Chin. J. Geochem. (2015) 34(3):289–298
DOI 10.1007/s11631-015-0047-5

ORIGINAL ARTICLE

A large carbon pool in lake sediments over the arid/semiarid region, NW China

Jianghu Lan[1] · Hai Xu[1] · Bin Liu[1,2] · Enguo Sheng[1,3] · Jiangtao Zhao[1] · Keke Yu[1,3]

Received: 8 October 2014 / Revised: 21 January 2015 / Accepted: 9 March 2015 / Published online: 27 March 2015
© Science Press, Institute of Geochemistry, CAS and Springer-Verlag Berlin Heidelberg 2015

Abstract Carbon burial in lake sediments is an important component of the global carbon cycle. However, little is known about the magnitude of carbon sequestered in lake sediments over the arid/semiarid region of China (ASAC). In this study, we estimate both organic and inorganic carbon burial since ~AD 1800 based on nine lakes in ASAC, and discuss the most plausible factors controlling carbon burial. Our estimates show that the annual organic carbon burial rate (OCBR) ranges from 5.3 to 129.8 g cm^{-2} $year^{-1}$ (weighted mean of 49.9 g cm^{-2} $year^{-1}$), leading to a standing stock of 1.1–24.0 kg cm^{-2} (weighted mean of 8.6 kg cm^{-2}) and a regional sum of ~108 Tg organic carbon sequestered since ~AD 1800. The annual inorganic carbon burial rate (ICBR) ranges from 11.4 to 124.0 g cm^{-2} $year^{-1}$ (weighted mean of 48.3 g cm^{-2} $year^{-1}$), which is slightly lower than OCBR. The inorganic carbon standing stock ranges from 2.4 to 26.0 kg cm^{-2} (weighted mean of 8.1 kg cm^{-2}), resulting in a sum of ~101 Tg regional inorganic carbon burial since ~AD 1800, which is slightly lower than the organic carbon sequestration. OCBR in ASAC shows a continuously increasing trend since ~AD 1950, which is possibly due to the high autochthonous and allochthonous primary production and subsequently high sedimentation rate in the lakes. This increasing carbon burial is possibly related to both climatic changes and enhanced anthropogenic activities, such as land use change, deforestation, and eutrophication in the lake. Furthermore, OCBR and ICBR are expected to continuously increase under the scenario of increasing precipitation and runoff and enhanced anthropogenic activities. The results of this research show that the buried carbon in lake sediments of the ASAC region constitutes a significant and large carbon pool, which should be considered and integrated into the global carbon cycle.

Keywords Organic and inorganic carbon burials · Lake sediments · ASAC · Carbon cycle

✉ Jianghu Lan
lanjh@ieecas.cn; lanjh115@163.com

[1] State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710061, China

[2] College of Resources and Environment, Zunyi Normal College, Zunyi 563002, China

[3] University of Chinese Academy of Sciences, Beijing 100049, China

1 Introduction

Inland water systems are important transfer points for balancing the global atmospheric, terrestrial biosphere, and oceanic carbon cycles (Kastowski et al. 2011). Carbon dioxide is directly and indirectly drawn-down from the atmosphere by biomass production and rock weathering, and transported by rivers to the ocean and/or lakes in both organic and inorganic carbon forms (Kastowski et al. 2011). In addition, carbon dioxide is directly drawn down from the atmosphere by hydrophytes, and subsequently sequestered in large amounts into sediments in organic form (Sobek et al. 2009). Based on Pareto distribution, Dean and Gorham (1998) suggested that the inland water carbon pools, including lakes, reservoirs, and wetlands, collectively cover less than 2 % of Earth's surface and constitute a carbon sink of about 300 Tg $year^{-1}$, which is three times larger than ocean carbon pools. Downing et al. (2006) proposed that about 4.6 million km^2 of continental land (more than 3 %) is covered by water, which is twice as large as previously assumed. Therefore, carbon burial in lake sediments should be a substantial and an important component of the global carbon cycle (Dean and Gorham 1998; Cole et al. 2007). Lake sediments play an important role in removing carbon from the actively cycling carbon pools (Sobek et al. 2009), and account for a large proportion of previously "missing" carbon by processing large amounts of terrestrially derived carbon, although certain fractions of carbon burial are returned to the atmosphere by degassing (Battin et al. 2009; Downing 2009). However, due to the small coverage of Earth's land surface, little attention has been directed to the role of carbon burial in lakes within the global carbon cycle.

In recent years, an increasing number of studies have focused on lake carbon burial (Kortelainen et al. 2004; Alin and Johnson 2007; Downing et al. 2008; Kastowski et al. 2011; Dong et al. 2012), among which nearly all studies focused on organic carbon burial, while inorganic carbon burial was, in most cases, overlooked. In addition, very few studies have focused on lake carbon burial in China even though the lake areas are large (Dong et al. 2012). In this study, we estimate the organic and inorganic carbon burial from nine lakes in the arid/semiarid region of China (ASAC) since ~AD 1800, and discuss the most plausible factors controlling carbon burial.

2 Background and methods

2.1 Background

The ASAC is located in northwestern China and has a total area of ~2.55 million km^2. It is situated in the temperate continental climatic zone, with annual temperatures ranging from 0 to 10 °C. Precipitation over the ASAC region is mostly <400 mm per year, which is much less than the corresponding evaporation (~2000 mm per year) (Table 1). These climatic conditions lead to low vegetative cover, vulnerable ecosystems, and strong physical weathering over most of the ASAC area. Six provinces and/or autonomous regions of China (Xinjiang, Gansu, Inner Mongolia, Ningxia, Shannxi, and Shanxi) are located within the ASAC.

2.2 Methods

In this study, nine well-studied lakes in ASAC were chosen for estimating carbon burial based on quality of published sedimentation rate and organic and/or inorganic carbon content (Fig. 1). To assess the burial rate of organic and inorganic carbon in each lake, the total organic carbon (TOC), total inorganic carbon (TIC), sedimentation rate, and dry bulk density (DBD) of the sediment are required. Once these parameters are derived it is possible to assess the organic carbon burial rate (OCBR) and inorganic carbon burial rate (ICBR) based on the following equations:

$$\text{OCBR} = \text{TOC} \times \text{sedimentation rate} \times \text{DBD} \quad (1)$$

$$\text{ICBR} = \text{TIC} \times \text{sedimentation rate} \times \text{DBD} \quad (2)$$

We then proceed to calculate the total burial of organic carbon and inorganic carbon in the ASAC based on estimated lake surface area derived by the Pareto distribution method. In the following sections we derive each one of the required parameters.

2.2.1 *Sedimentation rate*

Assessment of carbon burial in lake sediments requires knowledge of the sedimentation rate. The linear interpolation/extrapolation of sedimentation rates used in this study is calculated using age-depth models, which are usually established by ^{210}Pb and/or ^{137}Cs (Fig. 2).

The results show that the sedimentation rate may have increased since ~AD 1950. This rate change have played a significant role in carbon burial in lake sediments (see discussion below).

2.2.2 *Dry bulk density*

Estimating carbon burial in lake sediments requires DBD data; unfortunately, it is generally not reported in the literature. Therefore, we choose an empirical approach to estimate DBD. A large number of studies show that DBD of lake sediments is closely related to TOC. For example, based on six alpine lake sediment cores, Menounos (1997) found a significant, nonlinear relationship between TOC and DBD ($\text{DBD} = 1.881 - 0.385 \times \ln(\text{TOC})$; $R^2 = 0.89$). Avnimelech et al. (2001) examined the correlation between TOC and DBD in six different submerged sediments, including lake, pond, river, and sea floor sediments, and found that DBD is inversely related to TOC content ($\text{DBD} = 1.776 - 0.363 \times \ln(\text{TOC})$; $R^2 = 0.70$). Using three lakes in Minnesota, Dean and Gorham (1998) showed that DBD of lake sediments is mainly dependent on TOC content ($\text{DBD} = 1.665 \times \text{TOC}^{-0.887}$). Taking into consideration the effect of compaction, Campbell et al. (2000) presented an additional relationship between TOC and DBD. A complication in the DBD estimation may arise when TOC content is less than 5 %, because the data used to construct the best fit line does not include low TOC, as mentioned by Kastowski et al. (2011). Overall, DBD may be overestimated or underestimated when TOC is very low or very high (Kastowski et al. 2011). Here, we combine different empirical relationships between TOC and DBD in lake sediments generated

Table 1 Selected limnological characteristics of the nine lakes

Name	Location	Lake area km^2	Catchment area km^2	Mean water depth (m)	Annual temperature (°C)	Annual precipitation (mm)	Annual evaporation (mm)	pH	Salinity ($g\ L^{-1}$)	Reference
Erbinur lake	44°55′N, 82°40′E	522	50,321	1.2	8.3	95	1315	8.4–9.0	80–120	Ma et al. (2011); Wu et al. (2009)
Balikun lake	43°40′N, 92°47′E	116	4514	0.6	1.1	202	1638	8.9	59	Xue and Zhong (2011)
Bosten lake	42°05′N, 87°03′E	1000	55,600	8.0	8.3	70	2000	8.3–9.0	1.1	Wünnemann et al. (2006); Chen et al. (2006)
Wulun lake	47°13′N, 87°17′E	927	35,440	8.0	3.4	117	1844	7.7–9.2	2.1	Jiang et al. (2007); Liu et al. (Liu et al. 2008a, b)
Jili lake	46°55′N, 87°25′E	174	na	9.9	3.4	117	1844	8.2	0.4	Jiang et al. (2010)
Chaiwopu lake	43°30′N, 87°54′E	28	na	2.0	5.0	64	2716	9.04	6.8	Wu and Ma (2010)
Daihai lake	40°33′N, 112°39′E	133	2289	7.4	5.1	350–450	1924	8.8	4.4	Sun et al. (2006); Xiao et al. (2004, 2006)
Hulun lake	48°55′N, 117°08E	2339	153,669	5.7	−0.5	285	1650	8.9	1	Zhao et al. (2008)
Hongjiannao lake	39°06′N, 109°53E	60	1493	8.2	8.5	400	2000	8.9	3.5	Li et al. (2010); Shen et al. (2005)

from the former (Fig. 3) and divide the estimated DBD into two segments: when TOC content ranges from 2 % to 10 %, we use Eq. (3):

$$DBD = -0.3386 \times \ln(TOC) + 0.9527 \quad (3)$$

While when DBD is higher than 10 % or lower than 2 %, Eq. (4) is used:

$$DBD = 1.2726 \times TOC^{-0.8201} \quad (4)$$

However, when TOC is lower than a threshold value, a persistent increase in DBD should probably not occur with decreasing TOC content in lake sediments. Thus, DBD in lake sediments cannot appreciably be calculated by the equations proposed above. Extremely low TOC has often been reported in ASAC because of the low annual precipitation and high potential evaporation. Therefore, when the TOC content was less than 0.5 % we use a DBD value of 2.5 g cm^{-3} (Richerson et al. 2008).

In cases where no TOC data were available, we calculated TOC data from organic matter content (OM) (Eq. 5)— (Dean 1974, 1999) or loss on ignition at 550 °C (LOI_{550}) (Eq. 6)—(Santisteban et al. 2004):

$$TOC = [1/(2.13 \pm 0.4)] \times OM \quad (5)$$

$$TOC = 0.634 \times LOI_{550} - 1.830 \quad (6)$$

TIC was estimated in two ways: loss on ignition at 950 °C (LOI_{950}) using—(Santisteban et al. 2004):

$$TIC = 0.254 \times LOI_{950} - 0.039 \quad (7)$$

or calculated by dividing carbonate content by 8.33 (Dean 1999), which is the proportion of carbon in carbonate.

2.2.3 *Total lake surface area*

Evaluation of carbon burial in lake sediments of ASAC requires an estimate of the total lake surface area. Previous estimates suggested that large lakes dominate the global lake area with a total lake surface area of about 2–2.8 × 10^6 km^2 (Meybeck 1995; Kalff 2001; Shiklomanov and Rodda 2003). Downing et al. (2006) added

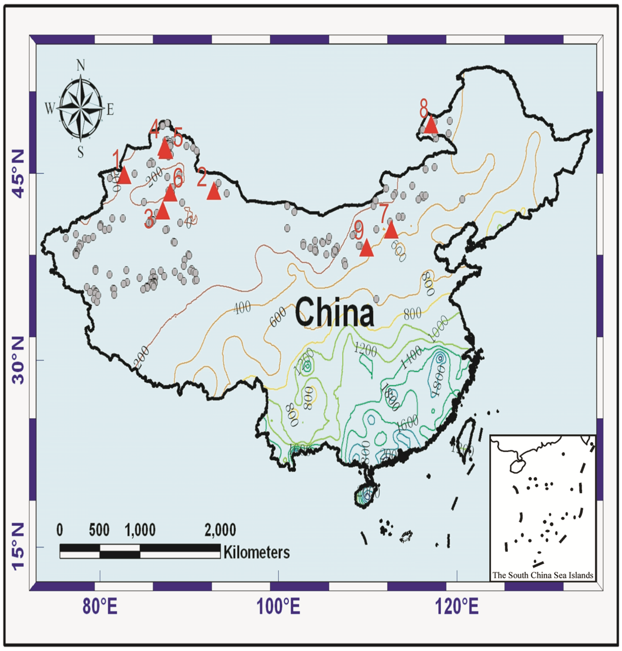

Fig. 1 Location map of the 9 studied lakes in ASAC, their properties are listed in Table 1. The site numbers correspond to: (*1*) Erbinur Lake, (*2*) Balikun Lake, (*3*) Bosten Lake, (*4*) Wulungu Lake, (*5*) Jili Lake, (*6*) Chaiwopu Lake, (*7*) Daihai Lake, (*8*) Hulun Llake, and (*9*) Hongjiannao Lake. The contours are the mean annual precipitation of China. The *circles* filled with *grey color* are all of the lakes in ASAC with area more than 1 km^2

small water bodies and using the Pareto distribution proposed that the global lake area is $\sim 4.6 \times 10^6$ km^2.

Ma et al. (2010, 2011) and Lehner and Döll (2004) provided comprehensive lake surface data in China. Based on satellite images from CBERS CCD and Landsat TM/ETM, Ma et al. (2010, 2011) suggested that there are presently 2693 natural lakes in China with an area larger than 1 km^2. The lake distribution, as proposed by Lehner and Döll (2004) can generally be described by the size-frequency function:

$$N_a = aA^{-b} \tag{8}$$

where N_a is the number of lakes larger and/or equal to a specific lake size A, and a and b are fitted equation parameters.

In this study, we mainly analyze lakes in ASAC larger than 1 km^2 and neglect those smaller than 1 km^2 due to lack of data. Based on comprehensive lake data in this area (Ma et al. 2010, 2011), we found that the number of lakes in ASAC follows the Pareto distribution, where the number of lakes increases exponentially with decreasing lake area (Fig. 4a) described by:

$$N_a = 404.73A^{-2.8923}, \ R^2 = 0.9607 \tag{9}$$

And the total surface area of this region also can be obtained from Ma et al. (2010, 2011), who implied that there is a total lake surface area of about 12,590 km^2, with 514 lakes > 1 km^2 and 19 lakes > 100 km^2 (Figs. 1, 4b).

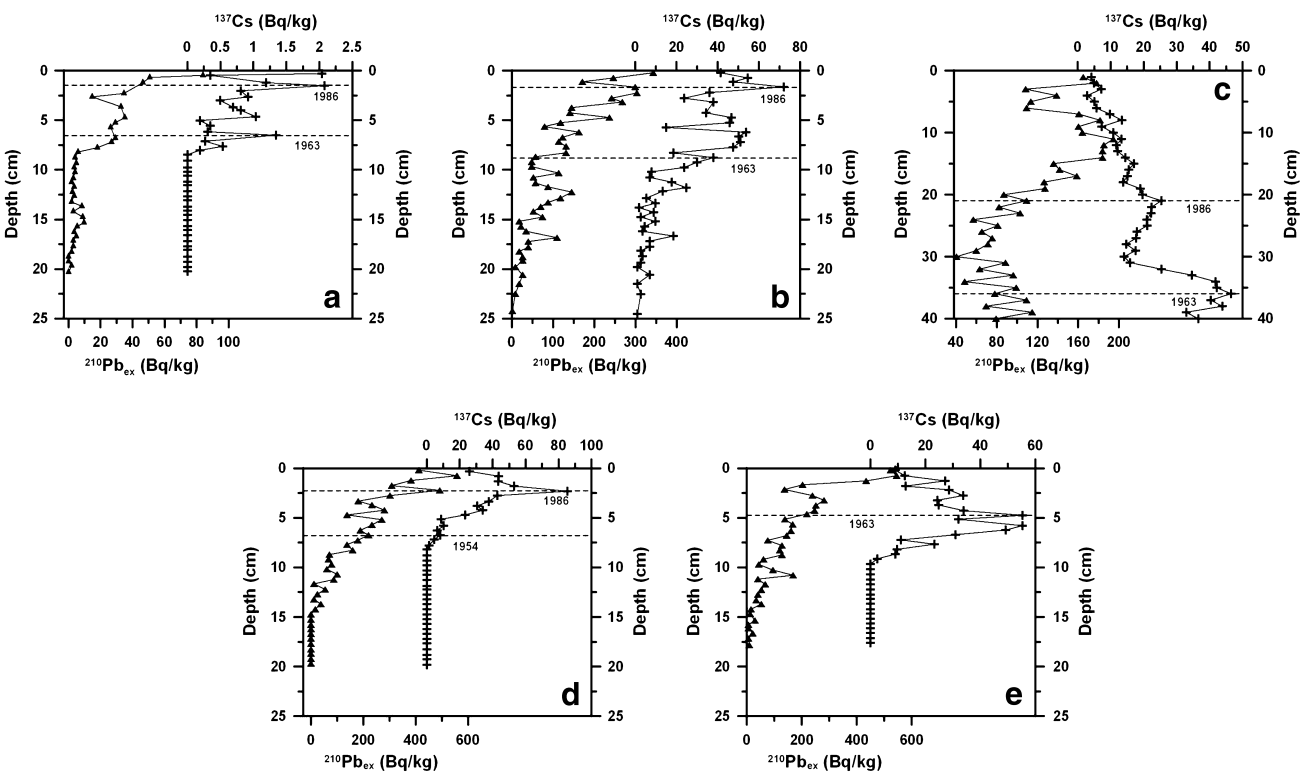

Fig. 2 The ^{210}Pb and ^{137}Cs activities in part of the selected lakes. **a** Erbinur Lake (Ma et al. 2011; Wu et al. 2009). **b** Bosten Lake (Chen et al. 2006). **c** Daihai Lake (Lan et al. 2011). **d** Wulungu Lake (Liu et al. 2008a, b). **e** Jili Lake (Jiang et al. 2010)

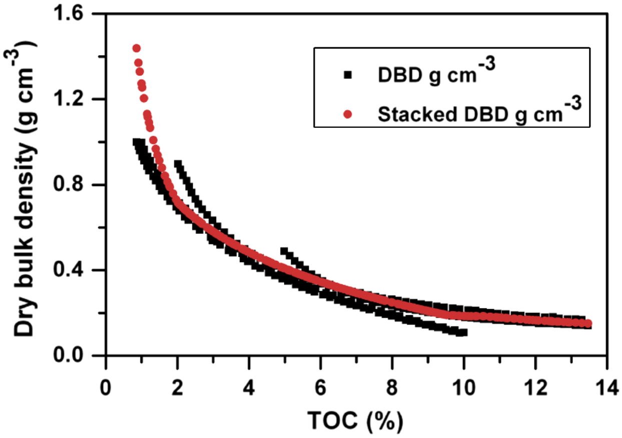

Fig. 3 The empirical relationship between total organic carbon (TOC) content and dry bulk density (DBD) in lake sediments. The *square dotted lines* are results from Menounos (1997), Avnimelech et al. (2001), Campbell et al. (2000), and Dean and Gorham (1998). The *red dotted line* is applied for this study, stacked from the formers

3 Results: estimating the carbon burial rate

Based on the parameters calculated above and using Eqs. 1 and 2, the results show that OCBR ranges from 5.3 to 129.8 g cm^{-2} year^{-1} with a weighted mean of 49.9 g cm^{-2} year^{-1}, resulting in an organic carbon standing stock of about 1.1–24.0 kg cm^{-2} (weighted mean 8.6 kg cm^{-2}) and a total regional organic carbon sequestration of ~108 TgC since ~AD 1800 for lakes larger than 1 km^2 in ASAC (Table 2).

The ICBR in ASAC was calculated as ranging between 11.4 and 124.0 g cm^{-2} year^{-1}, with a weighted mean of 48.3 g cm^{-2} year^{-1} resulting in an inorganic carbon standing stock of 2.4–26.0 kg cm^{-2} (weighted mean 8.1 kg cm^{-2}) and a TIC sequestration of ~101 TgC in lake sediments throughout the whole arid/semiarid area, both of which are slightly smaller than the corresponding organic carbon burial (Table 2).

4 Discussion

Carbon stored in atmospheric, oceanic, and terrestrial ecosystems are important parameters of the climate system and have thus received widespread attention (Fang et al. 2001; Sabine et al. 2004; Canadell et al. 2007; Bloom et al. 2010; Bond-Lamberty and Thomson 2010; Frank et al. 2010; Pan et al. 2011; Ballantyne et al. 2012). When constructing the various components of the carbon cycle, it is assumed that the oceans take up approximately one third of the CO_2 arising from fossil-fuel emissions, with the remaining two thirds divided between terrestrial ecosystems and the atmosphere. However, there still appears to be a missing carbon sink, which may be accounted for in terrestrial ecosystems (Siegenthaler and Sarmiento 1993). Thus it is crucial to assess the contributions of the various parts of the terrestrial ecosystems to the sequestration of carbon in order to better our understanding of the process that might occur under a regime of global warming. Models predict that in northwestern China, precipitation will increase as a consequence of global warming and enhance the water cycle (Shi et al. 2007). The consequence of this process to the carbon cycle will be enhanced carbon transport to lakes from their catchments and subsequent escape to the atmosphere or sequestering in lake sediments (Molot and Dillon 1996).

4.1 OCBR trend in ASAC since ~AD 1800

OCBR in most ASAC lakes, excluding Ebinur Lake, has generally increased since ~AD 1950 (Fig. 5a). However, the temporal variations among those lakes are considerably different.

To obtain a more comprehensive understanding of carbon burial in ASAC, we considered in more detail the impacts on carbon burial of precipitation, proportion of cropland and forest, population, and sedimentation rate.

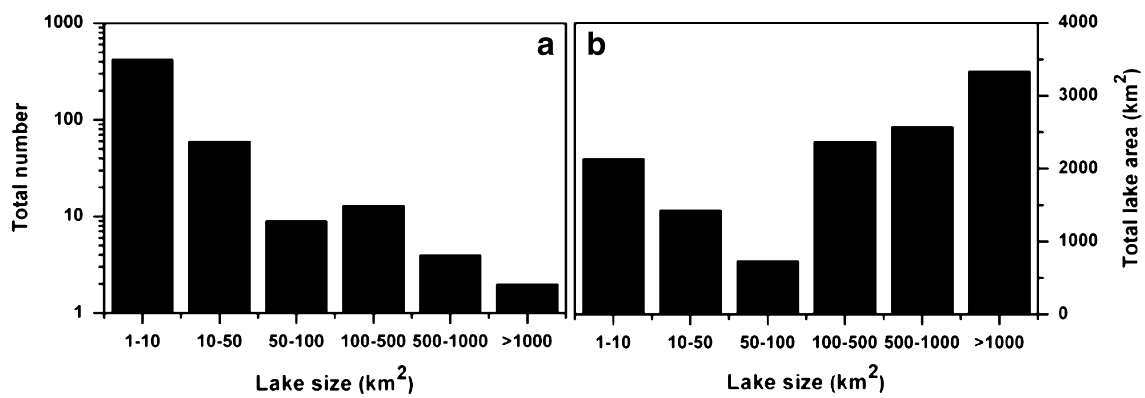

Fig. 4 Total lake number of each lake size class in ASAC (**a**) and total lake surface area (**b**)

Table 2 Organic and inorganic carbon burial in lake sediments of ASAC

Name	Organic carbon		Inorganic carbon	
	OCBR (g cm^{-2} $year^{-1}$)	Standing stock (kg cm^{-2})	ICBR (g $cm^{-2}year^{-1}$)	Standing stock (kg cm^{-2})
Erbinur lake	17.5	3.6	12.8	2.7
Balikun lake	5.3	1.1	11.4	2.4
Bosten lake	33.5	7.0	41.0	8.6
Wulun lake	18.9	4.0	15.1	3.2
Jili lake	19.1	4.0	na	na
Chaiwopu lake	65.1	13.7	na	na
Daihai lake	114.2	24.0	124.0	26.0
Hulun lake	45.5	9.6	22.4	4.7
Hongjiannao lake	129.8	10.4	111.2	8.9
Mean	49.9	8.6	48.3	8.1

na not available

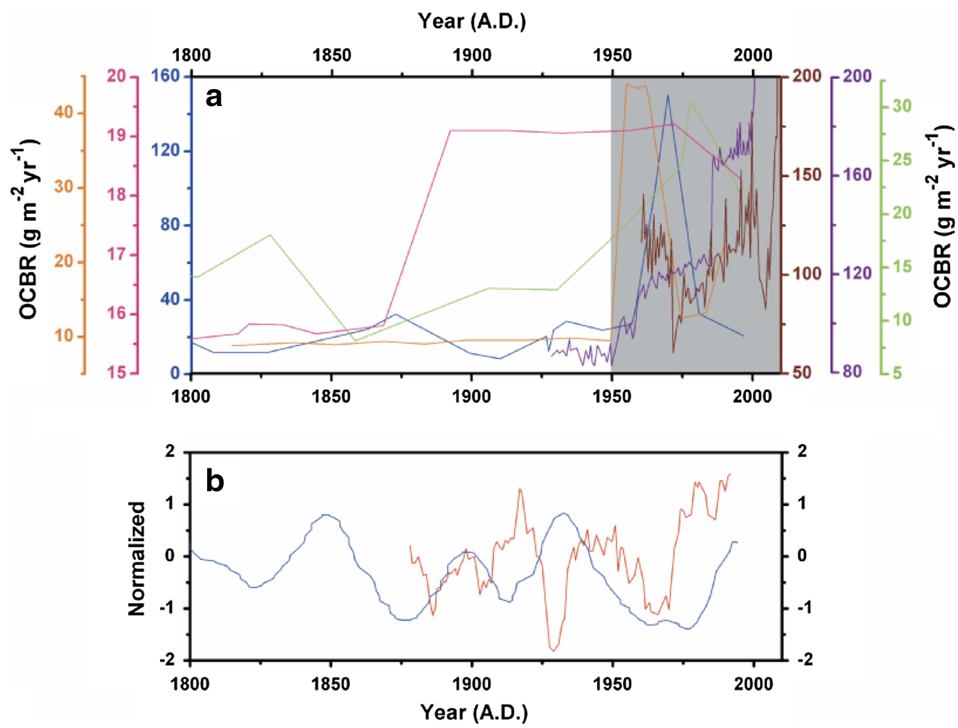

Fig. 5 **a** OCBR trends in lake sediments over the arid/semiarid, NW China, since ~AD 1800. Bosten Lake (*blue line*), Erbinur Lake (*pink line*), Daihai Lake (*wine line*), Hongjiannao Lake (*purple line*), Jili Lake (*yellow line*) and Wulungu Lake (*green line*). **b** Precipitation reconstructed from tree-ring $\delta^{18}O$ (*red line*) (Liu et al. 2004, 2008a, b) and tree-ring width (*blue line*) (Zhang et al. 2013)

Reconstructed precipitation patterns based on tree-ring width (Zhang et al. 2013) and $\delta^{18}O$ (Liu et al. 2004, 2008a, b) show considerable variation before AD 1970s, and a significant increase thereafter (Fig. 5b). Moreover, a stimulate model also shows an increasing trend of precipitation since ~AD 1975 (Shi et al. 2007). Both results may roughly indicate that increased precipitation corresponds with enhanced OCBR, attributed to high primary production and chemical weathering under increased precipitation and temperature. Thus, precipitation is plausibly a predominate factor for organic carbon burial.

Furthermore, the cropland area in Xinjiang province over the past 100 years has largely increased with the total population in China, especially after AD 1950 (Ge and Dai 2005), which dramatically changed the land use and land cover. For example, the cropland area in Xinjiang province increased from about 17 × 10^4 hm^2 in the 1920s to about 27 × 10^4 hm^2 in the 1950s, and then rapidly increased to larger than 60 × 10^4 hm^2 in 15 years (Ge and Dai 2005). The total forest area in ASAC substantially decreased during the period 1800–1950 (Ge and Dai 2005; He et al. 2007) due to deforestation by anthropogenic activity. It was, however, slightly increased after 1950 and sharply reforested since 1975 due to governmental policy. Enhanced cropland area and reduced forest area due to anthropogenic activity may release organic carbon to the atmosphere which previously was stored in soils and forests (Ge et al. 2008). On the other hand, higher sedimentation rates in lakes in areas with enhanced anthropogenic activity in their catchments suggest that organic carbon stored in the forest and soil and inorganic carbon stored in soil may be transported by rivers to lakes from catchments and then buried in lake sediments at higher rates. More organic and inorganic carbons are also sequestered by enhanced hydrophytes due to eutrophication in lakes. Therefore, increased OCBR and ICBR in recent lake sediments may be indirectly driven by in-catchment anthropogenic activity and directly enhanced by autochthonous hydrophyte blooms.

Gudasz et al. (2010) found that the mineralization of organic carbon in lake sediments is strongly and positively related to temperature, suggesting that carbon burial would decrease with increased temperature. However, they did not consider the enhancement of anthropogenic activity and the possibility of increased autochthonous and allochthonous primary production with global warming. In our opinion, no matter what complex processes are involved, the burial of carbon in lake sediments can be regarded as a net sink, and sequestration will increase with increasing carbon burial rate. This is also consistent with the results of other studies (Hollander et al. 1992; Dean and Gorham 1998; Downing et al. 2008; Kastowski et al. 2011; Dong et al. 2012; Heathcote and Downing 2012). Shi et al. (2007) simulated an increase by 19 % in precipitation and more than 10 % in runoff in northwestern China under future climate for doubled CO_2 concentrations using a regional climate model—RegCM2. Anthropogenic activity will probably increase with increasing population. Under such circumstances, carbon burial rates would be expected to increase by about 20 %, corresponding to OCBR and ICBR in ASAC conservatively increasing to 59.9 and 57.9 $gm^{-2}year^{-1}$, respectively.

4.2 Spatial patterns of carbon burial in ASAC

Although spatial patterns in lake carbon burial rates over the ASAC region are considerably different, some general features do stand out. For example, carbon burial rates in the eastern region are generally higher than those in the western region. Our estimates show that the OCBR in Daihai Lake, Hongjiannao Lake, and Hulun Lake in the eastern ASAC are 114.2, 129.8 and 45.5 $gm^{-2}year^{-1}$, respectively; while ICBR estimates for those lakes are 124.0, 111.2, and 22.4 $gm^{-2}year^{-1}$, respectively. These are higher than the corresponding values in the western region. We assume that the east–west variation of carbon burial rate results primarily from variations in the mode of mean annual precipitation in China (Fig. 1) and the strength of anthropogenic activity. Annual precipitation is much higher in the eastern than in the western ASAC (Fig. 1), which would lead to larger carbon sequestration and strong weathering in the eastern catchment ecosystems. And eastern China is more densely populated, and thus the impact of anthropogenic activity may be much stronger.

There are, however, some exceptions, such as Bosten Lake and Chaiwopu Lake. Both OCBR and ICBR in these lakes are higher than other lakes in the same climatic region and even higher than lakes in wetter regions. We propose that these lakes may be subjected to stronger anthropogenic impacts than other lakes (Zheng et al. 2012). In a recent study, Anderson et al. (2013, 2014) proposed that contemporarily OCBR in European lakes have increased at least four to five fold due to stronger anthropogenic impacts, not climate change. Thus, a second feature of carbon burial pattern in ASAC is that OCBR and ICBR are much higher in areas subjected to more intense anthropogenic activity. Furthermore, the two features of carbon burial rates indicate that a large carbon pool in ASAC is collectively driven by climatic change and enhanced anthropogenic activity.

4.3 Comparison with other regions

To assess the importance of OCBR in ASAC, we compare the values calculated in this work with OCBR in other regions in China and around the world. The OCBR in ASAC ranges from 5.3 to 129.8 g cm^{-2} $year^{-1}$ with a weighted mean of 49.9 g cm^{-2} $year^{-1}$ since ~AD 1800. Our results suggest that organic carbon sequestered by lakes with area >1 km^2 in ASAC (~73 Tg organic carbon) is much higher than that of the Yangtze floodplain (~41 Tg organic carbon) (Dong et al. 2012) in the same period (both since ~AD 1850). Although annual precipitation at the Yangtze floodplain is generally three to four times higher than at ASAC, anthropogenic activity at the Yangtze floodplain may also be much stronger than at ASAC and the total area of lakes >1 km^2 in the Yangtze floodplain (about 16,476 km^2) is also slightly higher than in ASAC (about 12,590 km^2) (Dong et al. 2012). OCBR in European lakes in the uppermost 20 cm sediments is 10.6 g cm^{-2} $year^{-1}$ on average (Kastowski et al. 2011). In agriculturally eutrophic impoundments, OCBR ranged from a low of 148 g cm^{-2} $year^{-1}$ to a high of 17,000 g cm^{-2} $year^{-1}$ (Downing et al. 2008), which is much higher than other reports and reinforces the importance of anthropogenic activity to carbon burial. Based on carbon mass balance studies of 20 small forested catchments and seven lakes in Ontario, Molot and Dillon (1996) calculated that approximately

18–31 Tg $year^{-1}$ of organic and inorganic carbon are stored in boreal lake sediments. In one lake—Lake Chaohu on the Yangtze floodplain—OCBR was about 5–30 m^{-2} $year^{-1}$, resulting in standing stocks of 1.15 kg cm^{-2} since AD 1850 (Dong et al. 2012). In a lake in the United States' state of Iowa, OCBR increased to 200 gm^{-2} $year^{-1}$ following agricultural development (Heathcote and Downing 2012). OCBR for the top 10 cm of eutrophic Lake Greifen, Switzerland, is 50–60 gm^{-2} $year^{-2}$ (Dean and Gorham 1998; Hollander et al. 1992), which also supports the importance of anthropogenic activity to carbon burial. On a global scale, Dean and Gorham (1998) suggest that global OCBR in the largest lakes (area >5000 km^2) and smaller lakes is 5 and 72 gm^{-2} $year^{-1}$, respectively. Subsequently, the total global organic carbon burial in lakes is 42 Tg $year^{-1}$. All of this suggests that ASAC is a large carbon pool, although the primary production in this region may be less than other regions.

4.4 A possible carbon sink from parts of the buried inorganic carbon

Little attention has been previously given to the inorganic carbon cycle in lakes, which is partly due to the understanding that inorganic carbon is mechanically transported from catchment to lake and/or directly inputted from precipitation (Dillon and Molot 1997; Urban et al. 2005), but not directly from atmospheric CO_2. However, part of the dissolved inorganic carbon (DIC), which comes from both carbonate and silicate weathering and/or directly from hydration with atmosphere (Liu et al. 2010, 2011; Liu 2011), may be kept in the water systems for a prolonged time span, and can be regarded as a temporary carbon sink. In addition, more than 70 % of riverine DIC is directly and/or indirectly withdrawn from atmospheric CO_2, and portions of the DIC in lake waters may potentially precipitate as alkaline minerals and be buried in lake sediments, as suggested by our most recent estimate (Xu et al. 2013). Therefore, although we do not know exactly how much of the inorganic carbon in lake sediments is a carbon sink, some portion may eventually form a carbon sink and balance the global carbon cycle.

Recently, based on three methods, Wang et al. (2012) determined the soil organic carbon (SOC) and soil inorganic carbon (SIC) in northwest China, and showed that all three methods produce consistently low values for SOC and high values for SIC. These results also imply the potential importance of inorganic carbon for lake carbon burial. The combined organic and inorganic carbon burial in the lakes in ASAC constitutes a large carbon sink and deserve more attention and integration into the global carbon cycle.

5 Summary

We estimated the carbon burial in lake sediments over the ASAC region, and showed that carbon burial in lake sediments since ~AD 1800 amounted to ~209 TgC, with organic and inorganic carbon burials ~108 and ~101 TgC, respectively. Since ~AD 1950, OCBR shows increasing trends, which are possibly related to climatic changes and enhanced anthropogenic activities. If global warming continues, the increased precipitation and runoff over the ASAC region may lead to increased OCBR and ICBR in lake sediments of ASAC. These constitute a large carbon pool in the ASAC region and need to be given more attention in the future.

Acknowledgments The authors are grateful to Yoni Goldsmith (Lamont–Doherty Earth Observatory, Columbia University) for suggestions on this manuscript. This work is jointly funded by the Chinese Academy of Science (CAS) Strategic Priority Research Program (Grant No. XDA05120404), the National Basic Research Program of China (No. 2013CB955903), the State Key Laboratory of Loess and Quaternary Geology (No. SKLLQG1406) and the Western Light Talent Culture Project of CAS.

References

Alin SR, Johnson TC (2007) Carbon cycling in large lakes of the world: a synthesis of production, burial, and lake-atmosphere exchange estimates. Glob Biogeochem Cycles 21:GB3002

Anderson NJ, Dietz RD, Engstrom DR (2013) Land-use change, not climate change, controls organic carbon burial in lakes. Proc R Soc B 280:20131278

Anderson NJ, Bennion H, Lotter AF (2014) Lake eutrophication and its implications for organic carbon sequestration in Europe. Glob Change Biol 20:2741–2751

Avnimelech Y, Ritvo G, Meijer LE, Kochba M (2001) Water content, organic carbon and dry bulk density in flooded sediments. Aquacult Eng 25:25–33

Ballantyne AP, Alden CB, Miller JB, Tans PP, White JWC (2012) Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years. Nature 488:70–72

Battin TJ, Luyssaert S, Kaplan LA, Aufdenkampe AK, Richter A, Tranvik LJ (2009) The boundless carbon cycle. Nat Geosci 2:598–600

Bloom AA, Palmer PI, Fraser A, Reay DS, Frankenberg C (2010) Large-scale controls of methanogenesis inferred from methane and gravity spaceborne data. Science 327:322–325

Bond-Lamberty B, Thomson A (2010) Temperature-associated increases in the global soil respiration record. Nature 464:579–582

Campbell ID, Campbell C, Vitt DH, Kelker D, Laird LD, Trew D, Kotak B, LeClair D, Bayley S (2000) A first estimate of organic carbon storage in Holocene lake sediments in Alberta, Canada. J Paleolimnol 24:395–400

Canadell JG, Le Quéré C, Raupach MR, Field CB, Buitenhuis ET, Ciaisf P, Conwayg TJ, Gillettc NP, Houghtonh RA, Marlandet G (2007) Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proc Natl Acad Sci 104:18866

Chen FH, Huang XZ, Zhang JW, Holmes JA, Chen JH (2006) Humid little ice age in arid central Asia documented by Bosten Lake. Sci China Ser D Earth Sci 49:1280–1290

Cole JJ, Prairie YT, Caraco NF, McDowell WH, Tranvik LJ, Striegl RG, Duarte CM, Kortelainen P, Downing JA, Middelburg JJ, Melack J (2007) Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. Ecosystems 10:171–184

Dean WE (1974) Determination of carbonate and organic-matter in calcareous sediments and sedimentary-rocks by loss on ignition—comparison with other methods. J Sediment Petrol 44:242–248

Dean WE (1999) The carbon cycle and biogeochemical dynamics in lake sediments. J Paleolimnol 21:375–393

Dean WE, Gorham E (1998) Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. Geology 26:535–538

Dillon PJ, Molot LA (1997) Dissolved organic and inorganic carbon mass balances in central Ontario lakes. Biogeochemistry 36:29–42

Dong X, Anderson NJ, Yang X, Chen X, Shen J (2012) Carbon burial by shallow lakes on the Yangtze floodplain and its relevance to regional carbon sequestration. Glob Change Biol 18:2205–2217

Downing JA (2009) Global limnology:up-scaling aquatic services and processes to planet earth. Verh Int Ver Limnol 30:1149–1166

Downing JA, Prairie YT, Cole JJ, Duarte CM, Tranvik LJ, Striegl RG, McDowell WH, Kortelainen P, Caraco NF, Melack JM, Middelburg JJ (2006) The global abundance and size distribution of lakes, ponds, and impoundments. Limnol Oceanogr 51:2388–2397

Downing JA, Cole JJ, Middelburg JJ, Striegl RG, Duarte CM, Kortelainen P, Prairie YT, Laube KA (2008) Sediment organic carbon burial in agriculturally eutrophic impoundments over the last century. Glob Biogeochem Cycles 22:GB1018

Fang J, Chen A, Peng C, Zhao S, Ci L (2001) Changes in forest biomass carbon storage in China between 1949 and 1998. Science 292:2320–2322

Frank DC, Esper J, Raible CC, Büntgen U, Trouet V, Stocker B, Joos F (2010) Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate. Nature 463:527–530

Ge QS, Dai JH (2005) Farming and forestry land use changes in China and their driving forces from 1900 to 1980. Sci China Ser D Earth Sci 48:1747–1757

Ge QS, Dai JH, He FN, Pan Y, Wang MM (2008) Land use changes and their relations with carbon cycles over the past 300 a in China. Sci China Ser D Earth Sci 51:871–884

Gudasz C, Bastviken D, Steger K, Premke K, Sobek S, Tranvik LJ (2010) Temperature-controlled organic carbon mineralization in lake sediments. Nature 466:478–481

He FN, Ge QS, Dai JH, Lin SS (2007) Quantitative analysis on forest dynamics of China in recent 300 years. Acta Geogr Sin 62:30–40

Heathcote AJ, Downing JA (2012) Impacts of eutrophication on carbon burial in freshwater lakes in an intensively agricultural landscape. Ecosystems 15:60–70

Hollander DJ, Mckenzie JA, Lotenhaven H (1992) A 200-year sedimentary record of progressive eutrophication in Lake Greifen (Switzerland)—implications for the origin of organic-carbon-rich sediments. Geology 20:825–828

Jiang QF, Shen J, Liu XQ, Zhang EL, Xiao XY (2007) A high-resolution climatic change since Holocene inferred from multi-proxy of lake sediment in westerly area of China. Chin Sci Bull 52:1970–1979

Jiang QF, Shen J, Liu XQ, Ji JF (2010) Environmental changes recorded by lake sediments from Lake Jili, Xinjiang during the past 2500 year. J Sci 22:119–126 (in Chinese)

Kalff J (2001) Limnology: inland water ecosystems. Prentice, New Jersey

Kastowski M, Hinderer M, Vecsei A (2011) Long-term carbon burial in European lakes: analysis and estimate. Glob Biogeochem Cycles 25:GB3019

Kortelainen P, Pajunen H, Rantakari M, Saarnisto M (2004) A large carbon pool and small sink in boreal Holocene lake sediments. Glob Change Biol 10:1648–1653

Lan JH, Xu H, Liu B (2011) A preliminary study of sedimentation rate and geochemistry in Lake Daihai, southeastern of Inner Mongolia, China. J Earth Environ 2:278–284 (in Chinese)

Lehner B, Döll P (2004) Development and validation of a global database of lakes, reservoirs and wetlands. J Hydrol 296:1–22

Li S, Chen S, Zhang J (2010) Environmental changes recorded by lake sediments from Hongjiannao Lake during recent fifty years. J Anhui Agric Sci 38:2534–2537 (in Chinese)

Liu ZH (2011) Is pedogenic carbonate an important atmospheric CO2 sink? Chin Sci Bull 56:3794–3796

Liu Y, Ma L, Leavitt SW, Cai Q, Liu W (2004) A preliminary seasonal precipitation reconstruction from tree-ring stable carbon isotopes at Mt. Helan, China, since AD 1804. Glob Planet Change 41:229–239

Liu X, Herzschuh U, Shen J, Jiang Q, Xiao X (2008a) Holocene environmental and climatic changes inferred from Wulungu Lake in northern Xinjiang, China. Quat Res 70:412–425

Liu Y, Cai Q, Liu W, Yang Y, Sun J, Song H, Li X (2008b) Monsoon precipitation variation recorded by tree-ring $\delta^{18}O$ in arid Northwest China since AD 1878. Chem Geol 252:56–61

Liu ZH, Dreybrodt W, Wang HJ (2010) A new direction in effective accounting for the atmospheric CO2 budget: considering the combined action of carbonate dissolution, the global water cycle and photosynthetic uptake of DIC by aquatic organisms. Earth Sci Rev 99:162–172

Liu ZH, Dreybrodt W, Liu H (2011) Atmospheric CO_2 sink: silicate weathering or carbonate weathering? Appl Geochem 26:s292–s294

Ma RH, Yang GH, Duan HT, Jiang JH, Wang SM, Feng XZ, Li AN, Kong FX, Xue B, Wu JL, Li SJ (2010) China' lakes at present: number, area spatial distrbution. Sci China Earth Sci 54:283–289

Ma L, Wu J, Yu H, Zeng H, Abuduwaili J (2011) The medieval warm period and the Little ice age from a sediment record of Lake Ebinur, northwest China. Boreas 40:518–524

Menounos B (1997) The water content of lake sediments and its relationship to other physical parameters: an alpine case study. Holocene 7:207–212

Meybeck M (1995) Glob distribution of lakes. In: Lerman (ed) Physics and chemistry of lakes. Springer, Berlin, pp 1–35

Molot LA, Dillon PJ (1996) Storage of terrestrial carbon in boreal lake sediments and evasion to the atmosphere. Glob Biogeochem Cycles 10:483–492

Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala S, McGuire AD, Piao S, Rautiainen A, Sitch S, Hayes D (2011) A large and persistent carbon sink in the world's forests. Science 333:988–993

Richerson PJ, Suchanek TH, Zierenberg RA, Osleger DA, Heyvaert AC, Slotton DG, Eagles-Smith CA, Vaughn CE (2008) Anthropogenic stressors and changes in the Clear Lake ecosystem as recorded in sediment cores. Ecol Appl 18:A257–A283

Sabine CL, Feely RA, Gruber N, Key RM, Lee K, Bullister JL, Wanninkhof R, Wong CS, Wallace DWR, Tilbrook B, Millero FJ, Peng T, Kozyr A, Ono T, Rios AF (2004) The oceanic sink for anthropogenic CO_2. Science 305:367–371

Santisteban JI, Mediavilla R, Lopez-Pamo E, Dabrio CJ, Zapata MBR, Garcıa MJG, Castano S, Martınez-Alfaro PE (2004) Loss on ignition: a qualitative or quantitative method for organic matter and carbonate mineral content in sediments? J Paleolimnol 32:287–299

Shen J, Wang Y, Yang X, Zhang E, Yang B, Ji J (2005) Paleosandstorm characteristics and lake evolution history deduced from—the case of Hongjiannao Lake, Shaanxi Province. Chin Sci Bull 50:2355–2361

Shi Y, Shen Y, Kang E, Li D, Ding Y, Zhang G, Hu R (2007) Recent and future climate change in northwest China. Clim Change 80:379–393

Shiklomanov IA, Rodda JC (2003) World water resources at the beginning of the twenty-first century. Cambridge University Press, Cambridge

Siegenthaler U, Sarmiento J (1993) Atmospheric carbon dioxide and the ocean. Nature 365:119–125

Sobek S, Durisch-Kaiser E, Zurbrugg R, Wongfun N, Wessels M, Pasche N, Wehrlia B (2009) Organic carbon burial efficiency in lake sediments controlled by oxygen exposure time and sediment source. Limnol Oceanogr 54:2243–2254

Sun Q, Zhou J, Shen J, Chen P, Wu F, Xie X (2006) Environmental characteristics of Mid-Holocene recorded by lacustrine sediments from Lake Daihai, north environment sensitive zone, China. Sci China Ser D Earth Sci 49(9):968–981

Urban N, Auer M, Green S, Lu X, Apul DS, Powell KD, Bub L (2005) Carbon cycling in Lake Superior. J Geophys Res 110:C06S90

Wang X, Wang J, Zhang J (2012) Comparisons of three methods for organic and inorganic carbon in calcareous soils of northwestern China. PLoS One 7:e44334

Wu J, Ma L (2010) Characteristcs of the climate and environment in arid regions over the past 150 years recoreded by the core sediments of Chaiwopu Lake, Xinjiang, China. Quat Sci 30:1137–1144 (in Chinese)

Wu J, Yu Z, Zeng H, Wang N (2009) Possible solar forcing of 400-year wet–dry climate cycles in northwestern China=. Clim Change 96:473–482

Wünnemann B, Mischke S, Chen F (2006) A Holocene sedimentary record from Bosten Lake, China=. Palaeogeogr Palaeoclimatol Palaeoecol 234:223–238

Xiao J, Xu Q, Nakamura T, Yang X, Liang W, Inouchi Y (2004) Holocene vegetation variation in the Daihai Lake region: a direct indication of the Asian monsoon climatic history. Quat Sci Rev 23:1669–1679

Xiao J, Wu J, Si B, Liang W, Nakamura T, Liu B, Inouchi Y (2006) Holocene climate changes in the monsoon arid transition by carbon concentration in Daihai Lake of Inner Mongolia. Holocene 16:551–560

Xu H, Lan J, Liu B, Sheng E, Yeager KM (2013) Modern carbon burial in Lake Qinghai, China. Appl Geochem 39:150–155

Xue JB, Zhong W (2011) Holocene climate variation denoted by Barkol Lake sediments and its possible linkage to the high and low latitude climates. Sci China Earth Sci 54:603–614

Zhang T, Yuan Y, Liu Y, Wei W, Yu S, Chen F, Fan Z, Shang H, Zhang R, Qin L (2013) A tree ring based precipitation reconstruction for the Baluntai region on the southern slope of the central Tien Shan Mountains, China, since AD 1464. Quat Int 283:55–62

Zhao HY, Wu LJ, Hao WJ (2008) Influences of climate change to ecological and environmental evolvement in the Hulun Lake wetland and its surrounding areas. Acta Ecol Sin 28:1064–1071 (in Chinese)

Zheng B, Zhang E, Gao G (2012) The change of primary productivity of Lake Bosten in Xinjiang over the past 100-year. J Lake Sci 24:466–473 (in Chinese)