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

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4 **Z. T. Yu**^{1,2,3}, **X. J. Wang**^{1,4,5}, **C. Y. Zhao**¹, **E. L. Zhang**⁶, and **H. Y. Lan**²

5 ¹State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and
6 Geography, Chinese Academy of Sciences, 830011 Urumqi, China

7 ²College of Resources and Environmental Sciences, Xinjiang University, 830046
8 Urumqi, China

9 ³University of Chinese Academy of Sciences, 100049 Beijing, China

10 ⁴College of Global Change and Earth System Science, Beijing Normal University,
11 Xijiekouwai Street No.19, Haidian District, Beijing 100875, China

12 ⁵Earth System Science Interdisciplinary Center, University of Maryland, College Park,
13 20740 MD, USA

14 ⁶State Key Laboratory of Lake Science and Environment, Nanjing Institute of
15 Geography and Limnology, Chinese Academy of Sciences, 210008 Nanjing, China

16 Correspondence to: X. J. Wang (wwang@essic.umd.edu)

17
18 **Abstract**

19 Lake sediment is an important carbon reservoir. However, little is known on the
20 dynamics and sources of sediment organic carbon in the Bosten Lake. We collected
21 13 surface (0-2cm) sediment samples in the Bosten Lake and analyzed total organic
22 carbon (TOC), total nitrogen (TN), stable carbon isotopic composition in TOC
23 ($\delta^{13}\text{C}_{\text{org}}$) and grain size. We found a large spatial variability in TOC content (1.8-4.4%)
24 and $\delta^{13}\text{C}_{\text{org}}$ value (-26.77‰ to -23.98‰). Using a three end member mixing model
25 with measured TOC:TN ratio and $\delta^{13}\text{C}_{\text{org}}$, we estimated that 54-90% of TOC was
26 from autochthonous sources. Higher TOC content (>3.7%) was found in the east and

1 central-north sections and near the mouth of the Kaidu River, which was attributable
2 to allochthonous, autochthonous plus allochthonous, and autochthonous sources,
3 respectively. The lowest TOC content was found in the mid-west section, which might
4 be a result of high kinetic energy levels. Our study indicated that the spatial
5 distribution of sediment TOC in the Bosten Lake was influenced by multiple and
6 complex processes.

7

8 **1 Introduction**

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

18 There have been a number of studies from the North America (Dean and Gorham,
19 1998), West Europe (Bechtel and Schubert, 2009;Woszczyk et al., 2011), East Asia
20 (Khim et al., 2005;Wang et al., 2012) and other regions (Dunn et al., 2008), showing
21 large spatial variability in total organic carbon (TOC) of lake sediment. The
22 magnitude of TOC in surface sediment may depend on many factors, including
23 column water productivity, terrestrial inputs of organic materials, properties of
24 sediment, and rate of microbial activity (Burone et al., 2003;Gireeshkumar et al.,
25 2013). Among them, contributions of autochthonous and allochthonous sources have
26 direct impacts on the spatial distribution, which vary largely accross regions (Bechtel
27 and Schubert, 2009;Anderson et al., 2009), partly due to differences in lake
28 productivity and morphology (Barnes and Barnes, 1978). In general, lakes with high
29 productivity have more autochthonous TOC, but lakes with low productivity mainly

1 allochthonous TOC (Dean and Gorham, 1998). There is evidence of littoral sources of
2 TOC in small and shallow lakes, but autochthonous sources, derived from planktonic
3 organisms, in larger and deeper lakes, especially fjord lakes (Shanahan et al.,
4 2013;Sifeddine et al., 2011;Barnes and Barnes, 1978).

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

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

1 sediment, and to quantify the contributions of various sources to the sediment TOC in
2 the Bosten Lake.

3

4 **2 Materials and Methods**

5 **2.1 Site description**

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

22 **2.2 Field sampling and analyses**

23 For the present study, a Kajak gravity corer was used to collect surface sediments
24 from 13 sites in the main section of the Bosten Lake in August 2012 (Figure 1). The
25 sampling sites covered most parts of the lake, with water depths ranging from 3 m to
26 14 m. The sediment cores were carefully extruded and the top 2 cm sections were

1 sliced into 1-cm and placed in polyethylene bags that were kept on ice in a cooler
2 during transport and before analyses.

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

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

21 For the analyses of δ¹³C_{org}, approximately 0.2 g of the freeze-dried sediment sample
22 was pretreated with 5-10 ml 2M HCl for 24 h at room temperature to remove
23 carbonate, and then rinsed to a pH of approximately 7 with deionized water and dried
24 at 40-50 °C (Liu et al., 2013). The pre-treated samples were combusted in a Thermo
25 elemental analyzer integrated with an isotope ratio mass spectrometer (Delta Plus XP,
26 Thermo Finnigan MAT, Germany). Isotopic data were reported in delta notation
27 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_i) of three sources (i.e., soil, ~~high~~terrestrial plant and lake plankton, denoted by 1, 2 and 3, respectively):

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

(1)

$$r = f_1r_1 + f_2r_2 + f_3r_3 \quad r = f_1r_1 + f_2r_2 + f_3r_3$$

(2)

$$1 = f_1 + f_2 + f_3 \quad 1 = f_1 + f_2 + f_3$$

(3)

where δ and r were $\delta^{13}\text{C}_{\text{org}}$ 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~~terrestrial plant's contribution. Based on ~~our~~ recent ~~study~~studies conducted in the Yanqi Basin (Wang et al., 2015; Zhang, 2013), ~~average~~C:N ratio was 22.1 \pm 9.9 and 10 \pm 1.8, and ~~mean~~ $\delta^{13}\text{C}_{\text{org}}$ value was -26.4 \pm 1.2‰ and -23.6 \pm 1.3‰ for the native plants and surface soils around the lake, respectively. We used ~~these~~the values as the end-members for the mixing model.

We measured POC, particulate organic nitrogen (PON) and $\delta^{13}\text{C}_{\text{org}}$ in POC in the water column of the Bosten Lake (Wang et al., 2014). Lake ~~average~~POC and PON increased from 0.61 \pm 0.04 mg C L⁻¹ and 0.072 \pm 0.005 mg N L⁻¹ in spring to 0.70 \pm 0.16 mg C L⁻¹ and 0.088 \pm 0.02 mg N L⁻¹ in summer, and $\delta^{13}\text{C}_{\text{org}}$ value in POC was -22.9 \pm 2.56‰ in spring and -23.5 \pm 0.38‰ in summer. It is reasonable to assume that the seasonal changes were resulted from the production of lake plankton. Accordingly,

1 we estimated that lake plankton (including phytoplankton and zooplankton) would
2 have a C:N ratio of 5.3 and $\delta^{13}\text{C}_{\text{org}}$ value of -27.7‰, and used these values as the
3 end-members for the mixing model.

4 **2.4 Statistical methods and mapping**

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

9 **3 Results**

10 **3.1 Physical characteristics**

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

21 **3.2 Spatial distribution of TOC, TN, C:N and $\delta^{13}\text{C}_{\text{org}}$**

22 Concentration of TOC was highly variable, with higher values (4.3-4.4%) found in the
23 northern and eastern sections of the lake (Figure 3a). There was also high
24 concentration of TOC (4.1-4.2%) near the mouth of the Kaidu River (southwest). On
25 the other hand, lower TOC concentration (1.8-2.4%) was observed in the mid-west
26 section. Similarly, TN concentration (ranging from 0.28% to 0.68%) was lowest

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

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

12 **3.3 Contributions of different sources**

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

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

28

1 4 Discussion

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

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

27 Our study demonstrated large spatial variability in the TOC of the surface sediment in
28 the Bosten Lake, with higher values in the central north and east sections and near the
29 mouth of the Kaidu River, but lower values in the west section and mid-south section

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

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

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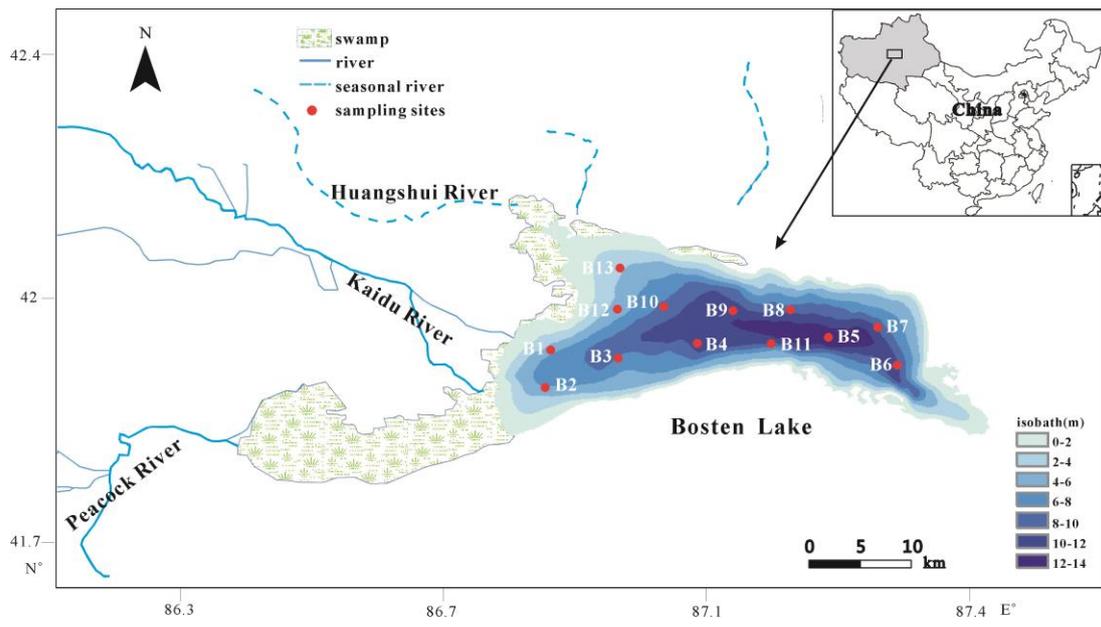
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1 Table 1. Correlation coefficient (r) between various variables for the sediments.

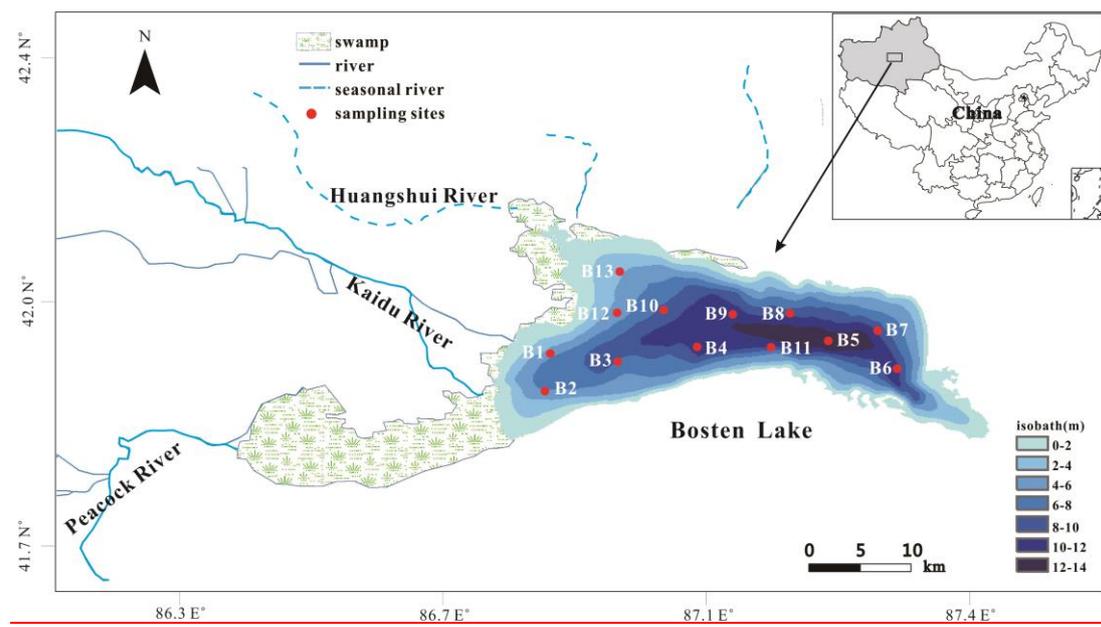
Variables	WD	DBD	d(0.5)	Clay	Silt	Sand	TOC	$\delta^{13}\text{C}_{\text{org}}$
TOC	0.50	-0.58 ^a	-0.71 ^b	0.18	0.77 ^b	-0.76 ^b		-0.15
TN	0.07	-0.83 ^b	-0.60 ^a	-0.05	0.79 ^b	-0.72 ^b	0.71 ^b	0.45
C:N	0.50	0.50	0.01	0.25	-0.19	0.11	0.14	-0.82 ^b
$\delta^{13}\text{C}_{\text{org}}$	-0.66 ^a	-0.46	-0.13	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 (~~m~~), DBD = dry bulk density (~~g cm⁻³~~), d(0.5) = median diameter=
3 (~~μm~~) and clay, silt and sand fractions (%) from the 0-2 cm sediments. Significance of
4 Pearson correlation is marked with ^a (p<0.05) and ^b (p<0.01) asterisks.



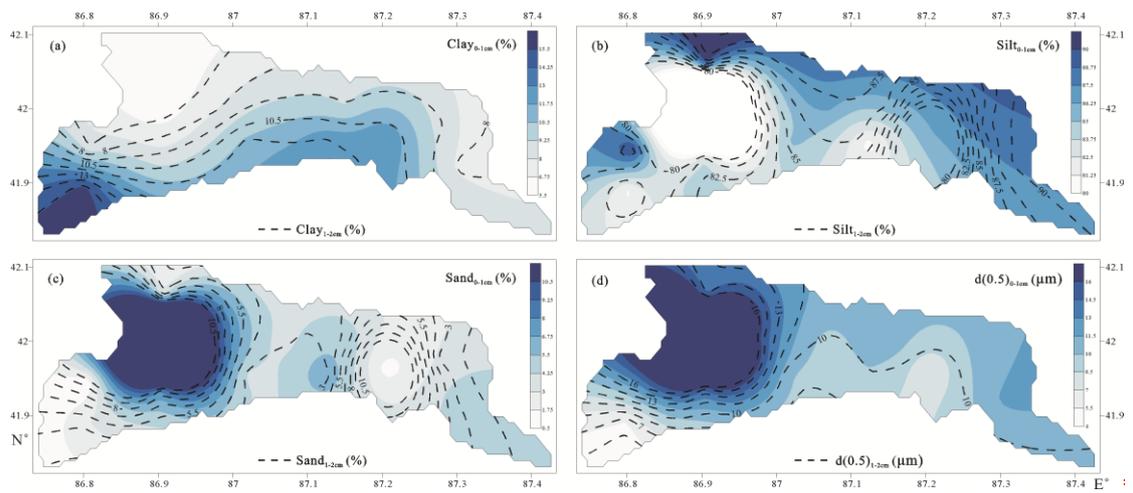
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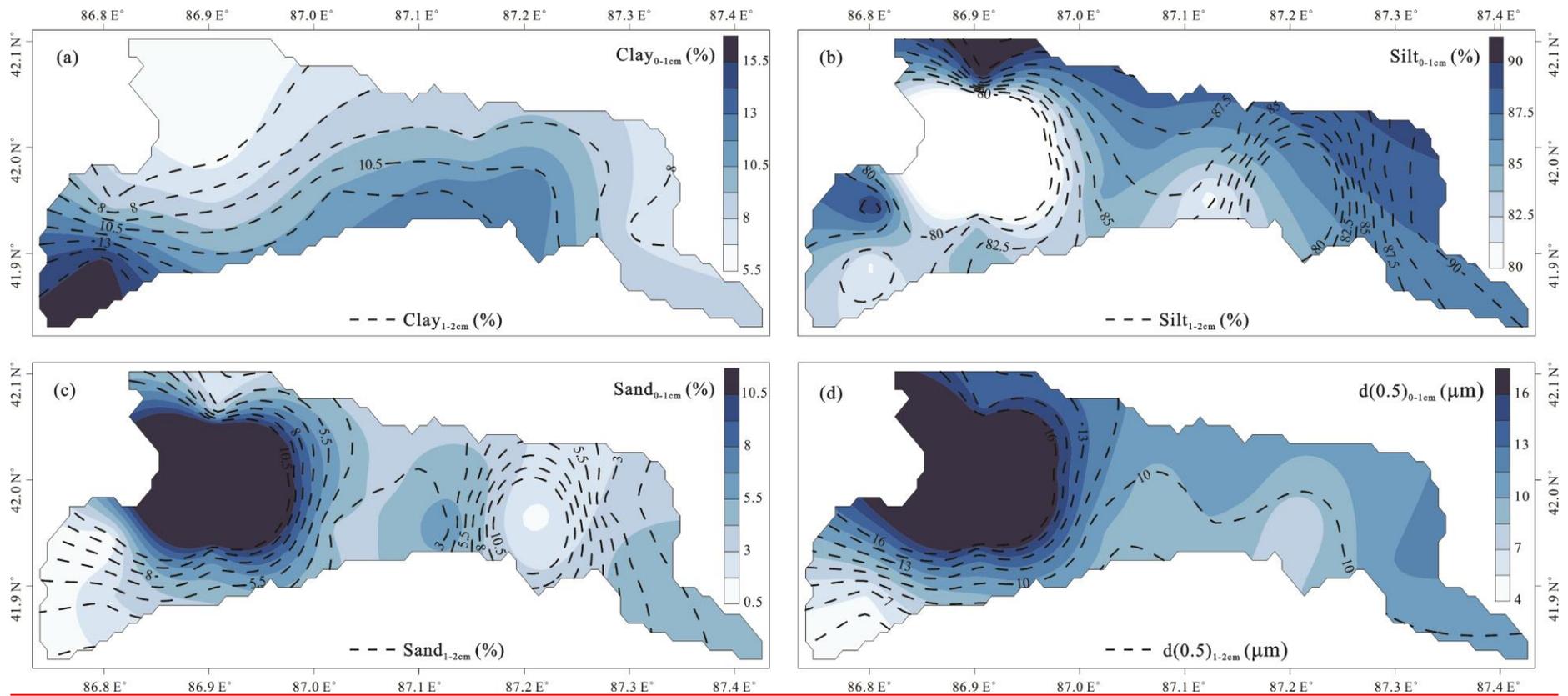
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4 Figure 1. Map of the Bosten Lake with the water depth and the 13 sampling stations
 5 (red dots). Bathymetric was measured in 2008 by Wu et al. (2013) and bathymetric
 6 contours were plotted by using software ArcGIS 9.3 and Corel DRAW X3.



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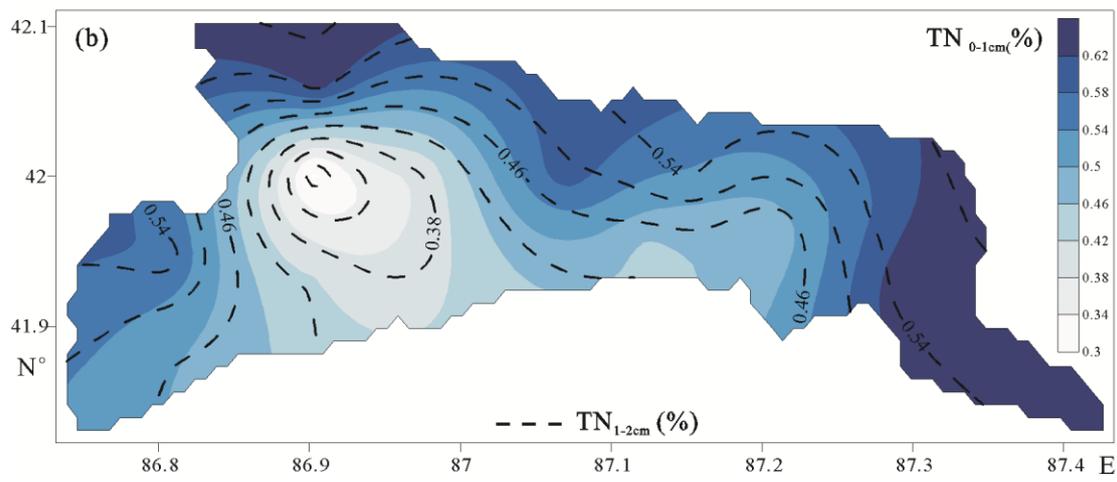
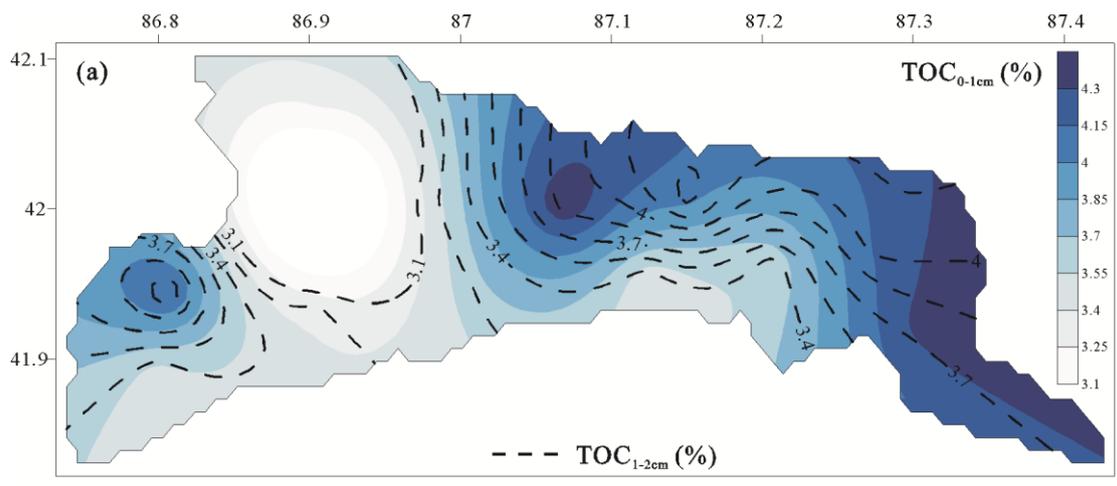


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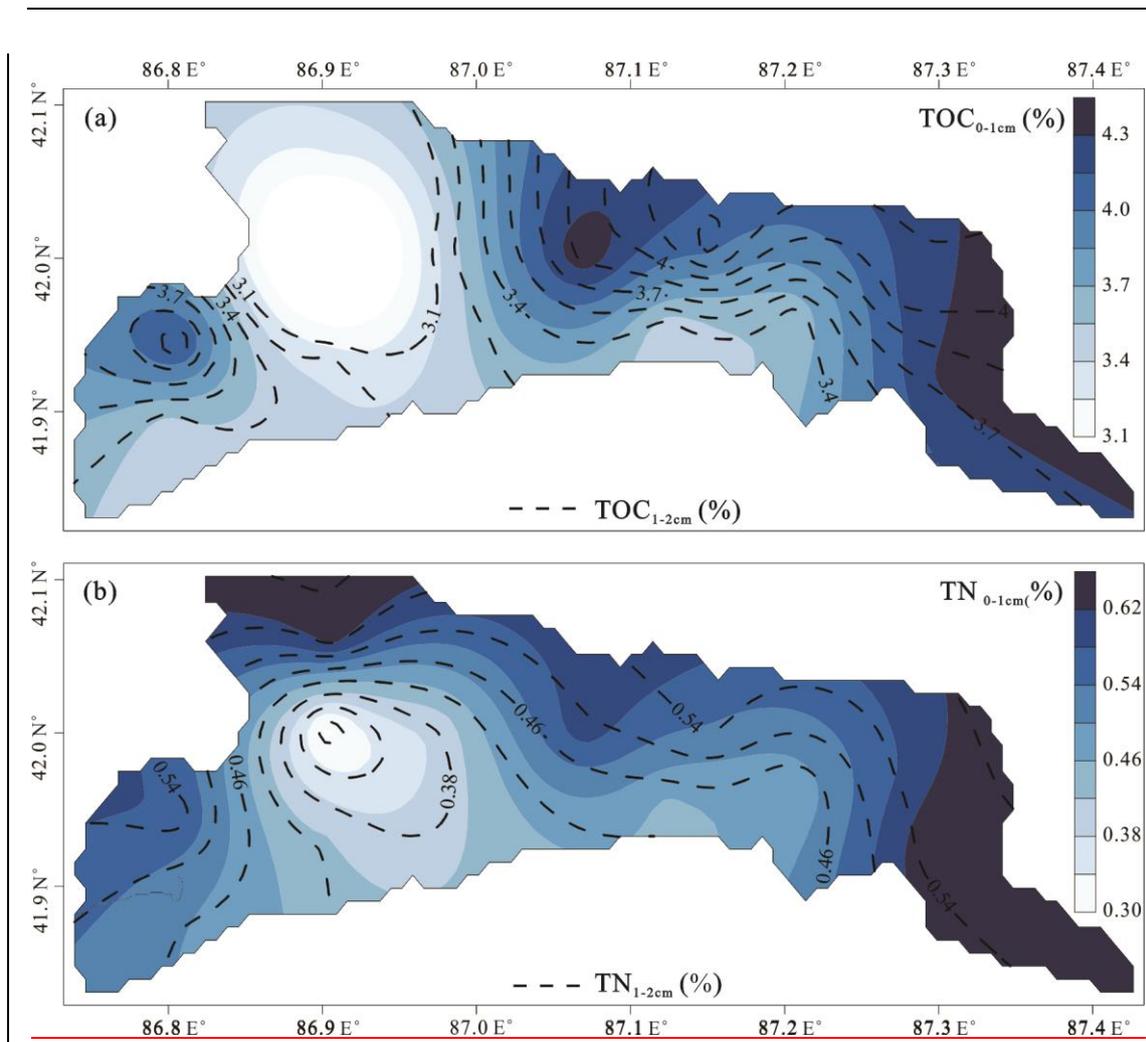
3 Figure 2. Distributions of (a) clay, (b) silt, (c) sand and (d) the median diameter ($d(0.5)$, μm) in the 0-1 cm (color map) and 1-2 cm (dashed lines).

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

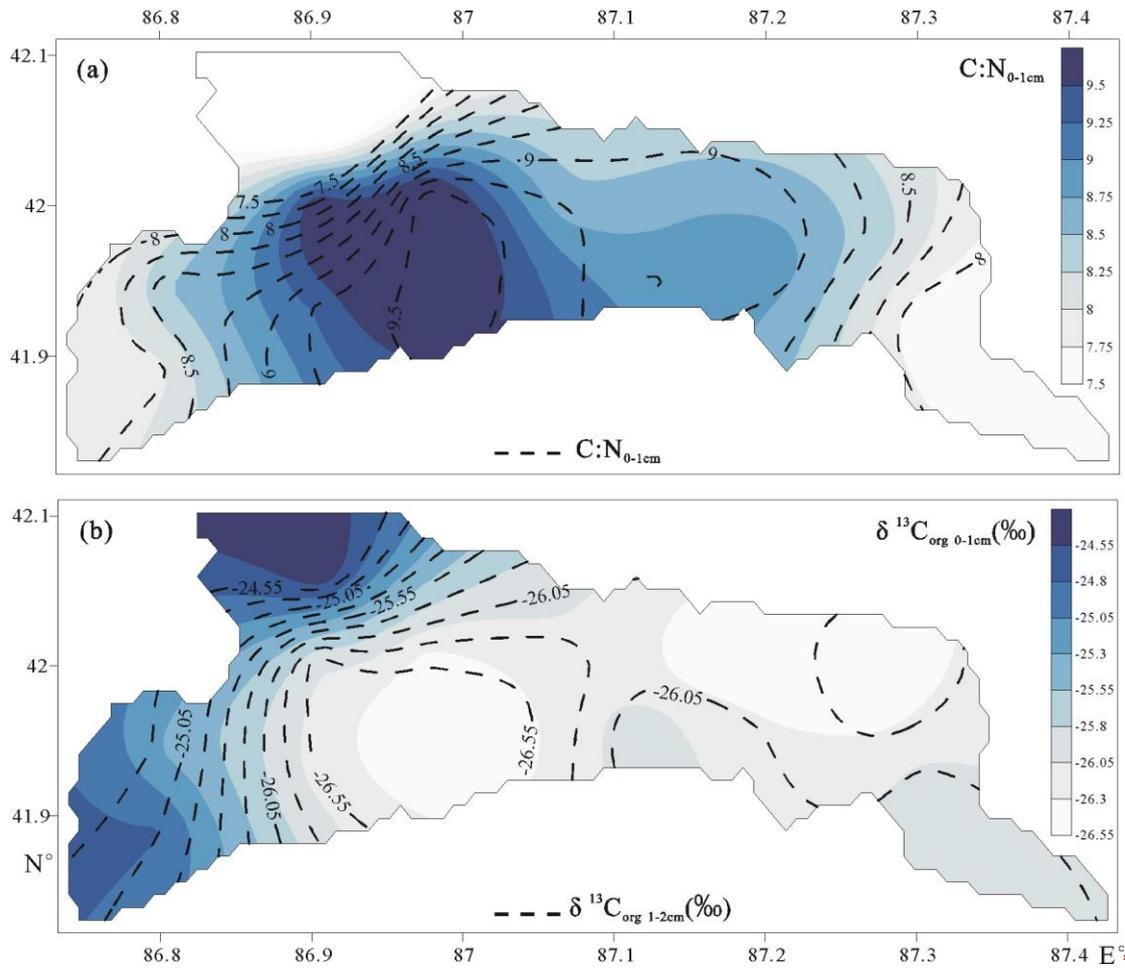
5 made using the Kriging method of gridding.



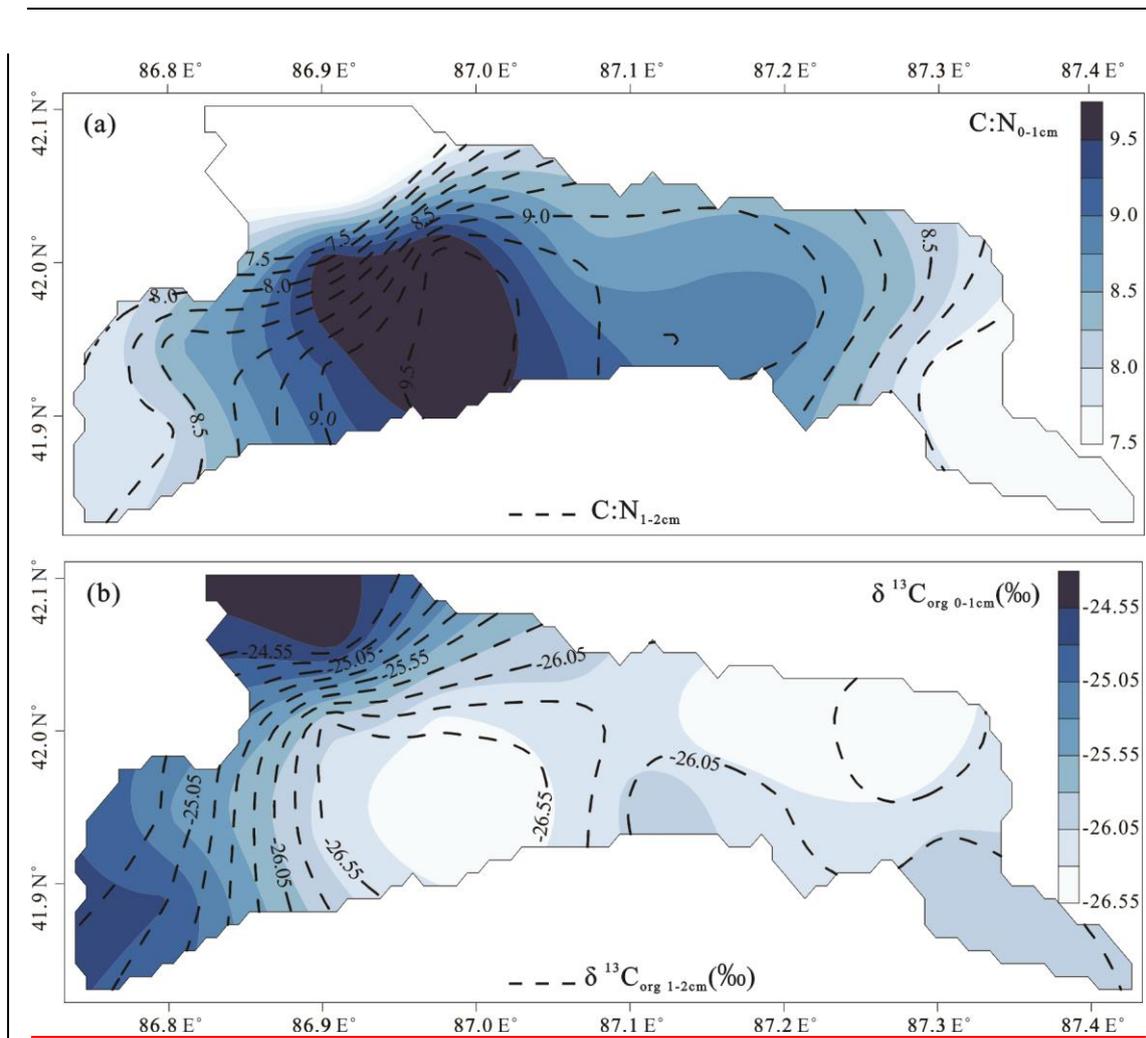
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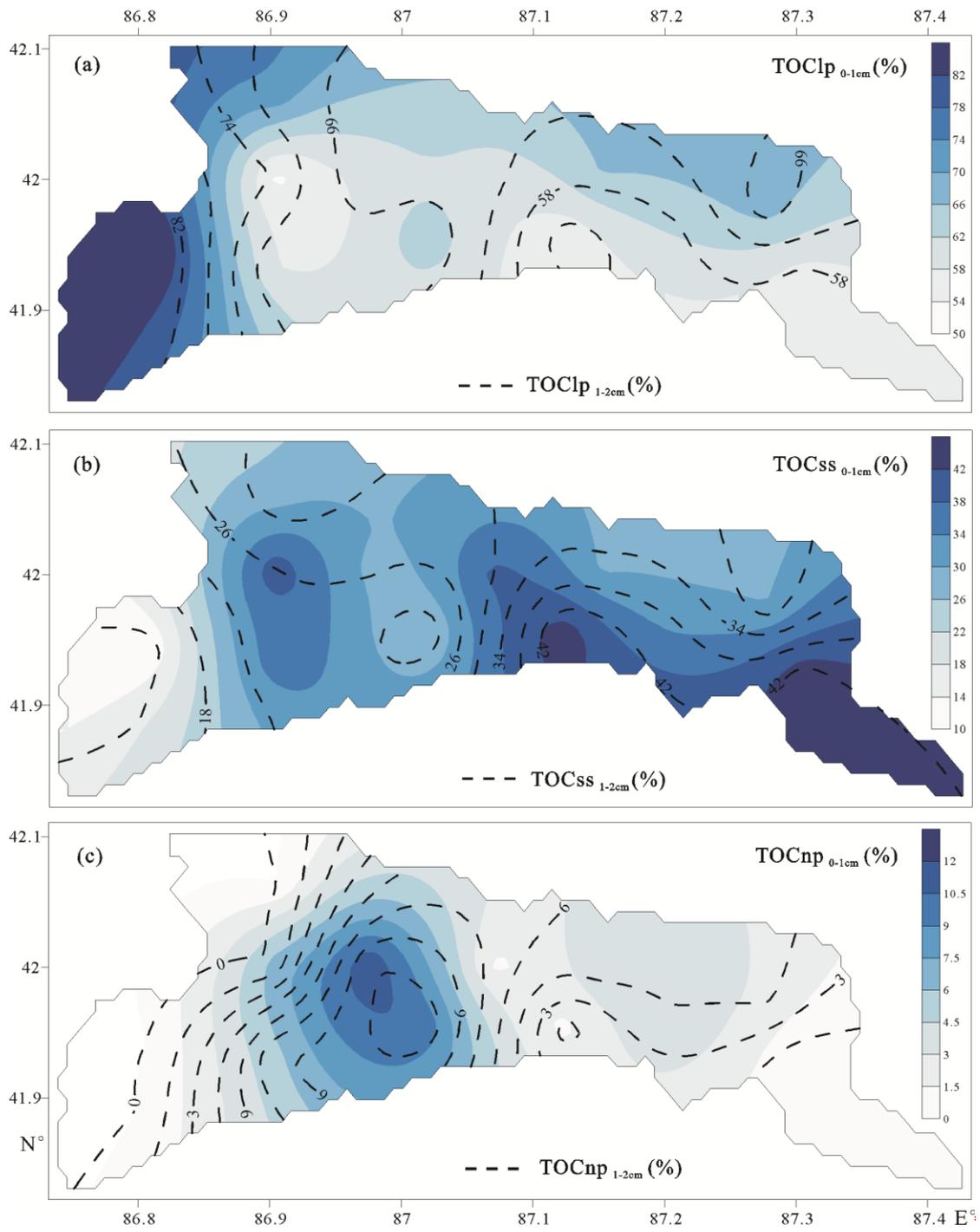
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 2 Figure 3. Spatial distributions of (a) total organic carbon (TOC) and (b) total nitrogen
 3 (TN) in the 0-1 cm (color map) and 1-2 cm (dashed lines).



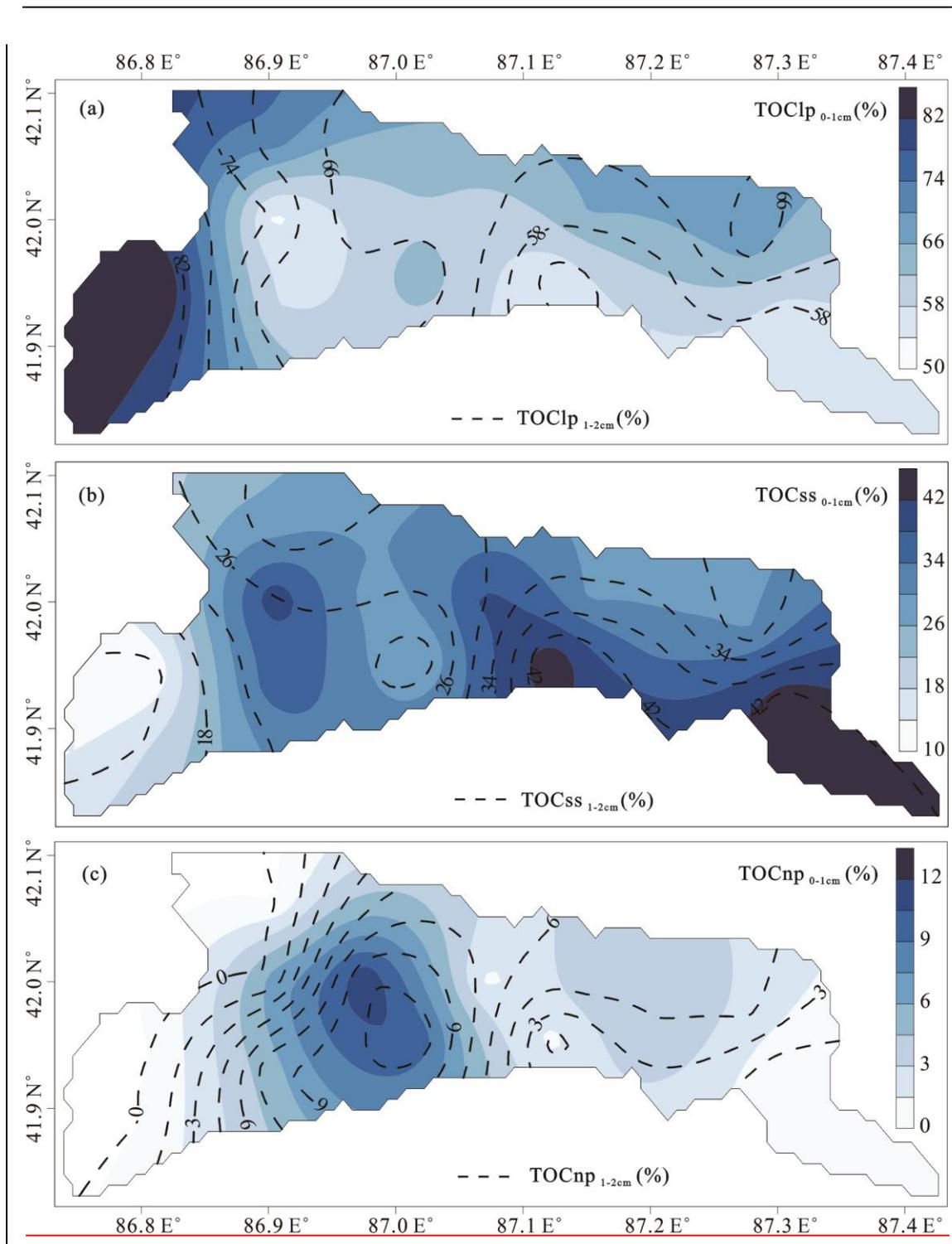
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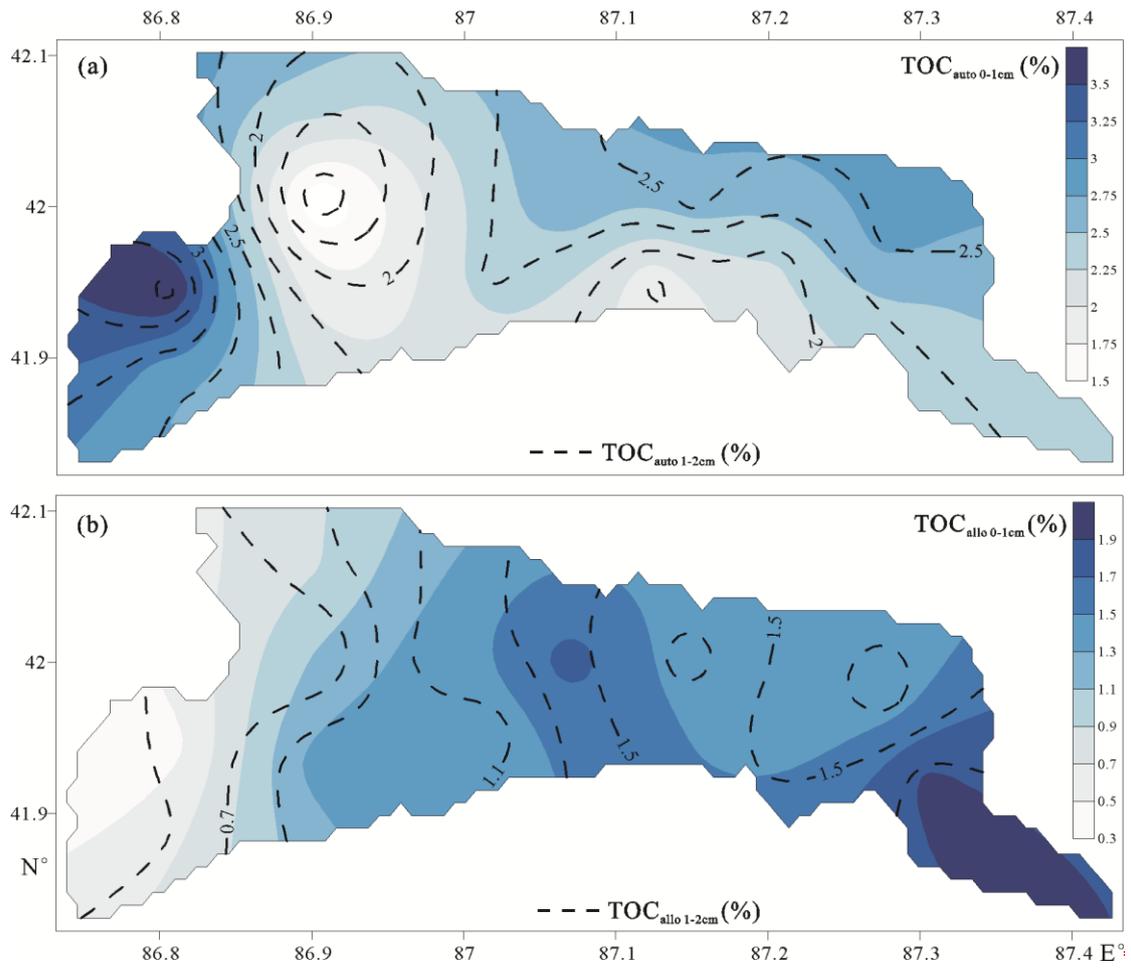
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 2 Figure 4. Spatial distribution of (a) C:N ratio and (b) carbon stable isotope ($\delta^{13}\text{C}_{\text{org}}$) of
 3 TOC in the 0-1 cm (color map) and 1-2 cm (dashed lines).



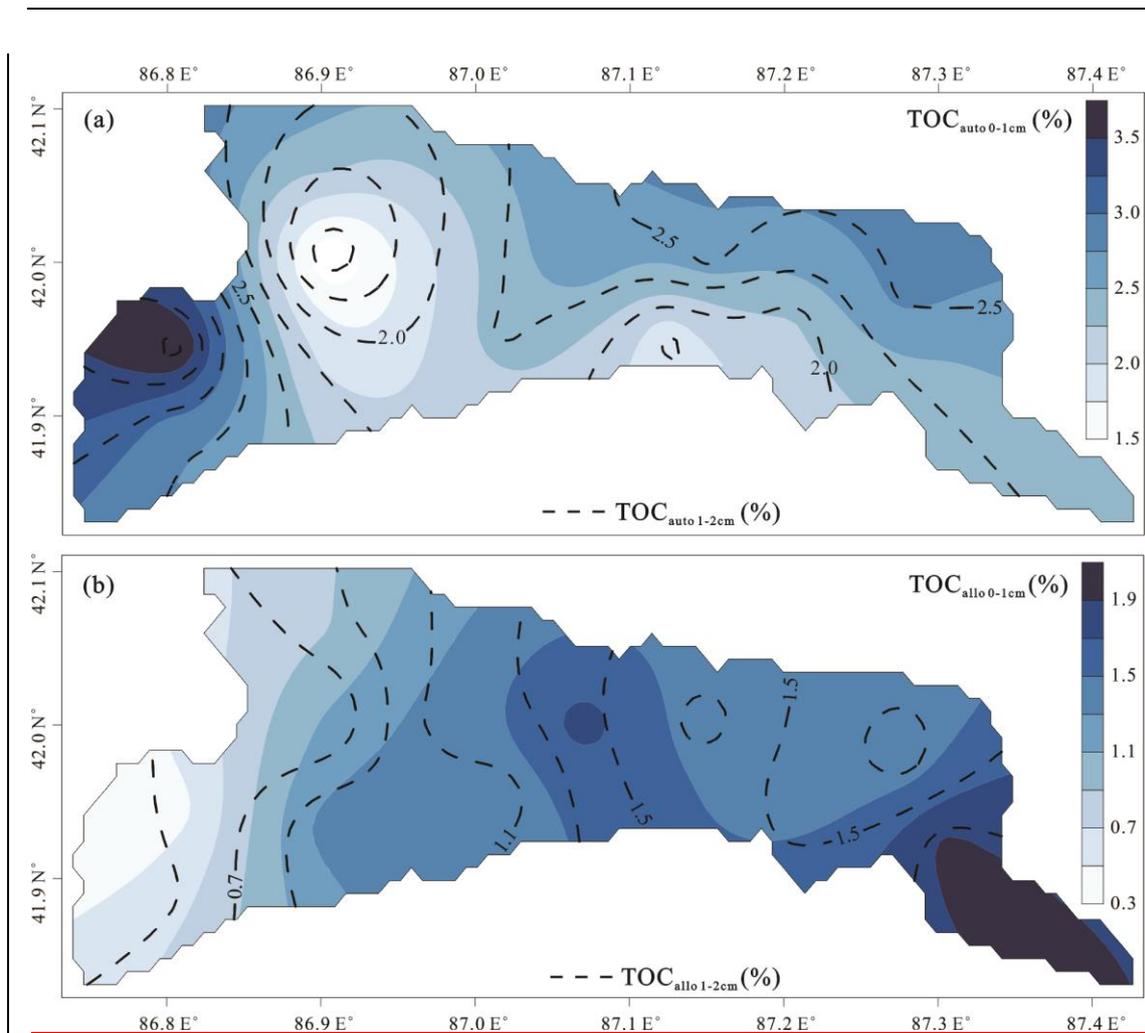
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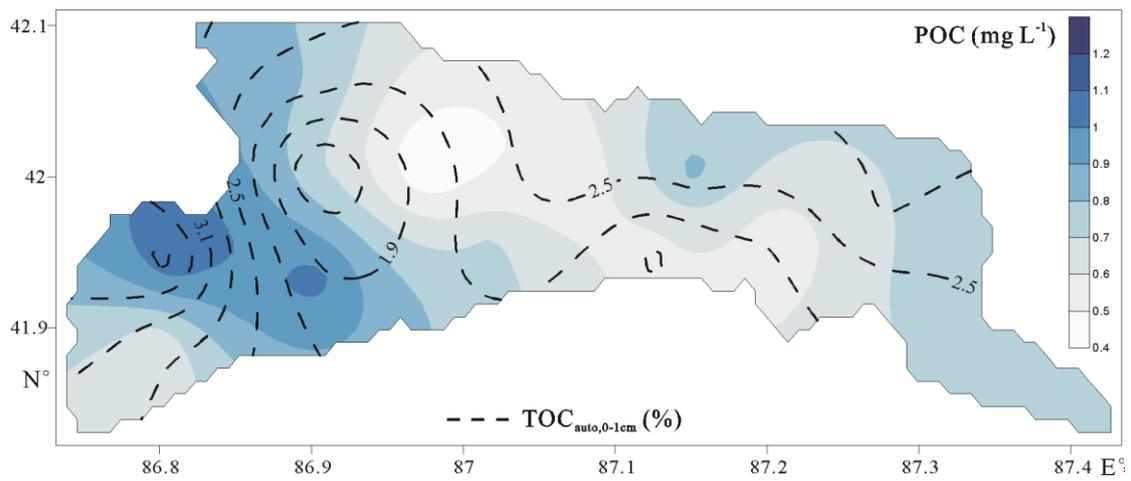
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 2 Figure 5. Spatial patterns of the relative contributions for TOC in the 0-1cm (color
 3 map) and 1-2 cm (dashed lines) sediments. (a) TOC from lake plankton (TOC_{lp}), (b)
 4 TOC from surface soils (TOC_{ss}), and (c) TOC from native plants (TOC_{np}).



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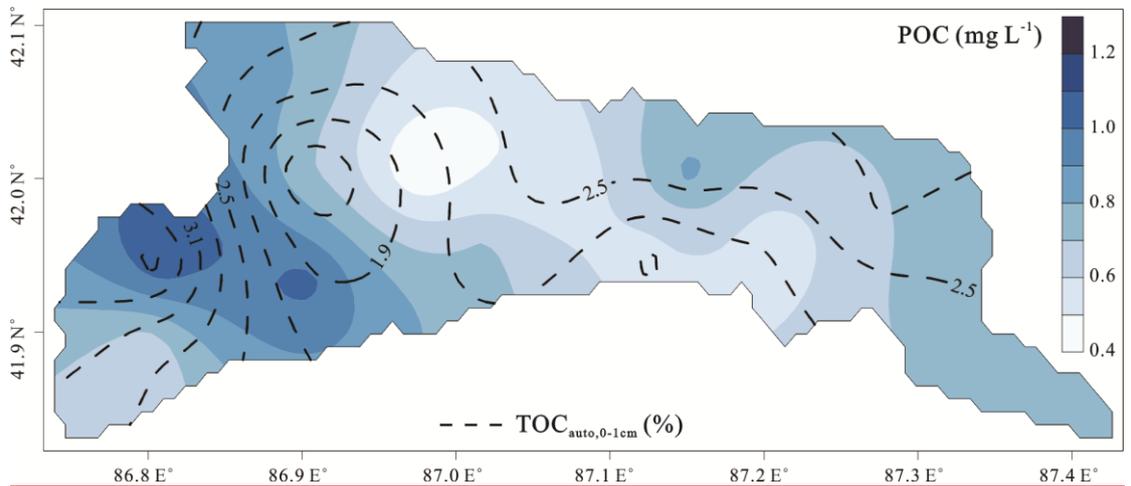
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 2 Figure 6. Spatial distributions of (a) autochthonous TOC (TOC_{auto}) and (b)
 3 allochthonous sources TOC (TOC_{allo}) in the 0-1 cm (color map) and 1-2cm (dashed
 4 lines) sediments.



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