Diel to interannual variation in carbon dioxide emissions from lakes and reservoirs

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Abstract

Accounting for temporal changes in carbon dioxide (CO_2) emissions from freshwaters remains a challenge for global and regional carbon budgets. Here, we synthesize 171 site-months of eddy covariance flux measurements of CO_2 from 13 lakes and reservoirs in the Northern Hemisphere (NH) and quantify dynamics at multiple temporal scales. We found pronounced sub-annual variability in CO_2 flux at all sites. Accounting for diel variation, only 11% of site-months were net daily sinks of CO_2. Annual CO_2 emissions had an average of 25% (range 3-58%) interannual variation. Nighttime emissions regularly exceeded daytime emissions. Sources of CO_2 flux variability were delineated through mutual information analysis. Sample analysis of CO_2 fluxes indicate importance of continuous sampling. Constraining short- and long-term variability is necessary to improve detection of temporal changes of CO_2 fluxes in response to natural and anthropogenic drivers.

Plain Language Summary

Lakes and reservoirs around the world are a major component of the global carbon cycle. Recent syntheses of measurements find their contributions to be on the order of 2-6% of total global fossil fuel emissions. However, these estimates are primarily derived from compilations with low frequency of sampling, from a few times a year up to weekly, often restricted to a single season, and with limited regard to year-to-year variations. Here, we conduct the first analysis of a globally distributed network of sub-hourly, multi-year lake and reservoir carbon dioxide emissions. These measurements were made using eddy-covariance flux towers, which continuously sample these emissions year-round. Across our 13 study sites, we found nighttime emissions regularly exceeding daytime emissions and persistent sub-monthly variability regardless of lake size or nutrient status. For sites with multiple years of data, we found an average 25% variation in estimated annual emissions depending on the year chosen. Together, these results point to a need for improved, systematic sub-weekly sampling of freshwater systems to better understand dynamics, reduce uncertainty in landscape to global carbon budgets, and project changes to atmospheric greenhouse gas burdens in a warming climate.

Index terms (5): 0428 Carbon cycling, 0426 Biosphere/atmosphere interactions, 0438 Diel, seasonal, and annual cycles, 0434 Data sets, 0458 Limnology
Keywords (6): eddy covariance; freshwater systems; lakes; reservoirs; carbon flux; synthesis

Key Points:

- Synthesis of high-frequency aquatic freshwater carbon dioxide flux observations reveals large diel, sub-annual, and interannual variation
- At all sites, nighttime emissions are larger than daytime, sub-monthly variability is present, and year-to-year variation averaged 25%
- Under-sampling of these dynamics leads to potential bias in estimates of contribution of freshwater systems to the global carbon cycle

1. Introduction

The global carbon budget is rapidly changing in response to human emissions (Friedlingstein *et al*., 2020; Hanson *et al*., 2006). Prior studies have estimated that 0.14-0.64 Pg C-CO_2 is annually released to the atmosphere through lakes and reservoirs (Aufdenkampe *et al*., 2011; Ciais *et al*., 2013; Cole *et al*., 1994, 2007; DelSontro et al., 2018; Drake *et al*., 2018; Holgerson *et al*., 2016; Raymond *et al*., 2013). However, most of these estimates are made with relatively limited sampling, generally constrained to the open-water or summer season during the daytime, and with limited consideration of interannual and shorter-scale variation (Butman *et al*., 2018; Ran *et al*., 2021).

Underrepresentation of temporal CO_2 flux variability in existing CO_2 flux inventories may bias estimates of lake CO_2 emissions (Deemer *et al*., 2016; Klaus *et al*., 2019). Recent studies have found nighttime emissions exceeding daytime emissions or uptake in reservoirs (Liu *et al*., 2016) and rivers (Gómez-Gener *et al*., 2021). A lack of frequent and long-term CO_2 observations also limits our ability to differentiate natural CO_2 flux variations from the consequences of anthropogenic perturbations (Hasler *et al*., 2016). Multiyear-scale time series that capture sub-annual variability of the aquatic CO_2 flux remain rare (Finlay *et al*., 2019; Huotari *et al*., 2011). Traditional in-situ aquatic sampling methods for CO_2 concentrations and fluxes in natural and artificial freshwaters also come with high uncertainty (Baldocchi *et al*., 2020; Golub *et al*., 2017), with one source being the heterogeneity of littoral and pelagic lake CO_2 fluxes (Spafford and Risk, 2018).

Advances in the past several decades, however, have enabled more long-term, continuous high-frequency (hourly) measurements in freshwater ecosystems, which are capable of capturing the dynamics of air-water fluxes at time scales of hours to years (Eugster *et al*., 2003; Huotari *et al*., 2011; Morales-Pineda *et al*., 2014). At these time scales, CO_2 fluxes have been shown to respond to variations in photosynthesis and respiration rates (Cole et al., 2007), wind speed and direction (Podgrasjek *et al*., 2015), carbonate equilibria (Atilla *et al*., 2011), ecosystem metabolism (Provenzale *et al*., 2018), convective mixing (Eugster *et al*., 2003; Mammarella *et al*, 2015), internal waves (Heiskanen *et al*., 2014), ice phenology (Reed *et al*., 2018), and hydrological and carbon inflows/outflows (Rantakari *et al*., 2005; Weyhenmeyer *et al*., 2015). These sources of variation may be overlooked by low-frequency and season-restricted sampling that dominate freshwater science (Desai *et al*., 2015).

Many previous studies were conducted using eddy covariance (EC) flux towers, which measure ecosystem-scale air-water CO_2 fluxes (Vesala *et al*., 2006). This method has also gained prominence for use in freshwaters (Vesala *et al*., 2012). While its application over lakes has mostly covered short periods of time (e.g., Eugster *et al*., 2003; Podgrajsek *et al*., 2015; Vesala *et al*., 2006), an increasing number of sites are now measuring lake-atmosphere fluxes continuously over multiple years (Franz *et al*., 2016; Huotari *et al*., 2011; Mammarella *et al*, 2015; Reed *et al*., 2018; Eugster *et al.*, 2020). Other methods for high frequency sampling have also included the use of forced diffusion autochambers (Spafford and Risk, 2018). Here, to identify modes of CO_2 flux variability missed by infrequent sampling that may lead to biases in estimates of annual CO_2 flux from lakes and reservoirs quantify diel to inter-annual dynamics of CO_2 fluxes, directly measured by EC from 13 lakes and reservoirs representing a broad nutrient-humic spectrum of sites in the Northern Hemisphere.

2. Materials and Methods

2.1 Study sites

Data on air-water CO_2 exchange and meteorological drivers were acquired from nineteen study sites across the Northern Hemisphere with at least one season of observations between 2005-2015, of which 13 were retained here for analysis (Table 1 and S1). The six remaining submitted sites were withheld for challenges in meeting uncertainty and gap filling criteria (see Supplemental Methods). These sites were collected based on organization of a workshop (Desai *et al*., 2015) and an open call through listservs. Selected sites included 9 lakes and 4 reservoirs, mostly located between 40-68°N latitude, coinciding with the largest area of Earth covered with lakes. Eight sites had data available over multiple seasons, but only a few also had measurements during winter ice cover. Lake area ranged from 0.036 km^2 to 623 km^2 (median: 15.2 km^2), with median mean depth of 6 m (range: 0.6 to 11 m); most developed a seasonal thermocline and were dimictic or monomictic (Table S1). Two water bodies had a significant fraction of submerged and emergent macrophytes (SE-Tam and DE-Zrk) within the footprint of the flux tower.

2.2 Measurements

The EC technique directly measures the exchange of momentum, heat and matter (water vapor, CO_2, or other trace gasses) at the air-water interface and is a reliable method for measuring surface exchanges with the atmosphere (Vesala *et al*., 2006). The flux towers were located on floating platforms, lake shoals or islands, or on shore depending on the site (Table S1). The towers were additionally equipped with instruments providing half-hourly to hourly measurements of biophysical variables (e.g. net radiation (Rnet), air temperature (TA) and humidity, photosynthetically-active radiation (PAR), 2-D wind direction and speed, water surface temperature (TW), aquatic CO_2 or O_2 concentration, and water level), although data availability and frequency varied among the sites. Data were harmonized to uniform formats and units, screened for fetch, de-spiked, and gap-filled using a common flux post-processing standard prior to calculation of diel and monthly averages (Pastorello *et al*., 2020 and supporting material text). Note that a negative CO_2 flux indicates uptake by the ecosystem from the atmosphere and a positive flux means the reverse.All data are published in the Environmental Data Initiative repository (Golub *et al*., 2022).

2.3 Data analysis

We analyzed the half-hourly CO_2 fluxes and three major groups of biophysical covariates. The first group included variables related to wind forcing acting on the water surface (i.e. friction velocity, wind speed, momentum flux). The second group encompassed variables related to temperature cycles and proxies of energy in the system (i.e. TA, TW, ΔT (TW - TA), sensible (H) and latent heat (LE) fluxes). The last group included the variables associated with solar radiation -- proxies for primary productivity (i.e. ΔpCO_2 (pCO_{2water}- pCO_{2air}), PAR). To determine the standardized difference between two means with repeated unpaired measurements and imbalanced population sizes, we used the Cohen's *d* test where the mean difference between the mean daily CO_2 fluxes is divided by the pooled variance. A coefficient *d* of 0.20, 0.50, 0.80

indicates small, medium, and large standardized differences between the two means, respectively.

To determine the degree of NEE predictability by biophysical drivers (i.e. TA, TW, H and LE, friction velocity (Ustar), and Rnet), we also performed mutual information analysis (MI). Ultimately, this method can reveal dependencies between two variables with co-varying factors, making it a useful approach for ascertaining NEE dependencies on ecosystem variables (Knox et al., 2021). To take into account driver impacts on different temporal scales, we utilized a wavelet-based time scale decomposition approach to decompose half-hourly data into four temporal scales, hourly, diel, multiday, and seasonal, with further details in the supplement and Sturtevant *et al*. (2016).

Finally, a sample analysis was conducted on the oligotrophic (US-Too; 2012), mixotrophic (FI-Van; 2016), and eutrophic (DE-Zrk; 2014) lakes with the smallest data gaps. One thousands andom samples without replacement were taken for each of the following times: daytime-only (DT), daytime/nighttime-only (DT/NT), summer mid-day (SMD), growing season (GS), and annual. DT and NT were defined as 10am-3:30pm and 10pm-3:30am (local times) respectively. Hours between 11am and 1:30pm were considered mid-day while the GS counted fluxes between March 1st and September 30th. Each sample contained either 1, 5, or 10 counts of fluxes. To obtain a single flux value, the samples containing 5 and 10 fluxes were averaged. This sampling algorithm was created using Python version 3.8.3.

3. Results

3.1 Magnitude of CO_2 fluxes from lakes and reservoirs

Study sites represented a wide range of nutrient-color status and physical characteristics of water bodies, and as a result spanned a range of daily CO_2 fluxes, though with some common elements (Fig. 1). The mean daily CO_2 flux across all sites was 0.43±0.34 μmol CO_2 m^{-2} s^{-1} (range: -0.075 to 1.25 μmol CO_2 m^{-2} s^{-1}) with only 6% of observations indicating neutral fluxes or net CO_2 uptake. The spread of time-resolved fluxes varied between 102 and 798% of the site-specific daily mean (Fig. 1). Reservoirs had smaller but more variable fluxes relative to the lakes (0.32±0.71 vs. 0.41±0.31 μmol CO_2 m^{-2} s^{-1}), though the reservoir sample size is smaller and more geographically restricted. Two thirds of sites had at least 66% of daily fluxes within the cross-site flux mean ±1 SD (Cohen's *d*: $0.02<d<0.76$).

Annually, all sites were CO_2 sources to the atmosphere, except for DE-Zrk and LA-NT2, with large variability across sites (Fig. 2). This was also the case when comparing the same lake or reservoir type. On a single day (on average), the mixotrophic and eutrophic lakes and reservoirs were the largest and smallest C sources respectively. While most sites were a greater carbon source during the nighttime relative to the daytime, the difference in hourly fluxes was small (range ~0.5 C μmol m^{-2} s^{-1}), with the exception of DE-Zrk.

3.2 Temporal variability of CO_2 fluxes from lakes and reservoirs

Averaged diel CO_2 curves had regular patterns of daytime minima and nighttime maxima across all sites in most months (Fig. 2a). Daytime hourly fluxes were on average 35% (range 7-60%) lower than nighttime fluxes, though in 94% of site days, those were still net positive emissions. Despite the commonly observed daytime CO_2 flux dip, the flux decrease was large enough to convert our sites to daily net sinks of CO_2 in only 11% of site-months (Fig. 2a). The mean uncertainty of diel CO_2 was strongly influenced by extreme observations, with 192% mean uncertainty, but only 79% median uncertainty (Fig. 2b).

Maximum diel flux amplitudes typically occurred in July and August and ranged 0.24-1.09 μmol CO_2 m^{-2} s^{-1}. Relative to the summer amplitudes, shoulder season CO_2 flux amplitudes were on average 44-49% smaller in May and September and 26-37% in April and October. Diel variation was negligible at both ends of the ice-free season.

Monthly to sub-annual CO_2 flux variability was nearly twofold compared to diel flux variation. Surprisingly, we found frequent sub-monthly (20-30-day) variability across all water bodies, regardless of the system's physical or biogeochemical conditions. While most site-level variability fluctuated around the CO_2 flux averages, for some, amplitudes scaled with flux minima and maxima (Fig. S1).

Sites with multi-year data had relatively consistent sub-annual patterns across years, although the timing and amplitudes of sub-monthly variability varied among lake-years. When integrated over time-resolved daily CO_2 fluxes, both sub-monthly and sub-annual modes of variability accounted for two thirds of the site-level daily CO_2 flux variability (range 10-190%). Mean and median uncertainty were 167% and 67% of mean daily CO_2 flux, respectively .

Once scaled to ice-free season annual emissions, and assuming zero fluxes during ice cover, we found all water bodies were net sources of CO_2, despite missing any ice off/on related fluxes (Table 1). The cross-site mean and standard deviation of 23 site-years was 95±49 gC m^{-2} yr^{-1} (range: 14 to 224 gC m^{-2} yr^{-1}). Inter-annual variability (IAV) was calculated as a standard deviation of annual CO_2 flux for each site with multi-year data (Supplemental Fig. S2). The mean cross-site IAV was 22 gC m^{-2} yr^{-1} (25%) and ranged between 4 and 44 gC m^{-2} yr^{-1} (3-58%).

3.3 Drivers of CO_2 fluxes from lakes and reservoirs

While the continuous data allowed capturing CO_2 flux variability at different temporal scales, we still had a limited capacity to attribute which factors and processes governed the observed patterns of CO_2 flux. We found small standardized differences between CO_2 fluxes among site groups belonging to the three humic states (d<0.01), medium differences between oligotrophic and eutrophic states (d=0.24), and large CO_2 differences between mesotrophic and oligotrophic states (d=0.66), and between mesotrophic and eutrophic states (d=0.72). Commonly observed biophysical covariates explained an average of 32% of variance in half-hourly CO_2 fluxes (Fig. 4g). Wind-related variables were identified as key to explaining CO_2 flux variability in eight out of 13 sites. Biophysical variables related to exchanges of heat at the air-water interface, particularly ΔT and turbulent energy exchange (H and LE), correlated with CO_2 flux. The fitted regressions were non-linear and highly variable across sites, owing to ecosystem differences and presence of confounding factors (e.g. differential responses to co-dependent covariates).

Mutual information analysis revealed different drivers to be responsible for CO_2 fluxes on different temporal scales (Supplemental Fig. S3). On hourly scales, NEE at all sites was predicted mostly by TA and TW. The strongest links were found to occur at LA-NT2 and DE-Zrk (both eutrophic). Analysis on diel scales yielded a similar result. On multi-day scales, however, more linkage between NEE and drivers was found at CA-Dar, SE-Mer, and FI-Pal (all oligotrophic). While the seasonal scale MI analysis was subject to many gaps, it did show a more uniform NEE prediction magnitude across all sites and drivers relative to other timescales.

3.4 Sample Analysis

Random sampling among different temporal resolutions resulted in large differences between mean sampled NEE and mean continuous annual NEE (Fig 3). For DE-Zrk and FI-Van, the greatest percent error (PE) was for samples taken during SMD, calculated to be 868 ± 26% and 38 ± 2% (mean ± range), respectively. US-Too experienced the largest error during NT sampling, with a PE of 87 ± 31%. Increasing the number of NEE values per sample (i.e. going from 1 to 5 to 10 samples with the latter two NEE values calculated as the average) gave sporadic results, in that, agreement sometimes improved (FI-Van during growing season) and sometimes worsened (US-Too during nighttime). DT/NT and annual sampling were the most representative of continuous annual NEE among all sites regardless of lake/reservoir type. GS sampling showed PE that was well within the typical uncertainty for EC flux measurements (~20%) for FI-Van and US-Too. Sampling on an annual scale further constrained PE, including even DE-Zrk in addition to FI-Van and US-Too.

4. Discussion

4.1 Unresolved temporal variation in CO_2 fluxes

CO_2 fluxes from lakes and reservoirs exhibited large variability at diel to (inter)-annual scales, which could comprise unresolved sources of uncertainty or bias in current estimates of annual CO_2 fluxes from infrequent and season-restricted sampling. Though our study lakes were not randomly selected and cannot be directly used to upscale (Stanley *et al*., 2019), they were broadly reflective of common mid-latitude freshwater systems spanning a broad range of humic-status and mixing regimes. Additional considerations for sampling across lake size and catchment area (Hanson *et al*., 2007; Holgerson *et al*., 2016) and hydrological setting (Jones *et al*., 2018) would be required to design a representative estimate for global upscaling.

We were able to investigate, however, the role of temporal variation on a range of systems that broadly reflect many lakes and reservoirs. Our reported continuous daily fluxes corresponded to the upper end (88th percentile) of previously published flux magnitudes (Table S2). The observed temporal variation suggests that temporal restrictions in sampling may add a significant source of underestimation bias in existing inventories of CO_2 fluxes from lakes and reservoirs of similar type and size (Klaus *et al*., 2019).

In particular, we noted significant diel variation found in all study sites, with routinely higher emissions at night, consistent with a recent study over rivers (Gómez-Gener *et al*., 2021). The diel reduction of dissolved CO_2 concentrations and fluxes are often associated with ecosystem metabolism (Hanson *et al*., 2003) and was supported by negative correlations with PAR (Fig. 4g). Water temperature (Provenzale *et al*., 2018), carbonate equilibria fluctuations (Atilla *et al*., 2011), water-side convection (Eugster *et al*., 2003; Mammarella *et al*, 2015; Podgrajsek *et al*., 2015), and internal waves (Heiskanen *et al*., 2014) can additionally govern diel CO_2 dynamics. Our observed diel amplitudes were within 21-43% of sub-hourly flux amplitudes derived from dissolved CO_2 concentrations (Hanson *et al*., 2003; Morales-Pindea *et al*., 2014) or previously published EC-measured fluxes (Liu *et al*., 2016; Vesala *et al*., 2006). Our results support the notion that existing global lake carbon budgets are underestimates of net emissions.

We also found common sub-monthly modes of CO_2 flux variability across all of our sites. Similar variability in the continuous observations have been reported for dissolved CO_2 (Atilla *et al*., 2011; Huotari *et al*., 2009; Morales-Pineda *et al*., 2014; Vachon and del Giorgio, 2014) and CO_2 fluxes (Franz *et al*., 2016; Eugster *et al*., 2020), indicating the prevalence of oscillatory patterns in CO_2 time series at both sides of the air-water interface. Variability has been previously attributed to the interplay of wind forcing (Liu *et al*., 2016), upwellings of CO_2-rich waters (Morales-Pineda *et al*., 2014), biologically-driven (metabolic and trophic) changes in carbonate equilibria (Atilla *et al*., 2011), convective mixing (Huotari *et al*., 2009) and TW (Atilla *et al*., 2011). However, this is the first study to find a consistent pattern in a wide range of systems, regardless of size. We also observed changes to the prevalence of underlying sub-monthly CO_2 flux variability through the year at several sites, likely reflecting seasonal ecosystem changes, such as spring/fall turnover (Baehr *et al*., 2004), radiative and heat exchanges (Heiskanen *et al*., 2014), and hydrological inflows (Vachon *et al*., 2017).

4.2 Implications for the global carbon budget

After our daily fluxes were scaled to annual totals, our estimates of annual CO_2 emissions were in the upper end reported for lakes and reservoirs (Table S2). All systems were sources of CO_2 in most years, though there have been sites that reported significant carbon sinks (e.g., Shao *et al*. 2015; Reed *et al*., 2018) and additional propagation of uncertainty from data gap filling and filtering (e.g., of nighttime uptake) can push some of our study sites toward sinks, though weakly. While our lakes are not fully representative for all lakes on Earth, we postulate that improved temporal resolution of site-level CO_2 fluxes is one of the sources of differences between this study and published annual fluxes (Table S2). The results also imply that a proposed recommended number of samples per year (4-8) (Klaus *et al*., 2019; Natchimuthu *et al*., 2017) is likely insufficient to constrain annual CO_2 fluxes from lakes and reservoirs. Rather, approaches to increase nighttime, open-water season, weekly, and generally higher-frequency sampling would increase the accuracy of annual estimates, given our observed diel and sub-monthly variations.

Additionally, sites with multiple years of data all showed non-trivial interannual variation. The estimate of average IAV of CO_2 fluxes (25%) is modest compared to that (88%) observed in terrestrial ecosystems (Baldocchi *et al*., 2018), probably reflecting the lower number and diversity of ecosystems with multi-year measurements or more buffering against climate extremes by large water bodies. However, given that CO_2 flux from freshwaters positively scales with the productivity of terrestrial ecosystems at shorter timescales (Butman *et al*., 2016; Hastie *et al*., 2018; Walter *et al*., 2021), it is possible that the interannual variation of carbon displaced from land will propagate onto CO_2 outgassed through freshwaters (Drake *et al*., 2018; McDonald *et al*., 2013), providing a possible pathway to constrain freshwater IAV. Neglecting this variation is an additional source of bias in our current view on global CO_2 emissions from lakes and reservoirs.

Given that EC CO_2 fluxes are affected at both sides of the air-water interface (Wanninkhof *et al*., 2009), a better constraint of the contribution of lakes to the global carbon cycle will also require reporting and synthesis of additional continuous waterside data (e.g. temperature, dissolved CO_2 and O_2), site-level ecosystem characteristics (e.g. nutrient-color legacies, ecosystem metabolism, and aquatic vegetation such as algae) and sampling an increased site diversity within climatic zones (Lehner and Döll, 2004). With more frequent air and aquatic observations, we will better constrain CO_2 fluxes at different time scales, assess the prevalence of temporal patterns in CO_2 fluxes, and reduce uncertainty in eddy flux measurements over freshwaters (e.g., Ejarque *et al*., 2021) and therefore improve model estimates of responses of these ecosystems to climate change. Such work will be needed to quantify and evaluate landscape (Buffam *et al*., 2011; Zwart *et al*., 2018) to global (DelSontro *et al*., 2018) carbon budget components from lakes and reservoirs.

4.3 Lake and reservoir carbon flux drivers among types

In this study, water temperature (TW) has been shown to be a large predictor of lake and reservoir NEE, agreeing with past work (Zwart et al., 2019; Eugster *et al*., 2020). There is a high degree of spatiotemporal variability between these two variables. For example, NEE at LA-NT2 and DE-Zrk (eutrophic reservoir and eutrophic shallow lake respectively) was most highly predicted by TW on short timescales (hourly and diel), indicating these ecosystems to be most susceptible to releasing carbon in the future due to a warming climate. This large link may also be explicable through lake type. Eutrophic lakes are defined as being nutrient rich, meaning that they contain larger phosphorus, nitrogen, or dissolved organic carbon concentrations than their oligotrophic counterparts (Reed *et al*., 2018). On multiday timescales, however, the distinguishability of the NEE/TW linkage is absent relative to all other sites. At least for these two sites, this points to the greatest relative NEE impact of TW to be on short timescales, suggesting a rapid influence on the carbon cycle at these two eutrophic reservoirs. Predictability was seemingly weaker at the other lake sites. Another variable with high NEE predictability was air temperature (TA). This was particularly true for the same sites and timescales. However, it is certainly possible that these fluxes have an indirect relationship with TA in the form of DOC concentration magnitudes (Sobek *et al*., 2005).

5. Conclusions

Across 13 study sites with EC flux observations, on average all lakes and reservoirs were net annual sources of CO_2 to the atmosphere. However, the time series revealed large diel to (sub)-monthly CO_2 flux variability across sites, among a broad range of biogeochemical and physical site characteristics. These modes of variability accounted for two thirds of daily and a quarter of annual CO_2 flux variation, with sub-annual variability dominating over diel and inter-annual flux variabilities. After integrating these modes of variability into time-resolved fluxes, the CO_2 flux estimates were at the upper end of published CO_2 emissions for lakes and reservoirs. Our results support the idea that long-term, frequent measurements at both day and night of carbon dynamics in freshwater aquatic systems are critical to resolve lake C flux magnitudes and detect long-term trends of lake carbon fluxes. Omitting these temporal scales will not only limit our knowledge of lake C fluxes, but also restrict our understanding of biophysical driver impacts.

We advocate for establishing and maintaining a long-term observation network that combines EC flux measurements with highly detailed site-specific carbon budget studies over key lake and reservoir ecosystems representing broader geographical gradients.

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Open Research

We have deposited all EC lake observations and gap-filled values in the Environmental Data Initiative repository Golub *et al*. (2022). Several sites are also accessible from Fluxnet affiliated archives as noted in Table S2.

Author Contribution Statement

M.G. designed experimental protocol and conducted the data syntheses. N.K.-A. conducted additional analyses and revisions. A.R.D, N.K.-A., and M.G. wrote the manuscript. T.V., I.M., G.B., and G.W. supervised research, contributed observations, and edited the manuscript. All other authors contributed with flux observations and commented on the manuscript.

Competing Financial Interests

The authors declare no competing financial interests.

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Figures

Fig. 1. Normalized histograms of daily CO_2 fluxes over ice-free season in nine lakes and four reservoirs, showing that all studied ecosystems emitted CO_2 to atmosphere in the majority of site-days. Vertical solid lines and their numerical representation indicate mean daily CO_2 flux. Shaded areas show observations with negative CO_2 flux, which by convention, indicate net CO_2 uptake.

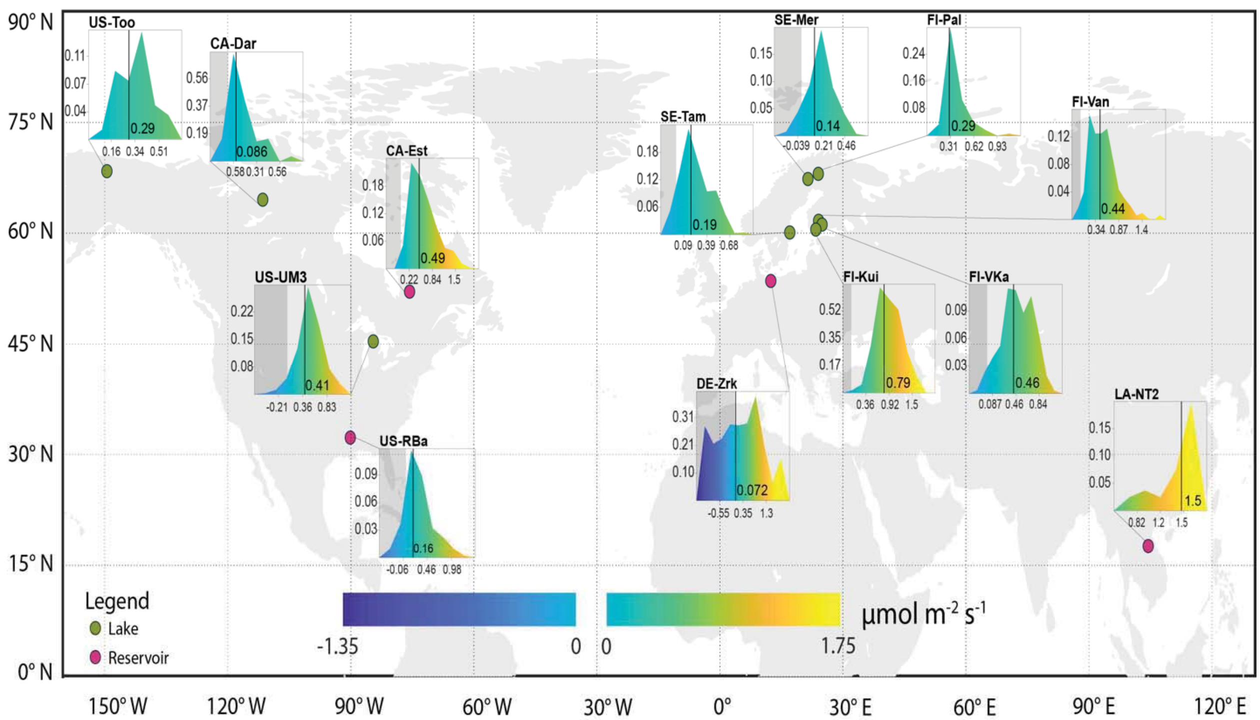


Fig. 2. Daily (A), cumulative (B), and summer diel cycle (C) of NEE for all 13 sites. Oligotrophic, mixotrophic, and eutrophic lakes and reservoirs are represented by red, blue, and green lines respectively. Averaged NEE is reported for sites with multiple years of data.

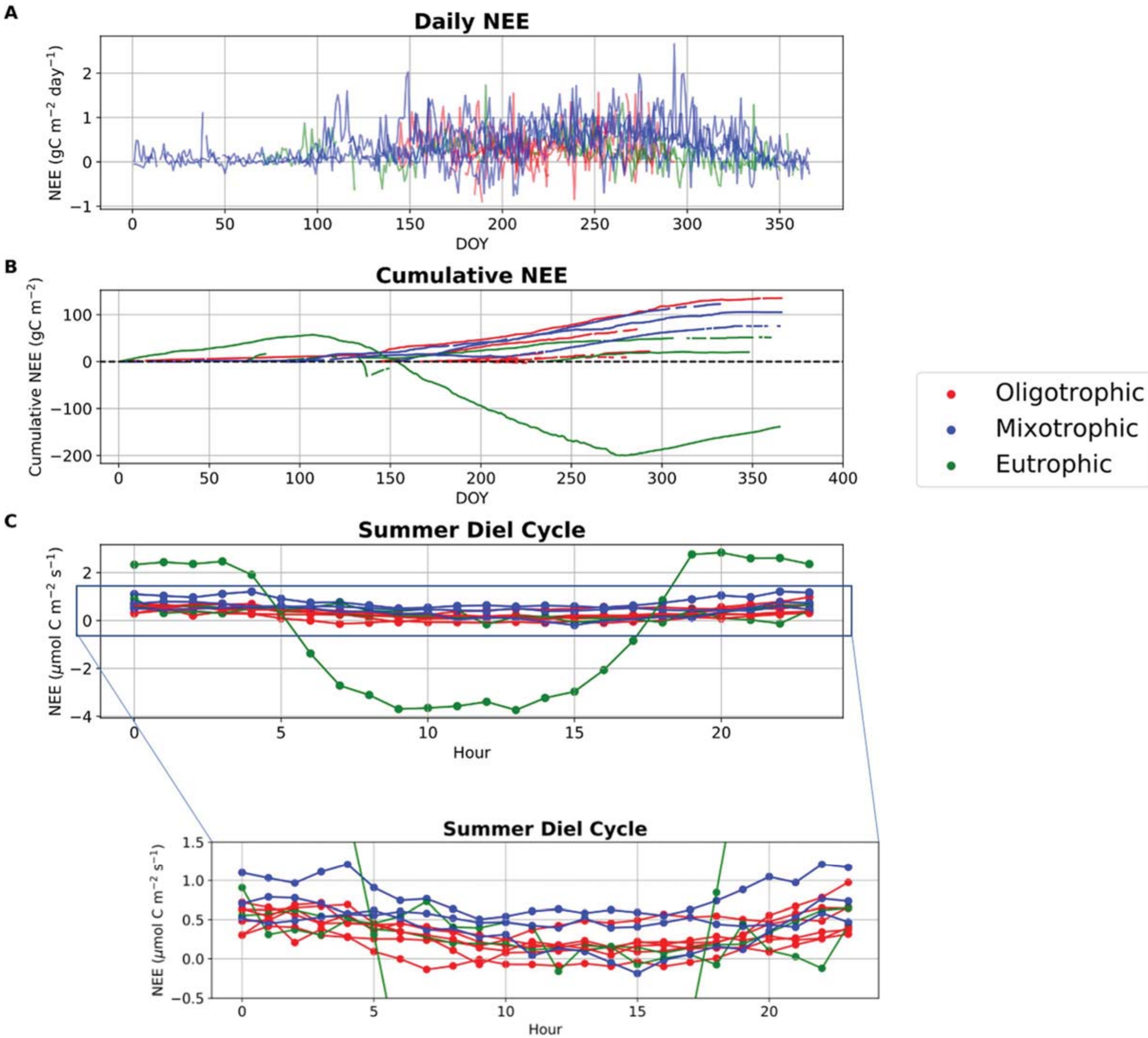
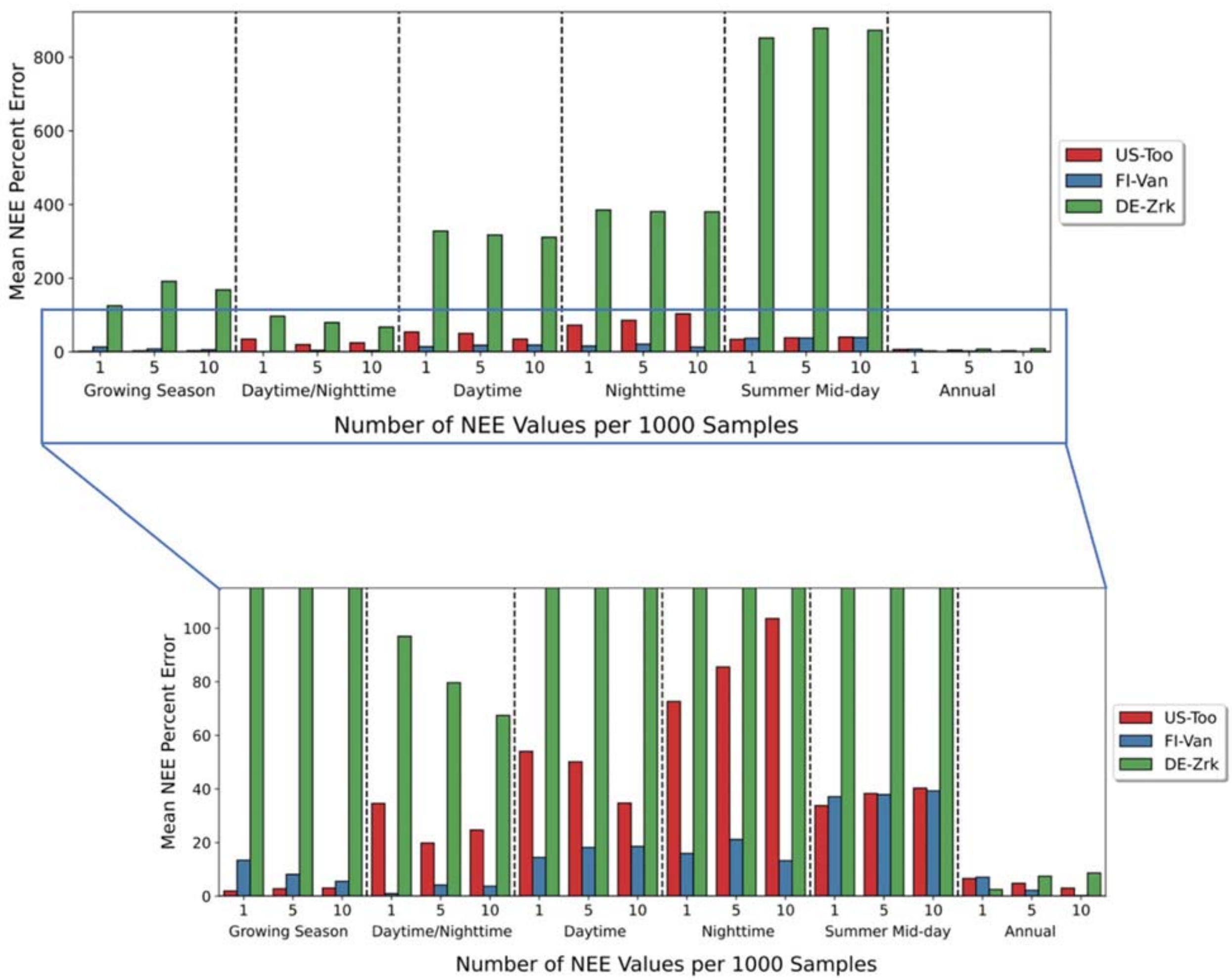


Fig. 3. Sample analysis for the mixotrophic (blue), eutrophic (green), and oligotrophic (red) lakes and reservoirs with the least data-gaps. Each bar shows percent error between randomly sampled mean NEE (without replacement) and mean continuous annual NEE. A zoomed in version of the plot is shown to better distinguish differences between FI-Van and US-Too.

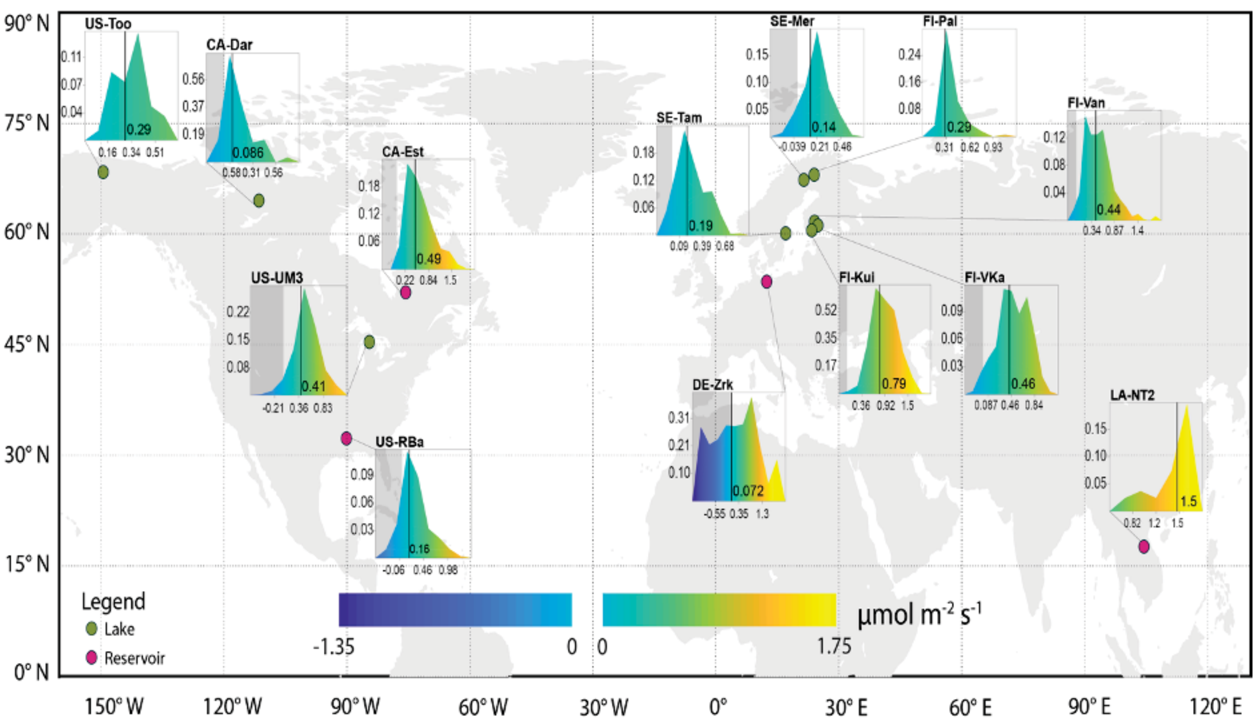


Tables

Table 1. Comparison of ice-free CO_2 flux at temporal (i.e. annual, seasonal, diurnal and nocturnal) scales derived from high-frequency eddy covariance measurements over lakes and reservoirs. One standard deviation of the mean represents uncertainty of sub-annual CO_2 fluxes. The numbers in brackets represent the number of observations integrated at a given time scale.

Lake ID	Name	Year	Air-water CO2 fluxes			
			Annual Totals [gC m-2 yr-1]	Seasonal daily mean [mgC m-2 d-1]	Daytime flux [mgC m-2 hr-1]	Nighttime flux [mgC m-2 hr-1]
CA-Dar	Daring Lake	2006	na	89±157 (n=95)	0.8±10.7 (n=1685)	12.2±7.5 (n=497)
CA-Est	Eastmain Reservoir	2008	119.1 (n=214)	581±398 (n=214)	22.4±27.5 (n=2790)	26.2±23.4 (n=2117)
		2009	137.2 (n=214)	610±433 (n=214)	21.9±24.2 (n=2786)	30.1±25.1 (n=2127)
		2010	na	431±335 (n=214)	18±20.8 (n=2804)	17.9±19.5 (n=2108)
		2011	75.9 (n=214)	367±272 (n=173)	15.2±18.8 (n=2399)	15.7±15.7 (n=1568)
		2012	na (n=214)	na	na	na
DE-Zrk	Zarnekow Polder Reservoir	2013	-126.1 (n=214)	81± 880 (n=170)	-78.6±111.6 (n=2240)	103.1±47.5 (n=1678)
		2014	-190.7 (n=214)	-250± 835 (n=214)	-86±104.1 (n=2817)	81.4±42 (n=2098)
		2015	-29.5 (n=214)	396±1148 (n=214)	-41.2±101.2 (n=2791)	84.2±54.6 (n=2139)
FI-Kui	Kuivajarvi Lake	2010	31.4 (n=214)	643±140 (n= 58)	22.8±13.9 (n= 670)	30.2±13.8 (n= 656)
		2011	107.9 (n=214)	1047±304 (n=153)	39.7±17.1 (n=2075)	48.3±21.2 (n=1455)
		2012	91.5 (n=241)	684±274 (n=169)	24.4±16.5 (n=1981)	32.4±18.4 (n=1893)
FI-Pal	Pallasjärvi Lake	2013	21.9 (n=173)	304±154 (n=93)	8.8±9.8 (n=1201)	17.2±9.9 (n=939)
FI-VKa	Valkea-Kotinen Lake	2003	59.7 (n=209)	544±155 (n=208)	22±7 (n=2385)	23.4± 8.8 (n=1848)
		2004	46.4 (n=239)	450±261 (n=238)	16.5±16.4 (n=2986)	21±13.6 (n=2464)
		2005	31.1 (n=227)	384±215 (n=226)	11.4±15.3 (n=2940)	22.6±9.1 (n=2103)
		2006	40.6 (n=254)	472±263 (n=253)	15.8± 13 (n=2983)	23.4±13.4 (n=2824)
		2007	43.6 (n=222)	539±232 (n=221)	20.8±11.3 (n=3033)	24.5±13.5 (n=2038)
		2008	-10.9 (n=101)	na	na	na
		2009	na	na	na	na
FI-Van	Vänajavesi Lake	2016	105 (n=237)	457±334 (n=237)	17.6±18.7 (n=2943)	20.8±17.8 (n=2505)
		2017	na	na	na	na
LA-NT2	NamTheun 2 Reservoir	2008	na	1762±186 (n=10)	61±17.8 (n=125)	87±39.2 (n=106)
		2009	na	1623±345 (n=15)	73.5±28.2 (n=146)	63.2±29.7 (n=200)
		2010	na	861±183 (n= 4)	36±16.3 (n= 47)	35.3±13.5 (n= 46)
		2011	na	na	na	na
SE-Mer	Merasjärvi Lake	2005	9 (n=165)	145±149 (n=117)	4.7±9.4 (n=1877)	8.6±9.3 (n=835)
SE-Tam	Tamnaren Lake	2010	8.5 (n=216)	189±125 (n= 49)	6.9± 9.9 (n= 493)	8.6±11.4 (n= 628)
		2011	28.5 (n=291)	124±161 (n=290)	4.9±11.2 (n=3619)	5.3±10 (n=3027)
		2012	na	386±176 (n=105)	10.8±12.3 (n=1663)	27.4±16.2 (n= 743)
US-UM3	Douglas Lake	2013	46.8 (n=275)	432±318 (n=102)	10.5±25.9 (n=1374)	28.5± 39 (n= 965)
		2014	60.1 (n=275)	412±313 (n=142)	9.6±24.9 (n=1889)	27.7±38.7 (n=1380)
US-RBa	Ross Barnett Reservoir	2007	20.3 (n=365)	162±308 (n=129)	5±23.5 (n=1324)	8.4±27.4 (n=1659)
US-Too	Toolik Lake	2012	na	304±130 (n=62)	8±13 (n=1120)	28±27.5 (n=308)

Figure 1.



US-Too
CA-Dar
CA-Est
SE-Tam
SE-Mer
FI-Pal
FI-Van
US-UM3
FI-Kui
FI-VKa
DE-Zrk
US-RBa
LA-NT2
Legend
Lake
Reservoir
-1.35
0
0
1.75
μmol m-2 s-1
90° N
75° N
60° N
45° N
30° N
15° N
0° N
150° W
120° W
90° W
60° W
30° W
0°
30° E
60° E
90° E
120° E

Figure 2.

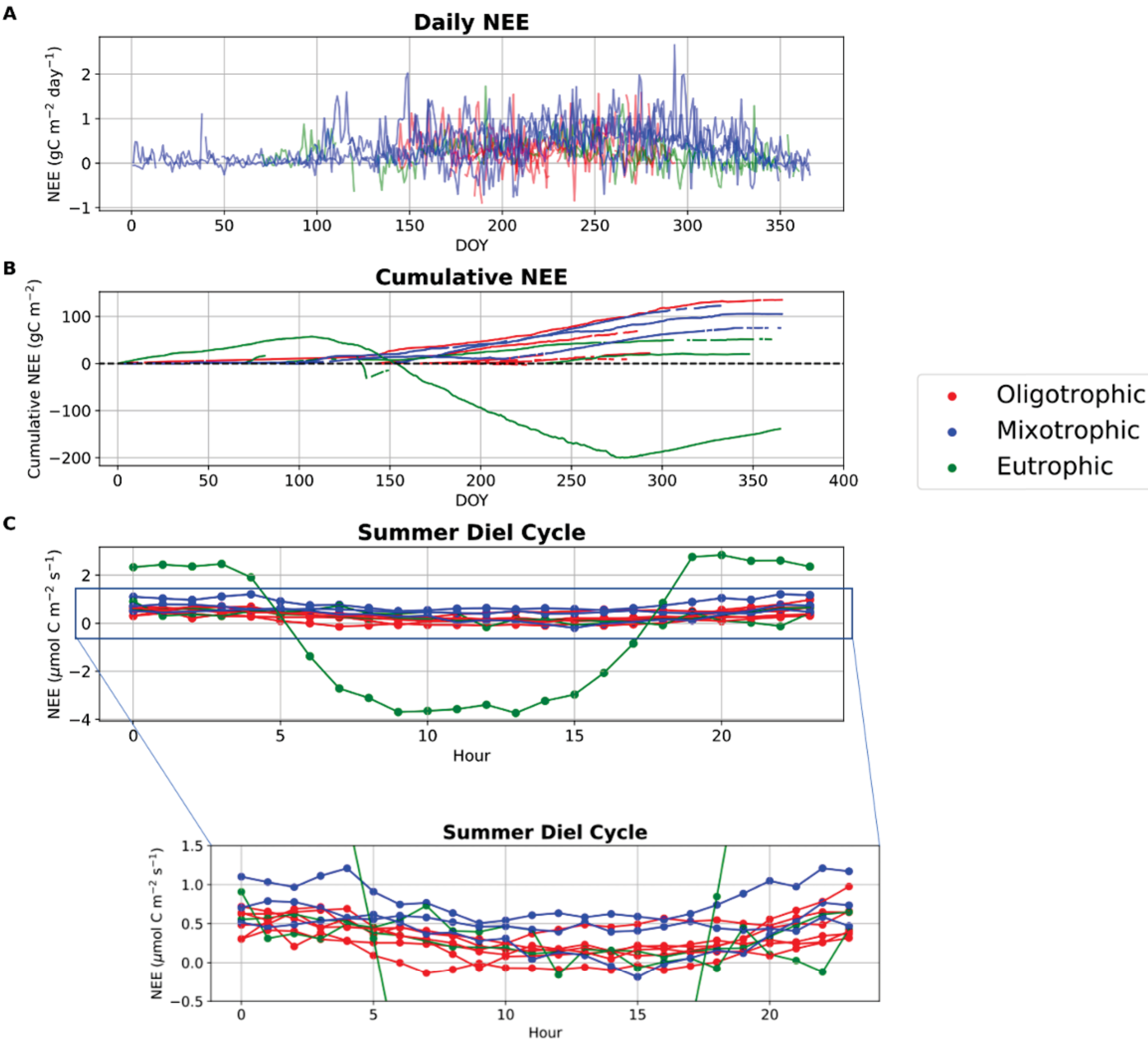
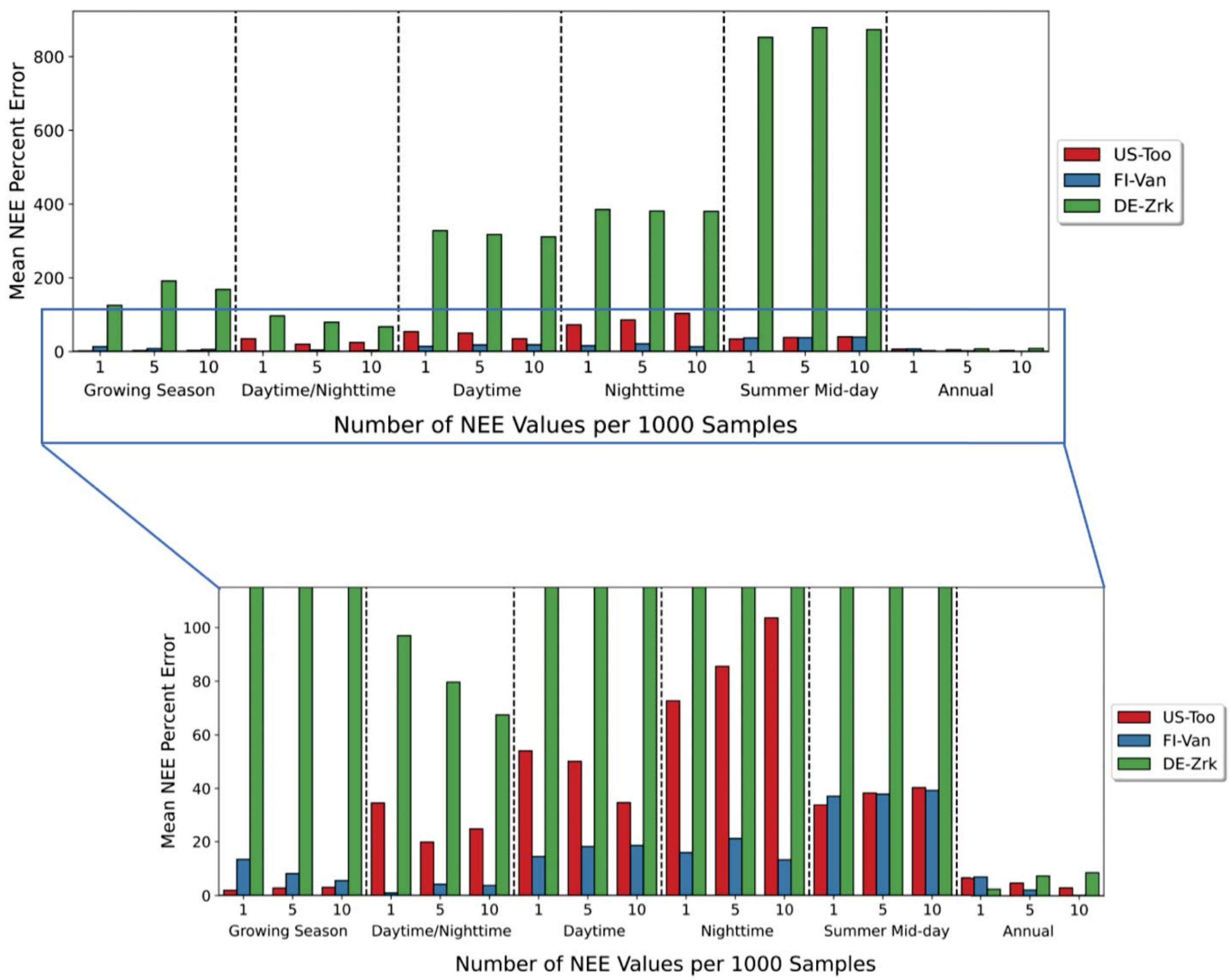

A
Daily NEE
NEE (gC m^{-2} day^{-1})
DOY
B
Cumulative NEE
Cumulative NEE (gC m^{-2})
DOY
C
Summer Diel Cycle
NEE (μmol C m^{-2} s^{-1})
Hour
Summer Diel Cycle
NEE (μmol C m^{-2} s^{-1})
Hour
Oligotrophic
Mixotrophic
Eutrophic

Figure 3.


Mean NEE Percent Error
0
200
400
600
800
US-Too
FI-Van
DE-Zrk
1
5
10
Growing Season
Daytime/Nighttime
Daytime
Nighttime
Summer Mid-day
Annual
Number of NEE Values per 1000 Samples
Mean NEE Percent Error
0
20
40
60
80
100
US-Too
FI-Van
DE-Zrk
Growing Season
Daytime/Nighttime
Daytime
Nighttime
Summer Mid-day
Annual
Number of NEE Values per 1000 Samples