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Organic Carbon Burial in the Aral Sea of Central Asia

Sen Feng [1,2,3], Long Ma [1,2,3,*], Jilili Abuduwaili [1,2,3], Wen Liu [1,2,3], Galymzhan Saparov [2,4] and Gulnura Issanova [2,5]

1 State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China; fengsen19@mails.ucas.ac.cn (S.F.); jilil@ms.xjb.ac.cn (J.A.); liuwen@ms.xjb.ac.cn (W.L.)
2 Research Center for Ecology and Environment of Central Asia, Chinese Academy of Sciences, Urumqi 830011, China; saparov.g@mail.ru (G.S.); gul_nur.777@mail.ru (G.I.)
3 University of Chinese Academy of Sciences, Beijing 100049, China
4 Kazakh Research Institute of Soil Science and Agrochemistry Named after U. U. Uspanov, Almaty 050060, Kazakhstan
5 Faculty of Geography and Environmental Sciences, Al-Farabi Kazakh National University, Almaty 050040, Kazakhstan
* Correspondence: malong@ms.xjb.ac.cn; Tel.: +86-991-7827371

Abstract: The burial of organic carbon in lake sediments plays an important role in the terrestrial carbon cycle. Clarifying the current status of carbon burial in the lakes of Central Asia is of great significance for the application of carbon balance assessments. With the analysis of the total organic carbon and nitrogen and the carbon isotope and organic carbon burial rate in the core sediment of the North Aral Sea, the status and influencing factors of organic carbon burial over the past 70 years can be revealed. The results showed that the main source of organic carbon was predominantly from lacustrine aquatic plants. However, the contribution of terrigenous organic carbon increased from the 1950s to the 1960s. The burial rate of organic carbon in North Aral Sea sediments was consistent with the overall change in the regional temperature. The burial rate of organic carbon showed an upward trend as a whole with an average of 28.78 $g \cdot m^{-2} \cdot a^{-1}$. Since 2010, the burial rate of organic carbon has stood at the highest level in nearly 70 years, with an average of 55.66 $g \cdot m^{-2} \cdot a^{-1}$. The protection of a lake by human beings can not only significantly improve the lake's aquatic ecosystem but also help to increase the burial rate of the lake's organic carbon.

Keywords: Aral Sea; lake sediments; organic carbon burial; stable carbon isotope; human activities; climate change

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1. Introduction

In the context of global warming, the carbon cycle has gradually become the focus of global change research [1]. Studies have shown that the amount of organic carbon buried in global lakes is close to half of the amount buried in the ocean [2], and the organic carbon buried in sediments cannot participate in the short-term biosphere–atmosphere carbon cycle, thus, inhibiting the production of greenhouse gases in natural systems [3]. Lakes as carbon storage are of great significance in maintaining the global carbon balance and mitigating climate change [4].

Although the global terrestrial carbon sink has been restricted by tropical forests in recent years, arid zone ecosystems dominate the interannual changes and overall trends of global terrestrial carbon sinks [5]. The central Asian arid zone is the main body of the world's largest non-zonal arid zone [6], and the inland lakes in central Asia are widely distributed, with changes in carbon burial playing an important role in the regional and global carbon cycle and carbon balance.

As an important environmental proxy indicator, organic carbon in lakes in the arid area of Central Asia has been widely used in the research of lake environmental change reconstruction [7,8], the identification of hydrological and environmental anomalies [9,10], and the reconstruction of watershed agricultural development [11]. Organic carbon burial in lake sediments is a series of biochemical processes that are closely related to factors, such as climate change, organic carbon sources, lake characteristics, and human activities [12].

In the context of global warming, the increase in microbial respiration and the mineralization rate of organic matter in water bodies and sediments may lead to a decline in the rate of organic carbon burial, and sediments may change from "carbon sink" to "carbon source" [13]. Many studies have shown that, with the increasing intensity of human activities, lake environments and ecosystems have experienced significant changes [14–16], and in-depth study of the temporal and spatial changes of organic carbon burial in lake sediments and their relationship with lake ecology, climate environment, and human activities will not only help to understand the evolution of the lake ecological environment more deeply but also make it possible to more scientifically assess the role of lake organic carbon burial in the global carbon cycle.

The Aral Sea region has a dry climate, a shortage of water resources, and an uneven distribution; however, the Aral Sea was once the fourth largest lake in the world [17]. Rapid population growth and socioeconomic development have led to the continuous development and utilization of natural resources, leading to multiple environmental problems [18]. The Aral Sea has shrunk sharply in recent years, and its changes have become one of the focuses of research regarding lakes in Central Asia [19–21].

More in-depth studies have been carried out on the shrinkage of the Aral Sea [22–24], the microbiome of the Aral Sea [25–27], and the ecological environment of the basin [28–32]. The research on lake sediments has become more abundant, e.g., environmental reconstructions of the salt water, geological structure, etc. through biological indicators [33–35]; the use of sedimentary records of titanium changes to restore the wind intensity and frequency characteristics of western Central Asia since the Late Holocene [36]; the ecological risk assessment of potentially toxic elements in the North Aral Sea [16]; etc.

In recent decades, the natural variations superimposed on the impact of human activities have made environmental changes more complicated. Therefore, the response of organic carbon burial in lake sediments to watershed environmental changes may show more complex changes. In this paper, by using the sedimentary records of organic carbon and its stable isotopes in lake sediments, the characteristics of organic carbon burial in the North Aral Sea since the 1950s and its relationship with environmental changes in the basin were analyzed. The results can be used not only as basic data for the long-term reconstruction of environmental changes, but also as a scientific basis for a more scientific assessment of the role of lake organic carbon burial in the regional and even global carbon cycle.

2. Materials and Methods

2.1. Regional Setting

The Aral Sea is located on the border of Kazakhstan and Uzbekistan (43°24′–46°56′ N and 58°12′–61°59′ E; Figure 1), supplied by the longest river in Central Asia (Syr Darya River) and the largest runoff River (Amu Darya River), with the Aral Sea Basin covering Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, Afghanistan, and Iran. When the elevation of the lake surface water was 53 m, the maximum water area reached 68,000 km^2, while the longest area from north to south was 435 km and the width from east to west was 290 km [37].

Since the 1960s, due to the continuous decrease of runoff into the lake, the water level of the Aral Sea has continued to decline. In 1986, the Aral Sea was divided into two parts: the southern part being the Great Aral Sea (South Aral Sea) and the northern part being the Small Aral Sea (North Aral Sea). After the division of the Aral Sea, the Syr Darya became the main water supply source of the Little Aral Sea [23], with the North Aral Sea located in Kazakhstan. Since the 1960s, the temperature in the Aral Sea basin has increased significantly, and the precipitation has also shown an increasing trend, although the overall increase is relatively small [38] (Figure 2).

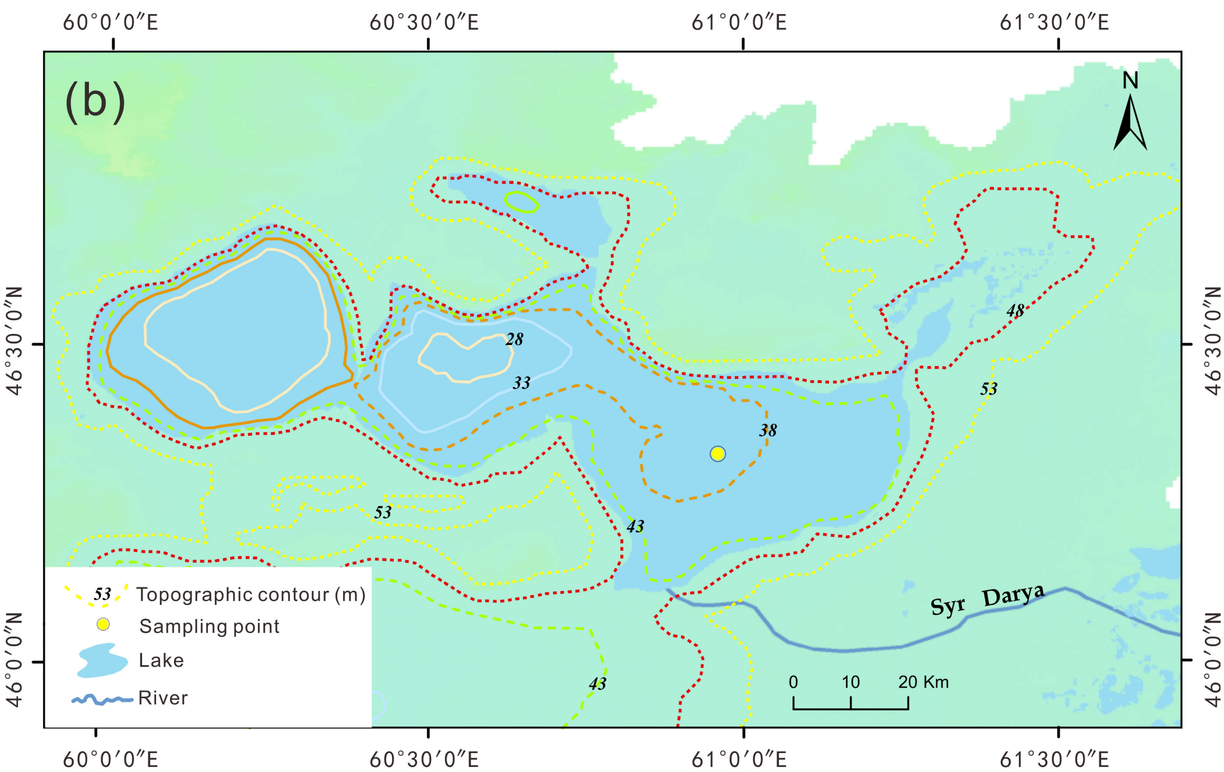

Figure 1. The location of the Aral Sea Basin (**a**) and the sampling point in the North Aral Sea (**b**).

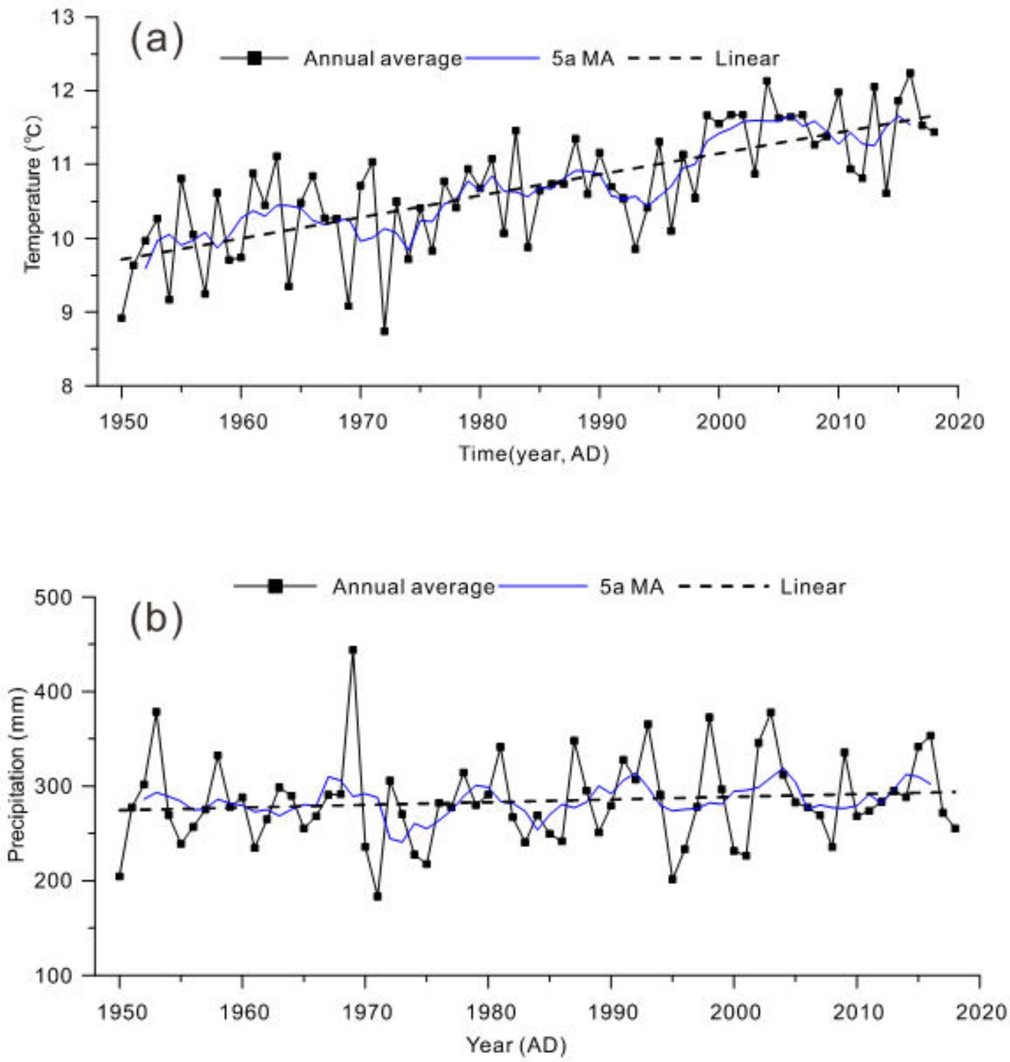

Figure 2. (**a**) Temperature change of the Aral Sea Basin from 1950 to 2018; (**b**) the annual average precipitation variations of the Aral Sea Basin. The blue lines demonstrate the five-year moving average (5a MA) and the dashed lines for the linear fitting. Note: This figure is original and the data used for Figure 2 were extracted from the CRU datasets [38].

2.2. Sample Collection and Laboratory Analysis

A 30-cm long sediment core was collected by a Uwitec gravity sampler (Uwitec, Austria) in the North Aral Sea in June 2018, and the sampling location is shown in Figure 1 (NAS-01; 60°57′37.87″ E and 46°19′31.12″ N). Sub-samples were taken at 1-cm intervals on site, sealed, and stored in plastic bags for dating and analysis of the environmental proxy indicators. The specific activity of ^{137}Cs was used to determine the age of the sedimentary strata, the activity was measured, and the depth–age model was based on the former published literature [16].

The total organic carbon (TOC) and total nitrogen (TN) were determined using a CE-440 element analyzer (Exerter Analytical Inc., North Chelmsford, MA, USA) with a relative error (RE) of <2% [39]. The determination and analysis of organic carbon isotopes ($\delta^{13}C_{org}$) was achieved using a MAT-251 isotope mass spectrometer (Thermo Finnigan, Bremen, Germany) (relative error < 0.05‰, expressed in per mil (‰) relative to Vienna Peedee belemnite), and the experiments were performed at the State Key Laboratory of Lakes and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences.

The organic carbon burial rate (OCBR; $g \cdot m^{-2} \cdot a^{-1}$) of the Aral Sea was calculated from the TOC content (%) in the sediments, the deposition rate SR ($m \cdot a^{-1}$), and the dry matter bulk density (DBD) ($g \cdot m^{-3}$). The calculation formula is as follows:

$$OCBR = TOC \times SR \times DBD \quad (1)$$

$$DBD = M_d / V \quad (2)$$

where the sedimentation rate (SR) was calculated from the sediment depth–age model, and the dry matter bulk density (DBD) was derived from the ratio of the dry weight (M_d) of the sediment sample to the dry weight volume (V).

2.3. Source Determination of Organic Carbon in the Sediments of the North Aral Sea

Although organic matter accounts for a small proportion of lake sediments, they are sensitively reflected in the reconstruction of environmental changes in lakes and watersheds [12]. The change trend of the organic matter content reflects the dynamic changes in the organic chemical process of lakes [40]. The total organic carbon (TOC) content in lake sediments is usually regarded as the basic parameter of organic matter input, and the content is affected by factors, such as the lake primary productivity, lake water chemistry, atmospheric CO_2 concentration, and the preservation capacity of organic matter by the depositional environment [12].

The total nitrogen (TN) is usually used to indicate the nutritional status of lakes, and is closely related to the productivity of aquatic organisms [41]. The sources of organic matter in lake sediments can be divided into endogenous and exogenous sources. The former refers to lake aquatic organisms, which mainly include emergent plants, submerged plants, phytoplankton, and algae, while the latter refers to terrestrial plants in the watershed, which affect the growth and development of plants by influencing relevant factors, e.g., the temperature and precipitation. The development of aquatic plants is restricted by the nutritional status and temperature of the lake, while the growth of terrestrial plants in arid and semi-arid areas is more affected by precipitation [42].

The $\delta^{13}C_{org}$ value in sediments depends on the source of organic matter, and the $\delta^{13}C_{org}$ value of different organic matter sources is superimposed on the influence of natural factors, and the range of variation is quite different [43–46]. Terrestrial plants directly absorb CO_2 in the atmosphere, and thus their $\delta^{13}C_{org}$ value is negative. For example, the $\delta^{13}C_{org}$ value of C3 plants ranges from −30‰ to −23‰, and the $\delta_{13}C_{org}$ value of C4 plants ranges from −17‰ to −9‰ [43–46]. Meanwhile, in aquatic plants, the $\delta^{13}C_{org}$ value ranges from −17‰ to −9‰.

Emergent plants, phytoplankton, and floating-leaf plants use different sources of CO_2 under different conditions. Emergent plants are inseparable from CO_2 in the atmosphere, and therefore their $\delta^{13}C_{org}$ value is closer to that of C3 plants—between −30‰ and −24‰. Phytoplankton and algae depend on the status of dissolved CO_2 in lake water. When the dissolved CO_2 in a lake is abundant, the $\delta^{13}C_{org}$ value is close to that of C3 plants. On the contrary, the HCO_3^- in lake water is used, so that the $\delta^{13}C_{org}$ value becomes positive and can be as high as approximately −24‰ to −12‰. The carbon used by submerged macrophytes mainly comes from HCO_3^-, and the $\delta^{13}C_{org}$ value is between −20‰ and 12‰ [43–46].

The ratio of C/N is widely used to determine the source of organic matter in lake sediments [47,48]. Since organic nitrogen is usually found in protein and nucleic acid, the content of organic nitrogen in terrestrial higher plants is low; therefore, its C/N value is usually greater than 30, and aquatic plants have a high organic nitrogen content, and thus their C/N values are generally low. Among them, the C/N range of aquatic vascular plants is between 10 and 30, and that of plankton is between 4 and 10 [46]. As the C/N range of large submerged plants overlaps with terrestrial plants, the $\delta^{13}C_{org}$ value can be used to further determine the source of the organic matter [49,50].

3. Results

3.1. Changes in the Organic Matter of the Lake Sediments

The content changes of TOC and TN, the atom ratio of TOC and TN (C/N), and $\delta^{13}C_{org}$ in the sediments of the North Aral Sea are shown in Figure 3. The TOC content in the core sediments was between 0.17% and 1.44%, with an average content of 0.93%. From the beginning of the 1950s to the end of the 1960s (corresponding to a depth of 30–21 cm), the TOC content fluctuated in a small range, and there was an obvious sudden change from 1970 AD (22 cm).

The content of TN was between 0.01% and 0.20%, with an average content of 0.12%, and its change trend was more consistent with the change of the TOC. The average value of the C/N ratio was 8.4, with a maximum value of 13.9 and a minimum value of 6.9. The C/N ratio changed greatly in the lower part of the core (22–30 cm). In the upper part of the sediment core (0–21 cm), it slowly descended to the surface. The value of $\delta^{13}C_{org}$ ranged from −23.48‰ to −21.57‰, with an average of −22.46‰.

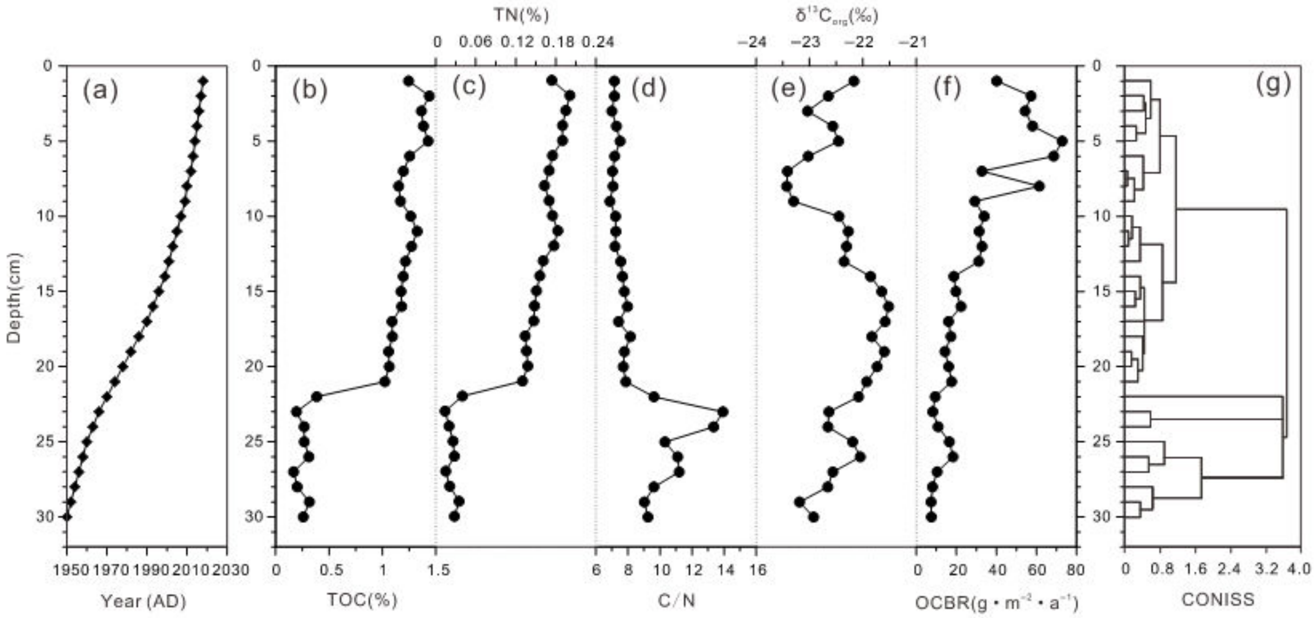

Figure 3. The depth–age model (**a**), the variation of the environmental proxies in the lake sediments of the North Aral Sea: (**b**) total organic carbon (TOC), (**c**) total nitrogen (TN), (**d**) atomic ratio of TOC and TN (C/N), (**e**) stable organic carbon isotope ($\delta^{13}C_{org}$), and (**f**) organic carbon burial rate (OCBR), and (**g**) stratigraphically constrained cluster analysis (CONISS) results for the environmental proxies.

The organic carbon burial rate (OCBR) varied from 7.36 to 72.82 $g \cdot m^{-2} \cdot a^{-1}$, with an average value of 28.78 $g \cdot m^{-2} \cdot a^{-1}$ (Figure 3). Before the 21st century (9–30 cm), the overall change in the OCBR showed an increasing trend, ranging from 7.36 to 33.89 $g \cdot m^{-2} \cdot a^{-1}$, with a relatively small range of change. At 2010 AD (8 cm), the OCBR increased significantly and began to show significant fluctuations around 2010, first increasing from 29.20 to 61.41 $g \cdot m^{-2} \cdot a^{-1}$, then rapidly decreasing to 32.73 $g \cdot m^{-2} \cdot a^{-1}$, before rising to the highest value of the core profile, which was 72.82 $g \cdot m^{-2} \cdot a^{-1}$, and then continuing to decrease.

3.2. Stage Characteristics of Organic Proxies in the Sediments of the North Aral Sea

Stratigraphically constrained cluster analysis (CONISS) can group the samples with the smallest internal differences into one class while keeping the original order unchanged, and the differences between classes are clear [51,52]. According to the CONISS results (Figure 3), the vertical change in the environmental proxies of organic matter in the North Aral Sea has clear characteristics of stage change. The three stages can be divided into three categories: (1) 1950–1970 AD (30–22 cm): During this stage, the TOC and TN contents in the sediment remained at a low level with a small change range, and the OCBR value was the lowest.

At the end of this period, the C/N value changed significantly, and the trend of change first increased and then decreased. (2) 1975–2010 AD (22–8 cm): Compared to the previous stage, the TOC and TN contents in the sediments increased significantly, the C/N ratio decreased, and the OCBR showed an increasing trend. (3) 2010 AD to present (8–0 cm): During this period, the TOC and TN contents of the sediments fluctuated in a small range, and the C/N value slightly decreased. The $\delta^{13}C_{org}$ value changed significantly and showed an upward trend. The OCBR first increased and then decreased.

4. Discussion

The TOC and TN change trends of the sediment cores in this study were highly similar, with obvious stage characteristics and a significant correlation ($r = 0.996$, $p < 0.01$), indicating that the sources of TOC and TN were consistent. The $\delta^{13}C_{org}$ value of the sedimentary core sequence was generally within the range of the $\delta^{13}C_{org}$ value of plankton (phytoplankton and algae), indicating that plankton may play a major role in the accumulation of organic matter in lake sediments.

The C/N value of the sediment core sequence was generally at a low level, except for in the mid-1950s to the mid-1960s, where the C/N was less than 10, and the C/N value has, overall, been between 4 and 10 since the 1970s. Combined with the change in the $\delta^{13}C_{org}$ value in the middle, this indicates that the organic carbon in Aral Sea sediments is mainly endogenous, and plankton is the main endogenous contributor.

As lake aquatic organisms are the main source of organic matter in the sediments of the North Aral Sea, the role of temperature and water environment on sediment organic matter is crucial. An existing study on the organic carbon of lake sediments in arid regions showed that the increase in temperature in the past 100 years will lead to an increase in the content of organic matter in lake sediments [52]. Under warm conditions, the suitable growth period of water plants is prolonged with an increase in the photosynthesis rate, and the productivity of organic matter increases [52], which further affects the accumulation of organic carbon in sediments.

From the OCBR variations (Figure 4), the sediment rate has been increasing over the past 70 years, which is consistent with the regional temperature. The overall climate in the basin tends to be warmer, thereby, accelerating the OCBR, which is conducive to the accumulation of organic carbon. At the same time, an increase in temperature is conducive to the mineralization and decomposition of organic carbon, thereby, inhibiting its accumulation in lakes and restricting the burial efficiency of organic carbon [53,54].

The research results indirectly indicate that the promotion effect of temperature on the input of organic matter may be stronger than its mineralization effect. Since most of the degradation of organic matter is carried out by microbial communities and extracellular enzymes [55], the temperature can directly affect its activity [56,57], which changes the decomposition of organic carbon in sediments by microorganisms, which, in turn, affects the rate of mineralization.

However, it can be seen from Figure 4 that, since 2015, the organic carbon burial rate in the North Aral Sea has shown a decreasing trend, and the increase in microbial respiration and the mineralization rate of organic matter in water bodies and sediments following the warming climate may lead to a decline in the rate of organic carbon burial.

The amount of precipitation has a certain effect on the development of terrestrial plants in the watershed. As the organic matter in the sediments of the North Aral Sea is mainly derived from endogenous sources, the change in exogenous organic matter should have a small impact on the OCBR. However, in the 1960s, the source of organic matter in the sediments of the North Aral Sea was significantly different, which was manifested in an increase in the content of the exogenous organic matter. From the 1950s to the 1970s, an increase in precipitation typically promoted the carbon storage of vegetation and soil in a watershed [60,61], thereby, increasing the input of organic carbon in sediments.

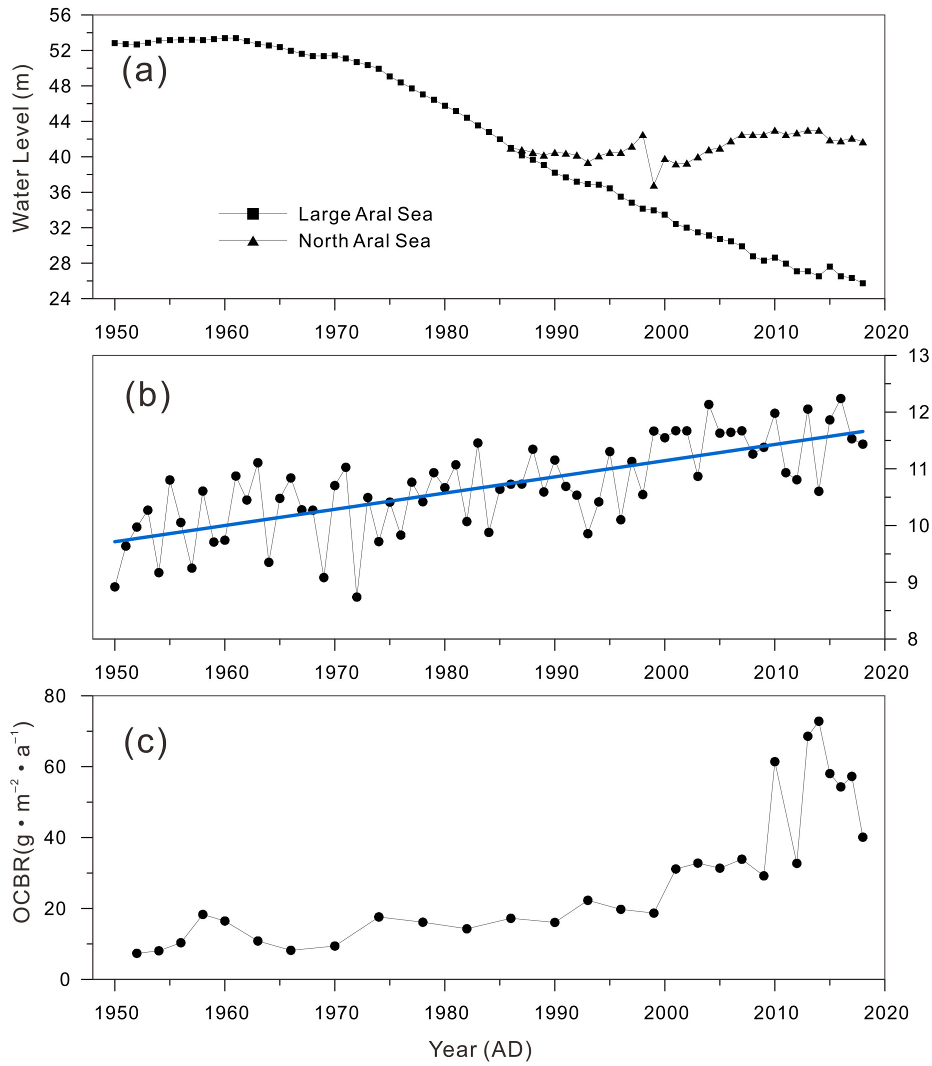

Figure 4. The water level changes of the Aral Sea (**a**) compared with (**b**) the mean annual temperature (MAT) of the Aral Sea Basin (the blue line is for linear fitting), and (**c**) the evolution of the organic carbon burial rate (OCBR) of lake sediments from the North Aral Sea from 1950 to 2020. Note: This figure is original; the water level data (1960–2018) in (**a**) was sourced from the reference [58], and the water level data (1950–1960) were from [59]; the data for (**b**) were also shown in Figure 2 with the same data source.

The local government built a sand dam in 1992, and human intervention reduced the amount of water flowing out of the North Aral Sea into the Large Aral Sea, which caused the level of the Small Aral Sea to rise [62]. Since the dam was completely destroyed in 1999 AD [63], the level of the water dropped sharply during this period. Since then, the World Bank and the government of Kazakhstan have invested in the construction of a 13-km dam to preserve the North Aral Sea [18].

On the whole, the water level of the North Aral Sea has been rising steadily since the separation of the North and the South Aral Sea, and has been at a high level since 2010 AD. An improvement in the lake water level is conducive to the recovery of the lake ecosystem, which is reflected in a significant increase in the organic carbon buried flux in the lake sediments

The organic carbon burial in lakes is closely related to the intensity of human activities, the sedimentary characteristics, the hydrology, and other ecological and environmental factors. Especially, the microbial community is of great significance to the degradation of organic matter [55,64]. The research on microorganisms in the North Aral Sea [25,27] and their influences on the decomposition rate, degradation rate, and mineralization of organic carbon should be regarded as an important part of the lake's carbon cycle and should receive due attention.

The organic carbon accumulation rates of different lakes differ greatly, and the organic carbon accumulation rates of different areas in the same lake may show great spatial differences. Based on the single core data, the estimation results of the organic carbon storage of the whole lake can deviate greatly. For large lakes, the extent to which a single or small amount of core data is representative of the organic carbon burial of the whole lake remains to be further evaluated in future studies.

Additionally, existing studies have proven that there is a significant negative correlation between the burial efficiency of organic carbon burial and the oxygen exposure time [65] and that the oxygen level also influences the microbiology community [66–68]. In this article, the impact of changes in the concentration of dissolved oxygen in the water body on the organic carbon of the sediments was not considered. In the future, it will be possible to study the quantitative relationship between the oxygen exposure and the burial efficiency of organic carbon in lake sediments through large-density spatial sampling of the lake surface sediments and lake water bodies of the Aral Sea.

5. Conclusions

The main source of organic carbon in the North Aral Sea sediments over the past 70 years is primarily from lacustrine aquatic plants. However, the contribution of terrigenous organic carbon increased from the 1950s to the 1960s. The burial rate of organic carbon in the North Aral Sea sediments showed an upward trend as a whole with an average of 28.78 $g \cdot m^{-2} \cdot a^{-1}$. Since 2010, the burial rate of organic carbon has remained at the highest level in nearly 70 years, with an average of 55.66 $g \cdot m^{-2} \cdot a^{-1}$.

The burial rate of organic carbon in the North Aral Sea sediments is consistent with the overall change in the regional temperature. After the Aral Sea was separated into the north and south parts, the water level of the North Aral Sea rose as a whole under the intervention of human activities. The protection of lakes by human beings can, thus, not only significantly improves the lakes' aquatic ecosystems but also help to increase the burial rate of lake organic carbon.

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