Article

Sediment Organic Carbon Sequestration of Balkhash Lake in Central Asia

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Abstract: As an important part of the global carbon pool, lake carbon is of great significance in the global carbon cycle. Based on a study of the sedimentary proxies of Balkhash Lake, Central Asia's largest lake, changes in the organic carbon sequestration in the lake sediments and their possible influence over the past 150 years were studied. The results suggested that the organic carbon in the sediments of Lake Balkhash comes mainly from aquatic plants. The organic carbon burial rate fluctuated from 8.16 to 30.04 g·m⁻²·a⁻¹ and the minimum appeared at the top of the core. The organic carbon burial rate continues to decline as it has over the past 150 years. Global warming, higher hydrodynamic force, and low terrestrial input have not been conducive to the improvement of organic carbon sequestration in Balkhash Lake; the construction of a large reservoir had a greater impact on the sedimentary proxy of total organic carbon content, which could lead to a large deviation for environmental reconstruction. This is the first study to assess the sediment organic carbon sequestration using the modern sediments of Central Asia's largest lake, which is of great scientific significance. The results contribute to an understanding of organic carbon sequestration in Central Asia and may provide a scientific basis for carbon balance assessment in regional and global scales.

Keywords: organic carbon sequestration; climate change; human activities; environmental change; lacustrine sediments; Balkhash Lake; Central Asia

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1. Introduction

Over the past century, surface processes in Central Asia have been significantly affected by global warming and human activities [1–4]. The changes in lakes and the ecological and environmental effects caused by climate fluctuations and human activities have had a profound impact on regional economic development [5–7]. Additionally, it is of great practical significance to study the ecological and environmental problems in Balkhash Lake caused by the combined influences of anthropogenic factors and climate change. With the increasing prominence of various climate and environmental issues, such as greenhouse gases and the greenhouse effect, and the objective need for carbon source and carbon sink evaluation in international climate negotiations, the issue of the carbon cycle has received increasing attention from the public [8–10]. Although lake water occupies a small surface area of the Earth, more and more studies have shown that lakes are a carbon sink with a disproportionate effect on the global carbon cycle [11–13], and the lake carbon storage plays an important role in mitigating climate change [14]. There are many lakes in Central Asia, but the research on lake sediments in Central Asia has mainly

focused on the evolution and reconstruction of the climate environment [15–18]. Sediment organic carbon is an important global carbon sink; however, an in-depth understanding of the influences of climate change and anthropogenic factors on sediment organic carbon sequestration is still lacking, making this region one of the most uncertain regions in the assessment of the global carbon balance.

Balkhash Lake, Central Asia's largest lake and the tail of the Ili River, and its issue have attracted worldwide attention [19–21]. As the main means of surface material movement in a watershed, lake sediments carry information about watershed climate and environmental changes [22], and this information can provide a reliable way of assessing environmental evolution over a long time scale [19,23–26]. Sugai [23] analyzed the multi-environmental proxy indicators of core sediments in Balkhash Lake and concluded that the core sediments were deposited during the early Holocene. Based on the diatom combinations in the sediments, Endo et al. [24] and Chiba et al. [25] reconstructed lake water levels and pH changes in Balkhash Lake over the past 8000 and 2000 years, respectively; furthermore, Feng et al. [26] used the pollen–climate response to quantitatively reconstruct the climate change history of the Balkhash Lake basin over the past 2500 years. Mischeke et al. [19] used ostracod species assemblages and shell chemistry to estimate the lake level and lower salinity over the last 2900 years. Although there is still a lack of understanding of the dynamic changes in carbon burial in Balkhash Lake, studies have found that arid regions may have great potential for carbon sequestration and carbon storage [18,19]. In particular, the responses of organic carbon sequestration to climate change are still unclear in Central Asia. In the context of global warming, does the rate of carbon burial in lake sediments increase or decrease? Existing studies on the sediments of Small Aral Sea show that the organic carbon burial rate is increasing significantly [27]. The water area of Balkhash Lake is significantly larger than the Small Aral Sea, is there a similar change in Balkhash Lake?

Focused on the burial pattern of organic carbon in modern sediments of Lake Balkhash, the largest lake in Central Asia, and its possible influencing factors, this paper examines the core sediments of Balkhash Lake as the main research object and discusses (1) the organic carbon burial information contained in the sediments of Balkhash Lake over the past about 150 years, (2) temporal variation of organic carbon sequestration and its relationship to environmental and main climatic factors. This research will provide the beneficial complement for a thorough understanding of organic carbon sequestration in Central Asia and will offer scientific data for carbon balance assessment in regional and global scales.

2. Regional Setting

Balkhash Lake is in southeastern Kazakhstan, and the length of the lake is approximately 614 km from east to west (Figure 1). The average width from north to south is approximately 30 km, the maximum width is approximately 74 km, and the water area is approximately 18,200 km² [21]. The average annual water level of the lake is approximately 342 m above sea level, the maximum water depth is 26.5 m, the average depth is 5.8 m, and the water storage volume is 105.4 km³ [28]. The Uzynaral Strait (approximately 3.5 km) north of the Saryesik Peninsula divides Balkhash Lake into two parts: the eastern part and the western part. The eastern lake is infused by the Aksu, Karatal, Lepsy, and Ayaguz Rivers. The eastern part of Balkhash Lake is approximately 318 km long and has an average width of 24 km, a maximum width of 47.5 km, a surface area of 7580 km², an average depth of 7.6 m, a maximum depth of 26.5 m, and a water volume of 57.6 km³ [28]; furthermore, the salinity is approximately 4.6–5.8 g L^{−1} [29]. The western lake is 296 km long and has an average width of 36 km, a maximum width of 70 km, an average water depth of 4.6 m, a maximum water depth of 11 m, a surface area of 10,630 km², and a water volume of 47.8 km³ [28]; furthermore, the salinity is 0.5–1.0 g L^{−1} [29]. The Ili River accounts for approximately 78% of the total inflow into Balkhash Lake [30].

Figure 1. The location of Balkhash Lake (a), core sampling point in Balkhash Lake (b), and the changes in the Balkhash Lake water level (c).

The area of the Balkhash Lake watershed is approximately $41.3 \times 10^4 \text{ km}^2$ [21], and it has sufficient light and heat resources, large temperature changes, strong evaporation, and low precipitation. The mean annual temperature of the Balkhash region is approximately 5.8°C , the total annual precipitation is 142 mm, the total annual evapotranspiration is 668 mm, the continentality index is 39.5, and the aridity index is 4.7 [21]. The estuary delta formed by the Ili River is approximately 8000 km^2 [31]. The agricultural land in the river basin decreased from $1.8 \times 10^6 \text{ ha}$ in the 1970s to $1.4 \times 10^6 \text{ ha}$ in 2013 [32]. Basin water resources are mainly used for irrigation, rice crops, industry, and water supply in residential areas and fisheries [28]. The proportion of water used for irrigation of agricultural land in the basin is also the largest among all water uses, exceeding 82% of the total water consumption [33].

Water level observations for Balkhash Lake began in 1938, and the previous water-level data from 1880 to 1937 were verified and calculated by former Soviet Union experts based on water balance, field investigation, and literature reports [25,34]. The water level of Balkhash Lake had an obvious periodic variation classified as “three dry and three abundant” [35]. The first low water level event occurred in 1884 and was the lowest on record, at 340.53 m above sea level. The second low water level event reached 340.69 m above sea level in 1946, and the water level then increased until 1953. The third low water level process occurred in 1987, and the lowest water level was 340.65 m. In contrast, the first

flood period occurred at the beginning of the 20th century, the second occurred in the 1960s and 1970s, and the most recent occurred in the 21st century.

3. Materials and Methods

3.1. Sampling and Laboratory Analysis

A gravity core sampler (Uwitec, Mondsee, Austria) was used to extract a 49 cm long sediment core (Figure 1), sliced at 1 cm intervals in situ [36]. The depth-age mode for the core sediment was based on a previously published article [36]. In this study, three measures of magnetic susceptibility were taken from each sample, and the average value was reported. The measurement error was <0.3%. Grain size was determined with a Malvern Mastersizer 2000 analyzer, which automatically determined the median diameter with a measurement precision of <1%. Detailed experimental procedures have been described in the literature [37,38]. The determination of TOC and total nitrogen (TN) was performed using a CE-440 elemental analyzer (EAI Company, Vienna, VA, USA), and the analytical error was below 5% [27,39]. $\delta^{13}\text{C}$ values were analyzed using a Finnigan-MAT 251 isotope ratio mass spectrometer [39]. Carbon isotope ratios are expressed in per mil (‰) relative to Vienna Pee Dee belemnite (V-PDB). The analytical precision for $\delta^{13}\text{C}$ of organic matter was 0.05‰. The calculation method for the organic carbon burial rate (OCBR) was based on the reference [27].

3.2. Statistical Methods

The statistical approach of Pearson correlation was used to evaluate whether there is linear statistical evidence between two variables, and the descriptive statistical analysis was used to present the general characteristics of environmental proxies for the core sediments of Balkhash Lake. The statistical methods were conducted by OriginPro 2022 (64-bit) Beta2 (Learning edition).

4. Results

4.1. Descriptive Statistics of Experimental Results

Table 1 presents the results for the physical and chemical environment indicators obtained from the BLK01 core sediments of Balkhash Lake. The average value for TOC was 1.40%, with a maximum of 1.69% and a minimum of 1.13%. The average TN was 0.16%, with a maximum value of 0.21% and a minimum value of 0.13%. The molar ratio of carbon and nitrogen (C/N) in the sediments of Lake Balkhash ranged from 11.53 to 8.53. The organic carbon burial rate fluctuated from 8.16 to 30.04 $\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$. The literature on soil organic carbon density (0–30 cm) in Central Asia has been published [40]. In the north of Balkhash lakeshore, the soil organic carbon content falls between $15 \times 10^6 \text{ g}\cdot\text{ha}^{-1}$ and $30 \times 10^6 \text{ g}\cdot\text{ha}^{-1}$, and the south was below $15 \times 10^6 \text{ g}\cdot\text{ha}^{-1}$ [40]. However, it is not possible to directly compare the carbon burial rate. The carbon density of the sediments of Balkhash Lake (0–30 cm) in the study site was $2.71 \times 10^8 \text{ g}\cdot\text{ha}^{-1}$. It can be seen that the density of organic carbon in lake sediments is significantly higher than that in watershed soils. The results showed that the silty fraction (4–64 μm) in the BK01 core sediment fluctuates between 81.25 and 65.52%, with an average of 73.55%; the content range of the sandy fraction (>64 μm) is 0.61–18.04%, the average value is 6.13%; the clay fraction (<4 μm) content fluctuation range is 14.77–27.77%, the average value is 20.32%. From the perspective of the coefficient of variation, the coefficients of variation of silt, sand, and clay content are 5.7, 97.4, and 20.9%, respectively. The coefficient of variation of the sandy fraction is the largest, and that of silt is the smallest, reflecting the relatively stable variation of silt content (Table 1).

Table 1. Descriptive statistical analysis of environmental proxies of lake sediments in Lake Balkhash ($n = 49$). Stable carbon isotopes ($\delta^{13}\text{C}_{\text{org}}$, ‰), organic carbon burial rate (OCBR, $\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$), total organic carbon (TOC, %), molar ratio of carbon and nitrogen (C/N), total nitrogen (TN, %), and the grain-size fractions of clay ($<4\ \mu\text{m}$, %), silty ($4\text{--}64\ \mu\text{m}$, %) and sandy ($>64\ \mu\text{m}$, %).

Proxies	Mean	Standard Deviation	Standard Error	Minimum	Median	Maximum	Coefficient of Variation
$\delta^{13}\text{C}_{\text{org}}$	−25.43	0.21	0.03	−25.93	−25.47	−24.84	−0.8%
OCBR	20.50	6.47	0.92	8.16	18.42	30.04	31.6%
TOC	1.40	0.17	0.02	1.13	1.40	1.69	12.1%
TN	0.16	0.02	0.00	0.13	0.16	0.21	11.4%
C/N	10.06	0.76	0.11	8.54	9.85	11.53	7.6%
Clay Fraction	20.32	4.29	0.61	14.77	18.13	27.77	21.1%
Silty Fraction	73.55	4.26	0.61	65.52	73.77	81.25	5.8%
Sandy Fraction	6.13	6.03	0.86	0.61	2.33	18.04	98.4%

4.2. Sediment Texture

From visual observation, the sediments of Balkhash Lake are brown silt. From the perspective of lithological classification, above 24 cm is silt, 24–29 cm is silty clay, and 30–49 cm is silt. From the Shepard diagram [41,42], the sediments of Balkhash Lake fall mainly into clay silt, silt, and sandy silt. The Pejrup diagram [43] also reflects that Balkhash Lake is in a high/very high hydrodynamic environment (Figure 2). In the vertical distribution of sediments, 9–30 cm is the layer with higher clay content, with an average content of 24.7%. The sand content below 31 cm is significantly higher than the upper layer.

Figure 2. (a) Vertical variation of sediment grain-size contents and the lithology classification of Balkhash Lake; (b) Shepard diagram and (c) Pejrup diagram.

4.3. Physical and Chemical Environment Indicators

Figure 3 shows the strong fluctuation from 1870 to 1920. There was also a marked decrease during the 1920s. Figure 3 reveals that there has been a gradual increase since the 1970s. There was a marked similarity between TOC and TN, and they were significantly correlated ($r = 0.76$, $p < 0.001$). The $\delta^{13}\text{C}_{\text{org}}$ values varied from -24.84 to -25.93 ‰. The graph shows a steady increase from 1870 to 1920. From 1920 to 1940, the change in organic carbon isotopes showed an obvious V-shape, and the lowest value appeared in 1930. Starting in 1940, the organic carbon isotopic values decreased until 1980, and there has been a slight increase since 1980. The minimum value of molar ratio of carbon and nitrogen (C/N) in the sediments of Lake Balkhash appeared at the top of the core. From the perspective of the changes over the past 150 years, the OCBR continues to decline, and the minimum appears at the top of the core.

Figure 3. The sedimentary environmental proxies in BLK01 core sediments of Lake Balkhash. (a) stable carbon isotopes ($\delta^{13}\text{C}_{\text{org}}$), (b) organic carbon burial rate (OCBR), (c) total organic carbon (TOC), (d) molar ratio of carbon and nitrogen (C/N), and (e) total nitrogen (TN).

5. Discussion

The organic matter revealed the differences in the isotopic composition of organic matter and the ratio of carbon to nitrogen atoms from lake aquatic plants, C3 land plants, and C4 land plants [44]. Most of the C/N values in the modern core sediments of Lake Balkhash fluctuated around 10 and combined with the variation range of organic carbon isotopes, we concluded that the source of the organic matter in the sediments of Lake Balkhash is mainly lake aquatic plants. Unfortunately, the major sources of lake organic

matter in relation to lake aquatic plants as a whole, just based on the traditional method in lake sedimentology studies. A study of the species of plants and animals in the future would be of great value in improving the reliability of our results. The organic material sources of the shallow salt water lake, Ebinur Lake [45], are very different from the Balkhash Lake, which reflected those differences in lake water salinity significantly affect lake primary productivity. However, this result was consistent with the organic carbon source of the sediments of Bosten Lake, the largest inland brackish lake in China [46]. The finer grain size, weaker hydrodynamic force, and high terrestrial input are all conducive to the burial and preservation of deposited organic carbon in this area [47]. None of the above conditions were available at the sampling points (Figures 2 and 3), resulting in a relatively low-carbon burial rate at the sampling points and relatively weak carbon sequestration capacity.

For arid regions, the content of organic carbon with terrigenous sources in lake sediments indirectly reflects aridity and humidity variation [37,48,49]. The above-mentioned studies have found that lake aquatic organisms are the main sources in the core sediments of Lake Balkhash, which was consistent with large lakes such as Qinghai Lake [50] and Bosten Lake [46] but was significantly different from some shallow lakes [51]. The influencing factors on organic matter in the core sediments of Lake Balkhash seemed to be very different. For lakes in arid climate backgrounds, the change in water salinity is the main limiting factor affecting lake productivity [52]. Correspondingly, the main factor affecting the primary productivity of lakes in humid areas is the change in nutrients [53–55]. Judging from existing studies on the water level and salinity of lakes in arid areas [56,57], the change in lake water level is negatively correlated with the change in salinity; for example, when the water level of Lake Balkhash declined, the abundance of planktonic species decreased, and the lake became more saline [25]. Therefore, the change in organic matter content in the core sediment of Lake Balkhash may reflect the variation in the lake water level. Generally, the organic carbon content will increase with the increase in water depth, indicating that the water depth increases and the oxygen content decreases are more conducive to the preservation of organic carbon. In the historical period, i.e., in the two periods (1900–1920 and the 1960s) with the highest water levels in Balkhash Lake, the OCBR in sediments also responded (Figure 4), reflecting the response of the lake water environment to lake primary productivity. The increase in the lake level may also have led to a decrease in oxygen in the bottom water, which is conducive to organic carbon sequestration, and the efficiency of organic carbon burial may have been higher [58]. However, the correlation between the two curves was not significant.

On the one hand, the temperature directly affects the bacterial yield, which affects the rate of mineralization and the organic carbon burial efficiency [27]. The increase in temperature enhances the decomposition and transformation of organic carbon by microorganisms [59]. The higher the lake water temperature, the stronger the mineralization, and the less organic carbon burial [59]. On the other hand, temperature affects the biological primary productivity of the lake, which in turn affects the organic carbon storage [27,37]. As seen in Figure 4, the temperature in the Balkhash Lake area showed a significant increase over the past 100 years [35], indicating that the intensity of mineralization caused by temperature was far greater than the increase in primary productivity caused by temperature. Compared with the studies on the sediments of Small Aral Sea [27] and Bosten Lake [60], lake organic carbon burial rates in different regions of Central Asia show different changes in the context of global warming. The organic carbon burial rate is increasing significantly in Small Aral Sea [27], which is significantly different from the study of Balkhash Lake in this paper. If there are no changes or increases in the primary productivity of lakes, the decline in the rate of carbon burial will directly cause lake sediments to change from carbon sinks to carbon sources, which will have a certain role in promoting global warming.

Figure 4. Comparison of environmental proxies of BLK01 core sediments in Lake Balkhash with regional climatic and environmental records. Environmental indicator parameters include: (a) the water level of Lake Balkhash, (b) organic carbon burial rate (OCBR), (c) total organic carbon (TOC), and (d) mean annual temperature (MAT).

In addition to the increase in global temperature after the Little Ice Age [61–63], another impact that cannot be ignored is human activities, especially the impact of reservoir construction. Kapchagay Reservoir is a large reservoir in the Almaty region in southeastern Kazakhstan and one of the largest artificial lakes in Kazakhstan. Its length is about 140 km, the width is about 22 km, and the maximum depth is 50 m [64]. It was formed by the construction of a dam on the Ili River in 1963. The total storage capacity of the reservoir is 28.14 billion cubic meters with a water surface area of 1847 km² [64]. Before the 1960s, the carbon burial rate and the organic carbon content showed a positive correlation change, reflecting the stability of sedimentary flux. After the 1960s, although the TOC content showed an increasing trend, the carbon burial rate showed a significant decreasing trend, leading to an increase in the relative content of TOC. This may be related to the construction of the reservoir. The construction of the reservoir began in 1960, and it was the equivalent of adding a sedimentation device in the upper reaches of the lake. The terrestrial debris material was deposited in the reservoir, while the amount of material entering the lake decreased. Additionally, the input of nutrients and pollutants caused by human use of land, and the changes in water quality caused by human activities, may lead to changes in lake productivity, which in turn will have a certain impact on the burial of lake organic carbon, but limited to the research in this paper, it is impossible to comprehensively study the changes of lake primary productivity and its influencing factors.

Lakes have a huge carbon storage function, and the organic carbon burial efficiency of lakes can be used to characterize the carbon sink capacity. The higher the lake carbon burial efficiency, the more conducive it is to the formation of carbon sinks. The greater the ability to absorb atmospheric CO₂, the more obvious the cooling effect. Through this paper and existing research [35], it was found that the organic carbon sequestration in Central Asia had changing trends. In the context of global warming, future study should focus

on the response of lake carbon burial efficiencies in different regions to warming, and on how carbon burial efficiencies are fed back into climate change after changes occur in the carbon burial efficiency, to clarify the mutual feedback process and mechanism between climate change and organic carbon sequestration. In previous studies, the TOC in lake sediments was used directly to reconstruct the paleoenvironmental change, and the results obtained in lakes where there was no significant difference in sediment flux were less biased. Through the research of this article, the decline in carbon burial rate is mainly due to climate warming. The construction of the reservoir did not change the trend of lake carbon burial, but it changed the relative content of organic carbon in lake sediments. Through the research in this article, it was found that if the sedimentation flux caused by human activities and other factors has changed greatly, the direct use of the relative content of organic carbon to reflect the paleoenvironmental change may cause a large deviation, which deserves attention for the future study of lacustrine sedimentology.

6. Conclusions

The organic carbon in the sediments of Lake Balkhash comes mainly from lake aquatic plants, and terrestrial plants contribute little to the organic carbon of the Balkhash Lake. The OCBR fluctuated from 8.16 to 30.04 $\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$ (mean value 20.5 $\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$). The OCBR continued to decline over the past 150 years, and the minimum appeared at the top of the core (8.16 $\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$).

Global warming, higher hydrodynamic force, and low terrestrial input are not conducive to the improvement of organic carbon sequestration in Balkhash Lake. The OCBR of Lake Balkhash, where the sampling point was located, is continuously decreasing.

The result will be used not only as a scientific basis for a more scientific assessment for carbon balance assessment in regional and global scales but also as a basic data for long-term reconstruction of environmental changes.

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