Spatial Patterns of Organic and Inorganic Carbon in Lake Qinghai Surficial Sediments and Carbon Burial Estimation

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Lake carbon burial is of vital significance in global carbon cycle and carbon budget, particularly in the large deepwater lakes. However, carbon burial in large deepwater lakes is hard to estimate due to the difficulty in obtaining high spatial-resolution samples. In this study, we investigated distributions of total organic carbon (TOC) and inorganic carbon (TIC), two main carbon components in lake sediments, based on dozens of surficial sedimentary samples ($n = 26$) covering whole Lake Qinghai, the largest saline lake in China. The results showed that the TOC content, with a range of 1.4–4.8%, was significantly higher in the lake area near the northern lakeshore where human activities are concentrated and lower in the lake areas near the Buha River mouth and the eastern lake area. In contrast, the TIC content, ranging from 1.5 to 3.8%, increased from the northwestern and southeastern lake areas toward the lake center, and mainly depended on hydro-chemical and hydraulic characteristics. The inorganic carbon burial (47.77 ± 19.73 Gg C yr^{-1}) was approximately equal to organic carbon burial (47.50 ± 22.68 Gg C yr^{-1}) and accounted for about 50% of the total carbon burial (95.27 ± 37.74 Gg C yr^{-1}), suggesting that saline lakes constitute a large inorganic carbon pool in addition to an organic carbon pool. Because of saline water body type in arid and semiarid regions and alpine Qinghai–Tibet Plateau, lakes in these regions have huge inorganic carbon burial potential and important contributions to the global carbon budget.

Keywords: Lake Qinghai, organic carbon, inorganic carbon, carbon cycle, carbon burial

INTRODUCTION

Because of the rich organism community and/or lots of carbonate precipitation as well as the ideal burial environment, lake sediments have a great burial capacity of atmospheric carbon (Einsele et al., 2001). Organic carbon (OC) burial was estimated to be 1.25 Mt yr^{-1} in European lakes (Kastowski et al., 2011) and ~12.6 Tg C yr^{-1} in lakes/ponds of the conterminous United States (Clow et al., 2015). It was concluded that organic carbon accumulation in global lakes displayed a rate (42 Tg yr^{-1}) that approached half of that in

the ocean (100 Tg yr^{-1}) (Dean and Gorham, 1998). Therefore, lakes play an important role in the carbon cycle and budget and are given considerable official and scientific concerns.

Carbon in lake sediments mainly comprises OC and inorganic carbon (IC). The former stems from terrestrial organism residues derived from watershed and aquatic organism residues derived from lake (Meyers and Ishiwatari, 1993), while the latter consists of lithogenic carbonate inputted by runoff, wind, and endogenic carbonate (including biogenic carbonate) (Anas et al., 2015). Little attention, however, was paid to IC burial in lake sediments. In fact, the inorganic carbon content in sediments of many hydrologically closed temperate lakes was comparable to or even higher than that of organic carbon (Einsele et al., 2001; Gyawali et al., 2019; Chen et al., 2021). Particularly, inorganic carbon could be an essential component in carbon burial in those hydrologically closed lakes.

Previous studies on carbon burial in large lakes mainly focused on several specific sites and lack high-resolution systematic investigation. However, spatial patterns of organic and inorganic carbon in sediments of large deepwater lake and related controlling factors remain complicated and rarely studied on account of the higher cost of high spatial-resolution sampling. Since sedimentary organic and inorganic carbon tend to be susceptible to plenty of drivers, such as carbon sources, climate, sedimentary environments, and human activities (i.e. land use and nutrient supply) (Tenzer et al., 1997; Rumolo et al., 2011; Yu et al., 2015; He et al., 2021), estimation of carbon burial in a large lake based merely on several sites is questionable. High-resolution sampling in a large lake is advantageous to eliminate the inaccuracy of several sites and identify the impacts of human activities and natural conditions on carbon as an implication for environmental restoration and construction surrounding the lake.

Lake Qinghai is located in the northeastern Tibetan Plateau and is the largest saline lake in China. It has been endowed with an enormous scientific and social value for its unique location and high climatic sensitivity (Qin and Huang, 1998; Ji et al., 2005; Henderson et al., 2007; An et al., 2012). Both organic and inorganic carbon contents in sediments were considered to be indicators of environmental and climatic changes, and thus were used for paleoclimatic reconstruction on different timescales (Yu and Kelts, 2002; An et al., 2012; Liu et al., 2014b). In the context of global warming and intensified human activity, as a geographical and paleoclimatic archive at the third pole, the carbon sequestration capacity of Lake Qinghai also needs to be evaluated based on a systematic investigation of the carbon content. For Lake Qinghai, Einsele et al. (2001) and Xu et al. (2013) evaluated carbon burial of its Holocene sediments and modern sediments, respectively. However, the distribution of the sedimentation rate (Xu et al., 2010), eutrophic elements (Chen et al., 2012), and the modern sedimentation process (Shang et al., 2009) in Lake Qinghai surficial sediments showed significant spatial variability. Similarly, to a certain degree, as human-induced changes occur manifestly around and in the lake (Zhang et al., 2013; Luo et al., 2017; Lian et al., 2019), carbon in the sediments of Lake Qinghai could also exhibit spatial heterogeneity due to non-anthropogenic and anthropogenic factors, which is currently unknown.

Here, high-resolution surficial sediments ($n = 26$) uniformly covering the whole Lake Qinghai were collected. Based on total organic carbon (TOC), total inorganic carbon (TIC), total nitrogen content (TN), organic matter C/N atomic ratio, mineralogical methods, and regional socioeconomic statistics, this study aims to 1) explore the source of OC and IC in Lake Qinghai sediments, 2) investigate the contributions of natural and anthropogenic factors to the spatial variation of TOC and TIC across the lake basin, and 3) further estimate the carbon burial in Lake Qinghai.

MATERIALS AND METHODS

Lake Qinghai (99°36′-100°47′E, 36°32′-37°15′N, ~3,193.8 m a s^1.) (**Figure 1**), located in the temperate continental climate and arid/semiarid region in the northeastern Tibetan Plateau, is the largest saline lake in China (lake size: ~4,400 km^2, average water depth: ~21 m, maximum depth of 31.4 m) (Liu et al., 2003; Dong et al., 2018). The mean annual air temperature and precipitation are 1.2 °C and 336.6 mm, respectively (Wang et al., 1998). Strong westerlies and/or northwesterly winds prevail over Lake Qinghai during all seasons, except summer (Dong et al., 2018). The Buha River, Shaliu River, Haergai River, Quanji River, and Heima River are the main tributaries of the lake; of which, the Buha River on the west is the largest with a runoff contribution of ~46.9% (Chang et al., 2017). Catchment zonal soil mainly consists of chestnut soil; the bedrock of the lake's surrounding is dominated by metamorphic rocks and acidic magmatic rocks, and there is limited limestone in the west (Xu et al., 2013). Main vegetation comprises temperate steppe, shrub, alpine grassland, and meadow (Shang et al., 2009).

As an important tourist attraction and one of the national nature reserves, Lake Qinghai is significantly affected by humans with environmental damage or/and ecological construction in recent years. There are four counties in the Lake Qinghai Basin: Tianjun County where the Buha River flows through, Gonghe County in the area south of Lake Qinghai, Gangcha County near to the Shaliu River, and Haiyan County in the area north of the lake where industrial and agricultural activities are concentrated. The Lake Qinghai Basin is an important livestock base, within which there are five large state-owned farms and ranches. Tourism around the lake is under rapid development. Besides, various ecosystem protection and construction projects covering the Lake Qinghai Basin are being implemented, such as degraded grassland management projects, desertification land control projects, and wetland protection projects.

Twenty-six surficial sediment samples (top of 1 cm) covering the whole lake were altogether collected from Lake Qinghai with Kajak gravity corer in September 2017, and 3 surficial soil and 6 fluvial sediment samples from the drainage area were sampled in September 2019 (**Figure 1** and **Table 1**). We measured the volume of each sample before lyophilization and weighed each dry sample after lyophilization for 26 lake sediments.
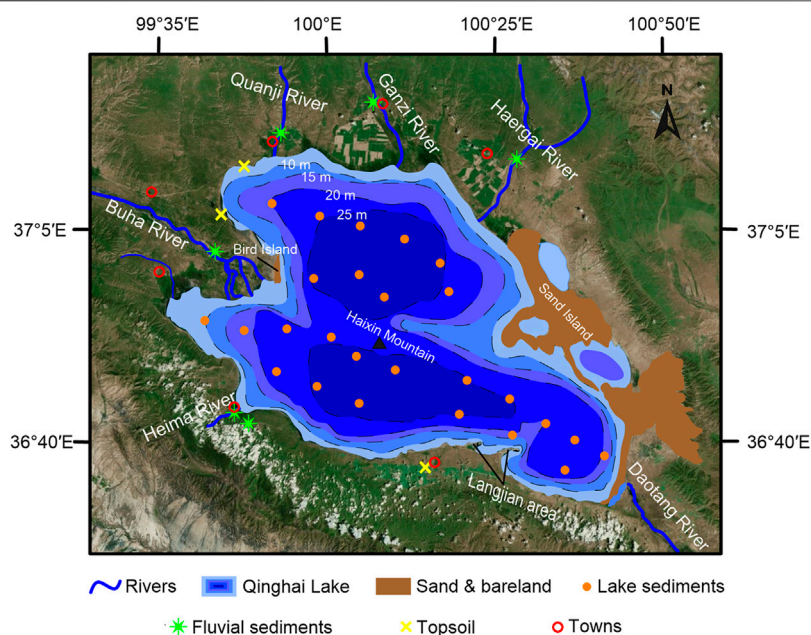
FIGURE 1 | Lake Qinghai Basin and sampling sites.

Total organic carbon, total nitrogen content, total inorganic carbon, and mineral compositions in collected samples were measured. For TOC and TN measurements, 0.5 g of each sample was weighed into a 50 ml centrifuge tube, pretreated with HCl (10%) and heated in a water bath (60°C) for 3 h, rested for 12 h to remove the carbonates, and then rinsed with distilled water repeatedly after 3–4 times centrifugation (5,000 r/min). Finally, samples were freeze-dried and ground, and measured on the EA 3000 elemental analysis instrument at the State Key Laboratory of Lakes and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. Measured TOC was the organic carbon content of the carbonate-free sample. Thus, the TOC content in the bulk sample should be calibrated as $TOC_{measured} \times (1-$ carbonate content).

For TIC measurement, Fourier transform infrared spectrometry (FTIR) was used to quantify the carbonate content of each sample following the specific steps of Ji et al. (2009) and Meng et al. (2015) because this technique has high precision, small measurement error, simply pretreatment, and high measurement efficiency (Ji et al., 2009). Samples were ground and dried at 70 °C and placed in a sample cup for analyzing in a Thermo Nicolet 6700 FTIR with a diffuse reflectance attachment from wavenumbers 4000–400 cm^{-1} at Nanjing University. The absorption peaks at 2,513–2,522 cm^{-1} representing total carbonate was measured for its reflectance band area (**Figure 2A**). The quantitative equation of the total carbonate content, namely, y = 0.000181x+0.0237 (y: total carbonate content, x: band area at 2,513 cm^{-1}; R^2 = 0.988, RMSE = 0.0197), was constructed by adding a certain amount of pure carbonate into the carbonate-free matrix that was made by thoroughly removing the carbonate of Lake

Qinghai sediments using HCl. The detection limit of carbonate in sediments was 0.1%, and the measuring error of this method was lower than 2% (Meng et al. (2015). Concerning the content of authigenic carbonate relative to the total carbonate content (TCC), we decided to use the calculation results of Xu et al. (2010) that authigenic carbonates accounted for approximately 95% of the total carbonates in Lake Qinghai sediments. Therefore, the TIC content of Lake Qinghai sediments could be estimated with TCC×95% × 12/100. To further determine mineralogical types of carbonates in Lake Qinghai sediments, surrounding soils, and fluvial sediments, the X-ray diffraction analysis (XRD) was also performed on selected representative samples with the Panalytical multifunctional X-ray powder diffractometer 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) and the inorganic carbon burial rate (ICBR) were calculated based on TOC, TIC, sedimentation rate (SR), and dry bulk density (DBD), according to Dean and Gorham. (1998):

$$OCBR = TOC \times SR \times DBD, \qquad (1)$$
$$ICBR = TIC \times SR \times DBD, \qquad (2)$$
$$DBD = M_d/V, \qquad (3)$$

where M_d = weight of dry sample and V = volume of wet bulk sample (measured before lyophilization). Sedimentation rates of 26 sites were roughly evaluated by Kriging interpolation with the sedimentation rates reported in the study by Xu et al. (2010). As an alpine deepwater lake, previous studies found that Lake Qinghai has stable sedimentary environment in each site, showing a relatively low and stable modern deposition rate in

TABLE 1 | Location, water depth, total organic carbon content (TOC), total nitrogen content (TN), total inorganic carbon content (TIC), and atomic C/N ratio of surficial samples.

Samples	Longitude(E)	Latitude (N)	Water depth (m)	TOC (%)	TN (%)	TIC (%)	C/N
QHH-1[a]	99.880361	37.132358	20.1	3.5	0.42	1.5	9.3
QHH-2[a]	99.993894	37.107975	26.6	4.8	0.70	2.8	7.5
QHH-3[a]	100.096543	37.087114	28	3.4	0.32	3.0	12.55
QHH-4[a]	100.203045	37.063362	27.5	3.5	0.48	3.1	8.5
QHH-5[a]	100.289308	37.01611	26.7	4.6	0.55	3.3	9.8
QHH-6[a]	100.311155	36.960505	26.3	2.1	0.19	3.3	12.42
QHH-8[a]	100.153319	36.949207	27.3	2.6	0.39	3.8	7.9
QHH-9[a]	100.09104	36.992795	28	4.1	0.53	3.0	9.0
QHH-10[a]	99.981435	36.986548	27.4	2.7	0.37	2.9	8.5
QHH-11[a]	99.711628	36.905486	12	1.7	0.21	2.7	9.8
QHH-12[a]	99.809412	36.884322	18.6	1.6	0.20	3.1	9.4
QHH-13[a]	99.913588	36.887739	24.7	2.7	0.48	3.0	6.5
QHH-14[a]	100.021982	36.871759	27.8	3.3	0.50	3.5	7.8
QHH-15[a]	100.083171	36.836496	28	4.3	0.72	3.3	6.9
QHH-16[a]	100.178293	36.808335	27.7	3.3	0.40	3.4	9.4
QHH-17[a]	100.090199	36.742439	26.6	1.4	0.14	3.3	11.76
QHH-18[a]	99.986649	36.776789	25.1	4.7	0.53	3.1	10.4
QHH-19[a]	99.888801	36.803265	21.9	3.5	0.56	2.8	7.2
QHH-20[a]	100.692207	36.640219	24.5	1.9	0.33	2.8	6.8
QHH-21[a]	100.619016	36.670668	26.5	3.1	0.38	3.4	9.6
QHH-22[a]	100.546961	36.703588	25.2	1.9	0.28	3.1	8.1
QHH-23[a]	100.460871	36.75204	27	3.5	0.48	3.2	8.5
QHH-24[a]	100.356369	36.786932	27.5	3.9	0.56	3.1	8.0
QHH-25[a]	100.335989	36.720764	27	4.0	0.55	2.8	8.4
QHH-26[a]	100.468641	36.677763	23.5	1.8	0.22	2.7	9.3
QHH-27[a]	100.595719	36.611497	26	3.3	0.50	2.9	7.6
QHH19-2[b]	100.253677	36.617973	—	—	—	2.7	—
QHH19-6[b]	99.755945	37.109203	—	—	—	1.2	—
QHH19-7[b]	99.810662	37.204389	—	—	—	2.8	—
QHH19-3[c]	99.81916	36.705414	—	—	—	0.63	—
QHH19-4[c]	99.784312	36.722319	—	—	—	0.68	—
QHH19-5[c]	99.736698	37.03716	—	—	—	3.7	—
QHH19-8[c]	99.899197	37.268998	—	—	—	0.84	—
QHH19-9[c]	100.126498	37.329748	—	—	—	0.78	—
QHH19-10[c]	100.477309	37.218026	—	—	—	2.4	—

[a]Lake sediments.
[b]Soils.
[c]Fluvial sediments.

recent decades (Zhang et al., 2009; Fu et al., 2015). Modern SR data of Lake Qinghai reported by Xu et al. (2010) were derived from 11 cores covering the whole Lake Qinghai. Therefore, we believe the SR data of Xu et al. (2010) were relatively reliable.

RESULTS

The distribution of TOC showed great spatial difference in Lake Qinghai surficial sediments ranging from 1.4 to 4.8% (with average of 3.1%, CV = 0.32) (**Figure 3A** and **Table 1**). The western and eastern lake areas had a low TOC value (mean value of 2.4%), while a high content (mean value of 3.7%) occurred in the northern and central areas. (**Figure 3A**). Specifically, there were eight prominent low-content sites (i.e., QHH-11 (1.7%) and QHH-12 (1.6%) near the Buha river mouth, QHH-17 (1.4%) in the southern lake area, and QHH-20 (1.9%), QHH-22 (1.9%), and QHH-26 (1.8%) in the eastern lake area) and seven relative higher content sites (i.e., QHH-2 (4.8%), QHH-5 (4.6%), QHH-9 (4.1%),
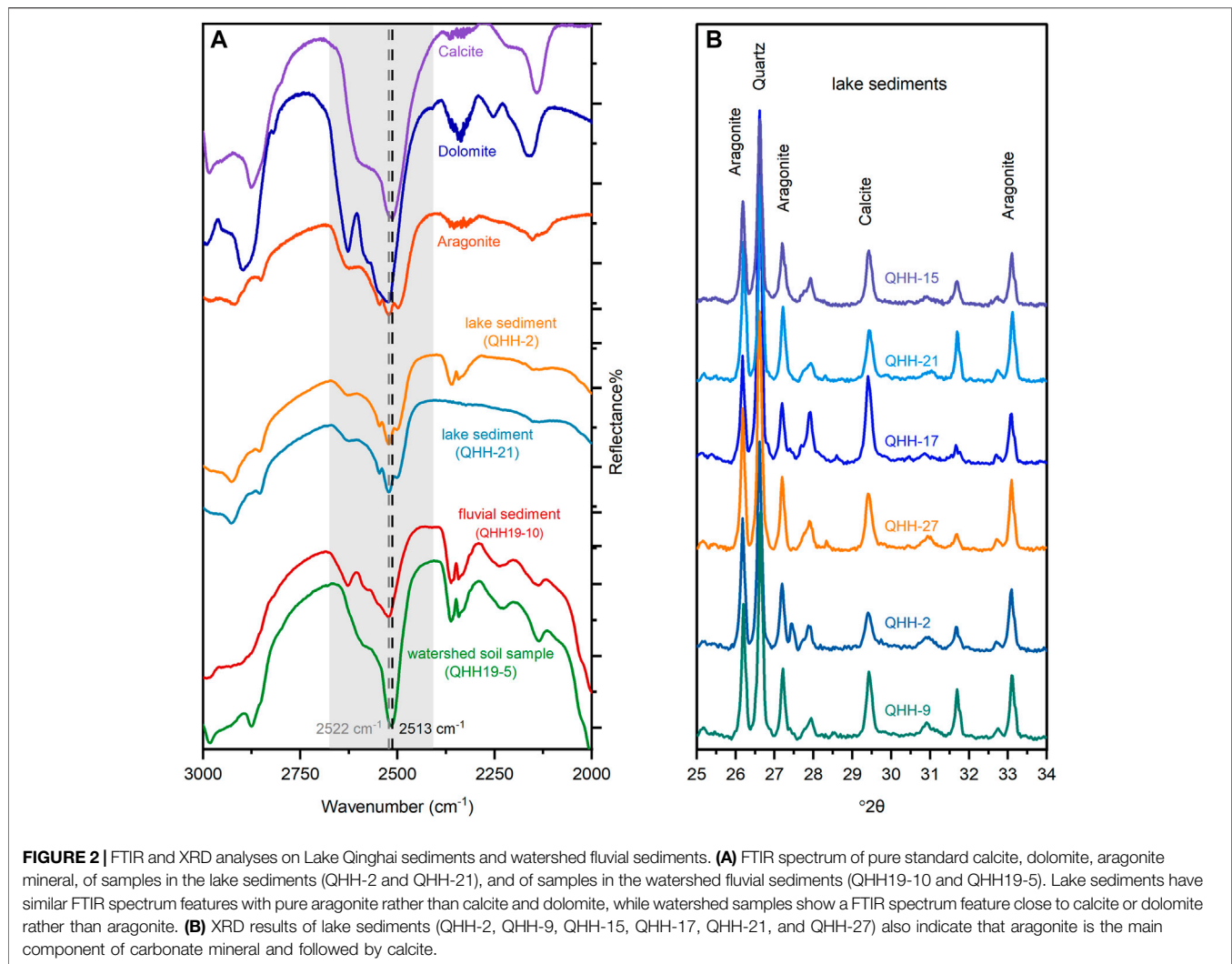
QHH-15 (4.3%), QHH-18 (4.7%), QHH-24 (3.9%), and QHH-25 (4.0%)) (**Table 1**). TN ranged in concentration from 0.14 to 0.72% (**Table 1**). Atomic C/N ratios varied but were all between 6.5 and 12.5 (mean 8.9) (**Table 1**; **Figure 4A**).

The range of TIC content was 1.5–3.8% in Lake Qinghai sediments (3.0% on average, CV = 0.14) (**Table 1**). The spatial distribution of TIC content is shown in **Figure 3B**. There was a general increasing trend of TIC content from the northwestern and southeastern lake areas to the central lake area, with the lowest value (1.5%) near the northwestern shore of the lake (QHH-1) and the highest in the central QHH-8 (3.8%) (**Figure 3B** and **Table 1**).

DISCUSSION

Source of Organic and Inorganic Carbon
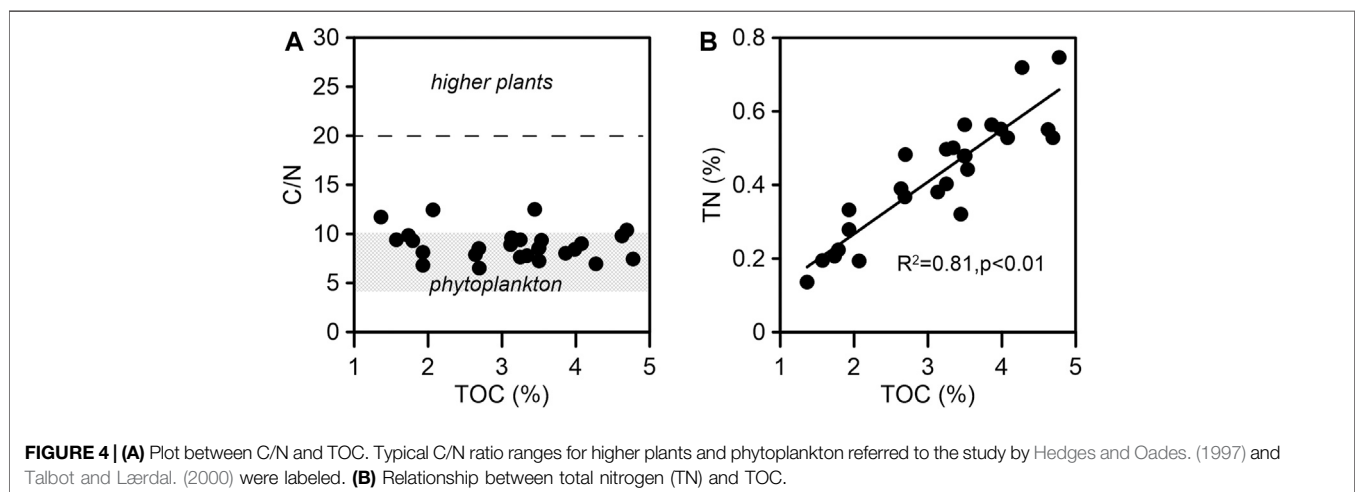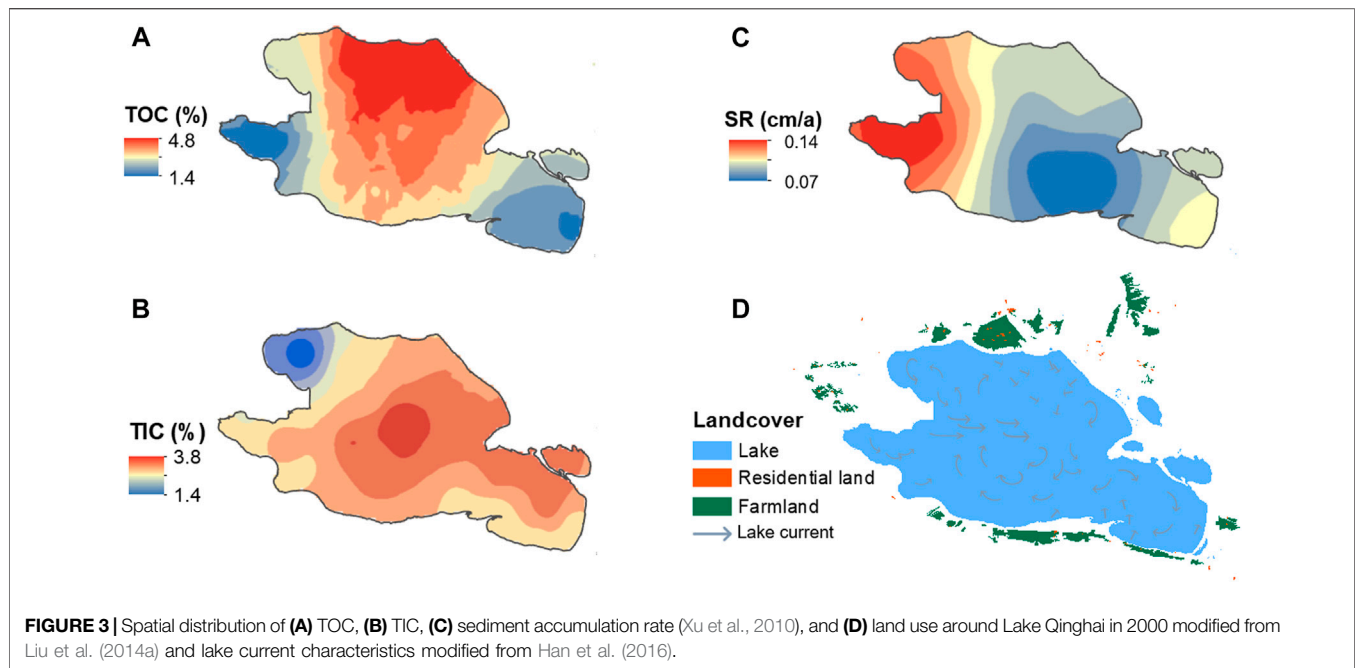The carbon source in lake sediments is related to the budget of carbon burial. There was a strong linear relationship between

FIGURE 2 | FTIR and XRD analyses on Lake Qinghai sediments and watershed fluvial sediments. **(A)** FTIR spectrum of pure standard calcite, dolomite, aragonite mineral, of samples in the lake sediments (QHH-2 and QHH-21), and of samples in the watershed fluvial sediments (QHH19-10 and QHH19-5). Lake sediments have similar FTIR spectrum features with pure aragonite rather than calcite and dolomite, while watershed samples show a FTIR spectrum feature close to calcite or dolomite rather than aragonite. **(B)** XRD results of lake sediments (QHH-2, QHH-9, QHH-15, QHH-17, QHH-21, and QHH-27) also indicate that aragonite is the main component of carbonate mineral and followed by calcite.

TOC and TN ($R^2 = 0.81$, $p < 0.01$, **Figure 4B**), demonstrating that organic nitrogen was the dominant form of total nitrogen (Schubert and Calvert, 2001; Liu et al., 2010). The organic matter C/N atomic ratio is commonly used to qualitatively distinguish the contribution of terrestrial vegetation and aquatic organisms to organic carbon in lake sediments. Terrestrial vascular plants are poor in nitrogen, so the C/N ratio is high, while aquatic plants are nitrogen rich with a low C/N ratio (Meyers and Lallier-vergés, 1999; Müller and Mathesius, 1999). It was suggested that the C/N ratio of phytoplankton is less than 10 (Hedges and Oades, 1997). C/N ratios greater than 20 were believed to denote terrestrial sources of organic matter, while values in 10–20 were considered to be signals of a mixture of aquatic plants and higher plants (Talbot and Johannessen, 1992; Tyson, 1995; Talbot and Lærdal, 2000). The C/N atomic ratios of Lake Qinghai surficial sediments ranged from 6.5 to 12.5, with values of 22 samples below 10 (**Table1**; **Figure 4A**). Therefore, organic matter in Lake Qinghai sediments may be mainly of endogenous origin. The investigation of organic carbon isotopic compositions of long-chain n-alkanes of modern

sediments and aquatic plants also revealed that the organic matter in Lake Qinghai sediments was mainly derived from the endogenous aquatic organisms (Liu et al., 2015). In addition, the preservation of organic carbon in sediments is an important aspect of OC burial. A recent study found that the contribution of TOC degradation to dissolved inorganic carbon was less than 10% in Lake Qinghai (Sun et al., 2019). This may result from the stratification of lake water and the permanently anoxic bottom environment (Sobek et al., 2009). Therefore, TOC in Lake Qinghai was mainly derived from aquatic organisms and well preserved in sediments.

Mineralogical and geochemical methods were used to determine the source and composition of TIC (carbonate) in Lake Qinghai sediments. Among the carbonate mineral types, aragonite is unstable so it hardly exists in ancient bedrock (Kunzler and Goodell, 1970; Martín-García et al., 2019), which is consistent with investigation of modern sediments around the Lake Qinghai Basin (Meng et al., 2019). Thus, aragonite in lake sediments should be autogenetic that precipitated from lake water or/and derived from biogenic origin; this was also supported by

FIGURE 3 | Spatial distribution of (A) TOC, (B) TIC, (C) sediment accumulation rate (Xu et al., 2010), and (D) land use around Lake Qinghai in 2000 modified from Liu et al. (2014a) and lake current characteristics modified from Han et al. (2016).

FIGURE 4 | (A) Plot between C/N and TOC. Typical C/N ratio ranges for higher plants and phytoplankton referred to the study by Hedges and Oades. (1997) and Talbot and Lærdal. (2000) were labeled. (B) Relationship between total nitrogen (TN) and TOC.

the result that no aragonite was found in the basin soil and fluvial sediments (**Figure 2**). The mineralogical measurement using both FTIR and XRD found that aragonite dominated the carbonate mineral in Lake Qinghai sediments. Within FTIR spectra, the absorption peak shapes of fluvial sediments and topsoil samples are similar to those of pure calcite, and the characteristic peak position is at ca. 2,513 cm^{-1} (**Figure 2A**), whereas the shapes of lacustrine sediments are similar to those of pure aragonite, and the characteristic peak position is at ca. 2,522 cm^{-1} (**Figure 2A**). The XRD results (**Figure 2B**) further supported the judgment that aragonite (d$_{104}$ = 3.39) was the dominant component of carbonate in Lake Qinghai surficial sediments, which was consistent with the results from the study by Yu and Kelts. (2002). In addition, the δ^{18}O values of carbonate in Lake

Qinghai sediments were more positive than those in the surrounding topsoil and were close to equilibrium δ^{18}O values of lake water (Liu et al., 2018), which also supported the mainly authigenic origin of carbonate in the lake. The evidence demonstrated the rationalization of the assumption selected in this study that authigenic carbonates accounted for approximately 95% of the total carbonates in Lake Qinghai surface sediments based on estimation of Xu et al. (2010).

Spatial Variation of Organic and Inorganic Carbon

TOC and TIC contents in Lake Qinghai had different spatial patterns. TOC content was the highest in the northern lake area

and declined outward, with a prominent low value in the shallow part facing the Buha River mouth and the eastern lake area (**Figure 3A**). The spatial variation of TOC was associated with different driving forces. High TOC content in the northern lake area was corresponding to a relatively lower sedimentation rate and intense human activities in the north bank, along which farmland and residential land concentrates (**Figures 3C**,D). The sedimentation rate in the northern lake area was relatively lower despite the three rivers' inflow (**Figure 1**, **Figure 3C**). The limited dilution effect of terrestrial detrital materials was conducive to the accumulation of organic carbon. In addition, anthropogenic nutrient loading by fertilizer use and domestic wastewater increased the trophic level of the northern lake area, generating such high level of TOC concentration in this part.

The low TOC content at the shallow part near the Buha River mouth (water depth: 10–18 m, **Figure 1** and **Table 1**) was the result of the high sedimentation rate and low fine-grain proportion. The high sedimentation rate in the Buha River mouth (**Figure 3C**) reflected a wealth of terrestrial debris input diluting sedimentary organic carbon concentration (Xu et al., 2010). Besides, a good correlation was found between organic matter concentration and the surface area of grains in sediment (Mayer, 1994; Hedges and Keil, 1995) because fine-grained components are effective to organic carbon preservation and are easily resuspended and migrated away from shallow water to the deep water zone (Thompson and Eglinton, 1978; Tenzer et al., 1997). The proportion of coarse particles in the littoral zone and estuary areas is greater than that of coarse particles in the deep lake zone due to continually discharged terrestrial clastic minerals (Håkanson and Jansson, 2002). Therefore, there was quite a low TOC content in the area near the Buha River mouth. For the eastern lake area with a low TOC content, there was a considerable area of sand and bare land in the east bank with no river flowing in (**Figure 1**). Rare human settlements appeared there, resulting in no point source pollution. These possibly resulted jointly in a lower TOC content. In summary, the distributions of TOC in Lake Qinghai were mainly related to sedimentation rates, human activities, and the grain size.

In contrast to TOC, the TIC content displayed a pattern that approximated concentric circles rising from the lakeshore to the center (**Figure 3B**). Supersaturation of carbonate in lake water determined TIC deposition in Lake Qinghai (Liu et al., 2003). However, inflow rivers are unevenly distributed (**Figure 1**). The lake area accepting riverine fresh water may experience salinity reduction and a decrease in carbonate saturation, hence a diminishment of carbonate deposition and TIC content in the sediment. Quite the opposite, in the central part of the lake where there is shortage of freshwater replenishment, evaporation has more intensive influence on the lake water, which may cause relatively more carbonate precipitation (Shen et al., 2001).
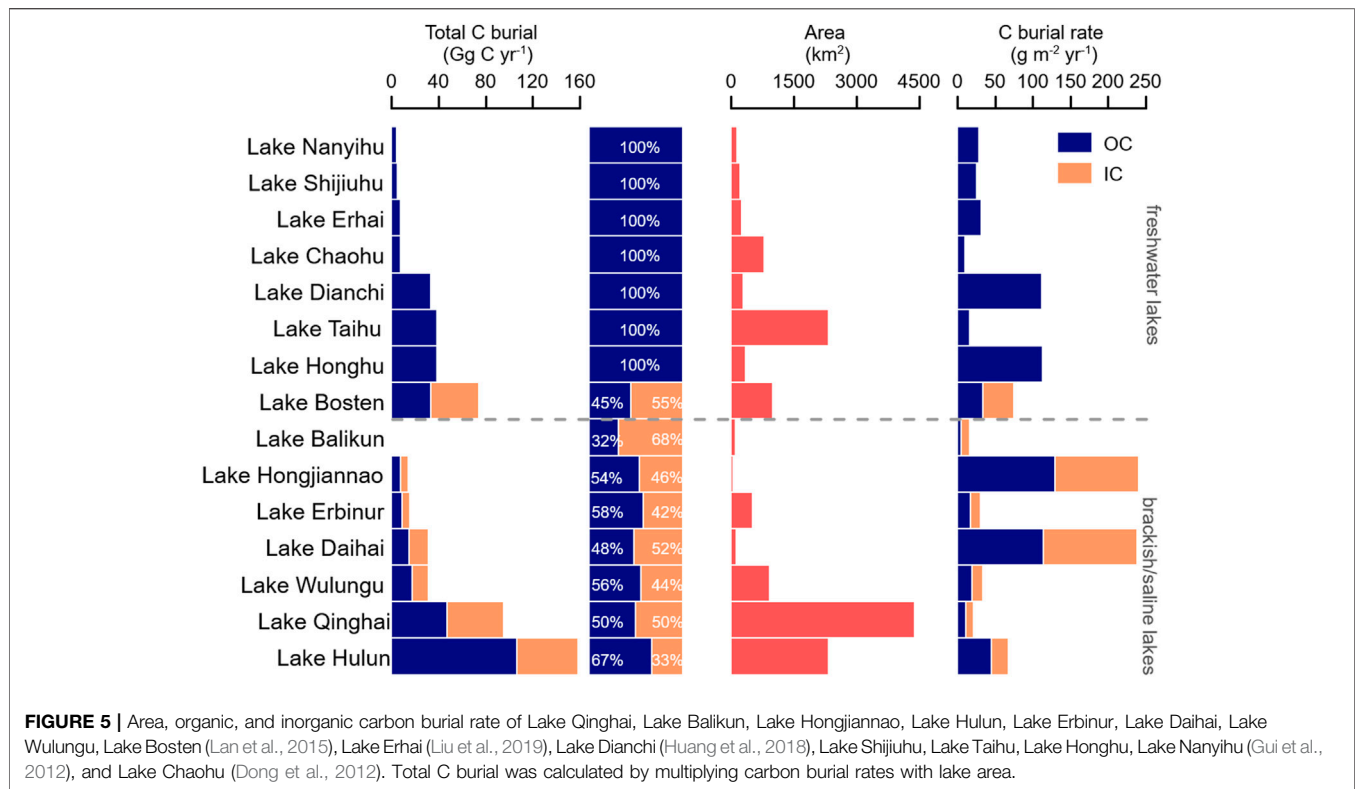
On the other hand, the prevailing northwest wind-induced overall eastward and clockwise water currents (**Figure 3D**) (Han et al., 2016). Sediment focusing related to waves and currents may redistribute carbonate minerals to the central and deep basins (Håkanson and Jansson, 2002; Terasmaa and Punning, 2006). This can be reflected by the significantly low TIC content in the upwind northwestern lake area (**Figure 3B**). Therefore, TIC distribution in Lake Qinghai can be mainly attributed to the hydro-chemical characteristics of its lake water and hydraulic conditions controlled by prevailing northwest wind.

Total C Burial Estimation in Lake Qinghai Surficial Sediments

In order to investigate how much carbon was sequestered in Lake Qinghai in recent years, total organic and inorganic carbon burial were estimated by multiplying carbon burial rates with the lake area. Consequently, OCBRs ranged from 4.54 to 30.50 (average value of 10.80) $g\,C\,m^{-2}\,yr^{-1}$, while ICBRs were between 3.32–24.46 (mean value of 10.86) $g\,C\,m^{-2}\,yr^{-1}$. Correspondingly, total OC burial was $47.50 \pm 22.68\,Gg\,C\,yr^{-1}$ and IC burial was $47.77 \pm 19.73\,Gg\,C\,yr^{-1}$. Thus, total annual carbon burial in Lake Qinghai was concluded to be $95.27 \pm 37.74\,Gg\,C\,yr^{-1}$, which is slightly higher than $76\,Gg\,C\,yr^{-1}$ as reported in the study by Xu et al. (2013), which is estimated based on samples mainly derived from central and eastern Lake Qinghai. On the one hand, at least for the last 100–200 years, contemporary lake C burial was likely to be higher than that of the historical value (Dietz et al., 2015; Heathcote et al., 2015; Zhang et al., 2019). On the other hand, the difference in carbon burial estimation for this large lake might be made possible by sampling at different sites. In this study, estimated from OCBRs and ICBRs of each sedimentary sample at 26 sites, total OC and IC burial were vastly different with coefficients of variation of 0.48 and 0.41, respectively. To prevent over/underestimation, it is necessary to consider the spatial heterogeneity while assessing the total C burial of a whole lake based merely on a single sample or sedimentary core, even if sampling in deepwater areas with a stable sedimentary environment of a lake.

The OCBR of Lake Qinghai ($14.7\,g\,C\,m^{-2}\,yr^{-1}$) was in line with the global mean value of $10–15\,g\,m^{-2}\,yr^{-1}$ (Tranvik et al., 2009) and close to the average level in the Tibet Plateau Lake Region ($14.3\,g\,m^{-2}\,yr^{-1}$) (Zhang et al., 2017), but it was lower than that of other lake regions in China (Zhang et al., 2017). To be specific, for the last 150 years, the mean OCBR of lakes was $25.4\,g\,m^{-2}\,yr^{-1}$ in the Northeast Mountain and Plain Lake Region, $30.6\,g\,m^{-2}\,yr^{-1}$ in the Eastern Plain Lake Region, $30.4\,g\,m^{-2}\,yr^{-1}$ in the Inner Mongolian-Xinjiang Lake Region, and $24.3\,g\,m^{-2}\,yr^{-1}$ in the Yunnan-Guizhou Plateau Lake Region (Zhang et al., 2017). A possible reason of lower OCBRs in Lake Qinghai may be the lower trophic level and primary productivity, owing to a lower temperature and less anthropogenic pollution (Wang et al., 1998; Bi et al., 2018). The oligotrophic Lake Alchichica, Mexico, with similar hypolimnetic anoxia conducive to organic carbon preservation, had OCBRs ($14.9\,g\,m^{-2}\,yr^{-1}$) (Alcocer et al., 201 4) comparable to those of Lake Qinghai. Taken equally, lakes of the high northern latitudes had low OCBRs due to frigid climatic patterns and scarce anthropogenic impacts. For example, OCBRs ranged

FIGURE 5 | Area, organic, and inorganic carbon burial rate of Lake Qinghai, Lake Balikun, Lake Hongjiannao, Lake Hulun, Lake Erbinur, Lake Daihai, Lake Wulungu, Lake Bosten (Lan et al., 2015), Lake Erhai (Liu et al., 2019), Lake Dianchi (Huang et al., 2018), Lake Shijiuhu, Lake Taihu, Lake Honghu, Lake Nanyihu (Gui et al., 2012), and Lake Chaohu (Dong et al., 2012). Total C burial was calculated by multiplying carbon burial rates with lake area.

$1–10 \, \mathrm{g \, m^{-2} \, yr^{-1}}$ for SW Greenland lakes (Anderson et al., 2019) and from 5.3 to $24.6 \, \mathrm{g \, m^{-2} \, yr^{-1}}$ for Arctic Sweden (Lundin et al., 2015).

Lake Qinghai had obviously lower OCBRs than many eutrophic lakes, such as Lake Greifen in Switzerland ($50–60 \, \mathrm{g \, C \, m^{-2} \, yr^{-1}}$) (Hollander et al., 1992), Rostherne Mere ($96.10 \, \mathrm{g \, C \, m^{-2} \, yr^{-1}}$), and Tatton Mere ($62.51 \, \mathrm{g \, C \, m^{-2} \, yr^{-1}}$) in the United Kingdom (Scott, 2014). In Minnesota, the United States, OCBRs in ~89% of agriculturally affected lakes were above $50 \, \mathrm{g \, C \, m^{-2} \, yr^{-1}}$ (Anderson et al., 2013). Notably, the eutrophic Lake Chaohu that has undergone heavy pollution had a lower OCBR of $10.01 \, \mathrm{g \, m^{-2} \, yr^{-1}}$ than Lake Qinghai (Wu et al., 2016) (**Figure 5**). The exorbitant nutrient levels even led to a decreased carbon sequestration capacity of Lake Chaohu. It was deduced that this owed much to the degradation and decomposition of macrophytes when the lake switched to be cyanobacteria-dominated (Wu et al., 2016).

Large lakes generally have slow C sedimentation rates (Algesten et al., 2004), however, the large Lake Hulun (2,330 km^2) showed a relatively higher OCBR ($45.5 \, \mathrm{g \, m^{-2} \, yr^{-1}}$) (Lan et al., 2015) (**Figure 5**). Lake Hulun has long suffered natural eutrophication resulting from the combined influences of climate warming and drying, water volume reduction, and increased evaporation (Chuai, 2011). In brief, increased primary productivity of a lake, whether it is the consequence of growing temperature or anthropogenic nutrient loading, can thereby promote organic carbon accumulation, resulting in high OCBRs in lake sediments.

Different from open freshwater lakes that mainly deposit organic carbon, inorganic carbon burial contributed approximately 50% to the total carbon burial in Lake Qinghai (**Figure 5**). Because of the supersaturation of carbonate minerals in water bodies, inorganically precipitated carbonate generally exists in brackish and saline lakes (Einsele et al., 2001; Lammers and Depaolo, 2010; Balci et al., 2018). The semi-enclosed status and high salinity condition in Lake Qinghai lead to a mass of carbonate precipitation and sequestration, resulting in a large IC burial proportion. High IC burial proportion was also found in multiple lakes that have similar hydro-chemical characteristics to Qinghai-Tibet alpine and arid/semiarid regions (**Figure 5**). For example, IC burial accounted for 68, 46, 42, 52, 44, and 33% of the total C burial in Lake Balikun, Lake Hongjiannao, Lake Erbinur, Lake Daihai, Lake Wulungu, and Lake Hulun, respectively (Lan et al., 2015) (**Figure 5**). It should be noted that a tiny minority of freshwater lakes also have abundant carbonate minerals. For example, IC burial in freshwater Lake Bosten was even higher than OC burial (Lan et al., 2015), possibly due to the formation of biogenic carbonate or seasonal changes in water chemistry (Kelts and Hsü, 1978; Loeppert and Suarez, 1996). Anyway, saline lakes compose a crucial inorganic carbon pool in addition to an organic carbon pool.

Owing to a large area and high IC burial, total annual C burial of Lake Qinghai surficial sediments ($95.27 \pm 37.74 \, \mathrm{Gg \, C \, yr^{-1}}$) was higher than that in many other lakes. Among the 15 lakes shown in **Figure 5**, Lake Qinghai ranked first in the area and second in total annual C burial despite the relatively lower carbon burial rates. Most lakes (10 of 15) with a smaller surface area showed a lower

total C burial even with a much higher organic and/or inorganic carbon burial rate (**Figure 5**). Based on a total lake area of 3,185.06 km^2, only 11.5 Gg C yr^{-1} of organic carbon was estimated to be sequestrated annually in sediments of lakes in SW Greenland (Anderson et al., 2019). The organic form of carbon exists in all lakes, but some specific lakes have additional authigenic IC precipitation (Cole et al., 2007), which increases the total carbon burial (**Figure 5**). Therefore, the lake area and water body types are main factors that strongly affect the carbon burial in different lakes, which tallies with the conclusion of Clow et al. (2015).

A large number of lakes (most are closed or semi-closed saltwater type) are spread over the Qinghai–Tibet Plateau, with an area more than 50% of the total area of lakes in China (Wan et al., 2016). Carbon burial in Tibet Plateau lakes is therefore undoubtedly an important component of regional and even global carbon cycle which remain unstudied. More attention and exploration are required for comprehensive understanding of organic and inorganic carbon burial in lake sediments at the Third Pole.

CONCLUSION

Organic carbon of Lake Qinghai was mainly derived from aquatic organisms and well preserved in lake sediments. The TOC content ranged from 1.4 to 4.8% (mean 3.1%) with significant spatial divergence. It was higher in the northern lake area adjacent to the bank with strong human activities and lower in the Buha River mouth and the eastern lake area. The inorganic carbon was dominated by authigenic aragonite with content ranging 1.5–3.8% (mean 3.0%), showing a high value in the lake central area and a significantly low level in the northwestern lake area. This spatial pattern of TIC can be mainly attributed to hydro-chemical characteristics of its lake water and hydraulic conditions controlled by prevailing northwest wind. The OCBR of Lake Qinghai surficial sediments ranged from 4.54 to 30.50 g C m^{-2} yr^{-1}, while ICBRs varied from 3.32 to 24.46 g C m^{-2} yr^{-1}. Correspondingly, total annual organic carbon burial (47.50 ± 22.68 Gg C yr^{-1}) was approximately equal to inorganic carbon burial (47.77 ± 19.73 Gg C yr^{-1}). Both OC burial and IC burial contributed about 50%, suggesting that saline lakes are not only a crucial organic carbon pool but also an important inorganic carbon pool. Lake Qinghai sequestered 95.27 ± 37.74 Gg C yr^{-1}, demonstrating a huge carbon sequestration potential due to its

large area. Our study provides scientific and technological support for understanding, under the influence of human activities and hydraulic condition, the spatial variation characteristics of carbon in large and deepwater lakes with conditions analogous with Lake Qinghai. This is also an archive for further research on carbon burial in plateau lakes on different timescales.

DATA AVAILABILITY STATEMENT

AUTHOR CONTRIBUTIONS

CX performed the test, data processing, analysis and wrote the manuscript. MX conceptualized and designed the research, and reviewed the manuscript. SY reviewed and edited the manuscript. WZ processed the data and plotted. ZB processed the data and plotted. ZB analyzed the data and plotted. ZE funded the research.

FUNDING

ACKNOWLEDGMENTS

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