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The carbon source-sink function of Hulun Lake, a large shallow eutrophic lake in northern China

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Lakes are known to play a crucial role in the world-wide carbon cycling due to the efficient organic carbon burial as well as large amount of CO_2 emissions to the atmosphere. Despite the increasing importance of understanding these processes in the context of global warming and escalating human activities, the carbon source-sink dynamics of lakes remain elusive. In this study, we compared two approaches, a mass balance approach and the CO_2 emission-carbon burial balance method to investigate the role of lake as carbon source or sink in Hulun Lake (the largest lake in northeastern China) from June 2015 to May 2016. Both approaches converged on the same conclusion that Hulun Lake was a great carbon source. With the overall mass balance calculations, total carbon input was 112.4×10^3 t during our study period, with the largest input was from the inlet rivers (107.5×10^3 t). The total carbon output was 448.2×10^3 t, and the CO_2 emission accounted for about 99% of the output. The net carbon budget was -289×10^3 t, suggesting that Hulun Lake was a great carbon source. Furthermore, the total C-CO_2 emission was three times higher than sediment carbon accumulation, stressing Hulun Lake was an important carbon source. The carbon source function mainly results from low primary production, long lake water residence time, high allochthonous carbon inputs (carbon derived from external terrestrial and atmospheric sources) and intensive human activities (e.g., grazing intensity up to 2.0 livestock units/ha, approaching the maximum stocking rate for Inner Mongolian grasslands). While further research is necessary to generalize these findings, our results provide compelling evidence for the significant role of lakes in the carbon cycle, and highlighting the importance of considering both carbon burial and carbon emission in assessments of the carbon sink-source function.

KEYWORDS

carbon budget, mass balance, carbon evasion, carbon burial, Hulun Lake

1 Introduction

It is now evident that lakes play a significant role in both the regional and global carbon (C) cycles. They serve as integral parts of these cycles by receiving, transporting, processing, and storing carbon from both allochthonous and autochthonous sources (Chmiel et al., 2016; Mendonça et al., 2017; Raymond et al., 2013; Tranvik et al., 2009). On a global scale,

CO_2 emissions from lakes and reservoirs are estimated to be approximately 0.32 Pg C yr^{-1} (Raymond et al., 2013). These emissions are estimated to be equivalent to approximately 20% of the annual global CO_2 emissions from fossil fuel combustion (DelSontro et al., 2019). In addition, the carbon sequestered in lake sediments is roughly 0.09 Pg C yr^{-1}, which is about half the estimated carbon burial rate in the oceans (0.2 Pg C yr^{-1}) (Mendonça et al., 2017). Notably, both the fluxes of carbon emission and burial are expected to increase in the future due to global warming and anthropogenic disruption (Anderson et al., 2020; Hasler et al., 2016; Heathcote, 2012; Heathcote et al., 2015; Kosten et al., 2010; Xiao et al., 2020), underscoring the pivotal role that lakes play in the global carbon cycle.

Despite this, the function of lakes as net carbon sinks or sources within the regional carbon budgets still remains unclear. The carbon source-sink function of lakes can be determined by the balance between carbon evasion into the atmosphere and carbon burial in sediment. Concurrently, this function can alternatively be assessed through a mass balance approach that integrates carbon fluxes across the catchment, lake water and sediment, and the net carbon budget is derived from the difference between total carbon inputs and outputs (Yang et al., 2008). However, such carbon sink-source function of lakes has poorly investigated in previous studies. This is particularly evident in the application of the mass balance budget, where measurement methods are often time-consuming and costly. Specifically, the integration and comparison of the carbon burial-emission balance and the mass balance approach are rarely conducted, revealing significant gaps in the precise estimation of the carbon sink-source function of lakes and their contribution to the regional carbon cycle.

To our knowledge, the majority of existing research on lake carbon sink-source function has concentrated in boreal regions, with scant attention given to lakes under varying geographic and climatic conditions. This oversight is particularly pronounced in developing countries like China, where lakes constitute a significant part of the landscape and are major recipients of carbon from their surrounding catchments and the water bodies themselves (Wang et al., 2018). Over the past decades, several studies have examined the spatial and temporal dynamics of carbon burial and emission in China's lakes (Li et al., 2018; Wang et al., 2015; Wen et al., 2024; Yang et al., 2024; Yin et al., 2024; Zhang et al., 2017, 2023, 2024; Zhou et al., 2025). However, knowledge about the role of lakes as C source-sink is still inadequate, and different studies have yielded varying results. For example, research has shown that the eutrophic Lake Donghu in the Yangtze River Delta is a significant carbon sink (Yang et al., 2008), while the similarly eutrophic Lake Taihu acts as a carbon source, with its annual emission rate significantly surpassing the burial rate (80g C m^{-2} yr^{-1} and 5 C m^{-2} yr^{-1}, respectively) (Dong et al., 2012; Xiao et al., 2020). These discrepancies highlight the spatial heterogeneity of carbon source-sink functions among Chinese lakes and calls for more investigations to better understand the spatial pattern of carbon source-sink and the reasons behind this variability.

Here, we examine Hulun Lake, the largest lake in northeastern China, to assess its role as a carbon sink or source. Our evaluation integrates a mass balance approach with a comprehensive gas exchange-carbon burial balance method. The dual analytical framework was designed to address two primary inquiries: (1) whether Hulun Lake functions as a net carbon sink or source over the study period, and (ii) the main drivers that modulate its carbon sink-source function. This study is expected to provide essential information to strengthen the understanding of the contribution of lakes to the carbon cycle and refine lake management strategies in the context of intensified climate change and human activities.

2 Materials and methods

2.1 Study area

The study was conducted in Hulun Lake (48°30′40″-49°20′40″ N, 117°00′10″-117°41′40″E, Figure 1), a large, shallow lake situated on the cold and arid Hulunbuir Grassland in Inner Mongolia, China. Hulun Lake is the fifth largest fresh-water lake in China. It has a surface area of 2,339 km^2, a maximum water depth of 8 m, and a catchment of 37,214 km^2 within the borders of China. The lake is part of the Argun River water system and the majority of water is supplied by precipitation as well as by several rivers, of which the largest two are the Kelulun River and the Wuerxun River (Figure 1). The discharge from the outflow (Xinkai River) of Hulun Lake was negligible during our study period. Hulun Lake lies in the arid and semi-arid continental monsoon climate zone, which has an annual average precipitation of 285 mm and an annual average evaporation of 1650-1700 mm. The mean annual air temperature at the Hulun Lake site is −0.5 to 0.5°C, and it has a long icebound period for about 180 days each year (Xue et al., 2017; Zhang et al., 2018).

2.2 Sample collection and treatment

Sampling campaigns were conducted from June 2015 to May 2016. The lake surface water samples (a depth of 0.5 m) were collected during the early June and late August in 2015, which characterized the dry and wet seasons. Sampling locations were roughly evenly distributed in the lake (Figure 1). Water samples were also synchronously taken from the major inflow rivers (i.e. the Kelulun River and the Wuerxun River) and the groundwater during the same sampling periods. In total, thirty-one samples (including twenty lake samples, eight river samples and three groundwater samples) were collected from the Hulun Lake basin during each time period (Figure 1). The lake and inlet surface water samples were collected with a Niskin sampler (5L) and the groundwater samples were collected from three residential groundwater wells (Figure 1). All the water samples were stored in cool conditions and then transported to the laboratory. The particulate organic carbon (POC) from the lake and inlet water was collected by filtering water through 0.70 μm membrane GF/F glass fibre filters, dried (60°C for 48 h), acid-fumed to remove inorganic carbon, and measured using an Elemental Analyzer 3000 (Euro Vector, Italy). Filtrates from POC analysis were then used to measure dissolved

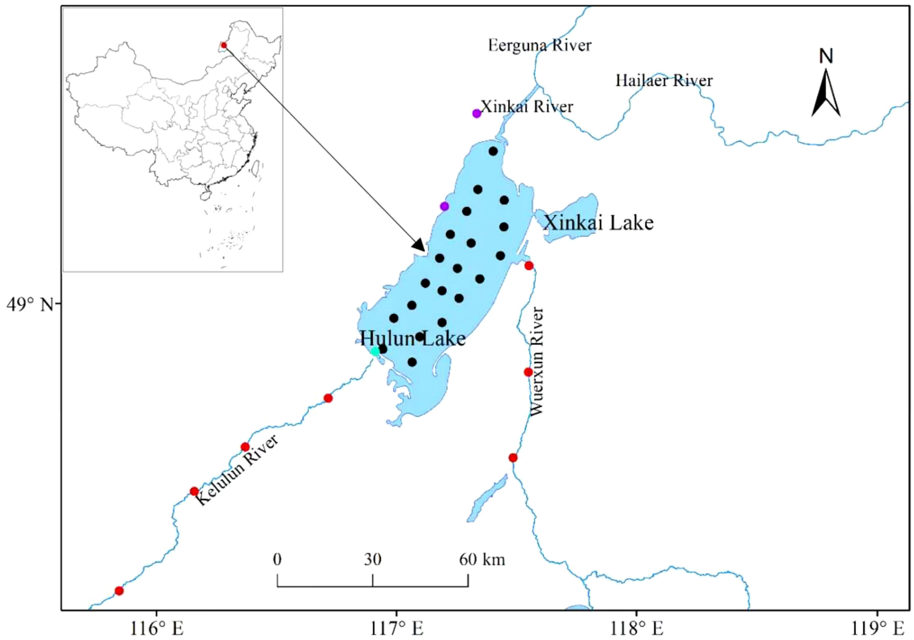

FIGURE 1
The location of Hulun Lake and the sampling sites (Black dots mark the lake water sample sites, red dots signify those from the major inflow rivers, and purple dots denote groundwater sample sites. The green dot represents the atmospheric deposition site and also serves as an indicator for the inflow river and groundwater sites, which are in close proximity and thus indistinguishable on this map).

organic carbon (DOC) and dissolved inorganic carbon (DIC). DOC was analyzed using a Torch TOC Analyzer (Teledyne Tekmar, USA) by high-temperature catalytic oxidation. DIC was determined using the same TOC analyzer via acidification (pH ≤ 3.0) followed by CO_2 purge and non-dispersive infrared (NDIR) detection. The DOC and DIC were also analyzed for the groundwater samples using the same methods.

In addition, five polyethylene cylindrical vessels (50 cm height and 18 cm inner diameter) were installed in the southern part of the lake for total atmospheric deposition collection from June 2015 to May 2016 (Figure 1). The atmospheric fallout fluxes were determined for these collectors. 2 cm thick rounded glass beads (1cm in diameter) were placed in the vessels to avoid resuspension of collected particles. All collectors were mounted 5-10 m above ground to avoid the effect of background disturbance. For analysis of carbon content, atmospheric deposition samples were wiped from the bottom of buckets with a brush and remove the visible impurities (e.g., leaves, insects and bird manure). Then the samples were washed with distilled water and dried at 60°C overnight. The samples were crimped into small cubes and the total carbon content of atmospheric deposition was determined on an Elemental Analyzer 3000 (Euro Vector, Italy).

2.3 The mass balance calculations

In order to calculate the carbon budget in Hulun Lake from June 2015 to May 2016, the following steady-state mass balance equation was applied according to Yang et al. (2008):

$$TC_{INL} + TC_{GW} + TC_{DEP} + TC_{H} - TC_{OUT} - CO_{2E} - TC_{F} = \Delta F$$

where TC_{INL} denotes the import of total carbon via the two major inlet rivers. TC_{GW} indicates the direct inflow of total carbon via groundwater. TC_{DEP} and TC_{H} represent the carbon content from atmospheric deposition and dry deposition of hay, respectively. TC_{OUT} is the export of carbon via the lake outlet river. CO_{2E} is the emission of CO_2 to the atmosphere. TC_{F} is the carbon outflow from the fish harvest and ΔF is the net carbon budget (positive value denotes net carbon sink and negative value denotes net carbon source). Primary production by phytoplankton is excluded in this study, as the emission of CO_2 is the product of total primary production and respiration in the lake water (Sobek et al., 2006). We did not account for the domestic waste input here as smaller populations were distributed around this lake district (the population density in three major cities around Hulun Lake (Xin Barag Zuoqi, Xin Barag Youqi and Manzhouli) is less than 5 person km^{-2} in 2015, data were from Hulun Buir Statistic Almanac of 2016) and hence resulting in less waste production. Furthermore, the release of CH_4 into the atmosphere is not included in the mass balance equation because these rates are small relative to CO_2 (Bastviken et al., 2011; Pacheco et al., 2014). Hulun Lake is a shallow lake prone to strong wind influences (mean wind speed ≈4.2 m/s), which reduces sediment anoxia exposure. Although CH_4 production in oxic water columns is increasingly recognized (Bogard et al., 2014; Günthel et al., 2020; Tang et al., 2016), preliminary measurements during 2023-2024 ice-free periods show CO_2 emissions averaged ~73 times greater than CH_4 in Hulun Lake (unpublished data). This substantial flux difference confirms CO_2 dominates gaseous carbon efflux, justifying CH_4 exclusion. The different terms were calculated as follows:

Inflow of carbon from inlet rivers (TC_{INL}). The carbon export from two inlet rivers to Hulun Lake was calculated using the mean carbon concentrations in these inlet rivers multiplied by total annual runoff. The carbon concentration measurements cover both periods of low flow (dry season) and periods of high flow (wet season). The data of the annual runoff was provided by Administration Bureau of Inner Mongolia Hulun Lake National Nature Reserve.

Import of carbon with groundwater inflows (TC_{GW}). The carbon flux was calculated as the groundwater inflow multiplied with the average carbon concentration in groundwater. The groundwater inflow data was from Xue et al. (2017).

Carbon inputs via atmospheric deposition (TC_{DEP}). The average carbon input through atmospheric deposition is calculated as the mean of the five collectors. The atmospheric deposition flux was calculated as the product of the total mass deposited in the whole year divided by the area of the deposition collector. Then the total carbon input from atmospheric deposition into Hulun Lake was obtained by multiplying the carbon flux and the total lake area.

Carbon inputs from hay. In Hulun Lake, the hay being flowed by wind is an important carbon source. Carbon input from hay was obtained by multiplying the carbon content of hay and the hay mass. The carbon content of hay was determined using an Elemental Analyzer 3000 (Euro Vector, Italy) and the input of dry hay mass data was from Liang et al. (2016). The total carbon input flux from hay was calculated by multiplying the dry hay mass by the carbon content.

Outflow of carbon from the lake. The carbon outflow via the river was set to zero here since the discharge was negligible throughout our study period. For carbon outflow from the fish harvest, we calculated the carbon content of the fishes and collected the fish yields for the investigated period. *Hemiculter leucisculus*, *Cyprinus carpio*, *crucian carps* and *whitefish*, the dominated fish species in Hulun Lake accounting for over 90% of the total fish yield, were collected during the study period with trawl and were dissected into four parts: muscles, organs, bones and scales. After heating and grinding, carbon concentrations of the proportionate mixture of the four parts were determined by an Elemental Analyzer 3000 (Euro Vector, Italy) (Yang et al., 2008). The carbon outflow of each kind of fish was calculated by its fish yield and corresponding carbon content, and the total carbon outflow was estimated though adding all the four kinds of fish carbon outflow.

CO_2 emission. For Hulun Lake, we applied a steady state of DIC mass balance model to estimate the CO_2 fluxes to the atmosphere (Weyhenmeyer et al., 2015).

$$DIC_{external} + CO_{2\_internal\_prod} = CO_{2\_emission} + DIC_{outflow} + DIC_{internal\_loss}$$

where $DIC_{external}$ denotes DIC inputs from lake external sources. For Hulun Lake, it includes DIC inputs from two major inlet rivers, DIC from atmospheric deposition onto the lake surface area and DIC from inflowing groundwater. The total DIC concentration from lake external sources was the sum of DIC concentrations from the three different sources. $CO_{2\_internal\_prod}$ represents lake internal CO_2 production. Three types of lake internal CO_2 production were considered according to Weyhenmeyer et al. (2015), that is, CO_2 production at the sediment-water interface by microbial mineralization ($CO_{2\_sediment\_prod}$); CO_2 production in the water column by microbial mineralization of DOC ($CO_{2\_water\_prod}$); and CO_2 production in the water column by photochemical mineralization ($CO_{2\_photo\_prod}$). The DIC production during these three processes were estimated by corresponding predictive model or regression equation published in Weyhenmeyer et al. (2015). $DIC_{outflow}$ means the DIC outflowing from Hulun Lake. It only includes the outflow from fish harvest here. $DIC_{internal\_loss}$ is the lake internal DIC loss by photosynthesis and calcium carbonate precipitation, which could be estimated according to the annual accumulation of total organic carbon (TOC) and total inorganic carbon (TIC) in the surficial sediments (i.e., temporary carbon accumulation). $CO_{2\_emission}$ is the CO_2 emission from Hulun Lake.

Then the CO_2 emission to the atmosphere can be estimated using the following equation:

$$CO_{2\_emission} = DIC_{external} + CO_{2\_internal\_prod} - DIC_{outflow} - DIC_{internal\_loss}$$

2.4 The estimate of carbon accumulation in the sediment

To quantify temporary and permanent accumulation of TOC and TIC, we used ^{210}Pb-based data from fifteen ^{210}Pb-dated sediment cores collected at various locations across the lake, collectively spanning from the 1850s to 2014 (Zhang et al., 2018, 2019). Each core was sampled in 1 cm increments to measure total carbon content (TC), TOC, TIC, dry bulk density, and sedimentation rates based on unsupported ^{210}Pb and ^{137}Cs activities, applying the composite model (Zhang et al., 2018). The OC (IC) accumulation in surficial sediments was calculated by multiplying the average surficial OC (IC) accumulation rate by the total lake area. To estimate permanent TOC and TIC accumulation, the chronologies of all cores were constrained to post-1850 to align with established carbon burial baselines for Hulun Lake (Zhang et al., 2018, 2019). The surficial sediments corresponding to the most recent ~10 years were excluded from permanent OC calculations to account for potential post-depositional degradation (Gälman et al., 2008). Zhang et al. (2018) demonstrated that omitting these youngest sediments reduces the post-1950–2014 OC rate by only ~3%, indicating minimal degradation in Hulun Lake. Permanent TOC and TIC accumulation were calculated on a layer-by-layer basis. For each layer, the measured dry bulk density ($g\ cm^{-3}$), which already reflects compaction, was multiplied by its ^{210}Pb-derived sedimentation rate ($cm\ yr^{-1}$) and by its carbon content (%) (Zhang et al., 2018, 2019). Finally, whole-lake average OC (IC) accumulation rates since the 1850s were multiplied by the total lake area to obtain lake-scale burial fluxes, and the total carbon accumulation was then obtained by summing the OC and IC accumulation. For further details, see Zhang et al. (2018, 2019).

3 Result

3.1 The carbon accumulation and CO_2 emissions

The TOC in the surface sediments of Hulun Lake varied from 2.08% to 3.55%, with an average of 2.78%. The TIC content ranged from 1.72% to 3.67%, averaging 2.95%. Utilizing the dry bulk density, carbon content, and sedimentation rate data from the sediment cores as reported by Zhang et al. (2018, 2019), the average temporary accumulation rates for TOC and TIC were calculated to be approximately 30.75 g m^{-2} yr^{-1} (ranging from 4.51 to 83.45 g m^{-2} yr^{-1}) and 34.18 g m^{-2} yr^{-1} (4.33-109.13 g m^{-2} yr^{-1}), respectively. Consequently, the annual temporary sequestration of TOC and TIC was estimated to be about 62.67 t $yr^{-1}$and 69.66 t yr^{-1}, respectively, based on the total lake area of 2038 km^2 in 2015.

The TOC concentrations in various sediment cores from the 1850s in Hulun Lake fluctuated between 1.73% and 2.68%, averaging 2.10%. In contrast, the TIC concentrations ranged from 1.41% to 2.89%, averaging 2.29%. The total carbon (TC) content exhibited a broader range, from 3.14% to 5.46%, with an average of 4.39%. The long-term organic carbon accumulation rate (OCAR) and inorganic carbon accumulation rate (ICAR) spanned from 8.43 to 73.98 g m^{-2} yr^{-1} and 7.10 to 74.29 g m^{-2} yr^{-1}, respectively, with mean values of 31.42 g m^{-2} yr^{-1} and 36.15 g m^{-2} yr^{-1}. The total carbon accumulation rate (TCAR) showed an even wider range, from 14.74 to 184.12 g m^{-2} yr^{-1}, averaging 71.23 g m^{-2} yr^{-1}. Consequently, the calculated average total carbon burial rate was 145.2×10^3 t yr^{-1}, with a range from 30.0×10^3 t yr^{-1} to 375.2×10^3 t yr^{-1}, as detailed in Table 1.

The DIC inflow from external sources during our study period was approximately 29.1×10^3 t, as shown in Table 2. The contributions from the Kelulun River, Wuerxun River, atmospheric deposition, and groundwater to the DIC fluxes were approximately 8.5×10^3 t, 19.2×10^3 t, 1.1×10^3 t, and 0.3×10^3 t, respectively. The total internal CO_2 production within the lake was estimated at 1573×10^3 t. Among the three internal lake processes, we determined that $CO_{2\_water\_prod}$ was the most significant, accounting for over 70% of the total internal CO_2 production, which equates to 1264.4×10^3 t. In contrast, $CO_{2\_sediment\_prod}$ and $CO_{2\_photo\_prod}$ contributed less than 30% to the total internal CO_2 production, with approximately 307.9×10^3 t and 0.7×10^3 t, respectively. The internal loss of DIC was around 132.3×10^3 t. Consequently, the total CO_2 emissions from Hulun Lake during the study period were estimated to be 1469.8×10^3 t, and the corresponding C-CO_2 emissions were approximately 400.9×10^3 t.

TABLE 1 The sediment characteristics and permanent carbon accumulation in Hulun Lake since 1850s.

Parameters	Range *
TOC (%)	1.73-2.68 (2.10)
TIC (%)	1.41-2.89 (2.29)
TC (%)	3.14-5.46 (4.39)
DBD (g cm^{-3})	0.28-0.81 (0.53)
SR (cm yr^{-1})	0.07-0.72 (0.33)
OCAR (g m^{-2} yr^{-1})	8.43-73.98 (31.42)
ICAR (g m^{-2} yr^{-1})	7.10-74.29 (36.15)
TCAR (g m^{-2} yr^{-1})	14.74-184.12 (71.23)
Total carbon burial ($\times10^3$t yr^{-1})	30.0-375.2 (145.2)

*The number in the bracket represents the average value.

The C emissions across the water-air interface were nearly three times higher than the carbon burial in the sediments, indicating that Hulun Lake served as a significant carbon source.

3.2 The overall carbon mass balance

The total carbon input during the study period was approximately 112.4×10^3 t, as detailed in Table 3. The predominant source of this input, amounting to about 107.5×10^3 t, was land runoff, with notable contributions from the Kelulun River at 19.1×10^3 t and the Wuerxun River at 88.4×10^3 t. Carbon

TABLE 2 DIC mass balances for Hulun Lake.

Process	Sub-process	Carbon flux ($\times10^3$ t)
External DIC input	DIC from Kelulun River	8.5
	DIC from Wuerxun River	19.2
	DIC from atmospheric deposition	1.1
	DIC from groundwater	0.3
internal CO_2 production	$CO_{2\_sediment\_prod}$	307.9
	$CO_{2\_water\_prod}$	1264.4
	$CO_{2\_photo\_prod}$	0.7
DIC outflow		0
internal DIC loss	$DIC_{internal\_loss}$	132.3
CO_2 emission	$CO_{2\_emission}$	1469.8
C-CO_2 flux		400.9

TABLE 3 The carbon budget of Hulun Lake from June 2015 to May 2016.

Parameters	Mass ($\times10^3$ t)	Proportion (%)
Inflow		
Land runoff	107.5	95.6
Groundwater inflow	1.3	1.2
Hay input	1.3	1.2
Atmospheric deposition	2.3	2
Total input	112.4	
Outflow		
Gaseous C emission	400.9	99.9
Fish harvest	0.5	0.1
Total output	401.4	
Net budget	-289	

inputs from groundwater and hay were comparatively less significant, together accounting for roughly 2.4% of the total carbon input, with each source contributing approximately 1.3×10^3 t. Furthermore, carbon input from atmospheric deposition was also minimal, constituting about 2.0% of the total carbon input (2.3×110^3 t).

The total carbon output from Hulun Lake was approximately 448.2×10^3 t, with carbon emissions to the atmosphere constituting 400.9×10^3 t, which is 99.9% of the total carbon loss. The carbon outflow from fish harvest was about 0.5×10^3 t, representing roughly 0.1% of the total outflow, as presented in Table 3.

The net carbon budget for the study period was approximately -289×10^3 t, indicating that Hulun Lake functioned as a net carbon source, and a substantial portion of the carbon was mineralized within the lake's waters and sediments during this period.

4 Discussion

4.1 Comparison of carbon source-sink function of Hulun Lake with other lakes

The comprehensive carbon mass balance assessment conducted in Hulun Lake has yielded a net carbon budget of approximately -289×10^3 t, signifying that the lake is a substantial net carbon source to the atmosphere. The ratio of carbon emission to carbon burial within the lake is approximately 3, which further emphasizes the pivotal role of Hulun Lake as a significant carbon source. The convergence of findings from both employed methodologies on this conclusion underscores a robust agreement between the approaches, lending credence to the characterization of Hulun Lake's carbon dynamics. These findings are in line with previous studies that reported a high carbon emission to carbon burial ratio in boreal lakes (Algesten et al., 2004; Kortelainen et al., 2013) and a moderately high ratio in subarctic-arctic lakes (Lundin et al., 2015). For instance, carbon burial in a boreal Sweden lake was found to be only 5% of CO_2 emissions (Chmiel et al., 2016). Kortelainen et al. (2013) noted that CO_2 outgassing to the atmosphere was nearly 30 times greater than carbon burial in boreal lake sediments. The prominent role of carbon emissions in Hulun Lake is also consistent with studies from other regions, such as the contiguous United States, which emphasize that most lakes are net sources of CO_2 to the atmosphere at a rate of approximately 40 Gg C d^{-1} (Mcdonald et al., 2013). Additionally, the carbon source function of Hulun Lake aligns with the view that the majority of lakes in China serve as net sources of CO_2 to the atmosphere (Li et al., 2018). Similar to our study, the carbon evasion into the atmosphere in a large eutrophic lake in eastern China was about 16 times greater than carbon burial (Dong et al., 2012; Xiao et al., 2020). Yuan et al. (2023) also demonstrated that the mean multiyear carbon emission in Baiyangdian Lake is, on average, 30 times larger than carbon sequestration.

However, previous studies on the carbon source-sink dynamics of lakes have yielded mixed results. For example, Yang et al. (2008) and Wang et al. (2019) found that Donghu Lake and Hongfeng Lake, both situated in subtropical regions of China, functioned as net carbon sinks, as the ratios of carbon burial to carbon release were both greater than 1 (approximately 12.6 and 1.4, respectively). Similarly, Hall et al. (2019) reported that carbon sequestration in a headwater boreal lake sediment exceeded carbon evasion over a 40-year record. These discrepancies may be attributed to a variety of factors (such as lake morphology, physiochemical and biological parameters, climate, and human activities) that influence the carbon budget in lake ecosystems. Additionally, they may relate to methodological differences in calculating the carbon budget as well as the difference of study time scales. It is worth noting that that the carbon source-sink function of lakes can vary significantly across different time scales, given the spatial and temporal heterogeneity of both CO_2 exchange with the atmosphere and carbon burial in lake sediments (Lin et al., 2022; Ray et al., 2023; Rudberg et al., 2021; Santoso et al., 2017; Zhang et al., 2018). Hence, high temporal and spatial resolution of CO_2 flux and sediment carbon burial are still needed in future investigations to refine assessments of the carbon source-sink function and enhance our understanding of the carbon budget in lakes.

4.2 The role of lake sediment in the carbon budget

The OCAR in Hulun Lake sediment was estimated at 31.42 g C m^{-2} yr^{-1}. This value is comparable to rates reported for Dianchi Lake in southwestern China (27.73 g C m^{-2} yr^{-1}; Huang et al., 2018) and for lakes in the Conterminous United States (31 g C m^{-2} yr^{-1}; Clow et al., 2015). It is, however, significantly higher than rates observed in SW Greenland lakes (3.6 g C m^{-2} yr^{-1}; Anderson et al., 2019), Bosten Lake of northwestern China (17.7-20.1 g C m^{-2} yr^{-1}; Yu et al., 2015), Tibetan Plateau alpine lakes (e.g., 6.21-10.86 g C m^{-2} yr^{-1} in Heihai; Zhang et al., 2024), and Yangtze floodplain lakes (14.85 g C m^{-2} yr^{-1}; Dong et al., 2012). Furthermore, it remains lower than values reported for heavily eutrophic lakes, where OCAR can reach

200 g C m^{-2} yr^{-1} (Heathcote, 2012). Besides, the ICAR in Hulun Lake was approximately 36.15 g C m^{-2} yr^{-1}, comparable to values reported for some hard-water lakes in North America and arid and semi-arid regions of China (Finlay et al., 2010; Yu et al., 2015). In comparison, the carbon density in forest and grassland soils in China is estimated at 1061 g C m^{-2} and 854 g C m^{-2}, respectively (Fang et al., 2018). It appears that the intensity of carbon burial in Hulun Lake sediment is greater than that observed in forest and grassland ecosystems on a centennial timescale. This difference becomes even more pronounced when considering millennial timescales, highlighting the significant role of Hulun Lake sediment in regional carbon cycling.

Our study also showed that the carbon burial in Hulun Lake sediments exerted a comparatively small role in the annual C budget compared with the lake emission of CO_2 (Table 3). The CO_2 production in Hulun Lake sediments was only a moderate source (~20%) to the total CO_2 emission, and the C burial accounted on average for only 10% of the total CO_2 emission. The average contribution (~20%) was generally in line with a study by Chmiel et al. (2016), who reported that sedimentary carbon in a small boreal lake accounted for roughly 16% of the total annual CO_2 emissions. These studies, however, diverge from the OC mineralization patterns observed in other boreal lakes, where sediment OC mineralization was deemed to play a very significant or moderately significant role in CO_2 emissions (Brothers et al., 2012; Jonsson et al., 2001; Kortelainen et al., 2006). Given the flat and shallow lake bottom of Hulun Lake, the sediment OC mineralization was expected to be high since such conditions were in favor of the mineralization of OC (Sobek et al., 2009). However, previous study has pointed out minimal OC mineralization occurred in Hulun Lake due to its high sedimentation rate as well as low water temperature (Zhang et al., 2018). Consequently, the carbon mineralization within sediments in our study is identified as a minor contributor to the emissions of CO_2.

4.3 Importance of CO_2 emissions in the carbon budget

Lake CO_2 supersaturation has been observed worldwide and previous estimates indicated the mean CO_2 flux for global lakes was about 7.6-10.4 g C m^{-2} yr^{-1} (DelSontro et al., 2019; Holgerson and Raymond, 2016). The emission of CO_2 into the atmosphere in Hulun Lake was estimated to be 719.1 g m^{-2} yr^{-1}, significantly higher than the global average, and also higher than those from temperature lakes (ca.25-39 g m^{-2} yr^{-1}) (Buffam et al., 2011) and boreal lakes (ca.258.4 g m^{-2} yr^{-1}) (Weyhenmeyer et al., 2015), emphasizing the importance of CO_2 emission from Hulun Lake. Furthermore, while the national total lake CO_2 emissions in China are estimated to be about 15.98 Tg C yr^{-1} (Li et al., 2018), Hulun Lake alone contributes 9.2% of this total, despite comprising only 2.5% of the total lake area in China. This disproportionate contribution supports the argument that CO_2 emissions from lakes should be considered a critical component in regional and global carbon balance assessments. It is important to note, however, that the calculation of CO_2 emissions in our study was based on a mass balance approach, which does not incorporate direct measurement data for validation. As a result, the robustness of our annual CO_2 emission estimates may be somewhat limited compared to those derived from direct measurements. This highlights the need for future studies to employ high-frequency (e.g., monthly) and long time-series (e.g., spanning several years) monitoring of CO_2 concentrations and emissions to enhance the accuracy and reliability of carbon flux assessments in lakes.

4.4 Causes of the carbon source function of Hulun Lake

Previous studies have illustrated that eutrophic lakes tend to be net carbon sinks due to their high primary production (Michelle and John, 2011; Pacheco et al., 2014). However, Hulun Lake, despite being eutrophic, was CO_2-supersaturated and acted as a net carbon source during our study period. Temperate-lake models predict that lakes with low DOC and high TP tend to be autotrophic and serve as net carbon sinks (Hanson et al., 2004). Nevertheless, Hulun Lake's epilimnetic DOC (63.12 mg L^{-1}) and TP (0.21 mg L^{-1}) fall well outside the calibrated ranges of that model, which are 2–20 mg L^{-1} for DOC and 0.005–0.1 mg L^{-1} for TP. Therefore, this model may not be suitable for interpreting the carbon dynamics of Hulun Lake. Under these extreme conditions, we argue that Hulun Lake's role as a carbon source is primarily driven by low in-lake primary production, extended water residence time, substantial allochthonous carbon inputs, and intensive human activities.

The climate surrounding Hulun Lake is typically characterized by low temperatures, leading to reduced primary production. Studies have reported that the average net primary productivity (NPP) in the temperate steppe of Hulunbuir was estimated to be less than 250 g C m^{-2} yr^{-1} for the period from 2000 to 2017 (Shen et al., 2019). This value is significantly lower compared to other eutrophic lakes, such as Donghu Lake, with an NPP of 526 g C m^{-2} yr^{-1} (Yang et al., 2008), and Taihu Lake, with an NPP of 398 g C m^{-2} yr^{-1} (Xu et al., 2017). Considering the constrained primary production rate, it is clear that less aqueous CO_2 would be consumed, resulting in a higher emission of CO_2 from the lake waters into the atmosphere.

The high CO_2 evasion to the atmosphere was also strongly affected by the lake water residence time (Algesten et al., 2004). Since no out-flow was observed in recent years due to climate warming, the lake water residence time showed an obvious increase, and hence resulted in more organic carbon loss and CO_2 emission (Algesten et al., 2004).

Consequently, this process contributes to the relatively substantial CO_2 emissions observed in Hulun Lake.

Furthermore, Hulun Lake received a large amount of terrigenous carbon (both DIC and DOC) inputs from land runoff due to the high C content in inflowing rivers, which accounted for more than 95% of the total input. On one hand, the substantial input of DIC can directly elevate CO_2 concentrations, positioning the lake as a significant atmospheric CO_2 source. On the other hand, the high allochthonous DOC serves as a substrate for heterotrophic bacteria, driving extensive microbial mineralization (Hanson et al., 2004; Mcdonald et al., 2013; Sobek et al., 2005). Persistent wind-induced mixing (average wind speed: 4.2 m s^{-1}) helped maintain oxic conditions throughout the water column, thereby promoting aerobic mineralization while suppressing methanogenesis, a pattern consistent with shallow eutrophic lakes (Zhu et al., 2018). Low sedimentary carbon mineralization rates (Zhang et al., 2018) suggest limited contribution from anoxic degradation. As a result, microbial processes accounted for approximately 90% of internal CO_2 production (Table 2), predominantly via aerobic pathways, substantially enhancing lake-wide CO_2 emissions.

Anthropogenic activities also played an important role in determining the carbon source function of Hulun Lake. The land use and cover changes in Hulun Lake watershed (e.g., conversions of forests to grasslands and grasslands to other lands) was likely contributed to the soil and water loss, leading to greater transport of terrestrial DIC and DOC to lakes and thus more CO_2 would be produced from respiration (Wang et al., 2017). In addition, human-driven nutrient inputs can also alter the carbon burial and carbon emission in inland waters. Hulun Lake was used to surrounded by a wide grassland where pasture flourished several decades ago. However, the average grazing intensity in Hulunbuir grassland has increased from 1.7 live-stock units per hectare in 2006 to 2 live-stock units per hectare in 2015 (data were from http://tjj.hlbe.gov.cn/), close to the maximum stocking rate in Inner Mongolia (Chen et al., 2012; Hoffmann et al., 2008). The extensive grazing, especially around the rivers and wetlands, often led to the destruction of grassland, and hence promoted soil erosion and high nutrients input. It was estimated that the losing rate of TN and TP in grassland were about 1.75 mg/L and 0.63 mg/L, respectively (Liang et al., 2016). The increased nutrients can raise the CO_2 emission by stimulating the microbial activities as well as enhancing the respiration of aquatic organisms and degradation of OC, resulting in increasing CO_2 production and emission (Li et al., 2012; Wang et al., 2017). However, it should be noted here that the human-driven increased nutrient concentrations can also promote primary production and cause more carbon buried in lake sediments (Anderson et al., 2020; Heathcote, 2012). The ultimate impact of nutrient loadings on C source-sink change depends on the balance between CO_2 production and consumption (Perga et al., 2016; Xiao et al., 2020) and more work should be done to address this issue.

4.5 Uncertainties of the carbon budget calculations

Compared with previous studies (e.g., Xiao et al., 2020; Yang et al., 2021), our approach provides a more comprehensive framework for estimating the carbon source–sink function of Hulun Lake, integrating carbon input, output, burial, and emission. However, several sources of uncertainty may affect the final carbon budget, particularly in carbon flux estimation based on limited temporal sampling. The first source of uncertainty lies in the estimation of carbon loads from rivers and groundwater. These inputs were calculated using measured carbon concentrations from water samples collected before and after the wet season, combined with annual discharge data. The lack of carbon concentration data for the remaining months may introduce uncertainty into the input estimates. To assess this, we performed a sensitivity analysis assuming a 100% increase in carbon concentrations during the unsampled months. This adjustment raised total inflow carbon loads by more than 50%, yet the resulting change in the net carbon budget was only about 4%, suggesting limited sensitivity to input variability.

A second source of uncertainty is associated with CO_2 emission estimates, which were derived using an inorganic carbon mass-balance approach (Weyhenmeyer et al., 2015). In this method, CO_2 emission is calculated as the sum of external DIC input and internal CO_2 production, minus DIC losses through burial and outflow. Among these terms, internal CO_2 production, which includes sedimentary, water column, and photochemical processes, contributed over 90% of the total flux and is thus the most uncertain component. We therefore performed a ±10% sensitivity analysis on these internal CO_2 production terms. The results showed that total annual CO_2 emissions changed by approximately ±10.7%, confirming that while the emission estimates are moderately sensitive to internal production variability, the overall conclusion that Hulun Lake acts as a net carbon source remains robust.

Furthermore, the calculation of temporal OCBR in our study was based on sedimentation rates and the surficial TOC content from fifteen sediment cores. The TOC content was analyzed from cores collected in 2014, implying that the surface TOC content might have been lower than our study period values due to ongoing mineralization during particle settling and at the sediment-water interface. While the precise extent of post-deposition mineralization over time remains unknown, it is presumed to be relatively slow in Hulun Lake sediments due to the consistently low mean temperature and prolonged frozen periods. Consequently, the potential underestimation of TOC content is deemed negligible.

Additionally, the CO_2 emissions in our study were calculated using an inorganic carbon mass-balance approach (Weyhenmeyer et al., 2015), applied to the ice-free period. During the ice-covered season, CO_2 accumulates beneath the ice and is rapidly released into the atmosphere during ice breakup (Striegl et al., 2001). However, our sampling was conducted after ice-out, and thus the CO_2 pulse released at the moment of thaw was not captured in our flux calculations. This likely leads to an underestimation of total annual CO_2 emissions. Although the precise magnitude of this missing flux is unknown, previous studies in northern lakes (e.g., Denfeld et al., 2018) suggest that ice-out emissions may account for 17% of annual CO_2 release. Therefore, the reported CO_2 emissions and the emission-to-burial ratio in this study should be considered conservative estimates. Inclusion of ice-melt CO_2 release would likely further increase both values, reinforcing the conclusion that Hulun Lake functioned as a significant carbon source during the study period.

5 Conclusion

In this study, we use Hulun Lake in northeastern China as a case study to investigate the carbon sink-source function of lakes. Despite of some uncertainties, both the mass balance approach and the comparison of surface-to-air CO_2 flux with carbon burial in sediments indicate that Hulun Lake functions as a carbon source. The releasing of CO_2 to the atmosphere played a dominant role in the carbon output, and the ratio of CO_2 evasion to sedimentary carbon burial was greater than 1, stressing that the carbon retained in the sediment of Hulun Lake could not offset the carbon emitted into the atmosphere. Our research highlights the dual role of lakes, which act both as sources of atmospheric CO_2 and as significant repositories of carbon in their sediments. However, many factors that govern the import and export of carbon to and from lakes, as well as the internal carbon processing within lakes, are not yet fully understood. Given this knowledge gap, and considering the amplifying role of lakes within the landscape, it is imperative to conduct further assessments of the carbon budget in lakes for future studies.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

FZ: Writing – original draft, Conceptualization, Methodology, Investigation, Formal analysis. BX: Writing – review & editing, Resources, Supervision. SY: Writing – review & editing, Investigation, Supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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