Real-time and dynamic estimation of CO\(_2\) emissions from China’s lakes and reservoirs

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PUBLIC SUMMARY

- Lake CO\(_2\) emissions were estimated using real-time water quality monitoring data.
- China’s total lake and reservoir CO\(_2\) emission between 2021-2022 was 6.78 Tg C yr\(^{-1}\).
- General environmental controls were pH, dissolved oxygen, and air temperature.
Lakes and reservoirs act as active carbon (C) reactors and regulators. Both play a crucial terrestrial ecosystem C balance role via carbon dioxide (CO$_2$) exchange processes across the water-air interface. It has previously been confirmed that CO$_2$ flux from lakes and reservoirs generally exhibits significant spatiotemporal heterogeneity. Nevertheless, spatiotemporal CO$_2$ flux variation has seldom been considered in global and regional CO$_2$ emission estimates from lakes and reservoirs. By accounting for spatiotemporal CO$_2$ flux and water surface area variability, we evaluated spatial and temporal CO$_2$ emission dynamics from China’s inland lakes and reservoirs using national real-time water quality monitoring data and machine learning (ML) models. Between 2021–2022, we estimated total CO$_2$ emission flux at 6.78 (±2.5) Tg C yr$^{-1}$, where seasonal and regional distribution both exhibited significant heterogeneity. Our state-of-the-art estimate is significantly lower than previous estimates of 7.9–25 Tg C yr$^{-1}$ from the 1980s to the 2010s. Water quality parameters (pH and dissolved oxygen [DO]) and climate factors (air temperature) were identified as the general environmental CO$_2$ flux controls. For the first time, this study clarifies the spatiotemporal patterns and drivers of CO$_2$ flux from China’s inland lakes and reservoirs, providing a more complete C budget picture of China’s aquatic ecosystems.

INTRODUCTION

Carbon dioxide (CO$_2$) exchange across the water-air interface, quantified using CO$_2$ flux, plays an important role in aquatic carbon (C) cycling processes. In inland water, the absorption and release of CO$_2$ are determined by primary biogeochemical cycling processes, including phytoplankton photosynthesis, photochemical mineralization of dissolved organic carbon (DOC), and microbial respiration during DOC decomposition, all of which are extremely sensitive to multiple environmental stressors (i.e., wind, sunlight, temperature, and nutrients). Moreover, CO$_2$ exchange from lakes and rivers is also significantly influenced by surrounding landscape patterns. Complex environmental control mechanisms lead to significant spatiotemporal CO$_2$ exchange variability. Both long-term and direct observations taken from individual lakes and reservoirs have shown that CO$_2$ flux exhibits dramatic fluctuations at diel, seasonal, and annual scales as well as significant spatial disparity. However, under observational restrictions, our understanding of spatiotemporal lake and river CO$_2$ flux patterns is fragmented. Hence, capturing spatiotemporal CO$_2$ flux dynamics at the water-air interface is of great importance to inland water C budget assessments.

Global and regional CO$_2$ emission estimates from lakes and reservoirs have generally been scaled from collected site-level measurements, most of which had a sparse and heterogeneous spatial distribution, a prolonged timespan, and a dominance of diurnal observations. Moreover, upsampling spatiotemporally discrete CO$_2$ flux measurements to regional and global scales may cause widespread uncertainty in evaluating total CO$_2$ emissions from inland waterbodies. A recent global compilation of high-frequency CO$_2$ measurements from rivers indicated that nocturnal CO$_2$ emissions were significantly higher than diurnal emissions in temperate regions, while diel changes were much lower in boreal and tropical regions. Global CO$_2$ emissions from rivers (0.65–1.8 Pg C yr$^{-1}$) would increase by 0.2–0.55 Pg C yr$^{-1}$ when accounting for such high nocturnal emissions. Monthly CO$_2$ emissions from global rivers have also exhibited considerable fluctuation, ranging from 112 to 209 Tg C. To date, spatiotemporal CO$_2$ flux variation has rarely been accounted for in total CO$_2$ emission estimates from inland lakes and reservoirs at regional or global scales. Furthermore, satellite observations have demonstrated that variation in the surface extent of seasonal lakes and reservoirs is of particular interest, whose influence on upscaling CO$_2$ flux may be consequential. Reservoirs and ponds that seasonally dry (i.e., non-running inland water) have been recognized as CO$_2$ emission hotspots. Moreover, global CO$_2$ emissions from reservoir drawdown areas have reached 26.2 Tg C yr$^{-1}$, increasing reservoir CO$_2$ emissions by 53%. Although small ponds only account for 8.6% of all lakes and ponds globally, they contribute 15.1% of the total CO$_2$ emissions. Overall, global CO$_2$ emissions from inland lakes and reservoirs have been estimated to be between 0.32 and 0.64 Pg C yr$^{-1}$. However, there remains a large degree of uncertainty in CO$_2$ emission estimates from non-running inland water globally. This uncertainty is largely due to the absence of spatiotemporally dynamic CO$_2$ flux and water surface area data during the upsampling process as well as CO$_2$ emission overestimations from small lakes and lakes in tropical regions.

China is home to thousands of lakes and reservoirs (Figure S1), only accounting for ~1% of its total land area. However, these lakes and reservoirs could offset the C sink capacity of China’s terrestrial ecosystems by 4–6%. Nationally, total CO$_2$ emissions from lakes and reservoirs were estimated between 7.9 and 25 Tg C yr$^{-1}$ in the 1980s to 12.1 Tg C yr$^{-1}$ in the 2010s, while drivers that control spatiotemporal CO$_2$ emission transformation processes remain unclear. The diversity of geographical and climatologic factors in China’s inland lakes and reservoirs leads to different controlling mechanisms in the CO$_2$ exchange. Many environmental factors (e.g., nutrient loading, thermal structure, and inorganic and hydrological processes) have been recognized as being major controlling CO$_2$ emission factors within individual lakes and reservoirs in China. However, there remains a considerable knowledge gap concerning the general drivers that are used to explain CO$_2$ emission dynamics from China’s inland lakes and reservoirs.

To address the spatial and temporal constraints of large-scale CO$_2$ emission estimations while offering a more complete understanding of how CO$_2$ emissions from lakes and reservoirs respond to global climate change, this study used national high-frequency water quality monitoring data with the support of satellite remote sensing imagery and machine learning (ML) models to provide the first real-time and dynamic estimates of CO$_2$ emissions from China’s inland lakes and reservoirs. Based on these new estimates, this study aimed to (1) ascertain spatiotemporal CO$_2$ emission patterns from China’s inland lakes and reservoirs and (2) determine the environmental controls on CO$_2$ exchange processes in non-running inland water.

RESULTS

Spatial and temporal $F_c$ distribution

To better clarify diurnal differences in CO$_2$ exchange rates from China’s inland lakes and reservoirs, diurnal and nocturnal site level CO$_2$ flux (represented by $F_c$) was compared among all 205 sampled sites (Figure 1). Mean diurnal $F_c$ and mean nocturnal $F_c$ values were mostly positive, indicating that most lakes and reservoirs acted as C sources (Figure 1A). Diurnal $F_c$ values tended to be slightly higher than nocturnal $F_c$ values in cases where the former was positive (Figure 1A and 1B). Where maximum $F_c$ values occurred most frequently at 12 and 8 a.m. (Figure 1C), diurnal $F_c$ values tended to be...
lower than nocturnal $F_c$ values in cases where the former was negative (Figure 1A and 1B), where maximum $F_c$ values occurred most frequently at 8 and 4 a.m. (Figure 1C).

Seasonally, the partial pressure of CO$_2$ (pCO$_2$) in lakes and reservoirs varied from 4 to 10544 μatm, while mean pCO$_2$ values ranged between 827 and 1113 μatm. Moreover, 16.6%–33.5% of all sampled lakes and reservoirs yielded pCO$_2$ values less than 400 μatm, indicating a state of CO$_2$ undersaturation (Figure S7). Moreover, $F_c$ exhibited a lognormal distribution, and most $F_c$ values were distributed in the range between 10 and 50 mmol m$^{-2}$ d$^{-1}$, 16%–34% of sampled lakes and reservoirs exhibited a negative seasonal mean $F_c$ (Figure 2). Seasonal mean $F_c$ fell in the range between 15 and 23.8 mmol m$^{-2}$ d$^{-1}$, with a pattern of higher in summer and autumn, and lower in winter and spring. Our $F_c$ estimates were comparable to those from previous observations (23–27 mmol m$^{-2}$ d$^{-1}$).18

Regionally, stronger CO$_2$ emissions (>16 mmol m$^{-2}$ d$^{-1}$) mainly occurred in eastern and northern China, including the Northeast Plain and Mountain Lake (NPML) zone, the Eastern Plain Lake (EPL) zone, and the Inner Mongolia-Xinjiang Lake (IMXL) zone. Conversely, CO$_2$ emissions from lakes and reservoirs in China’s southwestern region, including the Yunnan-Guizhou Plateau Lake (YGPL) zone and the Tibetan Plateau Lake (TPL) zone, were generally weaker (<10 mmol m$^{-2}$ d$^{-1}$) (Figure 3). This is consistent with regional pCO$_2$ distribution (Figure S8). Given that a large proportion of the population and industry activity is distributed in eastern China, lakes and reservoirs in eastern regions generally suffer from higher C and nutrient input intensity, which largely explains the significant regional difference in the CO$_2$ emission.3,19

**CO$_2$ emissions from China’s lakes and reservoirs**

This study estimated total monthly CO$_2$ flux from lakes and reservoirs across five lake zones of China from June 2021 to May 2022 (Figure 4). Overall, the total CO$_2$ emission from these lakes and reservoirs was 6.78 ± 2.5 Tg C yr$^{-1}$ (Table 1). Regionally, more than half of all relevant CO$_2$ emissions originated from the EPL zone, where both $F_c$ and water surface area ranked second among all five lake zones. The NPML and TPL zones yielded the highest $F_c$ value (26.3 mmol m$^{-2}$ d$^{-1}$) and water surface area (~4×10$^5$ km$^2$), respectively (Figure 3 and S1); however, NPML zone surface area and TPL zone $F_c$ were both comparatively low, which resulted in their low total CO$_2$ emissions (i.e., 16.8% in the NPML zone and 10.4% in the TPL zone) (Figure 4B). Seasonally, only negligible differences in total CO$_2$ flux values were observed among spring, summer, and autumn (28%–31%), while winter CO$_2$ emissions (10%) were clearly lower than that estimated from the other three seasons (Figure 4C). This decrease in winter CO$_2$ emission flux can largely be attributed to extensive lake and reservoir ice cover in northern China under frigid weather conditions, which could decrease winter CO$_2$ evasion by 1.32 Tg C yr$^{-1}$ (Table S4, Supplemental Information S6). However, we also found that differences in seasonal CO$_2$ emission patterns were significant among all five lake zones (Figure 4A). In the EPL and TPL zones, CO$_2$ emission areal flux peaked in summer and autumn; in the NPML and IMXL zones, CO$_2$ emission areal flux peaked in spring.

**Major environmental CO$_2$ emission controls**

The geographical, hydrological, and climatological diversity of China’s lakes and reservoirs is the reason behind the dramatic regional and climatic variation in their C cycling processes. For example, the associated thermal stratification structure of reservoirs has been reported to dominate CO$_2$ exchange processes in southwestern and southeastern China.30,36 On the other hand, inorganic processes associated with pH have been shown as being the main controlling CO$_2$ absorption and emission factors in saltwater lakes within China’s northern desert regions and the Tibetan Plateau.26,33 For eutrophic lakes within the Yangtze River basin (e.g., Taihu Lake), CO$_2$ emissions are driven by eutrophication and temperature.33 For floodplain lakes (e.g., Poyang Lake), CO$_2$ exchange has been shown to be driven by hydrological changes associated with water level fluctuation.35

Driving mechanisms associated with CO$_2$ exchange in China’s inland lakes and reservoirs are known to be both complex and variable. Accordingly, this study explored the environmental controls on the pCO$_2$/F$_c$ using structural equation modeling (SEM), and intended to reveal the general environmental and climatologic drivers of CO$_2$ exchange from inland lakes and reservoirs across China (Figure 5, Supplemental Information S7). The SEM was established on two dependent levels, allowing for different factor interactions on water pCO$_2$ and $F_c$. Among the nine significantly correlated environmental factors, water physicochemical indicators of pH and dissolved oxygen (DO) exhibited a strong negative effect on pCO$_2$, physio-chemistry indicators of water surface temperature (WST), electrical conductivity (EC) and turbidity (Turb), as well as nutrients of ammonia nitrogen (NH$_3$-N), total nitrogen (TN)
and total phosphorus (TP), showed a moderate positive effect on pCO$_2$. Phytoplankton (indicated by chlorophyll concentration, Chl-a) showed a weak effect on pCO$_2$. SEM results further suggested that F$_c$ was primarily driven by pCO$_2$ in water, which explained 62% (square of the path coefficient) of F$_c$ variance. Meteorological factors, especially wind speed (WS) at a 10 m height, had a relatively weaker positive effect on F$_c$. Although the negative correlation between pCO$_2$/F$_c$ and water quality pH and DO parameters had previously been reported in specific lakes within the EPL and TPL zones, their association with pCO$_2$ and F$_c$ was explored in this study.

Figure 2. Seasonal distribution of F$_c$ in China’s inland lakes/reservoirs. Subplots (A)–(D) and (E)–(H) denote spatial distributions and histograms of F$_c$ during spring, summer, autumn, and winter, respectively. The dashed black and cyan lines denote means and medians of F$_c$, respectively, while shaded areas indicate 90% and 95% confidence intervals. The five lake zones labeled in the map represent the Tibetan Plateau Lake (TPL), the Yunnan-Guizhou Plateau Lake (YGPL), the Inner Mongolia-Xinjiang Lake (IMXL), the Northeast Plain and Mountain Lake (NPML), and the Eastern Plain Lake (EPL) zones, respectively. The four seasons were defined based on the standard meteorological season of the Northern Hemisphere (i.e., March, April, and May for spring; June, July, and August for summer; September, October, and November for autumn; December, January, and February for winter).
our analysis suggested that the influence of this relationship may be more extensive. We also investigated environmental controls on pCO$_2$/F$_c$ over different lake zones (Figure S1). pCO$_2$ showed stronger positive responses (path coefficients: 0.30–0.39) to physicochemical indicators of EC, Turb, and WST in eastern and northern China (i.e., IMXL, NPML, and EPL). The response of pCO$_2$ to nutrients was strongest in the IMXL zone and weakest in the NPML zone. However, climatic factors had almost no influence on F$_c$ in the YGPL zone, which differed from the other lake zones.

Therefore, results from this study led us to conclude that water quality management initiatives used to improve surface water acidification and hypoxia would simultaneously reduce C emissions while increasing the C sink capacity of China’s inland lakes and reservoirs. At a larger regional scale, the CO$_2$ evasion rate weighed by water surface area exhibited a significant positive correlation with regional mean air temperature (Figure S1, Supplemental Information S7), which indicated that climate warming would promote CO$_2$ emissions from China’s inland lakes and reservoirs. Especially in the IMXL and TPL zones, rising temperatures coupled with increasing precipitation would accelerate the melt of ices and snows and the release of organic C stored in glacier ice, which could speed up the C emissions into the atmosphere.\(^{20,40}\)

**DISCUSSION**

**Spatiotemporal F$_c$ patterns**

Statistically, lakes/reservoirs with higher diurnalCO$_2$ emissions were more than those with higher nocturnal CO$_2$ emissions in our dataset. The higher diurnal CO$_2$ emissions observed from China’s lakes and reservoirs were contrasted with those observed from rivers globally.\(^{13,41}\) The diurnal variation pattern was consistent with directly observed F$_c$ values in certain typical lakes and reservoirs in China.\(^{14,42,43}\) This may be attributed to higher daytime WS and gas transfer velocity, which could enhance daytime CO$_2$ emissions from lakes and reservoirs.\(^{16}\)

Results from this study reveal seasonal F$_c$ patterns at a national scale for the first time. We found that 34% of sampled lakes and reservoirs (i.e., 70 out of 205) transformed from C sources to C sinks within a year. Furthermore, seasonal F$_c$ patterns varied regionally. For example, F$_c$ values in the EPL and TPL zones were higher in summer and autumn and lower in spring and winter, while F$_c$ values in the NPML, IMXL, and YGPL zones were higher in spring and winter and lower in summer and autumn (Figure 3A). Additionally, significant seasonal F$_c$ fluctuations were observed among the five lake zones, where peak values exceeded valley values by factors of 1.5–2.8 across different seasons and regions. Apart from regional and seasonal differentiation, F$_c$ was also found to be dependent on lake area size. Compared with medium-sized lakes and reservoirs (10–50 km$^2$), small (<10 km$^2$) and large (>50 km$^2$) lakes and reservoirs tended to emit higher amounts of CO$_2$ to the atmosphere (Figure 3B). The higher flux observed from small lakes and reservoirs may be attributed to their high sediment yields and frequent mixing,\(^{25}\) while for large lakes and reservoirs, higher flux may be caused by high DOC concentrations.\(^{14}\)

**Uncertainties and limitations**

Compared with the estimates of 7.9–25 Tg C yr$^{-1}$ from literatures (Table 1),\(^{17,18,21}\) our state-of-the-art estimate (6.78 Tg C yr$^{-1}$) was relatively low. Multiple factors are attributed to this estimate discrepancy. Firstly, previous estimates did not account for diurnal and seasonal F$_c$ variations. Currently, all largescale CO$_2$ emission estimates from China’s inland water-bodies are dependent on the limited F$_c$ measurements collected from relevant studies, most of which were sampled during daytime hours, and the seasonal distribution was not homogeneous (fewer observations in winter). As we have demonstrated higher daytime F$_c$ and lower wintertime F$_c$ in China’s lakes and reservoirs (Figure 1 and 2), which could partially explain the evidently higher CO$_2$ flux estimated by previous studies. Secondly, there exists a wide discrepancy in evaluation periods. Considering that F$_c$ measurements collected from the literature may have been sampled during different years, previous estimates can only be used to indicate CO$_2$ emission levels over extended time periods (i.e., typically at a decadal scale). The latest estimates from the literature are from the 2010s.\(^{19,22}\) The estimate obtained from our study utilized sample data from 2021 to 2022, which thus provides an up-to-date assessment of CO$_2$ emissions from China’s inland lakes and reservoirs.

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**Table 1. Comparison among documented CO$_2$ emission estimates from China’s lakes and reservoirs.**

<table>
<thead>
<tr>
<th>Water surface area (×10$^5$ km$^2$)</th>
<th>Annual CO$_2$ flux (Tg C yr$^{-1}$)</th>
<th>Sampling period</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.94–1.05</td>
<td>6.78 (±2.5)</td>
<td>2021–2022</td>
<td>This study</td>
</tr>
<tr>
<td>1.2</td>
<td>7.9 (±10.4)</td>
<td>2010s</td>
<td>Wang et al., 2023(^{17})</td>
</tr>
<tr>
<td>1.08</td>
<td>12.1 (±2.1)</td>
<td>2010s</td>
<td>Ran et al., 2021(^{14})</td>
</tr>
<tr>
<td>1.09</td>
<td>25.15 (±4.3)</td>
<td>2000–2014</td>
<td>Li et al., 2018(^{13})</td>
</tr>
<tr>
<td>0.94</td>
<td>9.4 (±1.8)</td>
<td>1980s</td>
<td>Ran et al., 2021(^{14})</td>
</tr>
</tbody>
</table>

Note: numbers in parentheses represent standard deviations or confidence intervals.
reservoirs. Thirdly, previous estimates have rarely considered seasonal surface area fluctuations from lakes and reservoirs. In reality, impacts of water surface area variation on areal CO$_2$ emission assessments may be consequentially exceptional in some flood-prone lakes and regulated reservoirs. 29 China’s largest freshwater lake (Poyang Lake) is an example, where total CO$_2$ flux can reach up to 0.43 Tg C yr$^{-1}$. However, the dynamic range of Poyang Lake’s monthly inundation area varies widely (1116–2578 km$^2$). Therefore, estimated CO$_2$ flux from Poyang Lake would range from 0.22 Tg C yr$^{-1}$ to 0.52 Tg C yr$^{-1}$ without accounting for monthly inundation area dynamics (Figure S9, Supplemental Information S6).

Upscaling CO$_2$ flux from site to regional scales will result in considerable and unavoidable uncertainty. This mainly transpires from errors in the estimation of pCO$_2$ gas transfer velocity ($k_w$), and water surface area. Accordingly, we performed a Monte Carlo analysis to quantify variance in our estimate on regional CO$_2$ flux by providing uncertainty intervals for these three statistically independent components of error sources, and then randomly picked up values from the intervals for 10,000 iterations to obtain the distribution of the simulated estimates (Table S5, Supplemental Information S6). Overall, the simulation predicted a mean flux of 6.71 Tg C yr$^{-1}$ and a median flux of 5.82 Tg C yr$^{-1}$, under a large uncertainty range (1.2–14.8 Tg C yr$^{-1}$, 5th and 95th confidence interval percentiles). The mean flux of our simulated results was very close to the estimated flux of 6.78 Tg C yr$^{-1}$. Regionally, differences between estimated flux and simulated mean flux ranged between -0.21 Tg C yr$^{-1}$ and 0.11 Tg C yr$^{-1}$ across all five lake zones, which was relatively small (<20%) compared to regional CO$_2$ flux. The consistency between estimated and simulated flux at both regional and national scales demonstrated the high confidence of this proposed approach for CO$_2$ flux estimations in China’s inland lakes and reservoirs.

The TPL zone covers nearly half of China’s lake surface area. However, because this zone has only one sampling site, significant CO$_2$ emission evaluation bias may result. TPL presented as a C source in our estimate, with a flux of 0.71 Tg C yr$^{-1}$. This is comparable to a recent estimate of 1.16 Tg C yr$^{-1}$ by Jia et al. (2022), which was calculated using samples collected from 41 lakes and three reservoirs in 2020. 28 This estimate is obviously lower than the estimate of 3.87 Tg C yr$^{-1}$ by Ran et al. (2021), which was calculated by literature derived data in the 2010s. 26 It was also noted that saline lakes in the TPL were estimated to be a large C sink with a flux of -10.28±1.65 Tg C yr$^{-1}$ by eddy covariance method, 26 while water chemistry records and headspace equilibration method derived estimates suggested that TPL lakes was a large C source. 26 Given the significant geographical, climatological, physical, and chemical diversity of lakes and reservoirs in the TPL zone, quantifying its total CO$_2$ flux remains challenging, requiring more observations with long period, high frequency and different methods.

**Implications for China’s terrestrial C budget**

Being important reactors and regulators of C emissions, C storage, and C transportation, the total C emitted, accumulated, and transported from lakes and reservoirs may have a consequential effect on the terrestrial C balance. 5 This study estimated C flux from China’s lakes and reservoirs at 6.78 Tg C yr$^{-1}$ during the 2020s, accounting for both spatiotemporal variation in the F$_c$ and water surface area. This estimate accounted for 7–11% of CO$_2$ emissions from China’s inland waterbodies during the 2010s 13,21 and approxi-

![Figure 5. Environmental controls on pCO$_2$ and F$_c$ from China’s lakes and reservoirs.](https://www.the-innovation.org/geoscience)

- $k_w$: the gas transfer velocity (cm h$^{-1}$);
- $x_h$: is the Henry’s law constant adjusted for water temperature (mol L$^{-1}$ atm$^{-1}$);
- $\Delta$pCO$_2$: represents the difference in pCO$_2$ between water and the atmosphere (atm).

A positive $\Delta$pCO$_2$ value indicates that waterbodies emit CO$_2$ to the atmosphere whereas a negative value indicates that waterbodies absorb CO$_2$ from the atmosphere. $k_w$ was determined from optimal empirical models based on WS (Supplemental Information S5). These empirical models have been validated under different climatic and hydrologic conditions throughout China. Modeled $k_w$ values generally agreed well with direct $k_w$ measurements using floating chambers in the lakes and reservoirs of the EPL and TPL zones ($R^2=0.64$, $p<0.001$). 15 Atmospheric pCO$_2$ was obtained from NOAA’s Global Greenhouse Gas Reference Network of the Earth System Research Laboratory (ESRL). pCO$_2$ content in water was determined from water chemistry records (i.e., pH, WST, and alkalinity [A$_{L}$]) using CO2SYSv3 software. 22 pH and WST, sampled and measured at a 4-h frequency, were obtained from the China National Environmental Monitoring Centre (CNEMC) between June 2021 and May 2022.
Alk was estimated using five indicators (pH, DO, EC, TN, and TP) from CNEMC with a machine learning model, namely, Random Forest with bagged trees (RF-BAT), which was trained using the Global River Chemistry database (GLORICH) and validated using in situ measurements from typical lakes in China (Figure S3−4, Table S2−3). pCO2 overestimations in water under low pH (<6.5) and Alk (<1000 μeq/L) conditions were corrected using an empirical model developed by Liu et al. (2020).58 The pCO2 estimated from water chemistry data showed good agreement with direct measurements by headspace equilibration method (Figure S6).

Accounting for the fact that pCO2 and k are highly dependent on region, time, and surface area size,14–16,42–44 China’s inland lakes and reservoirs were divided into five lake zones (i.e., TPL, YGPL, IMXL, NPML, and EPL) according to their specific geographic, topographic, and climatic diversity (Figure S1).56 Lakes and reservoirs were simultaneously divided into three different size categories according to surface area differences (i.e., <10, 10−50, and >50 km²).58 We calculated areal CO2 flux ($F_c^R$, in Tg C) by surface area size and day within each lake zone using the following formula:

$$F_{c}^{R} = \sum_{region} \left( \sum_{class} \left( \sum_{day} (F_{c} \times SA) \right) \right)$$

(2)

where $F_c$ is the daily and regional mean $F_c$ of a specific lake/reservoir area size within a lake zone. SA is the monthly surface area of lakes and reservoirs, which was obtained from the satellite-based Reservoir and Lake Surface Area TimeSeries (RealSAT) dataset.17 Allowing for the fact that ice cover may prevent atmospheric exchange and subsequently lead to CO2 accumulation, frozen lakes/reservoirs were excluded from our $F_c$ calculation. Ice-covered areas were identified based on daily mean air temperature (AT), under the assumption that lakes/reservoirs were fully covered by ice when AT was less than −4°C.18 The influence of ice cover on CO2 emissions was quantified by comparing flux differences with and without ice cover (Table S4). A Monte Carlo simulation was used to evaluate the uncertainty associated with $F_c$ calculations (Table S5).

See Supplemental Information for more detail on the materials and methods used in this study.

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AUTHOR CONTRIBUTIONS

K.S. and Y.G. initiated this study and led the writing of the manuscript. K.S., J.J. and S.W. performed the data processing and analysis. All authors participated in the discussion and writing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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