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Key Points:

- Poyang Lake as a CO_2 source or sink significantly depends on water level
- Poyang Lake became a CO_2 sink since the Three Gorges Dam operation in 2003
- Dam explains 22% of differences in CO_2 fluxes in autumn impoundment period

Supporting Information:

Supporting Information may be found in the online version of this article.

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Three Gorges Dam Operations Affect the Carbon Dioxide Budget of a Large Downstream Connected Lake

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Abstract The effects of dams on carbon dioxide (CO_2) fluxes in downstream lakes remain elusive. Here we combined eddy covariance observations and random forest models to examine multi-decadal variations in CO_2 fluxes in the Poyang Lake, the largest freshwater lake in China, and quantified the contribution of the Three Gorges Dam (TGD), the world's largest hydraulic project. We found the lake fluctuated between CO_2 source and sink in 1961–2016, and tended to be CO_2 sink in the post-TGD period (2003–2016) when vegetation expanded early and spatially due to declining water level. TGD can explain approximately 6% of the total differences in annual CO_2 fluxes, with major contributions in the impoundment period (up to 22% in middle September to October). The results show a positive side of operational major hydraulic projects on lake carbon sink, and probably caution the negative side of carbon release after dam removal.

Plain Language Summary In the past century, dams have significantly altered the hydrological connectivity between rivers and lakes, which affect CO_2 exchange in the downstream lake systems. As the largest freshwater lake in China, Poyang Lake has also undergone drastic hydrological changes, attributable largely to the operation of the Three Gorges Dam (TGD), the world's largest hydraulic project ever, in 2003. Based on flux observations and machine learning method, we show that annual lake CO_2 exchange shifted toward carbon sink during 1961–2016. The TGD has a major impact on lake CO_2 fluxes, especially during the impoundment stage in middle September–October, explaining 22% of the flux differences between the pre- and post-TGD period. The results show a positive side of hydraulic projects albeit their adverse impact on ecological protection.

1. Introduction

Inland waters play a major role in global carbon cycle, contributing significant greenhouse gas (GHG) emissions to the atmosphere (Bastviken et al., 2011; Cole et al., 2007; Raymond et al., 2013). Lakes are an important part of inland waters, and are considered to be carbon dioxide (CO_2) sources at annual scale, despite of seasonal CO_2 sinks (Prairie et al., 2018). The total global lake CO_2 emission is estimated to be 0.07–0.86 $PgCa^{-1}$ but with high uncertainties (Aufdenkampe et al., 2011; Cole et al., 2007; Raymond et al., 2013; Tranvik et al., 2009). Lake CO_2 fluxes are influenced by both climate change and human activities (Drake et al., 2018; Holgerson & Raymond, 2016; Pilla et al., 2022; Sobek et al., 2005). The former has been well studied (Huttunen et al., 2003; Tranvik et al., 2009), whereas the latter is more complex and being debated.

Human activities affect carbon exchanges in inland waters by means of land cover change, nutrient dynamics as well as reservoir and dam construction (Pilla et al., 2022; Raymond et al., 2008). Over 40,000 large dams (>15 m high) have been constructed worldwide (Zarfl et al., 2015), leading to extensive changes in regional hydrological processes, geomorphology, aquatic habitat and downstream wetland ecosystems (Friedl & Wüest, 2002; Nilsson et al., 2005; Petts & Gurnell, 2005). It is well known that dams increase GHG emissions in the reservoirs (Descloux et al., 2017; Keller et al., 2020; Paranaíba et al., 2018; Teodoru et al., 2013; L. Yang et al., 2013), and affect phytoplankton productivity (Deemer et al., 2022) and GHG emissions (Calamita et al., 2021; Prairie et al., 2018) in the downstream rivers. Fewer studies have quantified the effects of altered riverine hydrology on GHG dynamics in downstream lakes.

The world's largest Three Gorges Dam (TGD) was built on the mainstream of the Yangtze River, China. The dam's massive water storage capacity (~22.15 km^3, 5% annual streamflow of the Yangtze River) has significantly altered hydrological rhythms of the Yangtze River and its downstream lakes (Hu et al., 2007; Lai et al., 2014; Liu et al., 2016; Zhang et al., 2012). Poyang Lake is one of the most affected lakes. It is the largest freshwater lake in China, and connects directly with the Yangtze River. Poyang Lake mainly outflows into the Yangtze River, and occasionally backflows occur during the flood season, affecting only a few kilometers of the lake (Hu et al., 2007). With a higher water level (WL), the river might block lake outflow; otherwise, the lake outflow is accelerated and the lake WL decreases rapidly. Given that climate change is already altering precipitation patterns in the basin, the WL of Poyang Lake has been continuously low since the 21st century, especially in the recession period, which has experienced a regime shift (Guo et al., 2022; Liu et al., 2013), attributed also to the decrease of discharge from basin and sand mining (Lai et al., 2014). The water impoundment of the TGD in the middle of September–October, reduces the WL of the Yangtze River during this period, subsequently the WL decline in the Poyang Lake (Zhang et al., 2012).

The ephemeral Poyang Lake transitions seasonally between water surface and wetland vegetation. Hydrological and ecological processes in this lake are naturally sensitive to WL changes (Wu & Liu, 2017). Extremely low lake WLs have been frequently observed since the TGD operation (Liu et al., 2013), leading to an expansion of wetland vegetation (Tan et al., 2016; Wan et al., 2018). Superimposing divergent rates of carbon exchanges over vegetation and water surface further complicates the spatial-temporal patterns of carbon dynamics. In reference to long-term climate background, to what extent carbon source or sink patterns are affected by TGD operation still remains elusive. Based on CO_2 flux observations, we constructed a long-term CO_2 flux data set for the Poyang Lake from 1961 to 2016, and separated the contributions of climate change and human activities, in particular the TGD operation. Our results are intended to draw the attention of carbon research community to the effects of hydraulic projects on regional carbon budget, both in the past and future.

2. Method

2.1. Description of the Poyang Lake and TGD

Poyang Lake (28.2°N–30.0°N, 115.5°E–116.5°E) is located in the middle reach of the Yangtze River basin, about 1,050 km downstream to the TGD (Figure 1). It plays an important role in flood control and domestic water provision, and serves as a vital waterway for transportation (Shankman & Liang, 2003; Zhu & Zhang, 1997). Belonging to a subtropical monsoon climate, the lake area has an annual mean rainfall of 1,620 mm and an annual mean temperature of 17.1°C (1958–2016). The lake receives discharges mainly from five rivers in its catchment, and is connected to the Yangtze River through the northern outlet, forming a complex flow regime featuring strong river-lake interactions (Hu et al., 2007; Shankman & Liang, 2003). Poyang Lake is an ephemeral lake, consists of permanent water surface and the drawdown zone. The water surface coverage (WSC) in lake dramatically changes from few hundred km^2 to the maximum area of 3,860 km^2, with WL variation from 9 to 21 m. The drawdown zone, flooded in high level period, is exposed in low level period and provides an ideal habitat for wetland vegetation growth. The dominant vegetation species are *Carexcinerascens*, *Phalarisarundinacea*, *Miscanthussacchariflorus*, and *Phragmitescommunis*. Based on the area of the large water surface (WSC = 80%) and permanent water surface (WSC = 30%), four hydrological periods were distinguished, namely, the water rising stage (WSC from 30% to 80%), the high-water stage (WSC ≥ 80%), the water recession stage (WSC from 80% to 30%) and the low-water stage (WSC ≤ 30%).

The TGD maintains a 145-m WL in flood season to reserve space for flood control, which is raised to 175 m after flood season. In the impoundment stage (mid-September to October), the intercepted water storage is about 22.15 km^3, or 5% annual streamflow of the Yangtze River (Lai et al., 2014). Here we define the time before 2003 as the pre-TGD period (1961–2002), and the time after 2003 as the post-TGD period (2003–2016).

2.2. CO_2 Flux Observations

The CO_2 fluxes were measured based on an eddy covariance (EC) site in the lake center (Figure 1). An open-path EC system was mounted on a 31-m tower, consisting of an infrared CO_2/H_2O gas analyzer and a CSAT3 three-dimensional sonic anemometer (EC150, Campbell Inc., USA). Half-hourly CO_2 flux data were collected from August 2013 to July 2016 (details see Text S1 in Supporting Information S1). Data preprocessing included

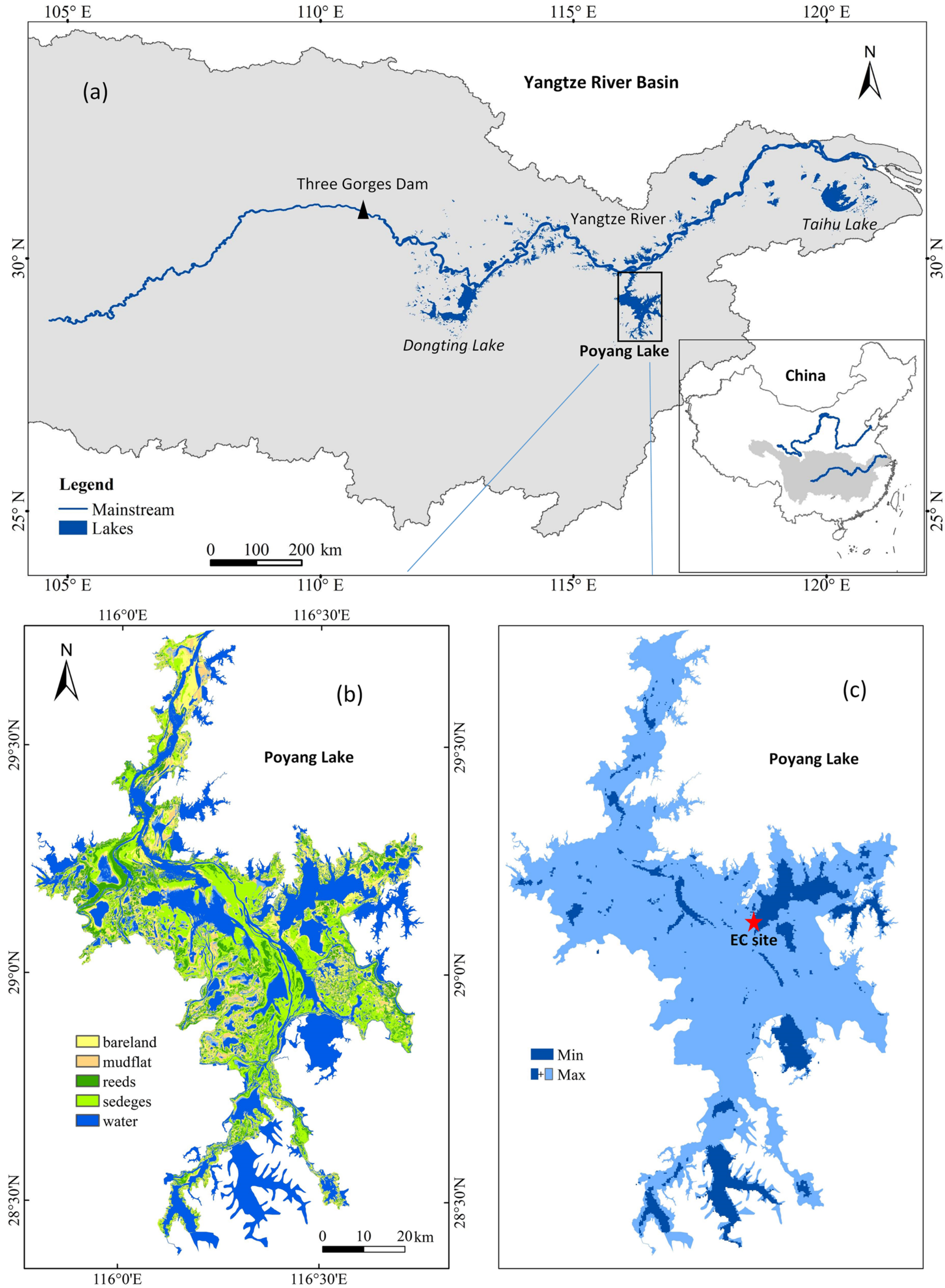

Figure 1. Location of the study area. (a) Middle and lower reaches of the Yangtze River basin including large lakes (>1 km^2) and the Three Gorges Dam, (b) Land cover over the Poyang Lake in low-water stage, (c) The maximum (light blue) and minimum (dark blue) inundated area of the Poyang Lake. The red star shows the location of CO_2 flux site at the lake center.

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spike removal (Foken et al., 2006), coordinate rotation (Wilczak et al., 2001), frequency response correction (Massman, 2000; Moncrieff et al., 2004), WPL correction (Webb et al., 1980) and flux footprint analysis (Kormann & Meixner, 2001). Linear interpolation and lookup table methods were used for gap filling (Falge et al., 2001). The observed CO_2 flux was partitioned into ecosystem respiration (Re) and gross primary productivity (GPP) by the nighttime partitioning method (Reichstein et al., 2005). Detailed processing steps can be found in Zhao and Liu (2017, 2018). Our EC site was elaborately built on a small island in the center of Poyang Lake. Based on its geographic position, the site represents the hydrological rhythm of the lake. Under stable (unstable) conditions, ~90% of the flux source area was located within an upwind distance of 6 (1–2 km) km (Figure S1 in Supporting Information S1). The source area alternates seasonally between water surface and drawdown zone, and the CO_2 fluxes shift from CO_2 emission of 4 g Cm^{-2} d^{-1} to CO_2 uptake of −5 g C $m^{-2}d^{-1}$ (Figure S2 in Supporting Information S1). Therefore, the total CO_2 flux for an ephemeral lake is defined as

$$Fc = Fc_{\text{water}} * \text{WSC} + Fc_{\text{land}} * (1 - \text{WSC}), \tag{1}$$

where Fc is the total CO_2 flux, consisting of Fc_{water} over water surface and Fc_{land} over land surface, WSC is the lake WSC.

2.3. Random Forest Modeling of CO_2 Fluxes

Random forest (RF) is a machine learning algorithm (Breiman, 2001), widely used for flux data upscaling and gap-filling (Bodesheim et al., 2018; Kim et al., 2020; Knox et al., 2019; Tramontana et al., 2015). This study applied RF to model daily CO_2 fluxes over the whole Poyang Lake based on hydrological, meteorological, and biological factors. Eight key predictors were selected, including WSC, WL, shortwave radiation (Rs), air temperature (Ta), relative humidity (RH), vapor pressure deficit (VPD), wind speed (WS) and normalized difference vegetation index (NDVI). Meteorological observations (1961–2016) were obtained from the lakeside Boyang and Nanchang stations, and their averages were used to represent meteorological conditions over the Poyang Lake. WL data were collected from the Xingzi hydrological station. WSC was calculated based on a cubic relation with WL ($R^2 = 0.91$) (Wu & Liu, 2015). The 8-day NDVI data (2000–2016) were extracted from the MOD13Q1/MYD13Q1 product (250 m). Daily NDVI was obtained thorough linear interpolation. NDVI data in 1961–1999 were estimated by using a RF model ($R = 0.95$). The predictors include day of year (DOY), WL, Ta, Ra, and RH.

RF models were trained from August 2013 to July 2016 when CO_2 flux observations were available. We set the tree number to be 200, and the number of leaf nodes to be 5. The observed CO_2 flux was used as the dependent variable, and the eight factors as independent variables. The WSC and NDVI data were determined based on footprint analyses. The training samples were randomly divided, 80% for calibration and the rest for validation. We ran the model for 200 times and reported the Pearson's correlation coefficient (R) and root mean square error (RMSE) values. RF models perform well with a mean $R = 0.89$ and a mean RMSE = 0.71 g C m^{-2} d^{-1} (Figure S3 in Supporting Information S1). The models were then used to reconstruct daily CO_2 fluxes for the whole lake by using lake-averaged input parameters during 1961–2016.

2.4. Distinguishing Hydrological and TGD Influences

The pre- and post-TGD differences in CO_2 flux ($\Delta Fc = Fc_{\text{post}} - Fc_{\text{pre}}$) were jointly controlled by hydrological and meteorological factors. We used RF models to simulate CO_2 fluxes (Fc_{simu}) based on pre-TGD hydrological data (WL, WSC). The difference from original post-TGD fluxes ($Fc_{\text{post}} - Fc_{\text{simu}}$) was considered to be hydrologically related, and the residual ($Fc_{\text{simu}} - Fc_{\text{pre}}$) was considered to be meteorologically related. To evaluate the TGD impact on lake CO_2 fluxes, we reconstructed WL data without TGD during the post-TGD period by using the Coupled 1D and 2D Hydrodynamic Analysis Model for the middle Yangtze River Basin (CHAM-Yangtze) (Lai et al., 2014). The model calibration and validation have been successfully done (Lai et al., 2014). The restored WL data were used to simulate lake CO_2 fluxes. The differences from original post-TGD fluxes were considered to be caused by the TGD.

3. Results

3.1. Long-Term Trend of CO_2 Flux in Poyang Lake Imposed by the TGD

The annual lake CO_2 fluxes ranged between −145.9 and 112.0 g C m^{-2} a^{-1} in 1961–2016 (Figure 2a). More CO_2 sinks are observed in the post-TGD years. The annual carbon sink increased from −16.8 g C m^{-2} a^{-1} in

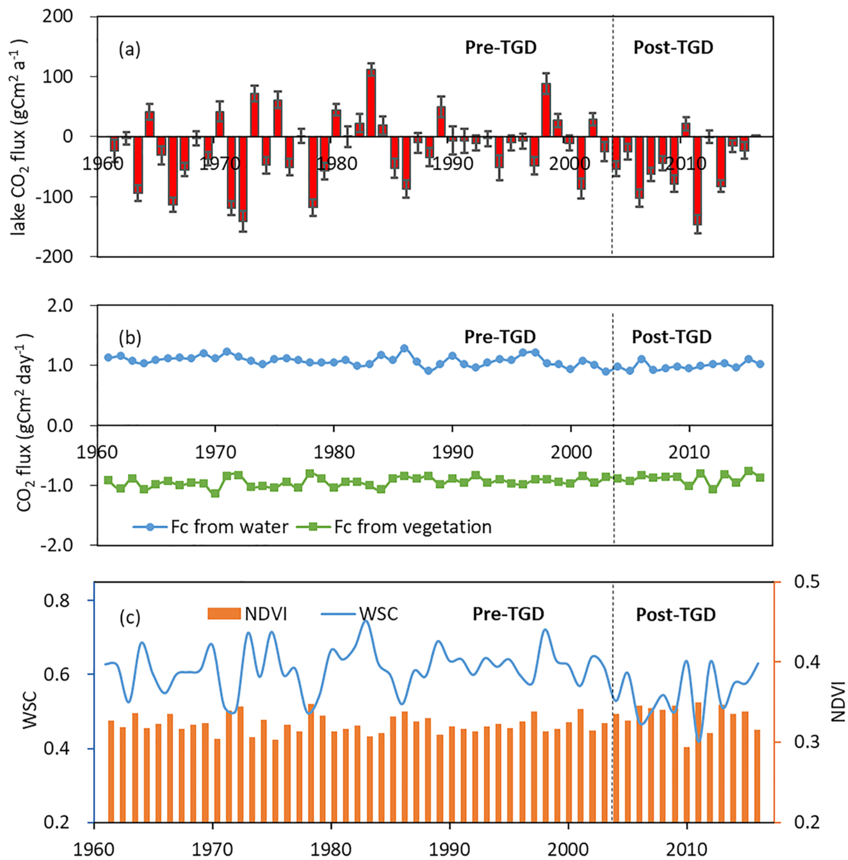

Figure 2. Long-term variations in (a) annual lake CO_2 fluxes, (b) daily averaged CO_2 fluxes from water surface (Fc_{water}) and vegetation (Fc_{veg}) in drawdown zone, and (c) annual mean water surface coverage and normalized difference vegetation index from 1961 to 2016.

the pre-TGD period to -45.2 g C m^{-2} a^{-1} in the post-TGD period on average. The annual flux was positively correlated with WSC ($R^2 = 0.86$), and was negatively correlated with NDVI ($R^2 = 0.72$) (Figure 2c). High WSC limits vegetation growth, and favors CO_2 emission from water surface. Dense vegetation featuring high NDVI values, however, promotes CO_2 sequestration. The lake tends to be carbon neutral when the WSC is about 0.61 (with WL of 13.7 m), above which is a CO_2 source and below is a CO_2 sink. Lake CO_2 flux can be divided as emission from water surface and uptake by vegetation in the drawdown zone. The former decreased by 9% from 1.08 g C m^{-2} d^{-1} in the pre-TGD period to 0.99 g C m^{-2} d^{-1} in the post-TGD period. The latter decreased by 6% from -0.95 to -0.89 g C m^{-2} d^{-1}.

3.2. Seasonal Differences of Lake CO_2 Fluxes Imposed by the TGD

WL shows a decreasing trend and an abrupt change in 2003 ($p < 0.01$) examined by Mann-Kendall test (Figure S4 in Supporting Information S1), which corresponding to the annual WSC dropped by 11% from 0.62 to 0.55 m. WSC decline is found in all months, especially by 12%–30% in the TGD impoundment period (September and October) (Figure 3a). The lake is a CO_2 source from May to October (peak in July), and a CO_2 sink in other months (peak in January) (Figure 3b). WSC decline weakened the CO_2 source intensity in spring and summer, and strengthened the carbon sink intensity in autumn. During the TGD impoundment, the CO_2 source intensity decreased by 34% in September, and the lake even turned into a carbon sink in October.

Hydrological factors explained 46% of the lake CO_2 flux changes after TGD operation, and meteorological factors explained the other 54%. The TGD raised lake WSC by 0.2%–2% in January–August, and lowered by 1%–7% in September–November (Figure 3c). Correspondingly, the TGD-related flux changes were 0.05–1.1 g C m^{-2} $month^{-1}$ from January to March, weakening carbon sink intensity in Spring. In autumn, the

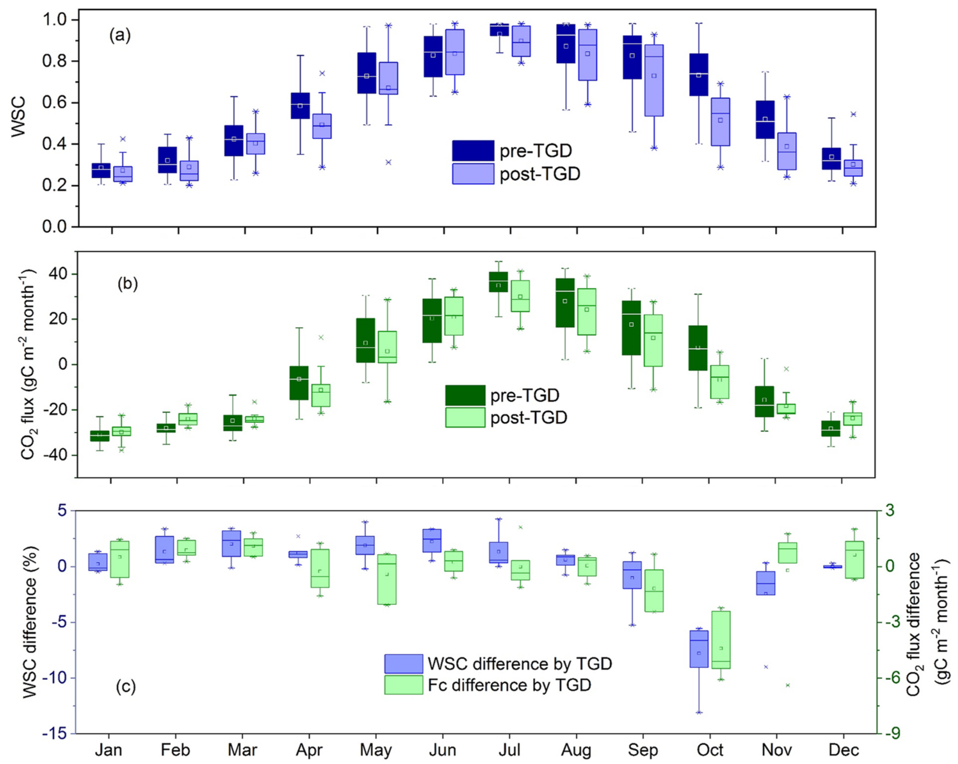

Figure 3. Monthly variations in (a) water surface coverage and (b) lake CO_2 fluxes during the pre- and post-Three Gorges Dam (TGD) period, and (c) their differences as a result of the TGD operation.

TGD enhanced carbon sink by −0.2 to −4.4 g C m^{-2} month^{-1} in September–October. At annual scale, TGD explained 6% flux changes between the pre- and post-TGD period, and up to 22% during the impoundment period (September–October). The TGD influence on downstream lake carbon fluxes cannot be ignored.

4. Discussion

4.1. CO_2 Source or Sink in Ephemeral Lakes

Inland waters are common CO_2 sources (Huotari et al., 2011; Loken et al., 2019; Morin et al., 2018; Xiao et al., 2020), whereas the Poyang Lake shows an alternating pattern of CO_2 source and sink on seasonal scales. In high-water stage the lake emits CO_2 at a rate of 1.06 ± 0.1 g C m^{-2} d^{-1} from water surface, close to tropical Amazonian reservoir (Barros et al., 2011; Marotta et al., 2009), higher than boreal lakes (Huotari et al., 2011) and subtropical lake in Brazil (Tonetta et al., 2017) (Table S1 in Supporting Information S1). After high-level stage the lake wetland uptakes CO_2 at a rate of −0.93 ± 0.08 g C m^{-2} d^{-1}, close to the Yellow River delta wetland (Chen et al., 2018), and lower than the Mediterranean reed wetland (Acosta et al., 2019), the subtropical estuarine wetland (W. Yang et al., 2017) and other wetland types with lower water table (J. Li et al., 2023; Xi et al., 2019) (Table S1 in Supporting Information S1).

Ephemeral lakes generally undergo large seasonal changes (Hill, 2020). Lake WL is the main driving force governing hydrological, ecological and biogeochemical processes via wet-dry landscape seasonality (Kolding & van Zwieten, 2012; Lobo et al., 2019). Under the joint influence of climate change and human activities, the annual variation of WL in Poyang Lake is manifested as inter-decadal variation (Figure S5 in Supporting Information S1). The WL since 2003 is significantly lower than that in the previous two decades, especially during the September-November recession period. In the post-TGD period, the duration of water rising stage and high-water stage is shortened on average by 11 and 16 days, respectively (Figure 4a). Nevertheless, the duration of water recession stage and low-water stage is extended on average by 7 and 20 days. The decline of lake water surface CO_2 emission (Figures 2 and 4b) might be affected by air temperature and WS. The rising Ta promotes organic matter decomposition and increase CO_2 emission rate from water surface (Xiao et al., 2020). When CO_2

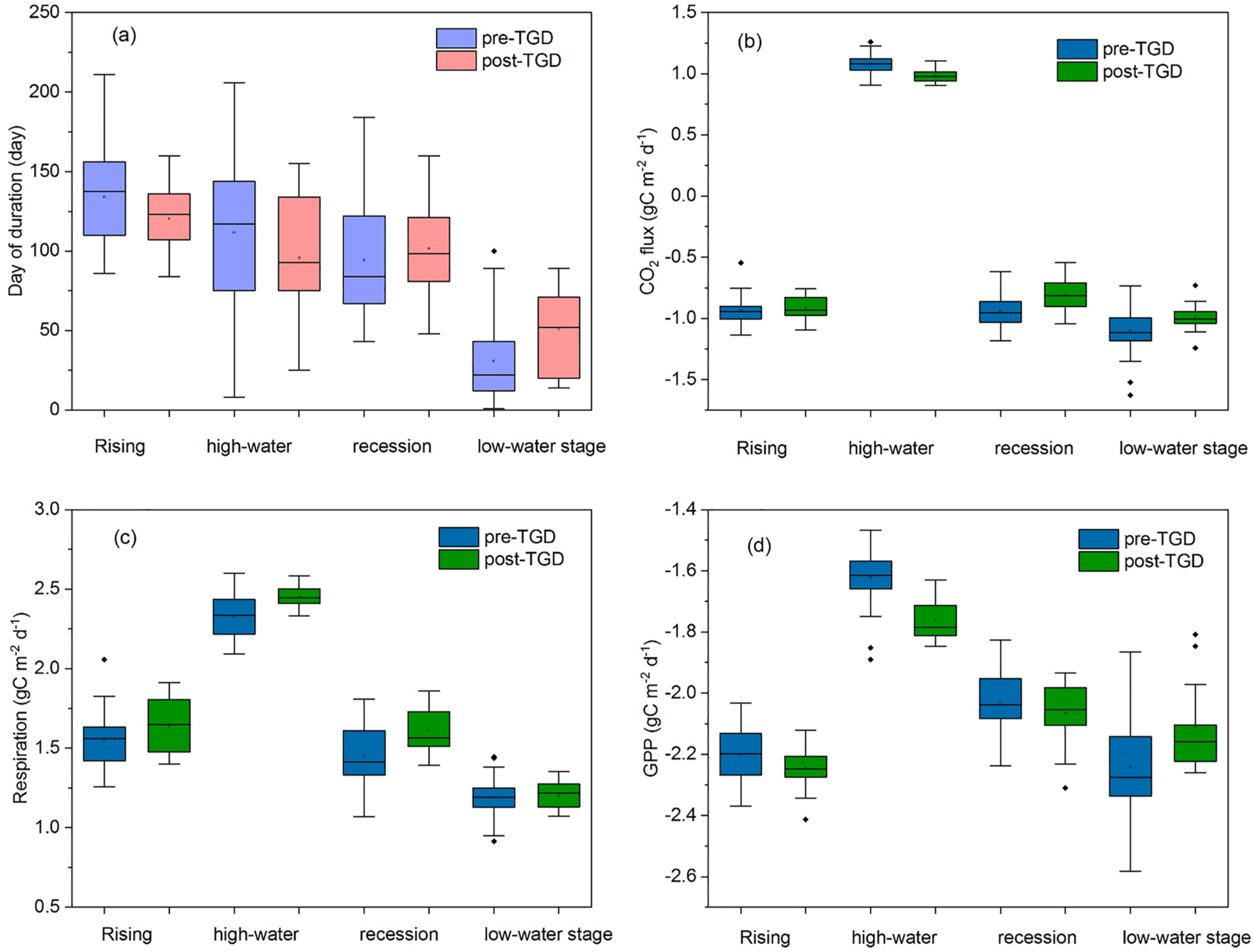

Figure 4. Seasonal dynamics of (a) duration of four hydrological stage, (b) CO_2 flux from water surface (Fc_{water}) in high-water stage and CO_2 fluxes from vegetation (Fc_{veg}) in other stages, (c) ecosystem respiration (Re) and (d) gross primary productivity between the pre- and post-Three Gorges Dam period in Poyang LakeFit.

is supersaturated in water, the dynamic turbulence at the water-air interface by wind instead plays a key role (Cole et al., 2007). There is a good correlation between CO_2 emission and WS at a daily ($R = 0.42$, $p < 0.05$) and annual scales ($R = 0.45$, $p < 0.05$) (Figure S6 in Supporting Information S1). In the last 60 years WS falls by ∼30% in the Poyang Lake, this might be the reason for the declining water CO_2 emission.

After dam operation, CO_2 uptaken by wetland vegetation barely changed during the water rising stage, whereas it decreased in the water recession and low-water stages despite significant increases in Ta and NDVI. During the post-TGD period, the increase of duration of the recession and low-water stage promoted vegetation growth and increased NDVI and GPP. Further analyses showed that both ecosystem respiration (Re) and GPP increased in the post-TGD period, however, the growth rate of respiration outpaced that of GPP (Figure S7 in Supporting Information S1). In addition, the extremely low WSC exposed the sediment and promoted the CO_2 emissions from dry sediment (Gómez-Gener et al., 2016; Keller et al., 2020). For the ephemeral lake, the proportion of WSC and the duration of low-water period greatly determine the accumulative area and time of carbon sink, and then affect the CO_2 source or sink pattern of the lake. The central Amazon flooded wetland is nearly carbon neutral (Abril et al., 2014). The Poyang Lake tend to be CO_2 sink in the post-TGD due to prolonged duration of the low-water period and vegetation expanded early and spatially caused by WSC (or WL) decreasing.

4.2. Implications for the Impact of Large-Scale Dams

Holding the largest number of dams in the world, the Yangtze River is strongly affected by human activities (K. Li et al., 2013). A regime shift to lower lake WLs has been observed in the Poyang Lake (Feng et al., 2016; Liu et al., 2013; Wu & Liu, 2015). The middle and lower reaches of the Yangtze River host more than 500 lakes (>1 km^2), including the three largest freshwater lakes in China (Figure 1). Developed in floodplains, these lakes are mostly shallow, connected, and sensitive to the Yangtze River. Since the TGD operation in 2003, lakes in this area have experienced obvious WL decline and surface area shrinkage (Cui et al., 2013; Hou et al., 2017; X. Li et al., 2020; Wang et al., 2014), which may promote the development of wetland vegetation and more carbon sequestration. Represented by the Poyang Lake, lakes in the middle and lower reaches of the Yangtze River likely turn from CO_2 source to sink, as a result of climate change and the TGD operation.

Seasonal or annual carbon sources have been reported in eutrophic lakes (Pacheco et al., 2014; H. Yang et al., 2008), the Lake Erie of North America (Shao et al., 2015), and the Lower Lakes of Australia (S. Li et al., 2016), which are mainly due to carbon uptake by phytoplankton in summer and autumn, or the effects of extreme drought. The tendency of Poyang Lake to become a carbon sink is due to decreasing WL, enhanced by the operation of the TGD. Globally, more than 3,700 dams will have been constructed in the 2020s and 2030s (Zarfl et al., 2015). These dams will undoubtedly change reservoir areas in the upstream and hydrological rhythms in downstream rivers and lakes. Dam construction tends to increase GHGs from reservoirs (Keller et al., 2020), however, the changes in river hydrological rhythm caused by dam construction may reduce GHGs emissions in downstream lakes. Therefore, the influence of dam construction should be more comprehensively considered from the perspective of the whole basin. However, the potential effects on lake carbon fluxes are elusive, contributing to large uncertainties in regional and global carbon estimates (Pilla et al., 2022). More attention should be directed to human activities (e.g., dam, reservoirs, levee construction and sand mining), and their impact on carbon budget in and transport through inland waters. The Poyang Lake is also an important CH_4 source (Hu et al., 2015). The climate effects of both GHGs should be considered in forthcoming researches.

4.3. Applicability of RF Models

RF models consider the key meteorological, hydrological and biological factors that affect CO_2 emission from water surface and CO_2 uptake by vegetation. The effects of chlorophyll-a and water CO_2 concentrations on CO_2 emission from the water surface were analyzed based on remote sensing inversion (Qi et al., 2023) in 2016. However, there found no obvious correlation between them (Figure S8 in Supporting Information S1). The absence of long-term data on water quality and nutrients puts limits on model validation, highlighting the importance of continuous field observation. Although the short-time interval (2013–2016) data were used for model training, the data range and frequency distribution basically overlapped with the major historical values, including Ra and WS (Table S2 and Figure S9 in Supporting Information S1). Furthermore, we evaluated the model dependence on sample length in three groups, in which respectively take 1-, 2-, and 3-year data as training samples. The independent training results showed that the model bias decreased and R increased in three groups, illustrating the reliability and uncertainty of the RF modeling (Figure S10 in Supporting Information S1). The TGD operation is supposed to have a large impact on hydrological rhythms of the Poyang Lake. Sensitivity analyses also show that CO_2 flux is most sensitive to the changes of WSC and Ta (Table S3 in Supporting Information S1). Therefore, RF models can well reflect the influence of TGD and climate change.

5. Conclusion

The TGD operation in 2013 changed the hydrological rhythms of the Yangtze River and the downstream shallow floodplain of the Poyang Lake. Carbon exchange processes in the lake were sensitive to WL changes. Based on EC observations and a RF model, we found that the Poyang Lake has shifted from a CO_2 source to a CO_2 sink since the TGD operation. This was attributed to declining lake WL as a result of climate change and human activities, and more directly carbon uptake by wetland vegetation. The ultra-large hydraulic project reinforced the declining trend of lake WL and promoted carbon sequestration. The results are expected to draw the attention from research community to the effects of large numbers of current and planned hydraulic projects. For all dams worldwide, many a little might make a mickle.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data used in this study is freely available from public data repositories. Original data have been deposited to Figshare (https://doi.org/10.6084/m9.figshare.21441501.v2). The MODIS NDVI products are available at https://e4ftl01.cr.usgs.gov/. Meteorological data are available from the National Meteorological Data Center of China at http://data.cma.cn/ in dataset of daily observations from China's meteorological stations. Applications forms are required. The lakes distribution in China products are available at http://lake.geodata.cn/data/datadetails.html?dataguid=47580217134605&docId=616.

Acknowledgments

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References

Abril, G., Martinez, J. M., Artigas, L. F., Moreira-Turcq, P., Benedetti, M. F., Vidal, L., et al. (2014). Amazon River carbon dioxide outgassing fuelled by wetlands. *Nature*, *505*(7483), 395–398. https://doi.org/10.1038/nature12797

Acosta, M., Chamizo, S., Serrano-ortiz, P., & Pavelka, M. (2019). Catena Autumnal fluxes of CH_4 and CO_2 from Mediterranean reed wetland based on eddy covariance and chamber methods, *183*(July). 104191, https://doi.org/10.1016/j.catena.2019.104191

Aufdenkampe, A. K., Mayorga, E., Raymond, P. A., Melack, J. M., Doney, S. C., Alin, S. R., et al. (2011). Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. In *Frontiers in ecology and the environment*. https://doi.org/10.1890/100014

Barros, N., Cole, J. J., Tranvik, L. J., Prairie, Y. T., Bastviken, D., Huszar, V. L. M., et al. (2011). Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. *Nature Geoscience*, *4*(9), 593–596. https://doi.org/10.1038/ngeo1211

Bastviken, D., Tranvik, L. J., Downing, J. A., Crill, P. M., & Enrich-Prast, A. (2011). Freshwater methane emissions offset the continental carbon sink. *Science*, *331*(6013), 50. https://doi.org/10.1126/science.1196808

Bodesheim, P., Jung, M., Gans, F., Mahecha, M. D., & Reichstein, M. (2018). Upscaled diurnal cycles of land-atmosphere fluxes: A new global half-hourly data product. *Earth System Science Data*, *10*(3), 1327–1365. https://doi.org/10.5194/essd-10-1327-2018

Breiman, L. (2001). Random forests. *Machine Learning*, *45*(1), 5–32. https://doi.org/10.1023/A:1010933404324

Calamita, E., Siviglia, A., Gettel, G. M., Franca, M. J., Scott Winton, R., Teodoru, C. R., et al. (2021). Unaccounted CO_2 leaks downstream of a large tropical hydroelectric reservoir. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(25), e2026004118. https://doi.org/10.1073/pnas.2026004118

Chen, Q., Guo, B., Zhao, C., & Xing, B. (2018). Characteristics of CH_4 and CO_2 emissions and influence of water and salinity in the Yellow River delta wetland, China. *Environmental Pollution*, *239*, 289–299. https://doi.org/10.1016/j.envpol.2018.04.043

Cole, J. J., Prairie, Y. T., Caraco, N. F., Mcdowell, W. H., Tranvik, L. J., Striegl, R. G., et al. (2007). Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget, 171–184. https://doi.org/10.1007/s10021-006-9013-8

Cui, L., Gao, C., Zhao, X., Ma, Q., Zhang, M., Li, W., et al. (2013). Dynamics of the lakes in the middle and lower reaches of the Yangtze River basin, China, since late nineteenth century. *Environmental Monitoring and Assessment*, *185*(5), 4005–4018. https://doi.org/10.1007/s10661-012-2845-0

Deemer, B. R., Yackulic, C. B., Hall, R. O., Dodrill, M. J., Kennedy, T. A., Muehlbauer, J. D., et al. (2022). Experimental reductions in subdaily flow fluctuations increased gross primary productivity for 425 river kilometers downstream. *PNAS Nexus*, *1*(3), 1–12. https://doi.org/10.1093/pnasnexus/pgac094

Descloux, S., Chanudet, V., Serça, D., & Guérin, F. (2017). Methane and nitrous oxide annual emissions from an old eutrophic temperate reservoir. *Science of the Total Environment*, *598*, 959–972. https://doi.org/10.1016/j.scitotenv.2017.04.066

Drake, T. W., Raymond, P. A., & Spencer, R. G. M. (2018). Terrestrial carbon inputs to inland waters: A current synthesis of estimates and uncertainty. *Limnology and Oceanography Letters*, *3*(3), 132–142. https://doi.org/10.1002/lol2.10055

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., et al. (2001). Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agricultural and Forest Meteorology*, *107*(1), 43–69. https://doi.org/10.1016/S0168-1923(00)00225-2

Feng, L., Han, X., Hu, C., & Chen, X. (2016). Four decades of wetland changes of the largest freshwater lake in China: Possible linkage to the Three Gorges Dam? *Remote Sensing of Environment*, *176*, 43–55. https://doi.org/10.1016/j.rse.2016.01.011

Foken, T., Göockede, M., Mauder, M., Mahrt, L., Amiro, B., & Munger, W. (2006). Post-field data quality control. In *Handbook of micrometeorology*. https://doi.org/10.1007/1-4020-2265-4_9

Friedl, G., & Wüest, A. (2002). Disrupting biogeochemical cycles—Consequences of damming. *Aquatic Sciences*, *64*(1), 55–65. https://doi.org/10.1007/s00027-002-8054-0

Gómez-Gener, L., Obrador, B., Marcé, R., Acuña, V., Catalán, N., Casas- Ruiz, J. P., et al. (2016). When water vanishes: Magnitude and regulation of carbon dioxide emissions from dry temporary streams. *Ecosystems*, *19*(4), 710–723. https://doi.org/10.1007/s10021-016-9963-4

Guo, Y., Lai, X., Wu, X., & Cheng, Y. (2022). Dry-season water level shift induced by channel change. *Wetlands*, *42*(112), 112. https://doi.org/10.1007/s13157-022-01615-w

Hill, M. C. (2020). Comparison of CO_2 flux in an Amazonian natural lake and hydroelectric reservoir, (509) (p. 30).

Holgerson, M. A., & Raymond, P. A. (2016). Large contribution to inland water CO_2 and CH_4 emissions from very small ponds. *Nature Geoscience*, *9*(3), 222–226. https://doi.org/10.1038/ngeo2654

Hou, X., Feng, L., Duan, H., Chen, X., Sun, D., & Shi, K. (2017). Fifteen-year monitoring of the turbidity dynamics in large lakes and reservoirs in the middle and lower basin of the Yangtze River, China. *Remote Sensing of Environment*, *190*, 107–121. https://doi.org/10.1016/j.rse.2016.12.006

Hu, Q., Feng, S., Guo, H., Chen, G., & Jiang, T. (2007). Interactions of the Yangtze River flow and hydrologic processes of the Poyang Lake, China. *Journal of Hydrology*, *347*(1–2), 90–100. https://doi.org/10.1016/j.jhydrol.2007.09.005

Hu, Q., Wu, Q., Yao, B., & Xu, X. (2015). Ecosystem respiration and its components from a Carex meadow of Poyang Lake during the drawdown period. *Atmospheric Environment*, *100*, 124–132. https://doi.org/10.1016/j.atmosenv.2014.10.047

Huotari, J., Ojala, A., Peltomaa, E., Nordbo, A., Launiainen, S., Pumpanen, J., et al. (2011). Long-term direct CO_2 flux measurements over a boreal lake: Five years of eddy covariance data. *Geophysical Research Letters*, *38*(18), 5. https://doi.org/10.1029/2011GL048753

Huttunen, J. T., Alm, J., Liikanen, A., Juutinen, S., Larmola, T., Hammar, T., et al. (2003). Fluxes of methane, carbon dioxide and nitrous oxide in boreal lakes and potential anthropogenic effects on the aquatic greenhouse gas emissions. *Chemosphere*, *52*(3), 609–621. https://doi.org/10.1016/S0045-6535(03)00243-1

Keller, P. S., Catalán, N., von Schiller, D., Grossart, H.-P., Koschorreck, M., Obrador, B., et al. (2020). Global CO_2 emissions from dry inland waters share common drivers across ecosystems. *Nature Communications*, *11*(1), 2126. https://doi.org/10.1038/s41467-020-15929-y

Kim, Y., Johnson, M. S., Knox, S. H., Black, T. A., Dalmagro, H. J., Kang, M., et al. (2020). Gap-filling approaches for eddy covariance methane fluxes: A comparison of three machine learning algorithms and a traditional method with principal component analysis. *Global Change Biology*, *26*(3), 1499–1518. https://doi.org/10.1111/gcb.14845

Knox, S. H., Jackson, R. B., Poulter, B., McNicol, G., Fluet-Chouinard, E., Zhang, Z., et al. (2019). FluXNET-CH_4 synthesis activity objectives, observations, and future directions. *Bulletin of the American Meteorological Society*, *100*(12), 2607–2632. https://doi.org/10.1175/BAMS-D-18-0268.1

Kolding, J., & van Zwieten, P. A. M. (2012). Relative lake level fluctuations and their influence on productivity and resilience in tropical lakes and reservoirs. *Fisheries Research*, *115–116*, 99–109. https://doi.org/10.1016/j.fishres.2011.11.008

Kormann, R., & Meixner, F. X. (2001). An analytical footprint model for non-neutral stratification. *Boundary-Layer Meteorology*, *99*(2), 207–224. https://doi.org/10.1023/A:1018991015119

Lai, X., Liang, Q., Jiang, J., & Huang, Q. (2014). Impoundment effects of the three-Gorges-dam on flow regimes in two China's largest freshwater lakes. *Water Resources Management*, *28*(14), 5111–5124. https://doi.org/10.1007/s11269-014-0797-6

Li, J., Jiang, M., Pei, J., Fang, C., Li, B., & Nie, M. (2023). Convergence of carbon sink magnitude and water table depth in global wetlands. *Ecology Letters*, *26*(October 2022), 1–8. https://doi.org/10.1111/ele.14199

Li, K., Zhu, C., Wu, L., & Huang, L. (2013). Problems caused by the three Gorges dam construction in the Yangtze River basin: A review. *Environmental Reviews*, *21*(3), 127–135. https://doi.org/10.1139/er-2012-0051

Li, S., Bush, R. T., Ward, N. J., Sullivan, L. A., & Dong, F. (2016). Air-water CO_2 outgassing in the lower lakes (Alexandrina and Albert, Australia) following a millennium drought. *Science of the Total Environment*, *542*, 453–468. https://doi.org/10.1016/j.scitotenv.2015.10.070

Li, X., Liu, P., Gui, Z., Ming, B., Yang, Z., Xie, K., & Zhang, X. (2020). Reducing lake water-level decline by optimizing reservoir operating rule curves: A case study of the three Gorges reservoir and the Dongting lake. *Journal of Cleaner Production*, *264*, 121676. https://doi.org/10.1016/j.jclepro.2020.121676

Liu, Y., Wu, G., Guo, R., & Wan, R. (2016). Changing landscapes by damming: The three Gorges dam causes downstream lake shrinkage and severe droughts. *Landscape Ecology*, *31*(8), 1883–1890. https://doi.org/10.1007/s10980-016-0391-9

Liu, Y., Wu, G., & Zhao, X. (2013). Recent declines in China's largest freshwater lake: Trend or regime shift? *Environmental Research Letters*, *8*(1), 014010. https://doi.org/10.1088/1748-9326/8/1/014010

Lobo, G. D. S., Wittmann, F., & Piedade, M. T. F. (2019). Response of black-water floodplain (igapó) forests to flood pulse regulation in a dammed Amazonian river. *Forest Ecology and Management*, *434*, 110–118. https://doi.org/10.1016/j.foreco.2018.12.001

Loken, L. C., Crawford, J. T., Schramm, P. J., Stadler, P., Desai, A. R., & Stanley, E. H. (2019). Large spatial and temporal variability of carbon dioxide and methane in a eutrophic lake. *Journal of Geophysical Research: Biogeosciences*, *124*(7), 2248–2266. https://doi.org/10.1029/2019JG005186

Marotta, H., Duarte, C. M., Sobek, S., & Enrich-Prast, A. (2009). Large CO_2 disequilibria in tropical lakes. *Global Biogeochemical Cycles*, *23*(4), 13–16. https://doi.org/10.1029/2008GB003434

Massman, W. J. (2000). A simple method for estimating frequency response corrections for eddy covariance systems. *Agricultural and Forest Meteorology*, *104*(3), 185–198. https://doi.org/10.1016/S0168-1923(00)00164-7

Moncrieff, J., Clement, R., Finnigan, J., & Meyers, T. (2004). Averaging, detrending, and filtering of eddy covariance time series. In *Handbook of micrometeorology: A guide for surface flux measurement and analysis*. https://doi.org/10.1007/1-4020-2265-4

Morin, T. H., Rey-Sánchez, A. C., Vogel, C. S., Matheny, A. M., Kenny, W. T., & Bohrer, G. (2018). Carbon dioxide emissions from an oligotrophic temperate lake: An eddy covariance approach. *Ecological Engineering*, *114*, 25–33. https://doi.org/10.1016/j.ecoleng.2017.05.005

Nilsson, C., Reidy, C. A., Dynesius, M., & Revenga, C. (2005). Fragmentation and flow regulation of the world's large river systems. *Science*, *308*(5720), 405–408. https://doi.org/10.1126/science.1107887

Pacheco, F. S., Roland, F., & Downing, J. A. (2014). Eutrophication reverses whole-lake carbon budgets. *Inland Waters*, *4*(1), 41–48. https://doi.org/10.5268/IW-4.1.614

Paranaíba, J. R., Barros, N., Mendonça, R., Linkhorst, A., Isidorova, A., Roland, F., et al. (2018). Spatially resolved measurements of CO_2 and CH_4 concentration and gas-exchange velocity highly influence carbon-emission estimates of reservoirs. *Environmental Science and Technology*, *52*(2), 607–615. https://doi.org/10.1021/acs.est.7b05138

Petts, G. E., & Gurnell, A. M. (2005). Dams and geomorphology: Research progress and future directions. *Geomorphology*, *71*(1–2), 27–47. https://doi.org/10.1016/j.geomorph.2004.02.015

Pilla, R. M., Griffiths, N. A., Gu, L., Kao, S. C., McManamay, R., Ricciuto, D. M., & Shi, X. (2022). Anthropogenically driven climate and landscape change effects on inland water carbon dynamics: What have we learned and where are we going? *Global Change Biology*, *28*(19), 5601–5629. https://doi.org/10.1111/gcb.16324

Prairie, Y. T., Alm, J., Beaulieu, J., Barros, N., Battin, T., Cole, J., et al. (2018). Greenhouse gas emissions from freshwater reservoirs: What does the atmosphere see? *Ecosystems*, *21*(5), 1058–1071. https://doi.org/10.1007/s10021-017-0198-9

Qi, T., Shen, M., Kutser, T., Xiao, Q., Cao, Z., Ma, J., et al. (2023). Remote sensing of dissolved CO_2 concentrations in meso-eutrophic lakes using Sentinel-3 imagery. *Remote Sensing of Environment*, *286*, 113431. https://doi.org/10.1016/j.rse.2022.113431

Raymond, P. A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., et al. (2013). Global carbon dioxide emissions from inland waters. *Nature*, *503*(7476), 355–359. https://doi.org/10.1038/nature12760

Raymond, P. A., Oh, N. H., Turner, R. E., & Broussard, W. (2008). Anthropogenically enhanced fluxes of water and carbon from the Mississippi River. *Nature*, *451*(7177), 449–452. https://doi.org/10.1038/nature06505

Reichstein, M., Kätterer, T., Andrén, O., Ciais, P., Schulze, E. D., Cramer, W., et al. (2005). Temperature sensitivity of decomposition in relation to soil organic matter pools: Critique and outlook. *Biogeosciences*, *2*(4), 317–321. https://doi.org/10.5194/bg-2-317-2005

Shankman, D., & Liang, Q. (2003). Landscape changes and increasing flood frequency in China's Poyang Lake region. *The Professional Geographer*, *55*(4), 434–445. https://doi.org/10.1111/0033-0124.5504003

Shao, C., Chen, J., Stepien, C. A., Chu, H., Ouyang, Z., Bridgeman, T. B., et al. (2015). Diurnal to annual changes in latent, sensible heat, and CO_2 fluxes over a Laurentian Great Lake: A case study in Western Lake Erie. *Journal of Geophysical Research: Biogeosciences*, *120*(8), 1587–1604. https://doi.org/10.1002/2015JG003025

Sobek, S., Tranvik, L. J., & Cole, J. J. (2005). Temperature independence of carbon dioxide supersaturation in global lakes. *Global Biogeochemical Cycles*, *19*(2), 1–10. https://doi.org/10.1029/2004GB002264

Tan, Z., Zhang, Q., Li, M., Li, Y., Xu, X., & Jiang, J. (2016). A study of the relationship between wetland vegetation communities and water regimes using a combined remote sensing and hydraulic modeling approach. *Hydrology Research*, *47*(S1), 278–292. https://doi.org/10.2166/nh.2016.216

Teodoru, C. R., del Giorgio, P. A., Prairie, Y. T., & St-Pierre, A. (2013). Depositional fluxes and sources of particulate carbon and nitrogen in natural lakes and a young boreal reservoir in Northern Québec. *Biogeochemistry*, *113*(1–3), 323–339. https://doi.org/10.1007/s10533-012-9760-x

Tonetta, D., Petrucio, M., & Staehr, P. (2017). Changes in CO_2 dynamics related to rainfall and water level variations in a subtropical lake. *Hydrobiologia*, *794*(1), 109–123. https://doi.org/10.1007/s10750-017-3085-7

Tramontana, G., Ichii, K., Camps-Valls, G., Tomelleri, E., & Papale, D. (2015). Uncertainty analysis of gross primary production upscaling using Random Forests, remote sensing and eddy covariance data. *Remote Sensing of Environment*, *168*, 360–373. https://doi.org/10.1016/j.rse.2015.07.015

Tranvik, L. J., Downing, J. A., Cotner, J. B., Loiselle, S. A., Striegl, R. G., Ballatore, T. J., et al. (2009). Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology & Oceanography*, *54*(6part2), 2298–2314. https://doi.org/10.4319/lo.2009.54.6_part_2.2298

Wan, R., Dai, X., & Shankman, D. (2018). Vegetation response to hydrological changes in Poyang Lake, China. *Wetlands*, *2*(S1), 1–14. https://doi.org/10.1007/s13157-018-1046-1

Wang, J., Sheng, Y., & Tong, T. S. D. (2014). Monitoring decadal lake dynamics across the Yangtze basin downstream of three Gorges dam. *Remote Sensing of Environment*, *152*, 251–269. https://doi.org/10.1016/j.rse.2014.06.004

Webb, E. K., Pearman, G. I., & Leuning, R. (1980). Correction of flux measurements for density effects due to heat and water vapour transfer. *Quarterly Journal of the Royal Meteorological Society*, *106*(447), 85–100. https://doi.org/10.1002/qj.49710644707

Wilczak, J. M., Oncley, S. P., & Stage, S. A. (2001). Sonic anemometer tilt correction algorithms. *Boundary-Layer Meteorology*, *99*(1), 127–150. https://doi.org/10.1023/A:1018966204465

Wu, G., & Liu, Y. (2015). Capturing variations in inundation with satellite remote sensing in a morphologically complex, large lake. *Journal of Hydrology*, *523*, 14–23. https://doi.org/10.1016/j.jhydrol.2015.01.048

Wu, G., & Liu, Y. (2017). Assessment of the hydro-ecological impacts of the three Gorges Dam on China's largest freshwater lake. *Remote Sensing*, *9*(10), 1069. https://doi.org/10.3390/rs9101069

Xi, M., Zhang, X., Kong, F., Li, Y., Sui, X., & Wang, X. (2019). CO_2 exchange under different vegetation covers in a coastal wetland of Jiaozhou Bay, China. *Ecological Engineering*, *137*(December 2018), 26–33. https://doi.org/10.1016/j.ecoleng.2018.12.025

Xiao, Q., Xu, X., Duan, H., Qi, T., Qin, B., Lee, X., et al. (2020). Eutrophic Lake Taihu as a significant CO_2 source during 2000–2015. *Water Research*, *170*, 115331. https://doi.org/10.1016/j.watres.2019.115331

Yang, H., Xing, Y., Xie, P., Ni, L., & Rong, K. (2008). Carbon source/sink function of a subtropical, eutrophic lake determined from an overall mass balance and a gas exchange and carbon burial balance. *Environmental Pollution*, *151*(3), 559–568. https://doi.org/10.1016/j.envpol.2007.04.006

Yang, L., Lu, F., Wang, X., Duan, X., Tong, L., Ouyang, Z., & Li, H. (2013). Spatial and seasonal variability of CO_2 flux at the air-water interface of the Three Gorges Reservoir. *Journal of Environmental Sciences*, *25*(11), 2229–2238. https://doi.org/10.1016/S1001-0742(12)60291-5

Yang, W., Yuan, C., Tong, C., Yang, P., Yang, L., & Huang, B. (2017). Diurnal variation of CO_2, CH_4, and N_2O emission fluxes continuously monitored in-situ in three environmental habitats in a subtropical estuarine wetland. *Marine Pollution Bulletin*, *119*(1), 289–298. https://doi.org/10.1016/j.marpolbul.2017.04.005

Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L., & Tockner, K. (2015). A global boom in hydropower dam construction. *Aquatic Sciences*, *77*(1), 161–170. https://doi.org/10.1007/s00027-014-0377-0

Zhang, Q., Li, L., Wang, Y. G., Werner, A. D., Xin, P., Jiang, T., & Barry, D. A. (2012). Has the three-Gorges dam made the Poyang Lake wetlands wetter and drier? *Geophysical Research Letters*, *39*(20), L20402. https://doi.org/10.1029/2012GL053431

Zhao, X., & Liu, Y. (2017). Phase transition of surface energy exchange in China's largest freshwater lake. *Agricultural and Forest Meteorology*, *244–245*, 244–245. https://doi.org/10.1016/j.agrformet.2017.05.024

Zhao, X., & Liu, Y. (2018). Variability of surface heat fluxes and its driving forces at different time scales over a large ephemeral lake in China. *Journal of Geophysical Research: Atmospheres*, *123*(10), 4939–4957. https://doi.org/10.1029/2017JD027437

Zhu, H., & Zhang, B. (1997). *Poyang Lake*. Press of University of Science and Technology of China.