

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

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20
21 **Abstract**

22 Lake sediment is an important carbon reservoir. However, little is known on the
23 dynamics and sources of sediment organic carbon in the Bosten Lake. We collected
24 13 surface (0-2cm) sediment samples in the Bosten Lake and analyzed total organic
25 carbon (TOC), total nitrogen (TN), stable carbon isotopic composition in TOC
26 ($\delta^{13}\text{C}_{\text{org}}$) and grain size. We found a large spatial variability in TOC content (1.8-4.4%)

1 and $\delta^{13}\text{C}_{\text{org}}$ value (-26.77‰ to -23.98‰). Using a three end member mixing model
2 with measured TOC:TN ratio and $\delta^{13}\text{C}_{\text{org}}$, we estimated that 54-90% of TOC was
3 from autochthonous sources. Higher TOC content (>3.7%) was found in the east and
4 central-north sections and near the mouth of the Kaidu River, which was attributable
5 to allochthonous, autochthonous plus allochthonous, and autochthonous sources,
6 respectively. The lowest TOC content was found in the mid-west section, which might
7 be a result of high kinetic energy levels. Our study indicated that the spatial
8 distribution of sediment TOC in the Bosten Lake was influenced by multiple and
9 complex processes.

10

11 **1 Introduction**

12 Inland water bodies such as rivers and lakes are unique components on the Earth. In
13 spite of their relatively small coverage (Downing et al., 2006), lakes often receive a
14 large amount of terrestrial materials from the watersheds (Battin et al., 2009; Anderson
15 et al., 2013), and store a significant amount of carbon in the sediments (Ferland et al.,
16 2012; Tranvik et al., 2009). Thus, inland lakes may play an important role in the
17 terrestrial carbon cycle. Compared to the oceans, lakes have active biogeochemical
18 processes with stronger “biological pump”, which often leads to higher sedimentation
19 rates and a large amount of organic carbon (OC) burial at the bottom of lakes (Dean
20 and Gorham, 1998).

21 There have been a number of studies from North America (Dean and Gorham, 1998),
22 West Europe (Bechtel and Schubert, 2009; Woszczyk et al., 2011), East Asia (Khim et
23 al., 2005; Wang et al., 2012) and other regions (Dunn et al., 2008), showing large
24 spatial variability in total organic carbon (TOC) of lake sediment. The magnitude of
25 TOC in surface sediment may depend on many factors, including column water
26 productivity, terrestrial inputs of organic materials, properties of sediment, and rate of
27 microbial activity (Burone et al., 2003; Gireeshkumar et al., 2013). Among them,
28 contributions of autochthonous and allochthonous sources have direct impacts on the
29 spatial distribution, which vary largely across regions (Bechtel and Schubert,

1 2009;Anderson et al., 2009), partly due to differences in lake productivity and
2 morphology (Barnes and Barnes, 1978). In general, lakes with high productivity have
3 more autochthonous TOC, but lakes with low productivity mainly allochthonous TOC
4 (Dean and Gorham, 1998). There is evidence of littoral sources of TOC in small and
5 shallow lakes, but autochthonous sources, derived from planktonic organisms, in
6 larger and deeper lakes, especially fjord lakes (Shanahan et al., 2013;Sifeddine et al.,
7 2011;Barnes and Barnes, 1978).

8 A number of techniques have been applied to quantify different sources of sediment
9 TOC (Fang et al., 2014;Hanson et al., 2014;Meyers and Ishiwatari, 1993;Bechtel and
10 Schubert, 2009). One of the common approaches is to use two or three end-member
11 mixing models with combined use of TOC to total nitrogen (TN) ratio (C:N) and
12 stable carbon isotope in organic material ($\delta^{13}\text{C}_{\text{org}}$) (Rumolo et al., 2011;Yu et al.,
13 2010;Liu and Kao, 2007). It is well known that there are large differences in C:N ratio
14 and $^{13}\text{C}_{\text{org}}$ value between exogenous and endogenous organic materials (Brodie et al.,
15 2011;Kaushal and Binford, 1999). For example, aqueous organic matters have low
16 C:N ratios (4-10) (Meyers, 2003) whereas vascular land plants have much higher C:N
17 ratios (>20) (Rumolo et al., 2011;Lamb et al., 2004;Sifeddine et al., 2011). On the
18 other hand, due to the difference in isotopic fractionation during photosynthesis,
19 $\delta^{13}\text{C}_{\text{org}}$ value is more negative (ranging from -33‰ to -22‰) in terrestrial C_3 plants
20 (Pancost and Boot, 2004;Wang et al., 2013) and lake plankton (Bertrand et al.,
21 2010;Vuorio et al., 2006) than in C_4 plants (ranging from -16‰ to -9‰) (Pancost and
22 Boot, 2004;Wang et al., 2013).

23 Bosten Lake, as the largest lake in Xinjiang of China, is a typical place for studying
24 lake carbon cycle. Previous studies have provided evaluations on water quality (Wu et
25 al., 2013), changes in lake level (Guo et al., 2014), and the controlling factors of
26 carbon and oxygen isotopic composition of surface sediment carbonate (Zhang et al.,
27 2009). A recent study indicated that particulate organic carbon (POC) variability in
28 the water column was affected by allochthonous sources in the Bosten Lake (Wang et
29 al., 2014). However, little has been done to assess the dynamics and sources of

1 sediment TOC in the Bosten Lake. Therefore, this study was designed to evaluate the
2 spatial distributions of major physical and biogeochemical parameters in the surface
3 sediment, and to quantify the contributions of various sources to the sediment TOC in
4 the Bosten Lake.

5

6 **2 Materials and Methods**

7 **2.1 Site description**

8 Bosten Lake (41°32'~42°14'N, 86°19'~87°26'E) is located in the lowest part of the
9 intermontane Yanqi Basin between the Taklimakan Desert and Tienshan Mountains,
10 Northwest China (Figure 1). It is the largest inland freshwater lake in China, which is
11 about 55 km long from east to west and about 25 km wide from south to north,
12 comprising a total lake surface area of approximately 1005 km², with a maximum
13 water depth of 14 m (Wu et al., 2013). The lake surface was 1045 m above sea level
14 in 2012 when sampling was carried out. The lake lies in the center of the Eurasian
15 Continent and is influenced by a temperate continental climate. The mean annual air
16 temperature is approximately 8.3 °C, the mean annual precipitation approximately 65
17 mm and the mean annual evaporation approximately 1881 mm (Zhang et al., 2009).
18 Winds come mainly from the southwest, indicating dominant influence by the
19 westerly throughout the summer season. Lake water input mainly comes from the
20 Kaidu River that is supplied by melting ice, precipitation and groundwater, whereas
21 water output includes outflow (57%) via the Peacock River and evaporation (43%)
22 (Guo et al., 2014). There are also small seasonal rivers (mainly during flood seasons),
23 e.g., the Huangshui River and Qinhshui River near the northwest of the lake.

24 **2.2 Field sampling and analyses**

25 For the present study, a Kajak gravity corer was used to collect surface sediments
26 from 13 sites in the main section of the Bosten Lake in August 2012 (Figure 1). The
27 sampling sites covered most parts of the lake, with water depths ranging from 3 m to

1 14 m. The sediment cores were carefully extruded and the top 2 cm sections were
2 sliced into 1-cm and placed in polyethylene bags that were kept on ice in a cooler
3 during transport and before analyses.

4 Following Liu et al. (2014), each sediment sample (~0.5 g) was pretreated, in a water
5 bath (between 60 and 80 °C), with 10-20 ml of 30% H₂O₂ to remove organic matter,
6 then with 10-15ml of 10% HCl to remove carbonates. The samples were then mixed
7 with 2000 ml of deionized water, and centrifuged after 24 hours of standing. The
8 solids were dispersed with 10 ml of 0.05 M (NaPO₃)₆, then analyzed for grain size,
9 using a Malvern Mastersizer 2000 laser grain size analyzer at the State Key
10 Laboratory of Lake Science and Environment (SKLLSE), Nanjing Institute of
11 Geography and Limnology, Chinese Academy of Sciences (CAS). The Malvern
12 Mastersizer 2000 automatically outputs the median diameter d(0.5) (µm), the diameter
13 at the 50th percentile of the distribution, and the percentages of clay (< 2 µm), silt
14 (2-64 µm) and sand (> 64 µm) fractions.

15 Sediment C and N contents were measured using an Elemental Analyzer 3000 (Euro
16 Vector, Italy) at the SKLLSE, Nanjing Institute of Geography and Limnology, CAS.
17 All samples were freeze-dried and ground into a fine powder, then placed in tin
18 capsules, weighed and packed carefully, according to Eksperiandova et al. (2011). For
19 the analysis of TOC, each sample (~ 0.3 g) was pretreated with 5-10 ml 2M HCl for
20 24h at room temperature to remove carbonate, dried overnight at 40-50 °C, then
21 analyzed for C content using the Elemental Analyzer.

22 For the analyses of δ¹³C_{org}, approximately 0.2 g of the freeze-dried sediment sample
23 was pretreated with 5-10 ml 2M HCl for 24 h at room temperature to remove
24 carbonate, and then rinsed to a pH of approximately 7 with deionized water and dried
25 at 40-50 °C (Liu et al., 2013). The pre-treated samples were combusted in a Thermo
26 elemental analyzer integrated with an isotope ratio mass spectrometer (Delta Plus XP,
27 Thermo Finnigan MAT, Germany). Isotopic data were reported in delta notation
28 relative to the Vienna Pee Dee Belemnite (VPDB).

1 2.3 Calculations of TOC sources

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

$$5 \quad \delta = f_1\delta_1 + f_2\delta_2 + f_3\delta_3 \quad (1)$$

$$6 \quad r = f_1r_1 + f_2r_2 + f_3r_3 \quad (2)$$

$$7 \quad 1 = f_1 + f_2 + f_3 \quad (3)$$

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

9 Given that there were limited crops around the lake and most crops' growing season
10 was less than five months each year, we assumed that native plants, mainly reed
11 (*Phragmites australis* (Cav.) Trin. ex Steud), Manaplant Alhagi (*Alhagi sparsifolia*
12 *Shap*) and Achnatherum splendens (*Achnatherum splendens* (Trin.) Nevski), were
13 responsible for terrestrial plant's contribution. Based on our recent studies conducted
14 in the Yanqi Basin (Wang et al., 2015; Zhang, 2013), C:N ratio was 22.1 ± 9.9 and
15 10 ± 1.8 , and $\delta^{13}\text{C}_{\text{org}}$ value was $-26.4 \pm 1.2\text{‰}$ and $-23.6 \pm 1.3\text{‰}$ for the native plants and
16 surface soils around the lake, respectively. We used the values as the end-members for
17 the mixing model.

18 We measured POC, particulate organic nitrogen (PON) and $\delta^{13}\text{C}_{\text{org}}$ in POC in the
19 water column of the Bosten Lake (Wang et al., 2014). Lake POC and PON increased
20 from $0.61 \pm 0.04 \text{ mg C L}^{-1}$ and $0.072 \pm 0.005 \text{ mg N L}^{-1}$ in spring to $0.70 \pm 0.16 \text{ mg C L}^{-1}$
21 and $0.088 \pm 0.02 \text{ mg N L}^{-1}$ in summer, and $\delta^{13}\text{C}_{\text{org}}$ value in POC was $-22.9 \pm 2.56\text{‰}$ in
22 spring and $-23.5 \pm 0.38\text{‰}$ in summer. It is reasonable to assume that the seasonal
23 changes were resulted from the production of lake plankton. Accordingly, we
24 estimated that lake plankton (including phytoplankton and zooplankton) would have a
25 C:N ratio of 5.3 and $\delta^{13}\text{C}_{\text{org}}$ value of -27.7‰ , and used these values as the
26 end-members for the mixing model.

1 Our approach may have uncertainties in determining TOC sources. However, the
2 uncertainties would be small given that the standard errors in $\delta^{13}\text{C}_{\text{org}}$ are small, and
3 C:N ratios diff greatly between sources. Thus, our method will not affect the main
4 conclusion in terms of TOC sources for the lake sediments.

5 **2.4 Statistical methods and mapping**

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

9

10 **3 Results**

11 **3.1 Physical characteristics**

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

22 **3.2 Spatial distribution of TOC, TN, C:N and $\delta^{13}\text{C}_{\text{org}}$**

23 Concentration of TOC was highly variable, with higher values (4.3-4.4%) found in the
24 northern and eastern sections of the lake (Figure 3a). There was also high
25 concentration of TOC (4.1-4.2%) near the mouth of the Kaidu River (southwest). On
26 the other hand, lower TOC concentration (1.8-2.4%) was observed in the mid-west

1 section. Similarly, TN concentration (ranging from 0.28% to 0.68%) was lowest
2 concentration in the mid-west and highest in the northwest and east sections (Figure
3 3b). Overall, the spatial distribution of TN was similar to that of TOC. The exception
4 was in the northwest area that had high TN value, but low TOC concentration.

5 Figure 4a showed a large spatial variability in the C:N ratio with a range from 4.6 to
6 8.6. In general, C:N ratio was higher in the central part relative to other parts. The
7 highest C:N ratio was found in the mid-west, and the lowest found in the northwest
8 area. The $\delta^{13}\text{C}_{\text{org}}$ values ranged from -26.77‰ to -23.98‰ (Figure 4b). The most
9 negative value was observed in the area of 41.9-42 °N and 86.9-87 °E, and the least
10 negative value near the mouth of the Huangshui River (northwest). Overall, values of
11 $\delta^{13}\text{C}_{\text{org}}$ were more negative in the eastern and central parts than in the northwestern
12 and southwestern parts.

13 **3.3 Contributions of different sources**

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

23 There were large differences in the spatial distributions of TOC between the
24 autochthonous and allochthonous sources. Autochthonous TOC revealed highest value
25 (~3.5%) near the mouth of the Kaidu River and lowest (~1.5%) in the mid-west of the
26 lake (Figure 6a). For the area east of 87 °E, autochthonous TOC showed a clear
27 increase from south to north. On the other hand, there was an apparent elevation in the
28 allochthonous TOC, from 0.5% in the west to 1.9% in the east (Figure 6b).

1

2 **4 Discussion**

3 The concentration of TOC in the surface sediment of the Bosten Lake ranged from
4 1.8-4.4%, which was relatively higher than those (0.2-2%) in the Tibetan Plateau
5 (Lami et al., 2010;Wang et al., 2012) and Yangtze floodplain (Wu et al., 2007;Dong et
6 al., 2012), but much lower than those (5-13%) in the lakes of the Yunnan-Guizhou
7 Plateau (Zhu et al., 2013;Wu et al., 2012). Low TOC contents in the Tibetan Plateau
8 lakes were a consequence of low biological productivity owing to the high altitude
9 and low temperature (Lami et al., 2010). Although lakes in the Yangtze floodplain had
10 higher productivity in the water column due to eutrophication (Qin and Zhu, 2006),
11 most of them were shallow lakes that were subject to frequent turbulence and
12 resuspension of sediments (Qin et al., 2006). In addition, warm-humid climate in the
13 Yangtze floodplain could promote decomposition of POC in the water column and
14 TOC in the sediments (Gudasz et al., 2010), which led to less TOC storage in the
15 surface sediments. On the other hand, lakes in the Yunnan-Guizhou Plateau were deep
16 with higher lake productivity, which had favorable TOC burial conditions (Jiang and
17 Huang, 2004).

18 Sediment organic compounds are either of terrestrial origins or derived from
19 phytoplankton and zooplankton remains and feces (Meyers, 2003;Meyers and
20 Ishiwatari, 1993;Barnes and Barnes, 1978). A number of studies have demonstrated
21 that TOC in small and shallow lakes are attributable to allochthonous sources, but
22 TOC in larger and deeper lakes to autochthonous sources that are derived from
23 planktonic organisms (Shanahan et al., 2013;Sifeddine et al., 2011;Barnes and Barnes,
24 1978). Our analyses showed that the majority of TOC was autochthonous in the
25 surface sediment of the Bosten Lake. We also found a significant negative relationship
26 between TOC and dry bulk density (Table 1), confirming that higher TOC (with
27 lighter weight) would be a result of sedimentation of non-terrestrial organic materials.

28 Our study demonstrated large spatial variability in the TOC of the surface sediment in
29 the Bosten Lake, with higher values in the central north and east sections and near the

1 mouth of the Kaidu River, but lower values in the west section and mid-south section
2 (Figure 3a). Further analyses showed that the highest autochthonous TOC was found
3 near the mouth of the Kaidu River and the highest allochthonous TOC in the east
4 section (Figure 6). There is evidence of high productivity near the sources of nutrients,
5 such as estuaries owing to extra nutrient input from riverine (Deng et al., 2006; Lin et
6 al., 2002). Nutrient conditions in the Bosten Lake may be largely affected by the
7 transportation of the Kaidu River, which has a significant decline from the mouth to
8 the east section. Similar finding was also observed in the Nam Co Lake (Wang et al.,
9 2012).

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

23 The magnitudes and spatial distribution of TOC in lake sediment may reflect multiple,
24 complex processes (Sifeddine et al., 2011; Woszczyk et al., 2011; Dunn et al.,
25 2008; Wang et al., 2012). Our analyses showed a significant negative relationship
26 between the $\delta^{13}\text{C}_{\text{org}}$ value and water depth (Table 1), implying that the shallow
27 sections in the Bosten Lake accumulated more allochthonous TOC (with less negative
28 $\delta^{13}\text{C}$). Apart from the lake own characteristics (such as lake current and depth), other
29 factors may have influences on the dynamics of TOC. For example, land use changes

1 such as agricultural development and fertilization would enhance the riverine input of
2 nutrients, leading to changes in lake productivity and subsequently altering TOC
3 burial in the sediment (Rumolo et al., 2011;Lami et al., 2010;Lamb et al., 2006).
4 There has been evidence of climate change and human activities over the past decades
5 in the surrounding region, which has caused remarkable lake level changes in the
6 Bosten Lake (Guo et al., 2014). All these changes would have impacts on the
7 production of POC and TOC burial. Further studies are needed to assess the spatial
8 and temporal variations in the water column biological production to better
9 understand the dynamics of OC in the Bosten Lake and the impacts of human activity
10 and climate change.

11

12 **Acknowledgments**

13 This study is financially supported by the National Key Basic Research Program
14 (2013CB956602), the Special Environmental Research Funds for Public Welfare of
15 the State Environmental Protection Administration (201309041), the Sino-German
16 project (GZ867) and National pioneer project (XDA05020202).

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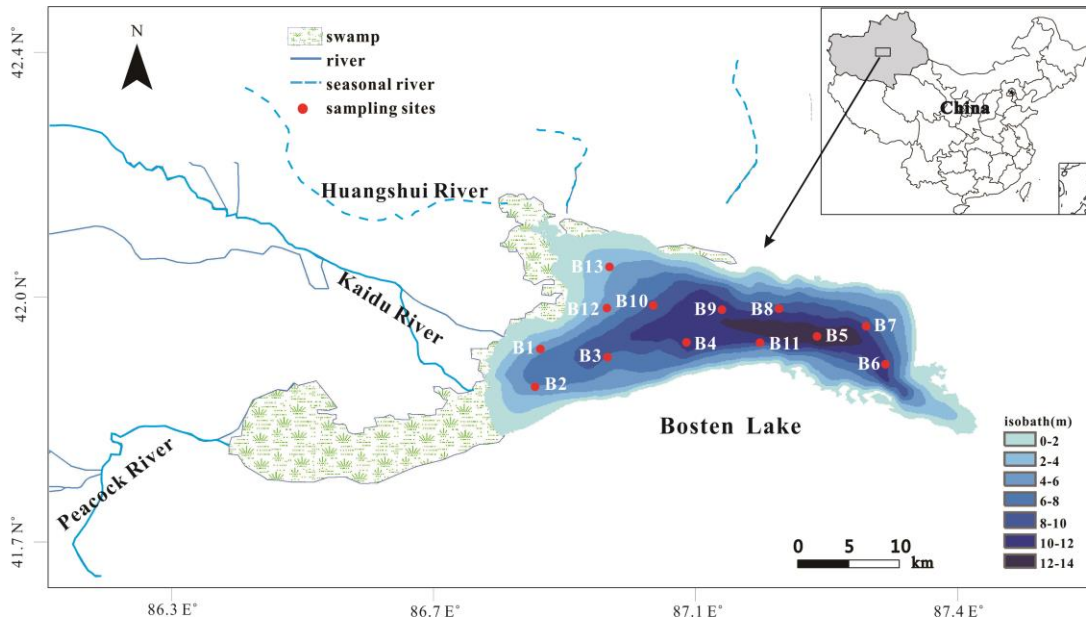
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1 Table 1. Correlation coefficient (r) between various variables for the sediments.

Variables	WD	DBD	d(0.5)	Clay	Silt	Sand	TOC	$\delta^{13}\text{C}_{\text{org}}$
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
$\delta^{13}\text{C}_{\text{org}}$	-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

2 WD = water depth, DBD = dry bulk density, d(0.5) = median diameter from the 0-2
3 cm sediments. Significance of Pearson correlation is marked with ^a (p<0.05) and ^b
4 (p<0.01) asterisks.

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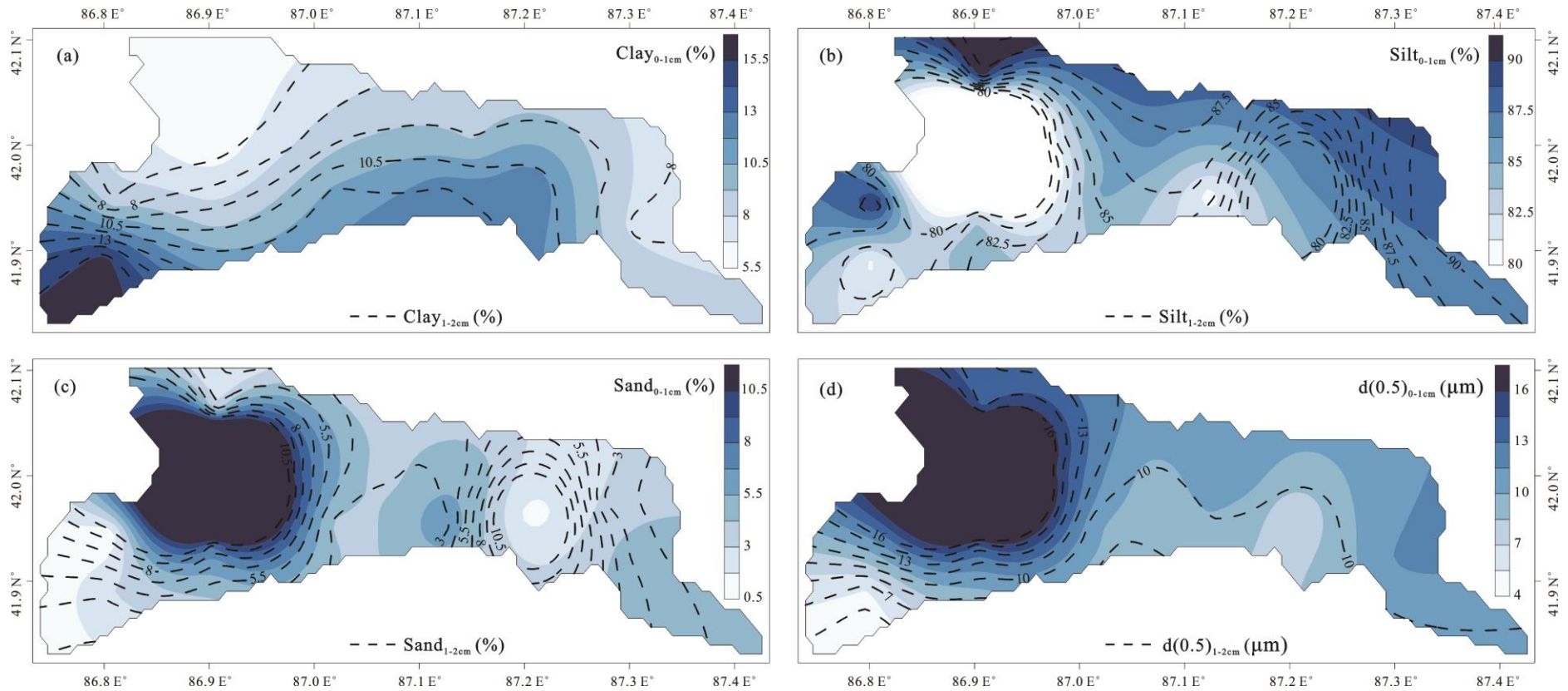


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3 Figure 1. Map of the Bosten Lake with the water depth and the 13 sampling stations
4 (red dots). Bathymetric was measured in 2008 by Wu et al. (2013) and bathymetric
5 contours were plotted by using software ArcGIS 9.3 and Corel DRAW X3.

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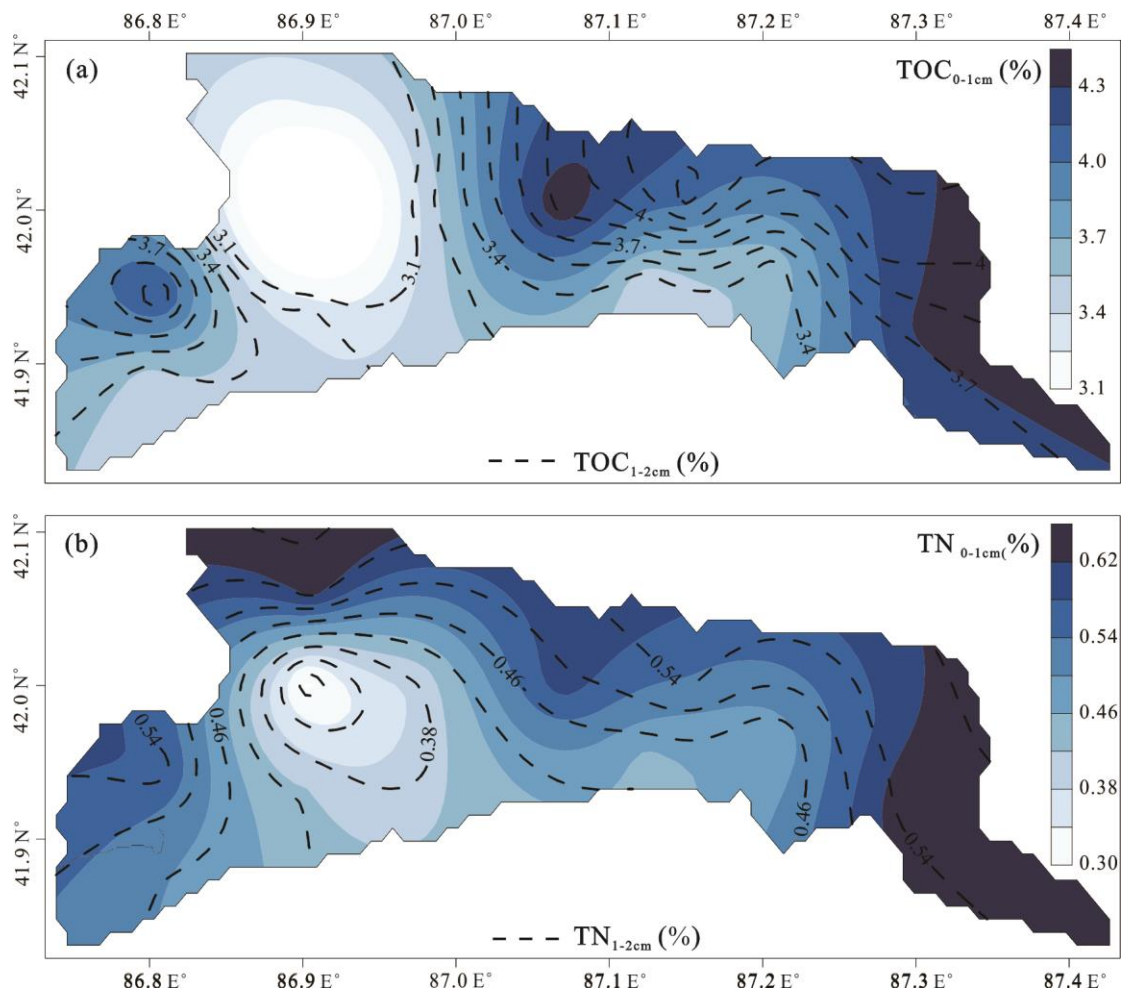
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3 Figure 2. Distributions of (a) clay, (b) silt, (c) sand and (d) the median diameter ($d(0.5)$, μm) in the 0-1 cm (color map) and 1-2 cm (dashed lines).

4 The spatial distribution maps (Figure 2-7) were produced using Surfer 9.0 (Golden Software Inc.) and the interpolated data in the maps was

5 made using the Kriging method of gridding.

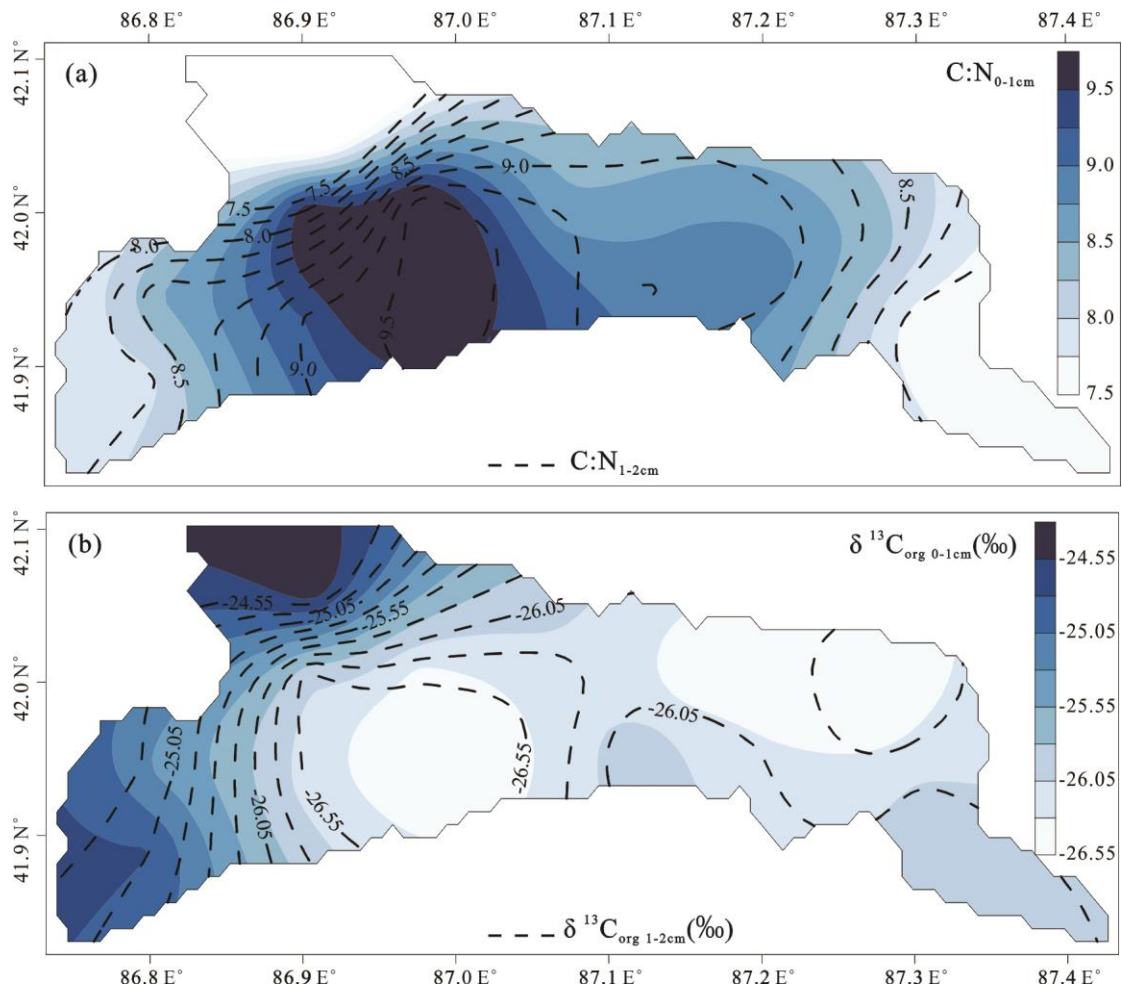
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3 Figure 3. Spatial distributions of (a) total organic carbon (TOC) and (b) total nitrogen
4 (TN) in the 0-1 cm (color map) and 1-2 cm (dashed lines).

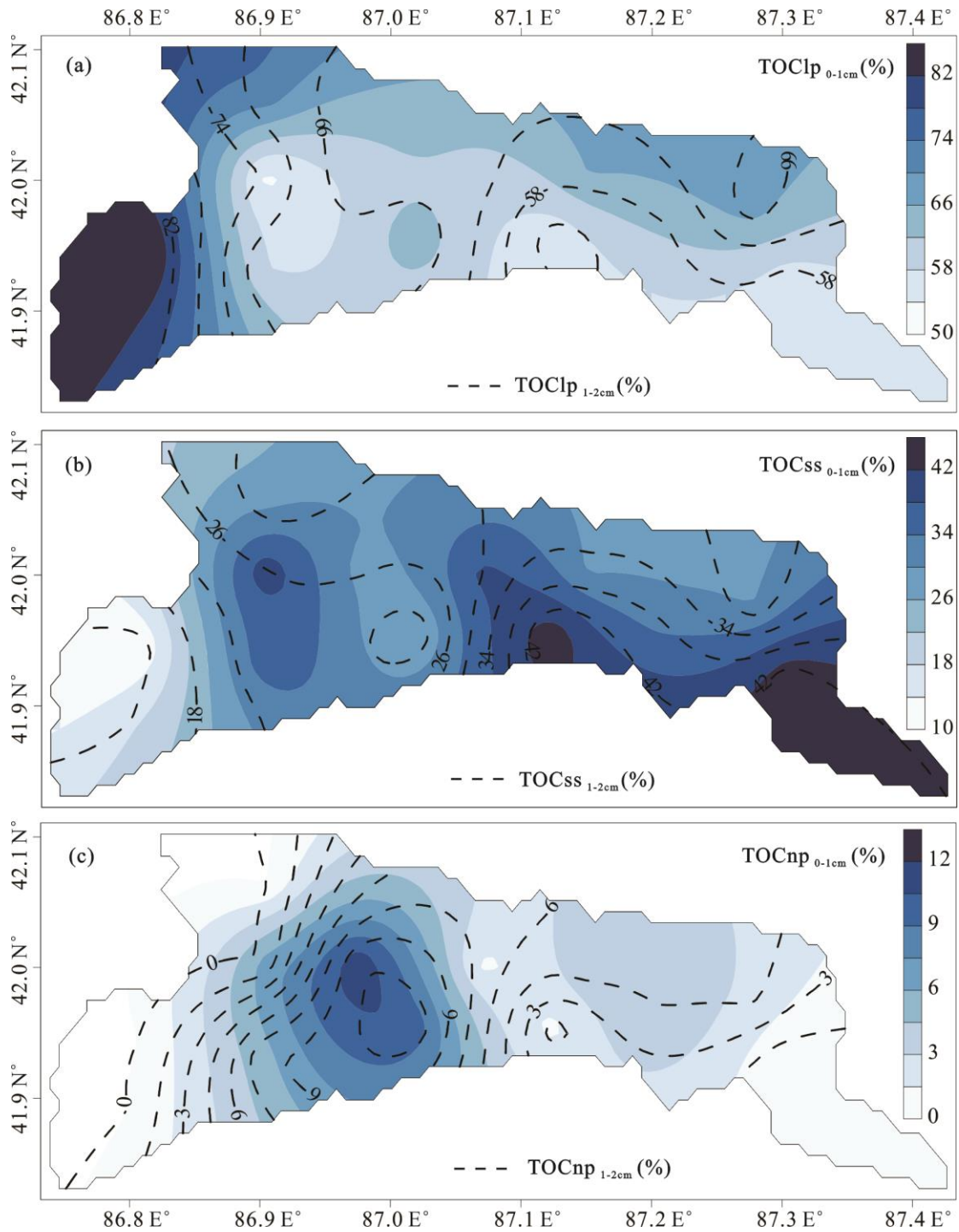
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3 Figure 4. Spatial distribution of (a) C:N ratio and (b) carbon stable isotope ($\delta^{13}\text{C}_{\text{org}}$) of
4 TOC in the 0-1 cm (color map) and 1-2 cm (dashed lines).

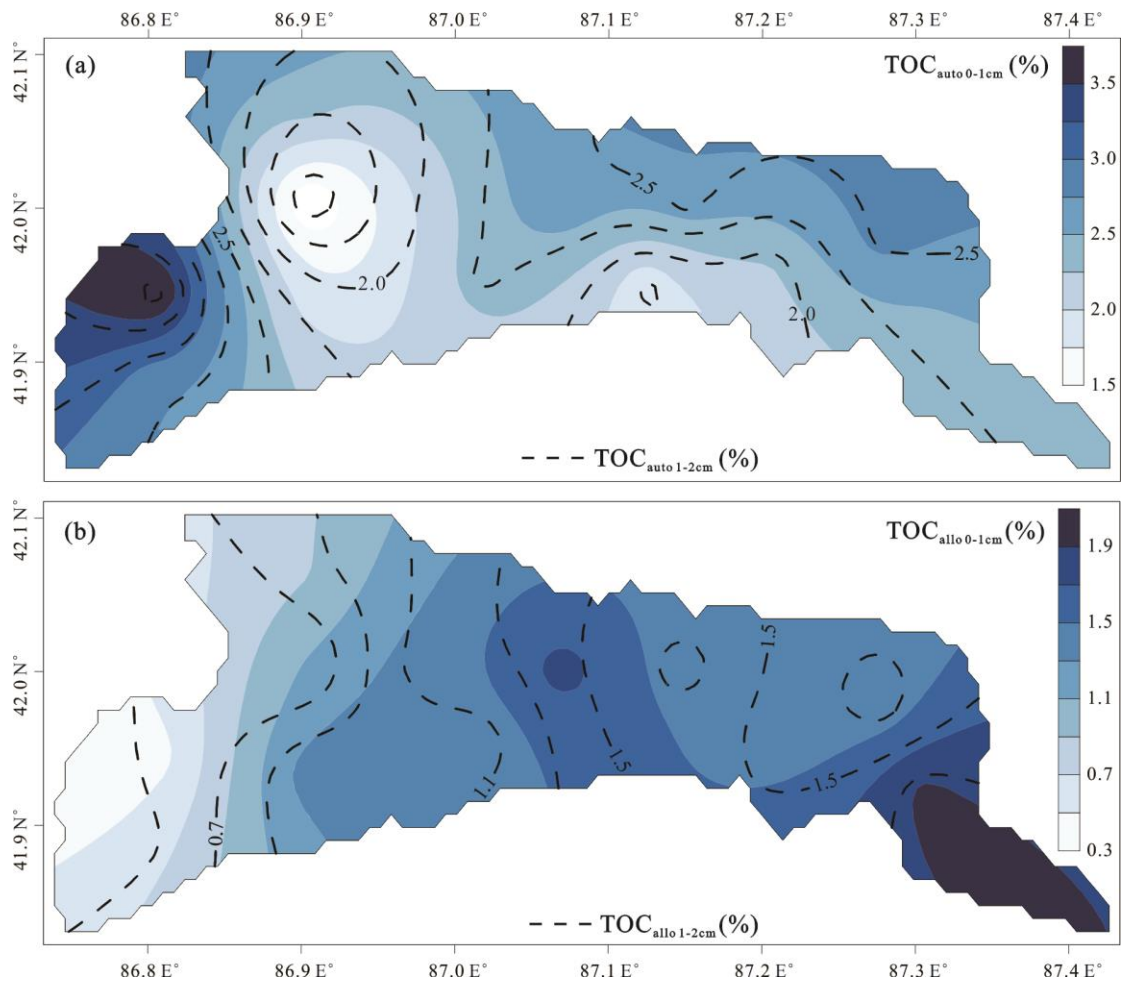
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3 Figure 5. Spatial patterns of the relative contributions for TOC in the 0-1cm (color
4 map) and 1-2 cm (dashed lines) sediments. (a) TOC from lake plankton (TOC_{lp}), (b)
5 TOC from surface soils (TOC_{ss}), and (c) TOC from native plants (TOC_{np}).

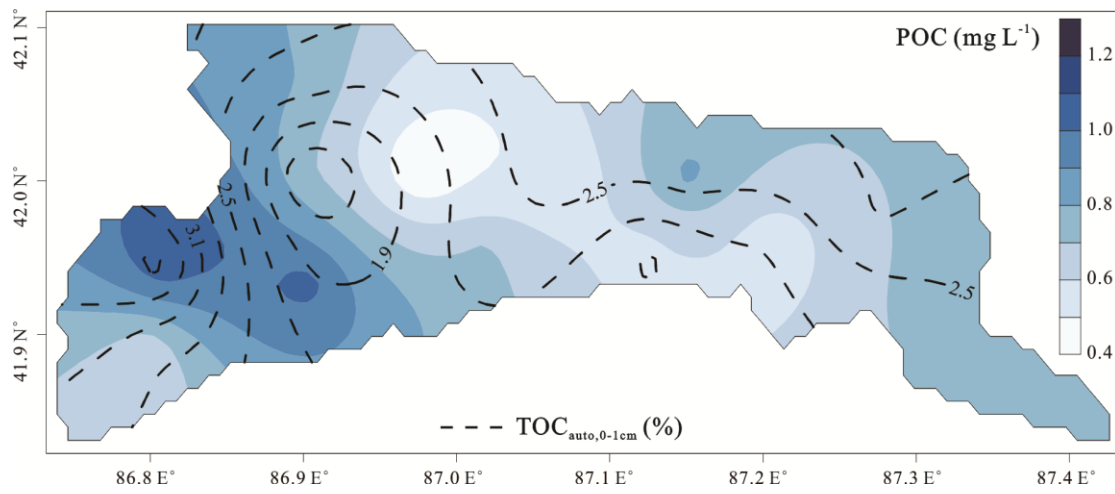
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3 Figure 6. Spatial distributions of (a) autochthonous TOC (TOC_{auto}) and
4 allochthonous sources TOC (TOC_{allo}) in the 0-1 cm (color map) and 1-2cm (dashed
5 lines) sediments.

1



2

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