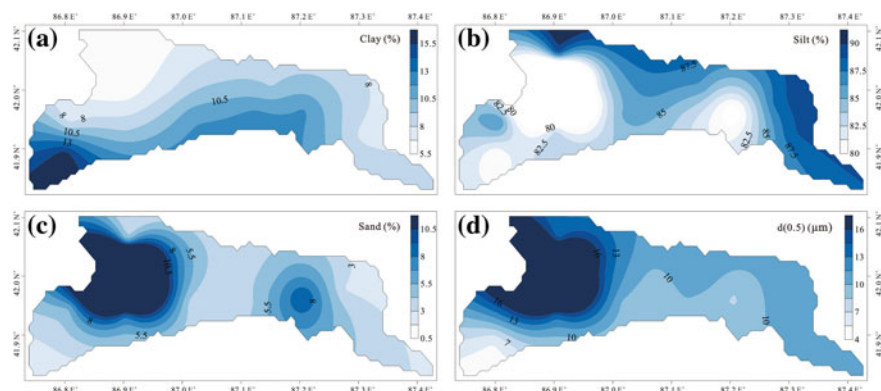
**Fig. 1** Sampling locations and the water depth in the Bosten Lake. Bathymetric data was obtained from Wu et al. (2013) and the contours were plotted using software ArcGIS 10.1 and Corel DRAW X7

sediment core was sliced into 1-cm, then placed in polyethylene bags, and stored in a cooler until analyses.

Each sample (~0.5 g) was pretreated, with 10–20 ml of 30%  $\text{H}_2\text{O}_2$  to remove organic matter in a water bath (60–80 °C), and then using 10–15 ml of 10% HCl to remove carbonates. The processed samples were mixed with 2000 ml of deionized water, and centrifuged after 24 h of standing. The solids were dispersed with 10–15 ml of 0.05 M  $(\text{NaPO}_3)_6$ , and then analyzed by a Malvern Mastersizer 2000 laser grain size analyzer. Related system software can automatically output the median diameter  $d(0.5)$ , the diameter at the 50th percentile of the distribution ( $\mu\text{m}$ ), and the percentages of clay ( $<2 \mu\text{m}$ ), silt (2–64  $\mu\text{m}$ ) and sand ( $>64 \mu\text{m}$ ) fractions, respectively.

Sediment TC and TN were measured by using an Elemental Analyzer 3000 (Euro Vector, Italy). Each sample was freeze-dried and ground into a fine powder, placed in tin capsules, then weighed and packed carefully. For the analysis of TOC, each sample (0.3–0.5 g) was pretreated with 5–10 ml 2 M HCl for 24 h at room temperature to remove carbonate, dried overnight under 60 °C, and analyzed using the elemental analyzer.

For the analyses of  $\delta^{13}\text{C}_{\text{org}}$ , we first removed carbonate with 5–10 ml 2 M HCl for 24 h at room temperature for all the freeze-dried sediment sample. After that, each pretreated sample was rinsed to a pH of ~7 with deionized water and dried at 40–60 °C. The samples were then combusted in the 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), with analytical precision of 0.1‰ for  $\delta^{13}\text{C}_{\text{org}}$ .



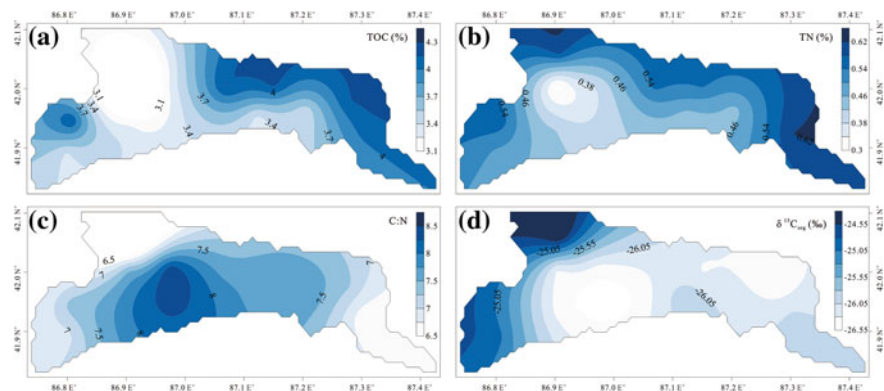
**Fig. 2** Spatial variations of **a** clay, **b** silt, **c** sand and **d** the median diameter ( $d(0.5)$ ,  $\mu\text{m}$ ) in the surface sediments of Bosten Lake. The distribution maps (Figs. 2–6) were produced using Surfer 9.0 (Golden Software Inc.) and the interpolated data in the maps were made by using the Kriging Method of Gridding

### 3 Grain Size Characteristics

As shown in Fig. 2, there were large differences in the spatial distributions of the grain size in the surface sediment. Apparently, clay content (5.9–16.3%) was low in the whole lake, with the lowest to the north and relatively higher contents in the southern area. Much high value of silt content (>80%) was found in the sediments, with the highest near the mouths of the Kaidu River and Huangshui River, but the lowest silt content in the mid-west (between the rivers' mouths). On the other hand, the proportion of sand particles was relatively low with the highest content between the two rivers' mouths (Fig. 2c). As expected, similar to that of sand, the  $d(0.5)$  showed a spatial distribution with the highest values in the mid-west part, indicating much strong hydrodynamic effect in this section.

### 4 Spatial Distributions of TOC, TN, C:N and $\delta^{13}\text{C}_{\text{org}}$

There was a large range in the surface TOC, in which higher values (4.1–4.4%) were found in three parts, i.e., the northern lake section, the eastern lake section and the southwestern lake section (near the Kaidu River's mouth), and lower TOC values (2.1–2.9%) were in the mid-west lake section (Fig. 3a). Similarly, TN ranged from 0.28 to 0.62%, showing the highest in the northwest and east areas, and the lowest value in the mid-west lake area (Fig. 3b). Overall, TN exhibited similar spatial distribution to TOC, except in the northwest lake section where showed lower TOC value, but higher TN concentration.



**Fig. 3** Spatial distributions of **a** total organic carbon (TOC), **b** total nitrogen (TN), **c** C:N ratio (TOC:TN) and **d** carbon stable isotope ( $\delta^{13}\text{C}_{\text{org}}$ ) of TOC in the surface sediments

As shown in Fig. 3c, C:N ratio (ranging from 4.8 to 8.5 revealed a large spatial variation in the surface sediment). Relative to other lake parts, the central part had generally higher C:N ratio, with the highest ratio found in the mid-west section, but the lowest near the mouth of Huangshui River. Value of  $\delta^{13}\text{C}_{\text{org}}$  varied from  $-26.65$  to  $-24.13\text{‰}$  in the surface sediments, which was the least negative in the northwest lake part (close to the Huangshui River's mouth), but the most negative in the area between  $86.9\text{--}87^{\circ}\text{E}$  and  $41.9\text{--}42^{\circ}\text{N}$ . Overall,  $\delta^{13}\text{C}_{\text{org}}$  value was much more negative in the central and eastern lake sections than in the western area in Bosten Lake.

## 5 Contributions of Different Sources

In this study, we used a three-end-member mixing model to quantify the contribution ( $f$ ) of different sources (i.e., lake plankton, soil and high plant, denoted by 1, 2 and 3, respectively):

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

$$r = f_1r_1 + f_2r_2 + f_3r_3 \quad (2)$$

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

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

Firstly, we assumed that the main native plants were responsible for high plant's contribution, because there were limited crops growing around the lake and crops' growing season was short (most was less than five months). According to the recent survey in Yanqi Basin (Zhang 2013), the mean C:N ratio was 10.0 and 22.1, and

$\delta^{13}\text{C}_{\text{org}}$  value was  $-23.6$  and  $-26.4\text{‰}$  for the surface soil and native plant around the lake, respectively. Thus, we used these values as our end members in the mixing model.

In addition, there were measurements of POC and its  $\delta^{13}\text{C}_{\text{org}}$ , and PON (particulate organic nitrogen) in the lake water column (Wang et al. 2014). The mean concentrations of POC and PON showed an increase, from  $0.61 \text{ mg C L}^{-1}$  and  $0.072 \text{ mg N L}^{-1}$  in spring to  $0.70 \text{ mg C L}^{-1}$  and  $0.088 \text{ mg N L}^{-1}$  in summer, and  $\delta^{13}\text{C}_{\text{org}}$  value changed from  $-22.9\text{‰}$  in spring to  $-23.5\text{‰}$  in summer. We assumed that lake plankton productivity was responsible for the changes in these parameters between spring and summer and estimated that the C:N and  $\delta^{13}\text{C}_{\text{org}}$  of lake plankton was 5.3 and  $-27.7\text{‰}$ , which were used as the end-members in the calculation.

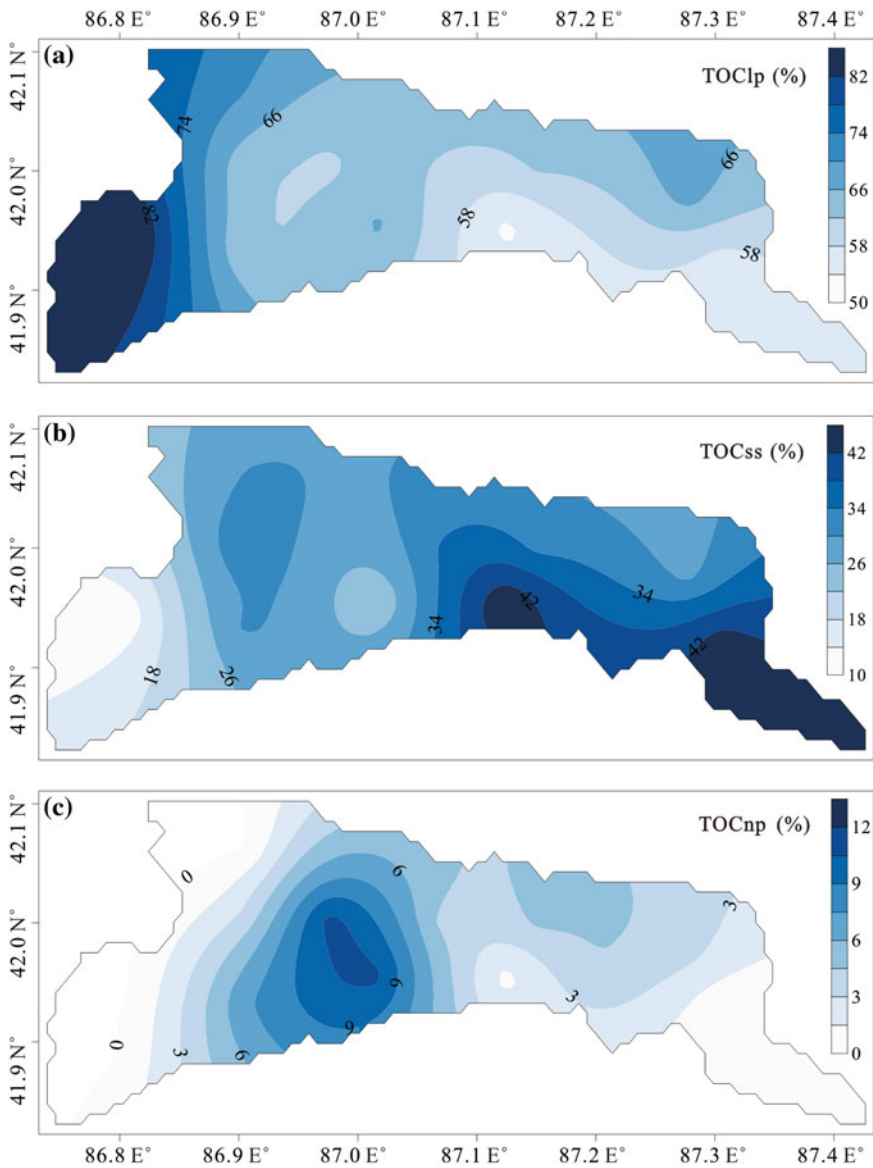
Figure 4 showed the contributions of autochthonous and allochthonous sources to TOC in the surface sediment. Lake plankton's contribution ranged from 54 to 90%, with the smallest contribution found in the southern and eastern deep sections, but the largest contribution in the western shallow section. Soil's contribution varied from 10 to 40%, and the largest contribution was observed in the southeastern lake area and near central-south lake area, but the smallest in the southwestern area. Clearly, native plant had extremely low contribution to TOC, with only a few sites having contributions greater 10–12% in Fig. 4c. The average contributions of lake plankton, soil and native plant to TOC were 66, 30 and 4%, respectively.

Figure 5 revealed significant differences in the spatial pattern between the autochthonous TOC and allochthonous TOC. The autochthonous TOC showed both the highest ( $\sim 3.5\%$ ) and lowest value ( $\sim 1.5\%$ ) in the western section, with the highest found near the river inlet (Fig. 5a). On the other hand, autochthonous sources presented a clear decrease trend from north to south in the area east of  $87^\circ\text{E}$ . Overall, the allochthonous TOC showed an apparent elevation from 0.5% in the west to 1.9% in the east (Fig. 5b).

## 6 Variation of TOC and Relationship with Water Column POC

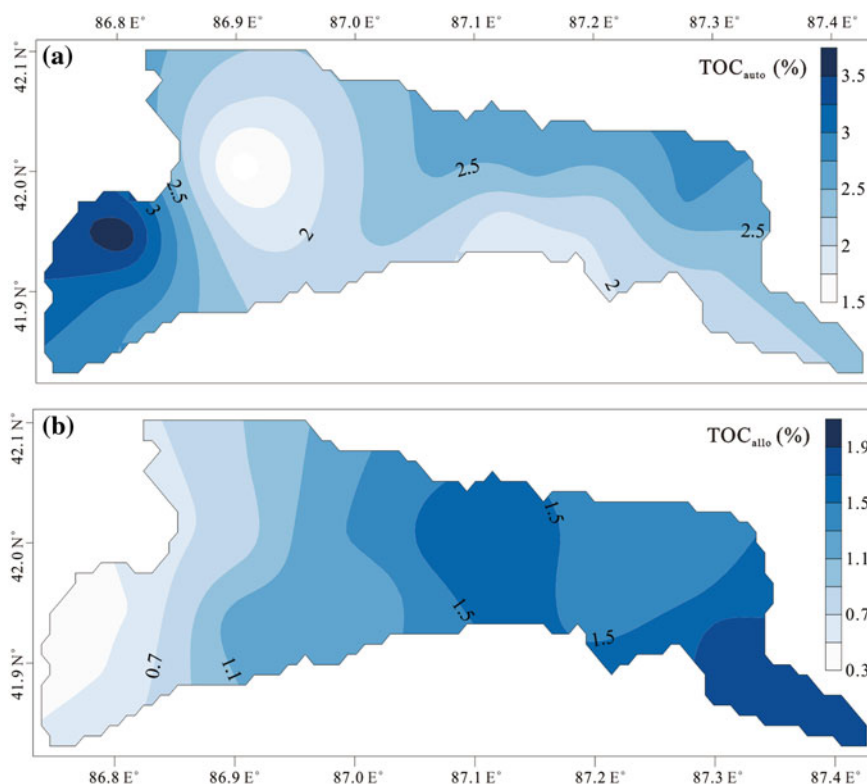
Our analyses demonstrated that the highest autochthonous TOC was found near the Kaidu River's mouth, but the highest allochthonous TOC in the eastern part of the lake (Fig. 5), which might be associated with the spatial distributions of nutrients in Bosten Lake. The transportation of various materials through the Kaidu River would have a significant downward trend from the west river mouth to the east lake section, which could largely influence the nutrient conditions in Bosten Lake. In general, lake productivity was high near the sources of nutrients, such as estuaries owing to the extra input of riverine nutrient (Deng et al. 2006; Lin et al. 2002).

To better understand the dynamics of TOC burial in Bosten Lake, we evaluated the spatial distribution of water column POC in summer and fall (Fig. 6). There were large differences in the magnitude and spatial pattern of POC between the



**Fig. 4** Spatial variabilities of relative contributions (percentages) to the TOC in surface sediment of Bosten Lake. **a** TOC from the lake plankton (TOC<sub>lp</sub>), **b** TOC from the surface soil (TOC<sub>ss</sub>), and **c** TOC from the native plant (TOC<sub>np</sub>)

two seasons. Overall, there was a similarity in the spatial pattern between summer POC and autochthonous TOC (see Fig. 5a) in spite of differences. Both variables

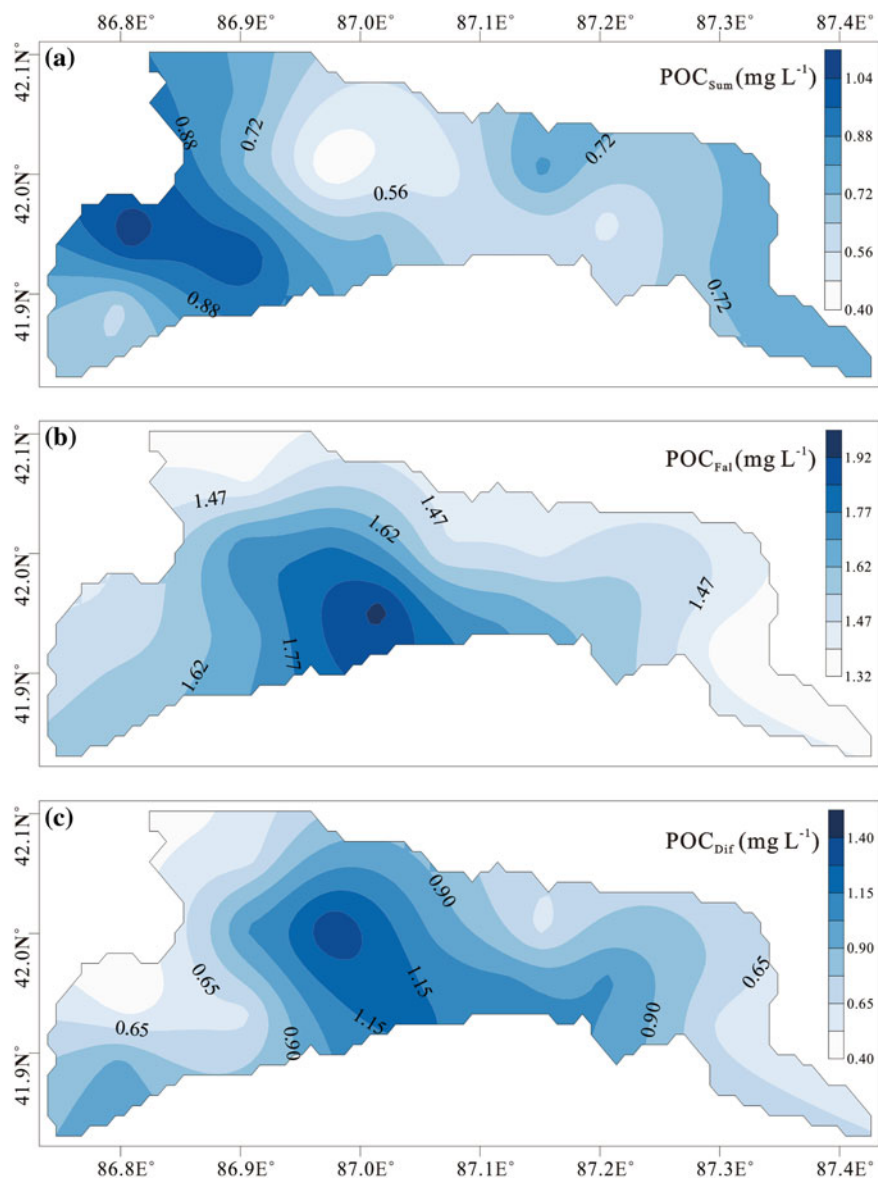


**Fig. 5** Spatial patterns of **a** autochthonous sources TOC (TOC<sub>auo</sub>) and **b** allochthonous sources TOC (TOC<sub>allo</sub>) in surface sediment

showed highest values near the river mouth. The two locations of the lowest POC ( $<0.6 \text{ mg L}^{-1}$ ) in summer were very close to those of the lowest autochthonous TOC.

Given that POC concentration was much greater in fall ( $1.35\text{--}1.94 \text{ mg L}^{-1}$ ) than in summer ( $0.4\text{--}1.03 \text{ mg L}^{-1}$ ), one might assume that a considerable proportion of POC in fall was from allochthonous sources. Interestingly, there were large differences in the spatial pattern between fall POC and allochthonous TOC (see Fig. 5b). For example, fall POC revealed highest value in the central part and lowest value in the far east of the lake whereas allochthonous TOC showed highest values in the eastern section; and there was a north-to-south elevation in the former but a west-to-east elevation in the latter. Assuming that the level of autochthonous POC was the same in summer and in fall, one might take the difference of POC ( $\Delta\text{POC}$ ) between fall and summer as allochthonous. However, the spatial variation of  $\Delta\text{POC}$  was different from that of allochthonous TOC, but similar to that of fall POC. While elevated POC in fall might be a result of allochthonous contribution, the spatial distribution of TOC burial could be affected by various processes (see discussion in next section).





**Fig. 6** Spatial distribution of POC concentration in the water column of Bosten Lake in **a** summer, **b** fall and **c** the difference. Data were from Wang et al. (2014)

**Table 1** Correlation coefficient ( $r$ ) between variables in surface sediment

Variables	WD	DBD	d(0.5)	Clay	Silt	Sand	TOC	$\delta^{13}\text{C}_{\text{org}}$
TOC	0.50	-0.58*	-0.71**	0.18	0.77**	-0.76**		-0.15
$\delta^{13}\text{C}_{\text{org}}$	-0.66*	-0.46	-0.13	0.03	0.21	-0.20	-0.15	
C:N	0.50	0.50	0.01	0.25	-0.19	0.11	0.14	-0.82**

WD = water depth (m), DBD = dry bulk density ( $\text{g cm}^{-3}$ ),  $d(0.5)$  = median diameter ( $\mu\text{m}$ ) and clay, silt and sand fractions (%) in surface sediment. Significance of Pearson Correlation is marked with \*( $p < 0.05$ ) and \*\*( $p < 0.01$ ) superscripts

## 7 Dynamics of TOC and Underlying Mechanisms

Previous studies have indicated that the magnitudes and spatial distribution of TOC in lake sediment may reflect multiple and complex processes (Dunn et al. 2008; Sifeddine et al. 2011; Woszczyk et al. 2011). While the magnitude of TOC burial was often determined by the level of POC in water column, the distribution of TOC might be influenced by many factors/processes. As illustrated in Figs. 2 and 3, the lowest TOC was found in the mid-west section where coarse particle components were dominant. In addition, TOC expressed a negative relationship with both sand content and  $d(0.5)$  value in surface sediment (Table 1). In general, high proportion of coarser particles reflected an environment with stronger water energy and more finer particles indicated stable sedimentary conditions (Jin et al. 2006; Molinaroli et al. 2009). Thus, it appeared that lower TOC concentration in the mid-west lake part was induced by both the lower level of POC and higher hydrodynamic circumstances.

Based on the significant negative relationship between the  $\delta^{13}\text{C}_{\text{org}}$  value and water depth (Table 1), we could imply that there was more allochthonous TOC (with less negative  $\delta^{13}\text{C}$ ) in the shallow sections of the Bosten Lake. Apart from the lake own characteristics (e.g., the current and water depth), other factors may also have influences on the distributions of TOC in surface sediment of the Bosten Lake. For example, there were significant land use changes (i.e., agricultural development with fertilization), which would increase the riverine input of exogenous materials (particularly nutrients), leading to variations in lake water productivity and subsequently changing the TOC storage in surface sediment (Lami et al. 2010; Rumolo et al. 2011).

## 8 Implications and Future Directions

There are obvious differences in TOC values of surface sediment across lake regions in China. For example, lower concentration (0.2–2%) was observed in lakes in the Tibetan Plateau (Lami et al. 2010; Wang et al. 2012) and in the Yangtze floodplain (Dong et al. 2012; Wu et al. 2007), but much higher concentration (5–13%) was found in the Yunnan-Guizhou Plateau (Wu et al. 2012; Zhu et al. 2013). The TOC

content is modestly high in Bosten Lake (1.8–4.4%), comparing with the lakes across China.

Climate change and human activities in the Yanqi Basion have resulted in remarkable changes in many aspects, including changes in the runoff of the Kaidu River and the lake level of Bosten Lake over the past decades (Guo et al. 2014), which would have impacted the spatial and temporal variations of TOC burial in the sediment of Bosten Lake. A recent study demonstrates that there has been pronounced interannual variability in carbon burial not only for TOC but also carbonate, particularly post 2000 (Yu et al. 2015b). Further studies are needed to evaluate the spatial-temporal variations of the water column biological production and carbon burial in sediments to better understand the dynamics of organic and inorganic carbon in different lake regions and the impacts of human disturbance and climate change.

## 9 Conclusion

Based on the surface (0–2 cm) sediment samples, we found a large spatial variability in TOC content (2.1–4.2%) and  $\delta^{13}\text{C}_{\text{org}}$  value (–26.65 to –24.13‰) in the Bosten Lake. Using a three end member mixing model, we estimated that 54–90% of TOC was from autochthonous sources. Higher TOC concentration (>3.7%) was found near the area of the Kaidu River mouth, in the central-north section and in the east section which was attributable to autochthonous, autochthonous plus allochthonous, and allochthonous sources, respectively. The lowest TOC content was found in the mid-west section, which might mainly be a result of high kinetic energy levels. Our study indicated that multiple and complex processes affected the TOC dynamics in surface sediment of the Bosten Lake.

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