New insights into diel to interannual variation in carbon dioxide emissions from lakes and reservoirs

Malgorzata Golub[1], Ankur Rashmikant Desai[2], Timo Vesala[3], Ivan Mammarella[4], Anne Ojala[5], Gil Bohrer[6], Gesa A Weyhenmeyer[7], Peter D. Blanken[8], Werner Eugster[9], Franziska Koebsch[10], Jiquan Chen[11], Kevin P. Czajkowski[12], Chandrashekhar Deshmukh[13], Frédéric Guérin[14], Jouni Juhana Heiskanen[4], Elyn R Humphreys[15], Anders Jonsson[16], Jan Karlsson[17], George W. Kling[18], Xuhui Lee[19], Heping Liu[20], Annalea Lohila[21], Erik Johannes Lundin[22], Timothy Hector Morin[23], Eva Podgrajsek[24], Maria Provenzale[4], Anna Rutgersson[25], Torsten Sachs[26], Erik Sahlée[27], Dominique Serça[28], Changliang Shao[29], Christopher Spence[30], Ian B. Strachan[31], and Wei Xiao[32]

[1]Dundalk Institute of Technology
[2]University of Wisconsin-Madison
[3]University of Helsinki, Institute for Atmospheric and Earth System Research
[4]University of Helsinki
[5]Natural Resources Institute Finland
[6]Ohio State University
[7]Ecology and Genetics/Limnology
[8]University of Colorado Boulder
[9]ETH Zurich
[10]GFZ German Research Centre for Geosciences
[11]Michigan State University
[12]University of Toledo
[13]APRIL Asia
[14]IRD - Marseille, France.
[15]Carleton University
[16]Department of Ecology and Environmental Science
[17]Umea University
[18]University of Michigan-Ann Arbor
[19]Yale University, School of Forestry and Environmental Studies
[20]Washington State University
[21]Finnish Meteorological Institute
[22]Swedish Polar Research Secretariat
[23]State University of New York College of Environmental Science and Forestry
[24]OX2
[25]Uppsala University
[26]Helmholtz Centre Potsdam - German Research Centre for Geosciences (GFZ)
[27]Earth Sciences
[28]Laboratoire d'Aérologie, Université de Toulouse, CNRS, UPS, France
[29]Institute of Agricultural Resources and Regional Planning, Chinese Academy of

Agricultural Sciences
[30]Environment and Climate Change Canada
[31]McGill University
[32]Nanjing University of Information Science and Technology

November 24, 2022

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 the magnitude and dynamics at multiple temporal scales. We found pronounced diel and sub-monthly oscillatory variations in CO_2 flux at all sites. Diel variation converted sites to daily net sinks of CO_2 in only 11% of site-months. Upscaled annual emissions had an average of 25% (range 3-58%) interannual variation. Given temporal variation remains under-represented in inventories of CO_2 emissions from lakes and reservoirs, revisions in CO_2 flux are needed using a better representation of sub-daily to interannual variability. 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.

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Name	Email	Affiliation-1
Malgorzata Golub	malgorzata.golub@dkit.ie	Dundalk Institute of Technology, Centre for Freshwater and Environmental Studies, Dundalk, Ireland
Ankur R. Desai	desai@aos.wisc.edu	University of Wisconsin-Madison, Dept. of Atmospheric and Oceanic Sciences, Madison, WI, USA
Timo Vesala	timo.vesala@helsinki.fi	University of Helsinki, Institute for Atmospheric and Earth System Research (INAR)/Physics, Faculty of Science, Finland
Ivan Mammarella	ivan.mammarella@helsinki.fi	University of Helsinki, Institute for Atmospheric and Earth System Research (INAR)/Physics, Faculty of Science, Finland
Anne Ojala	anne.ojala@luke.fi	Natural Resources Institute Finland, Helsinki
Gil Bohrer	bohrer.17@osu.edu	The Ohio State University, Dept. of Civil, Environmental and Geodetic Engineering, Columbus, OH, USA
Gesa A. Weyhenmeyer	Gesa.Weyhenmeyer@ebc.uu.se	Uppsala University, Dept. of Ecology and Genetics/Limnology, Uppsala, Sweden
Peter D. Blanken	blanken@colorado.edu	University of Colorado, Dept. of Geography, Boulder, CO, USA
Werner Eugster	werner.eugster@usys.ethz.ch	ETH Zürich, Zürich, Switzerland
Franziska Koebsch	Franziska.Koebsch@uni-goettingen.de	GFZ German Research Centre for Geosciences, Potsdam, Germany
Jiquan Chen	jqchen@msu.edu	Michigan State University, Deptartment of Geography, Environment and Spatial Science, East Lansing, MI; USA
Kevin Czajkowski	kevin.czajkowski@utoledo.edu	University of Toledo, Dept. of Geography and Planning, Toledo, OH, USA
Chandrashekhar Deshmukh	csd.cae@gmail.com	APRIL Asia, Laboratoire d'Aérologie, Observatoire Midi-Pyrénées, Toulouse, France
Frederic Guérin	frederic.guerin@ird.fr	IRD - Marseille, Toulouse, France.
Jouni Heiskanen	jouni.heiskanen@helsinki.fi	University of Helsinki, Faculty of Biological and Environmental Sciences, Helsinki, Finland
Elyn Humphreys	elyn.humphreys@carleton.ca	Carleton University, Geography and Environmental Studies, Ottawa, Canada
Anders Jonsson	anders.jonsson@emg.umu.se	Umeå University, Dept. of Ecology and Environmental Science, Umeå, Sweden
Jan Karlsson	jan.p.karlsson@emg.umu.se	Umeå University, Climate Impacts Research Centre (CIRC), Dept. of Ecology and Environmental Science, Umeå, Sweden
George Kling	gwk@umich.edu	University of Michigan, Dept. of Ecology and Evolutionary Biology, Ann Arbor, MI, USA
Xuhui Lee	xuhui.lee@yale.edu	Yale University, School of the Environment, New Haven, CT, USA
Heping Liu	heping.liu@wsu.edu	Washington State University, Dept. of Civil and Environmental Engineering, Pullman, WA, USA
Annalea Lohila	annalea.lohila@fmi.fi	Finnish Meteorological Institute, Climate System Research, Helsinki, Finland
Erik Lundin	erik.lundin@polar.se	Swedish Polar Research Secretariat, Abisko Scientific Research Station, Abisko, Sweden
Tim Morin	thmorin@esf.edu	State University of New York, College of Environmental Science and Forestry, Syracuse, New York, USA
Eva Podgrajsek	eva.podgrajsek@ox2.com	OX2, Stockholm

Maria Provenzale	mariaprovenzale@icloud.com	University of Helsinki, Institute for Atmospheric and Earth System Research (INAR)/Dept. Physics, Helsinki, Finland
Anna Rutgersson	Anna.Rutgersson@met.uu.se	Uppsala University, Dept. of Earth Sciences, Uppsala, Sweden
Torsten Sachs	torsten.sachs@gfz-potsdam.de	GFZ German Research Centre for Geosciences, Potsdam, Germany
Erik Sahlée	Erik.Sahlee@met.uu.se	Uppsala University, Dept. of Earth Sciences, Uppsala, Sweden
Dominique Serça	Dominique.Serca@aero.obs-mip.fr	Laboratoire d'Aérologie, Université de Toulouse, CNRS, UPS, France
Changliang Shao	shaochangliang@caas.cn	Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, China
Christopher Spence	chris.spence@canada.ca	Environment and Climate Change Canada, Saskatoon, SK, Canada
Ian B. Strachan	ian.strachan@mcgill.ca	McGill University, Dept. of Natural Resource Sciences, Ste. Anne de Bellevue, QC, Canada
Wei Xiao	wei.xiao@nuist.edu.cn	Nanjing University of Information Science and Technology, Yale-NUIST Center on Atmospheric Environment, Nanjing, Jiangsu, China

*Corresponding author: Ankur Desai desai@aos.wisc.edu, +1-608-520-0305

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 the magnitude and dynamics at multiple temporal scales. We found pronounced diel and sub-monthly oscillatory variations in CO_2 flux at all sites. Diel variation converted sites to daily net sinks of CO_2 in only 11% of site-months. Upscaled annual emissions had an average of 25% (range 3-58%) interannual variation. Given temporal variation remains under-represented in inventories of CO_2 emissions from lakes and reservoirs, revisions in CO_2 flux are needed using a better representation of sub-daily to interannual variability. 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 likely 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 oscillations 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 of freshwater ecosystems, 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:

- First 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 oscillations are 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, climatic modes of variability, and global changes (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; Drake *et al*., 2018; Holgerson *et al*., 2016; Raymond *et al*., 2013), offsetting 10-40% of the global terrestrial land sink. 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). For example, 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 to freshwater biogeochemistry and predict future CO_2 responses to the global change (Hasler *et al*., 2016). Decadal-scale time series that capture sub-annual variability of the CO_2 flux remain rare (Finlay *et al*., 2019; Huotari *et al*., 2011). Traditional in-situ aquatic sampling methods for CO2 concentrations and derived fluxes in natural and artificial freshwaters also come with high uncertainty (Baldocchi *et al*., 2020; Golub *et al*., 2017).

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 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 (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 have gained prominence for use in freshwaters (Vesala *et al*., 2012). The eddy covariance method directly measures air-water CO_2 fluxes within an ecosystem-scale footprint (Vesala *et al*., 2006). 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).

This recent growth of continuous measurements affords an opportunity to investigate the relative magnitude and importance of diel to interannual variation in lake and reservoir exchanges and discuss pathways to incorporating these insights into improving quantification of freshwaters in the global carbon cycle. Here, we quantify diel to inter-annual dynamics of CO_2 fluxes, directly measured by eddy covariance from 13 lakes and reservoirs representing a broad nutrient-humic spectrum of sites in the Northern Hemisphere. Our main aim was 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.

2. Materials and Methods

2.1 Study sites

Data on air-water CO_2 exchange and meteorological drivers were acquired from 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 remaining submitted sites were withheld for challenges in meeting uncertainty and gap filling criteria (see Supplemental Methods). This analysis represents the largest synthesis of lake and reservoir eddy-covariance CO_2 flux observations to-date. 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's covered with lakes. Most 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 eddy covariance technique directly measures the exchange of momentum, heat and matter (water vapor, CO_2, or other trace gases) at the air-water interface and is considered the most direct method of measuring surface exchanges with the atmosphere (Vesala *et al*., 2006). The measured fluxes are integrated across the EC flux footprint (i.e., the upwind area "seen" by the tower), capturing all sources and sinks of turbulent exchanges. The flux towers were located on floating platforms, lake shoals or islands, or on shore depending on the site (Table S1). The high frequency (10 or 20 Hz) measurements were made with open-path or closed-path infrared gas analyzers and processed into half-hourly average fluxes by site PIs according to standard methods (Aubinet *et al*, 2012). The towers were additionally equipped with instruments providing half-hourly to hourly measurements of biophysical variables (e.g. net radiation, air temperature and humidity, photosynthetically-active radiation (PAR), 2-D wind direction and speed, water temperature, aquatic CO_2 or O_2 concentration, water level), although data availability and frequency varied among the sites. Data were harmonized to uniform formats and units, screened for fetch, and de-spiked using a common flux post-processing standard (Pastorello *et al*., 2020) to reduce cross-site flux uncertainty due to methodological differences. All data were submitted to the Environmental Data Initiative repository (Golub *et al*., 2021).

2.3 Flux data processing

After despiking and quality control, the half-hourly averages of CO_2 fluxes retained 3-90% of observations during measurement periods (Table S1). A larger fraction of gaps relative to terrestrial systems were caused by the exclusion of out-of-lake and mixed tower footprints and flagging by quality control algorithms applied to flux computation. Despite these gaps, the available data provide an unprecedented number of direct CO_2 flux observations (171 site-months and 3,832 site-hours in total) that captured flux variability at multiple time scales (i.e. diel and seasonal) that are usually poorly represented in traditional limnological studies. For further analysis, all quality-controlled flux observations were identified, with missing observations gap-filled, uncertainty assessed for each time point, and continuous flux time series aggregated for diel, seasonal (sub-annual), and annual estimates.

Flux data were gap-filled using marginal distribution sampling (MDS) (Reichstein *et al*., 2005) within REddyProc (Wutzler *et al*., 2018). The MDS approach, which applies both a moving window and look-up table multiple imputation approach, used observations of shortwave incoming radiation, air temperature, and vapor pressure deficit (VPD) to fill data gaps.

The CO_2 uncertainty measured with the EC approach exhibits a variety of systematic and random errors, several of which can be quantified (Richardson *et al*., 2012; Rannik *et al*, 2016). Random errors in half-hourly averages of CO_2 flux over lakes can range from 26% to 40%, with uncertainty more pronounced in eutrophic systems (Jammet *et al*., 2017; Mammarella *et al*., 2015). The uncertainty in half-hourly flux averages was estimated as the standard deviation of observations used for gap-filling with the MDS algorithm.

The mean diel change of CO_2 and associated uncertainty was calculated by deriving the average and one standard deviation from all observations within the same month for each half-hour of the day. Lake-months with <15 observations per half-hourly average were discarded to avoid influences of unreliable means on calculated statistics. The monthly-averaged flux amplitudes were calculated as a difference between 95th percentile of nighttime observations (when shortwave incoming radiation was <10 W m^{-2}) and 5th percentile of daytime observations (>10 W m^{-2}).

Daily CO_2 flux values were calculated by averaging the 48 half-hourly fluxes. Daily CO_2 flux observations were binned according to Sturge's formula (i.e. log2(N)+1 where N represents the number of observations per lake) to accurately represent frequencies of flux distribution. To avoid the influence of extreme outliers on bin resolution, the bins were scaled to >1^{st} and <99^{th} percentiles. Annual CO_2 flux sums were calculated for the duration of ice-free season by summing daily fluxes. The ice-free period was determined from observational ice-on and ice-off data or predicted from 0.5°x0.5° gridded mean monthly air temperature (2000-2010) at a given latitude (Wei *et al.*, 2014). All but two sites (US-RBa and LA-NT2) had seasonal ice cover.

2.4 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 the variables related to temperature cycles and proxies of energy in the system (i.e. air temperature, water temperature, ΔT (T_{water}-T_{air}), sensible and latent heat fluxes). The last group included the variables associated with solar radiation -- proxies for primary productivity (i.e. ΔpCO_2 (ΔpCO_{2water}- ΔpCO_{2air}), PAR). Variables were included if they were measured at the site (Table S1). The robust linear least-squares second-order polynomial model with bisquare weighting method was used to compare bivariate relationships across lakes. To estimate confidence intervals around estimated parameters and curves, we bootstrapped residuals with 1,000 iterations. The analyses were performed with MATLAB ver. R2018a using Curve Fitting Toolbox. To determine the standardized difference between two means with repeated unpaired measurements and imbalanced population sizes, we used the Cohen's d test. The mean difference between the mean daily CO_2 fluxes was divided by the pooled variance. A coefficient d of 0.20, 0.50, 0.80 indicates small, medium, and large differences, respectively. One macrophyte-covered reservoir with distinct fluxes is provided in the Supplemental Materials.

3. Results

3.1 Magnitude of CO_2 fluxes from lakes and reservoirs

Study sites represented a wide range of nutrient-color statutes 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 m^{-2} s^{-1} (range: -

0.075 to 1.25 μmol m^{-2} s^{-1}) with only 6% of observations indicating neutral fluxes or net CO_2 uptake. The spread of time-resolved fluxes varied 102-798 % 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 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: $0.02<d<0.76$).

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, Table 1). 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 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 (Fig. 2a).

Monthly to seasonal CO_2 flux variability was nearly twofold compared to diel flux variation (Table 1). Surprisingly, we found frequent sub-monthly (20-30-day) oscillations across all water bodies, regardless of the system's physical or biogeochemical conditions (Fig. 3a). While most site-level oscillations 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 oscillations 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 (Fig. 3b).

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: 14-224 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. The mean cross-site IAV was 22 gC m^{-2} yr^{-1} (25%) and ranged 4-44 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 fluxes 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) (Fig. 4). 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 air-water temperature difference (ΔT) and turbulent energy exchange (latent and sensible heat fluxes) 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).

4. Discussion

4.1 Unresolved temporal variation in CO2 fluxes

We demonstrated that CO_2 fluxes from lakes and reservoirs exhibited significant and consistent 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 in 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.

Instead, we were able to investigate the role of temporal variation on a range of systems that broadly reflect many lakes and reservoirs. Our reported continuous daily fluxes corresponded with the upper end (88th percentile) of previously published flux magnitudes (Tables S2). The observed temporal variation suggests that infrequent and time of day or year scheduling restricted 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 note 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 (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 oscillations 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), indicating the prevalence of oscillatory patterns in CO_2 time series at both sides of the air-water interface. Oscillations have previously been 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 water temperature (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 oscillations 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 samples and open-water season weekly or 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 interannual variability 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 time-scales (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 interannual variability. Neglecting this variation is an additional source of bias in our current view on global CO_2 emissions from lakes and reservoirs (Fig. 4).

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). 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.

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 unraveled large diel to (sub)-monthly oscillatory CO_2 patterns 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, continuous, sub-weekly or sub-daily measurements of carbon dynamics in freshwater aquatic systems are necessary to detect long-term trends of lake carbon fluxes. Long-term, frequent measurements of lake fluxes are also needed to attribute natural and anthropogenic drivers to ecosystem changes that influence the global carbon cycle and its future projections. 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.

Acknowledgements

We thank all project participants for kindly sharing data and time. All flux tower data and code for processing data will be publicly available in the Environmental Data Initiative depository (DOI pending). MG and ARD acknowledge support from the U.S. National Science Foundation North Temperate Lakes LTER (NSF DEB-1440297, NTL LTER). Funding for US-UM3 was provided by the U.S. Department of Energy's Office of Science. IM and TV thank the support by EU projects RINGO (730944), Academy of Finland Centre of Excellence (118780), Academy Professor projects (312571 and 282842), ACCC Flagship funded by the Academy of Finland (337549) and the grant of the Tyumen region, Russia, Government in accordance with the Program of the World-Class West Siberian Interregional Scientific and Educational Center (National Project "Nauka"). GAW was financially supported by the Swedish Research Council (VR: Grant No. 2016-04153 and 2020-03222*)*. The deployment of the eddy covariance at the Nam Theun 2 Reservoir (Lao PDR) was funded by Electricité de France (EDF) and Nam Theun Power Company (NTPC). TS and FK were supported by the Helmholtz Association of German Research Centres through grants to TS (grant VH-NG-821) and FK (grant PD-129), the Helmholtz Climate Initiative REKLIM (Regional Climate Change), and infrastructure funding through the Terrestrial Environmental Observatories Network (TERENO). TS and FK thank the (staff of the) Department Chemical Analytics and Biogeochemistry at the Leibniz-Institute of Freshwater Ecology and Inland Fisheries (Berlin) for providing water chemistry data for DE-Zrk. The deployment of the flux tower at CA-Eastmain was supported by Hydro Quebec.

Open Research

We have deposited all eddy covariance lake observations and gap-filled values in the Environmental Data Initiative repository at: https://environmentaldatainitiative.org/ and a DOI will be provided once available, prior to acceptance. In the interim, reviewers can access all original and gap-filled flux data are available at: http://co2.aos.wisc.edu/data/lakeflux/synthesis/

or this staging site: https://portal-s.edirepository.org/nis/mapbrowse?scope=edi&identifier=835&revision=1 . 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. A.R.D 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.

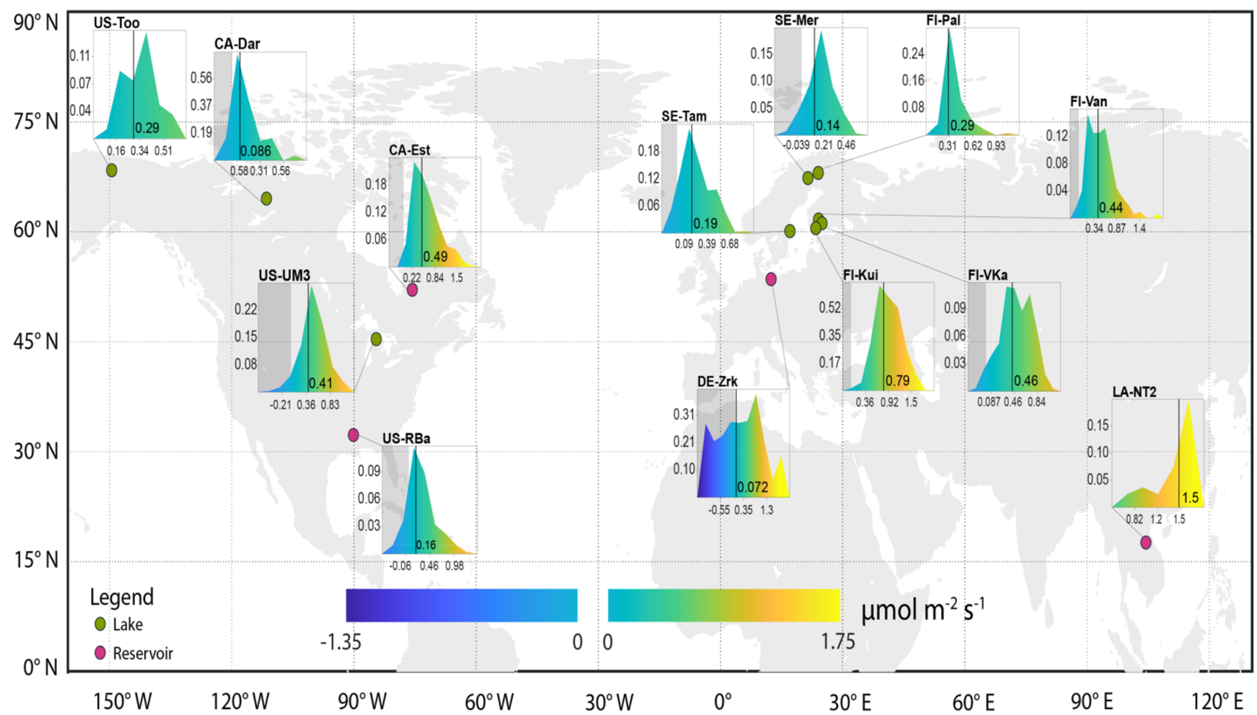


Fig. 2. a) Mean diel course of CO_2 fluxes across site-months (May-October) and site-years and b) associated uncertainty (one standard deviation of monthly-averaged half-hourly observations show consistent patterns of daytime flux reduction. Lines represent 6-hour moving average. Negative fluxes indicate net CO_2 uptake. Note separate flux scale for the macrophyte reservoir.

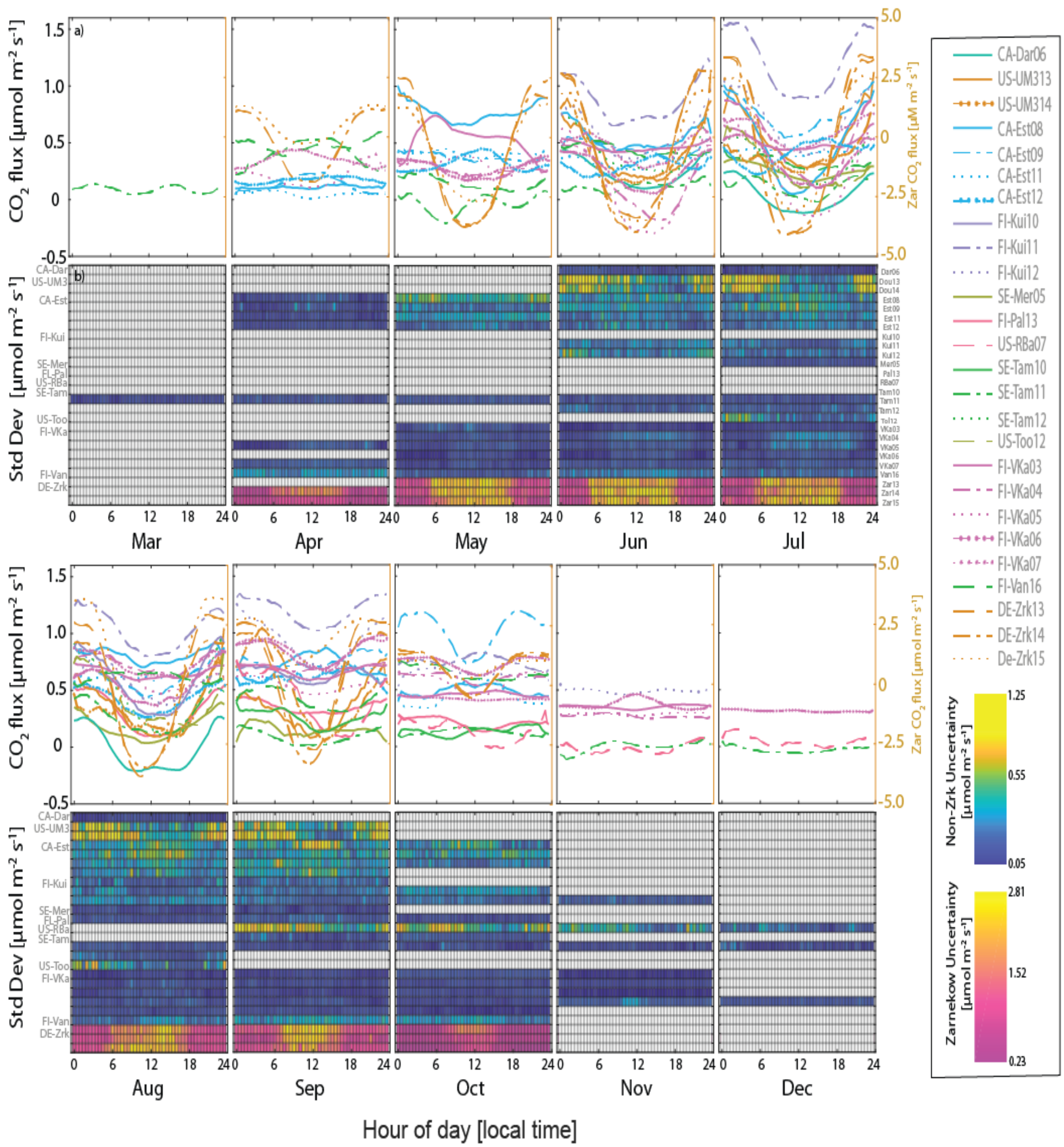


Fig. 3. a) Seasonal evolution of daily CO_2 fluxes across site-years and b) associated uncertainty (one standard deviation of daily values) indicate frequent sub-monthly oscillations across water bodies. Negative fluxes indicate net CO_2 uptake. Note separate flux scale for two reservoirs. Lines represent 10-day moving averages.

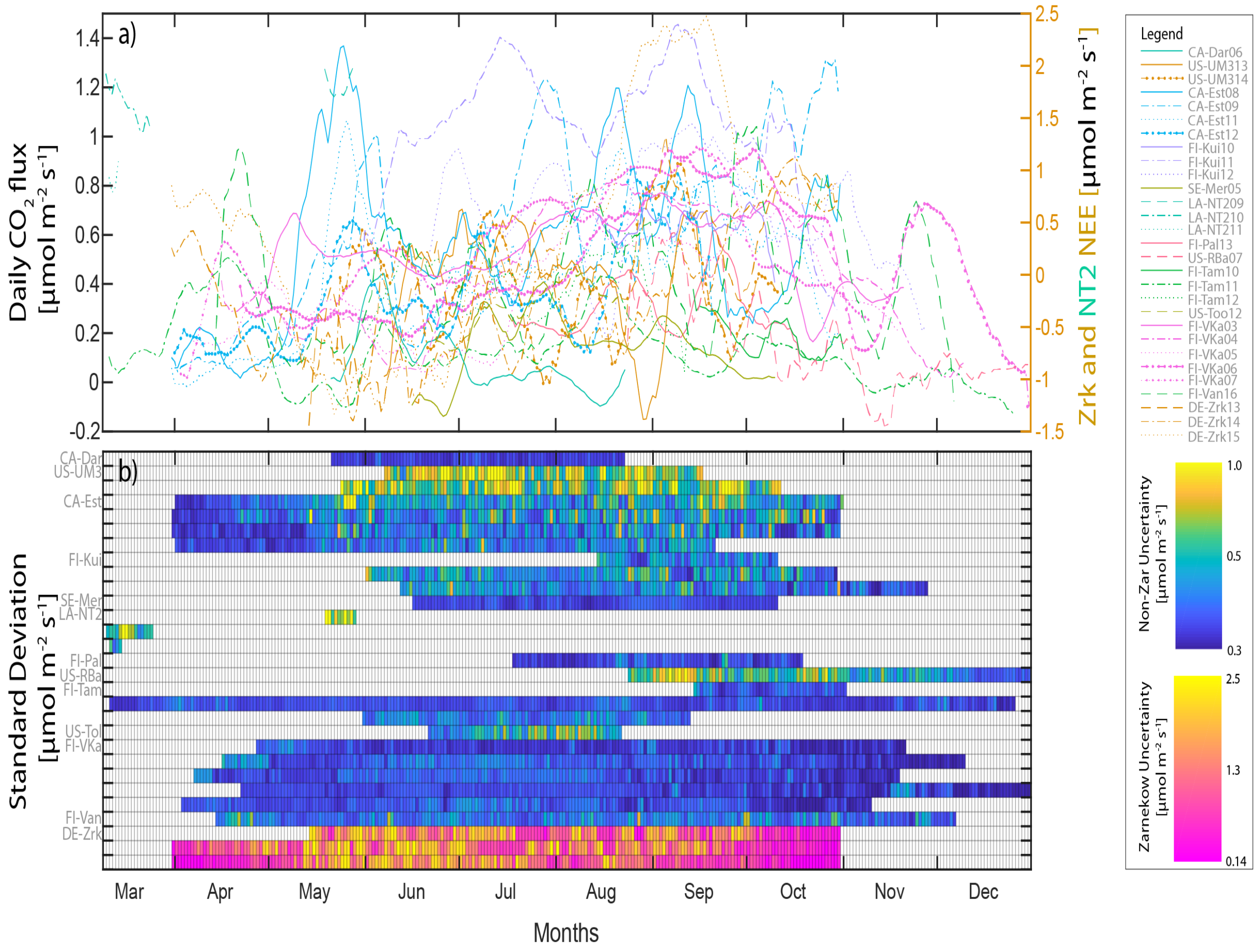
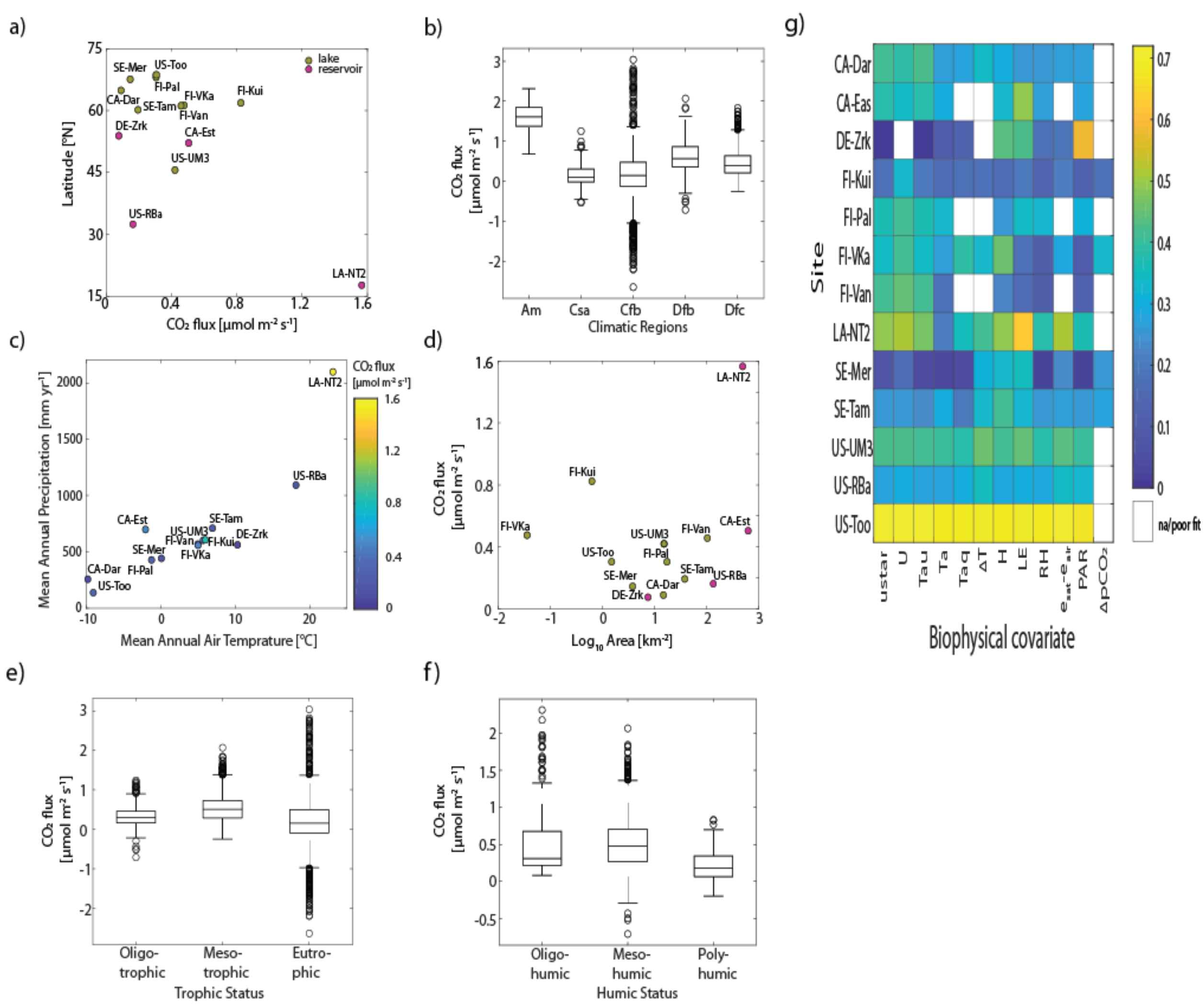


Fig. 4 Relationships of the mean daily CO_2 flux across a) latitude gradient, b) Koeppen-Geiger climatic zones, c) mean annual temperature and precipitation (2000-2010), d) surface area, e) trophic status, and f) color status. g) Pearson correlation (r2) of daily flux against biophysical covariates of friction velocity (ustar), wind speed (U), momentum flux (Tau), water temperature (Taq), air-water temperature gradient (DeltaT), sensible heat flux (H), latent heat flux LE), relative humidity (RH), vapor pressure deficit (E_{sat}-e_a), photosynthetic active radiation (PAR), and pCO_2 air-water gradient (for four sites with available data)



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	13.6 (n=153)	89±157 (n=95)	0.8±10.7 (n=1685)	12.2±7.5 (n=497)
CA-Est	Eastmain Reservoir	2008	124.4 (n=214)	581±398 (n=214)	22.4±27.5 (n=2790)	26.2±23.4 (n=2117)
		2009	130.4 (n=214)	610±433 (n=214)	21.9±24.2 (n=2786)	30.1±25.1 (n=2127)
		2011	92.3 (n=214)	431±335 (n=214)	18±20.8 (n=2804)	17.9±19.5 (n=2108)
		2012	78.6 (n=214)	367±272 (n=173)	15.2±18.8 (n=2399)	15.7±15.7 (n=1568)
DE-Zrk	Zarnekow Polder Reservoir	2013	17.3 (n=214)	81± 880 (n=170)	-78.6±111.6 (n=2240)	103.1±47.5 (n=1678)
		2014	-53.6 (n=214)	-250± 835 (n=214)	-86±104.1 (n=2817)	81.4±42 (n=2098)
		2015	84.7 (n=214)	396±1148 (n=214)	-41.2±101.2 (n=2791)	84.2±54.6 (n=2139)
FI-Kui	Kuivajarvi Lake	2010	137.6 (n=214)	643±140 (n= 58)	22.8±13.9 (n= 670)	30.2±13.8 (n= 656)
		2011	224.0 (n=214)	1047±304 (n=153)	39.7±17.1 (n=2075)	48.3±21.2 (n=1455)
		2012	164.7 (n=241)	684±274 (n=169)	24.4±16.5 (n=1981)	32.4±18.4 (n=1893)
FI-Pal	Pallasjärvi Lake	2013	52.6 (n=173)	304±154 (n=93)	8.8±9.8 (n=1201)	17.2±9.9 (n=939)
FI-VKa	Valkea-Kotinen Lake	2003	113.6 (n=209)	544±155 (n=208)	22±7 (n=2385)	23.4± 8.8 (n=1848)
		2004	107.5 (n=239)	450±261 (n=238)	16.5±16.4 (n=2986)	21±13.6 (n=2464)
		2005	87.1 (n=227)	384±215 (n=226)	11.4±15.3 (n=2940)	22.6±9.1 (n=2103)
		2006	119.9 (n=254)	472±263 (n=253)	15.8± 13 (n=2983)	23.4±13.4 (n=2824)
		2007	119.6 (n=222)	539±232 (n=221)	20.8±11.3 (n=3033)	24.5±13.5 (n=2038)
FI-Van	Vänajavesi Lake	2016	108.2 (n=237)	457±334 (n=237)	17.6±18.7 (n=2943)	20.8±17.8 (n=2505)
LA-NT2	NamTheun 2 Reservoir	2009	na	1762±186 (n=10)	61±17.8 (n=125)	87±39.2 (n=106)
		2010	na	1623±345 (n=15)	73.5±28.2 (n=146)	63.2±29.7 (n=200)
		2011	na	861±183 (n= 4)	36±16.3 (n= 47)	35.3±13.5 (n= 46)

SE-Mer	Merasjärvi Lake	2005	23.9 (n=165)	145±149 (n=117)	4.7±9.4 (n=1877)	8.6±9.3 (n=835)
SE-Tam	Tamnaren Lake	2010 2011 2012	40.8 (n=216) 35.9 (n=291) 82.7 (n=214)	189±125 (n= 49) 124±161 (n=290) 386±176 (n=105)	6.9± 9.9 (n= 493) 4.9±11.2 (n=3619) 10.8±12.3 (n=1663)	8.6±11.4 (n= 628) 5.3±10 (n=3027) 27.4±16.2 (n= 743)
US-UM3	Douglas Lake	2013 2014	118.7 (n=275) 113.4 (n=275)	432±318 (n=102) 412±313 (n=142)	10.5±25.9 (n=1374) 9.6±24.9 (n=1889)	28.5± 39 (n= 965) 27.7±38.7 (n=1380)
US-RBa	Ross Barnett Reservoir	2007	59.0 (n=365)	162±308 (n=129)	5±23.5 (n=1324)	8.4±27.4 (n=1659)
US-Too	Toolik Lake	2012	46.0 (n=153)	304±130 (n=62)	8±13 (n=1120)	28±27.5 (n=308)

Supplemental Material

S1. Supplemental Methods Text

Accounting for ice-cover

Current observations of CO_2 fluxes over lakes are mostly limited to an open water season due to wintertime measurement challenges and lack of consistent observations for all sites during ice covered season. These measurement challenges lead to a persistent under-sampling of ice-covered seasons and periods around ice-on/ice-off. Transitions to/from open-water are often accompanied with large CO_2 efflux (Anderson *et al*., 1999) and in some cases, comprise a significant proportion of annual CO_2 budget (Denfeld *et al*., 2018). Therefore, the annual CO_2 flux estimates in Table 1 are conservative.

When the observational CO_2 data extended beyond the predicted ice-free season, the length of ice-free days was adjusted to the first and/or last day of flux measurements. When the observational fluxes were missing data near ice-on/ice-off dates, the seasonal mean daily CO_2 flux for a given lake was imputed to derive annual open water emissions. We assumed negligible CO_2 transfer at the air-lake interface during the ice-covered season.

Footprint screening

Six out of 13 flux towers were placed on the lakeshore, shoals or islands (Table S1) to avoid problems with power supply, wave and ice exposure, or because of the original research question studied (e.g. CO_2 flux in heterogeneous landscape). This introduced an additional problem with CO_2 advection from catchments and flux contamination. While well-selected tower locations minimize the advection term to <3% of CO_2 flux (Morin *et al*., 2018), the towers located in the middle of the lake can also be affected by CO_2 advection, particularly small lakes surrounded by forest (Esters *et al*., 2021; Kenny *et al*., 2017). The contribution of advected air to annual CO_2 lake budgets in this project is unknown and might be substantial. Tower height also influences footprint area and likelihood of encountering secondary circulations (Kenney *et al*., 2017). To account for these at some level, data from sites and time periods with suspected significant contribution of mixed footprint were removed from this analysis. PI applied wind directional screening is also applied to avoid land contributions and noted in Table S1.

Gap-filling of missing observations

Observations gap-filled were the climatic (i.e. air temperature, incoming solar radiation, photosynthetically active radiation, horizontal wind speed, friction velocity, relative humidity, barometric pressure, net radiation, vapor pressure deficit) and the lake fluxes (i.e. sensible, latent, and CO_2 turbulent flux), and the in-water (i.e. surface water temperature, CO_2 concentration) variables. However, there is no consistent method of flux gap-filling existing for freshwater waterbodies. Here, we tested two approaches to gap-filling, the artificial neural network (ANN) (Morin *et al*., 2014) and marginal distribution sampling (MDS) (Wutzler *et al*., 2018). The MDS approach resulted in a smaller number of end-gaps, always used the same variables for gap-fill and was computationally efficient relative to the ANN approach. Since a standardized gap-filling protocol significantly reduces the uncertainty of compared NEE sums in multi-site syntheses (Moffat *et al*., 2007), we therefore used the MDS approach for computing filled fluxes and biophysical variables.

Uncertainty analysis

To reflect uncertainty, we calculated the standard error of the mean (i.e. square root of summed variances normalized by square root of number of observations, SEM) for daytime and nighttime half-hourly averages (Table S1). SEM for daytime observations varied from 0.196 μmol m^{-2} s^{-1} in FI-VKa to 1.82 μmol m^{-2} s^{-1} in DE-Zrk, whereas SEM for nighttime observations ranged from 0.200 μmol m^{-2} s^{-1} in FI-VKa to 1.38 μmol m^{-2} s^{-1} in US-UM3. The average nighttime CO_2 uncertainty was higher than daytime uncertainty in seven lakes.

The open-path (OP) gas analyzer measurements were on average one third more uncertain than the closed-path (CP) measurements (Table S1). The daytime SEM in OP ranged from 0.228 μmol m^{-2} s^{-1} to 0.932 μmol m^{-2} s^{-1} (mean: 0.565 μmol m^{-2} s^{-1}), while the daytime SEM in CP ranged from 0.196 μmol m^{-2} s^{-1} to 0.558 μmol m^{-2} s^{-1} (mean: 0.382 μmol m^{-2} s^{-1}). The CO_2 flux uncertainty in DE-Zrk measured with CP was higher (mean: 1.76 μmol m^{-2} s^{-1}) compared to uncertainties in lakes because a large proportion of emergent macrophytes within the flux tower footprint contributed to much stronger signal and flux magnitudes comparable to wetlands.

CO_2 fluxes over freshwater systems are small relative to fluxes to terrestrial systems, show low signal-to-noise ratio, and require the Webb-Pearson-Leuning (Webb *et al*., 1980) and Burba corrections (Burba *et al*., 2008) for covarying fluctuations of water vapor flux and temperature. The corrections terms, especially for OP measurements, can be larger than measured CO_2 quantities, leading to biased CO_2 flux especially when carbon flux is small and corresponding heat flux is large (Helbig *et al*., 2016) and result in physiologically unreasonable net CO_2 flux, such as nighttime uptake in eutrophic water bodies (Lee *et al*., 2014; Potes *et al*, 2017). The sites consistently showing such a nighttime uptake were excluded from this meta-analysis.

Intercomparison with other methods

We assume with sufficient sampling period, the continuous EC flux measurements are representative for ecosystems with similar biotic and abiotic conditions. The inter-comparison with other methods of estimating CO_2 flux from lakes (i.e. floating chambers, surface renewal model, and boundary layer models) showed varying degrees of agreement. Relative to CO_2 flux estimates, the simultaneous measurements with other methods typically agreed within 20%, though periods with large departures up to 2-3 times larger or smaller do occur (e.g., Anderson *et al*., 1999; Baldocchi *et al*., 2020; Eugster *et al*., 2003; Erkkilä *et al*., 2018; Jonsson *et al*., 2008; Podgrasjek *et al*., 2014; Vesala *et al*., 2006). The agreement varied on level of stratification, overlap in timing of measurements, season, and the selection of piston velocity models. There is good reason to believe that flux tower approaches can be a viable method for estimating lake/reservoir CO_2 fluxes, though studies that found greater discrepancies among independent methods and models require reconciliation.

Interannual variability calculation

One standard deviation of annual CO_2 fluxes was calculated to determine the inter-annual variation (IAV) of fluxes for sites with multi-year measurements. We acknowledge that calculating the standard deviation from a limited number of site-years (i.e. <5 years) can lead to uncertain estimates of IAV, however, it cannot be further constrained with this study dataset.

With more multi-year time series of continuous measurements, we will be able to determine the 5-year time threshold is sufficient to capture inter-annual CO_2 flux variability in freshwater ecosystems.

Regression analysis

We tested several models (e.g. quadratic, linear, exponential, gaussian, etc) available in the library of models in the Curve Fitting Toolbox in MATLAB with the variable number of models' parameters to select the most robust model. We selected the robust linear least-squares second-order polynomial model with bisquare weighting method. This statistical model maximized the goodness-of-fit (e.g. r2 and rmse), required less parameters to estimate and dealt with nonlinearities. To avoid influences of outliers on fitted curves, values beyond 1st and 99th percentile of each variable were removed before curve fitting.

Fluxes over a macrophyte reservoir (DE-Zrk)

A significant fraction of emergent macrophytes within a flux tower footprint of a shallow reservoir DE-Zrk increased the flux temporal dynamics by an order of magnitude relative to fluxes measured over open water lake surfaces (Table S2). Since the emergent macrophyte stands are common in shallow lakes and reservoirs, the unique CO_2 flux over such systems is worth describing separately.

The mean and standard deviation of daily CO_2 were 0.072±0.970 μmol m^{-2} s^{-1} (range: -0.858-1.352 μmol m^{-2} s^{-1}, Fig. 1, Table 1). Daytime to nighttime hourly fluxes were on average 250% lower, indicating a strong mid-day photosynthetic CO_2 fixation of macrophytes, roughly seven times higher than daytime CO_2 drawdown observed in open-water systems (Fig. 2). The negative correlation with PAR additionally confirmed a strong control of macrophyte photosynthetic activity over sub-daily CO_2 flux variation (Fig. 3). The maximum uptake of the monthly-averaged daily flux amplitudes typically occurred in July ranging 6.15-8.31 μM m^{-2} s^{-1} and declined towards both ends of the ice-free season. At annual timescale, CO_2 fluxes indicated a net source of C in two lake-years (Table 1). The mean interannual variability (IAV) of annual CO_2 flux 428%. Overall, the mean and median uncertainty of daily CO_2 flux were 162% and 421% for DE-Zrk (Fig. 3b). The flux values were several-fold underestimated relative to the published CO_2 flux estimates for this site (Franz *et al*., 2016) The CO_2 fluxes contributing to the tower footprint of DE-Zrk were distinct between the open water and the emergent vegetation categories. The lack of footprint heterogeneity was not considered in the uniform method of flux computation applied in this study but was the most significant source of discrepancies in estimated fluxes between these two studies.

S2. Supplemental references

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S3. Supplemental Tables

Supplemental Table S1. Additional site characteristics of the eddy flux tower sites synthesized in this study.

Supplemental Table S2. Summary statistics of the literature-compiled mean daily, annual and inter-annual CO_2 fluxes derived from at least four samples per year. Within-study flux variation is expressed as one standard deviation of the (published or calculated) mean. Numbers in brackets indicate the minimum and maximum flux values at given time scale

Supplemental Table S1. Additional site characteristics of the eddy flux tower sites synthesized in this study.

Site Descriptive Variable	CA-Dar	CA-Est	DE-Zrk	FI-Kui	FI-Pal	FI-Van	FI-Vka	LA-NT2	SE-Mer	SE-Tam	US-UM3	US-RBa	US-Tol
Site Name	Daring	Eastmain	Zarnekow Polder	Kuivajarvi	Pallasjärvi	Vanajavesi	Valkea-Kotinen	NamTheun 2	Merasjärvi	Tamnaren	Douglas	Ross Barnett	Toolik
Type (1)	L	R	R	L	L	L	L	R	L	L	L	R	L
Latitude, Longitude [dec deg]	64.86, -112.59	52.13, -75.9	53.88, 12.89	61.83, 24.28	68.01, 24.21	61.13, 24.26	61.24, 25.06	17.69, 105.3	67.55, 21.96	60.16, 17.32	45.57, -84.7	32.44, -90.0	68.63, -150.0
Climate (2)	Dfc	Dfc	Cfb	Dfb	Dfc	Dfb	Dfc	Am	Dfc	Cfb	Dfb	Csa	Dfc
Mean Annual Air Temperature [°C]	-9.7	-1.6	9.8	5.1	-1.7	4.1	4.1	23.2	-0.6	6.1	6.3	18.1	-8.8
Mean Annual Precipitation [mm yr-1]	246	738	557	550	444	534	533	2109	418	577	727	1385	135
Surface Area [km2]	14.8	623	7.5	0.63	17.3	103	0.036	489	3.8	38	15.2	134	1.5
Mean, Maximum Depth [m]	Na, Na	11, 15	0.6, 1.2	6.4, 13	9, 36	7, 25	2.5, 6.5	7.8, na	5.1, 17	1.3, 2	5.5, 14	3.6, 10.7	7, 25
Volume [km3]	Na	6.94	0.005	0.004	0.155	0.721	0.00009	3.9	0.019	0.42	0.083	0.482	0.011
Catchment to lake area ratio [km2]	Na	Na	Na	30	6.08	27	8.1	5.8	17.11	18.9	3.72	58.96	43.33
Impoundment Year [yr]	NA	2006	2004/2005	NA	NA	NA	NA	2008	NA	NA	NA	1963	NA
TP [µg L-1]	Na	18.1	235	15	5.5	28	16	45	6.6	79.92	9	90	5
TN [µg L-1]	Na	233	Na	400	132	Na	465	917	113	1336	454	1500	234.9
Chlorophyll a [µg L-1]	Na	2.9	Na	3.75	2.11	19	15.8	8.5	1.9	Na	0.4	10	1.4
pH [pH units]	6.75	6	8.2	6.5	7.06	Na	5.2	6.67	7	8.97	7.98	8	7.1
DOC [mg L-1]	2.7	6.5	22	12.9	2.72	9.6	11	2.66	6.2	23.16	10.45	Na	6.9
Macrophytes within footprint (3)	Na	Na	Cd, Cg, Lm, Pa, Sp, Tl	Na	Na	Na	Na	Na	Na	Bs, Es, Ms, Pau, Sa	Na	Na	Na
Trophic Status (4)	OT	MT	ET	MT	OT	MT	MT	ET	OT	ET	OT	ET	OT
Color Status (5)	OH	MH	Na	MH	OH	MH	MH	OH	MH	PH	MH	Na	PH
Depth Classification (6)	D	D	S	D	D	D	S	D	D	S	D	D	D
Mixis Type Classification (7)	Na	Na	Pm	Dm	Dm	FMm; ESm	FMm; EDm; SSm	WMm	Dm	Pm	Dm; EMm	WMm	Dm
Measurement Height [m]	4.1	15	2.63	1.7	2.5	2.75	1.5	3	1.7-2.6 (±.1)	4.3	1.5	4	Na
Sensor Type (8)	OP	OP	CP	CP	CP	CP	CP	OP	OP	OP	OP	OP	CP (?)
Fetch Screening	excl. 10-270	0-40; 220-360	1-360 (mixed footprint)	135-170; 290-345	180-330; 350-50	excl. 100-185	100-170; 290-350	1-360	excl. 155-210	excl. 30-90	excl. 180-270	1-360	1-360
Tower Location	island	island	platform	platform	shoal near shoreline	on shore	platform	platform	platform	island	shoal near shoreline	platform	platform
Source	Humphreys, unpubl.; Google Earth	Teodoru et al., 2011; Vachon et al., 2013 , Wang et al., 2018	Zak et al., 2008; Franz et al., 2016	Dinsmore et al., 2013; Heiskannen et al., 2015; Mammarella et al., 2015; Miettinen et al., 2015	Lohilla et al., 2015	Provenzale, unpubl.	Vesala et al., 2006; Arvola et al., 2014	Deshmukh et al., 2014; Chanudet et al., 2016; Martinet et al., 2016	Jonsson et al., 2008; Åberg et al., 2010	Podgrajsek et al., 2014 http://miljodata.slu.se	Kwon et al, 2014; Kenny et al., 2017; Morin et al., 2018 dx.doi.org/10.17190/AMF/1480315	Sobolev et al., 2009; Liu et al., 2016	Eugster et al., 2003; Luecke et al., 2014 Tan82;

1 Waterbody type: L-lake; R-reservoir

2 Climatic zone based on Koeppen-Geiger climate classification map (5 arc min) following Kottek et al., 2006 re-analyzed by Rudel et al., 2017: Dfc - snow climate, fully humid, cool summer, cold winter; Dfb - snow climate, fully humid, warm summer; Am - equatorial monsoon; Cfb - warm temperate climate, fully humid, warm summer; Cfa - warm temperate climate, fully humid, hot summer;

3 Submerged/floating (SF) and emergent (E) macrophytes: Cd – Ceratophyllum demersum (SF), Es – Elodea spp. (SF), Lm – Lemna minor (SF), Ms - Myriophyllum spicatum (SF), Pa - Polygonum amphibium (SF), Sp - Spirodela polyrhiza (SF), Bs - Butomus spp (SF). Cg – Carex gracilis (E), Pau – Phragmites australis (E), Sa - Schoenoplectus acutus (E), Tl - Typha latifolia (E);

4 Trophic status classification: OT - Oligotrophic (TP<10µgL-1); MT - Mesotrophic (10µgL-1>TP<30µgL-1); ET - Eutrophic (TP>30µgL-1)

5 Humic status classification: OH - Oligohumic (DOC<7 mgL-1); MH – Mesohumic (7<DOC<11 mgL-1); PH – Polyhumic (DOC>11mgL-1)

6 Depth classification: S - Shallow (mean depth <3m); D - Deep (mean depth>3m)

7 Mixing type classification: Dm - dimictic; FMm - fall monomictic; Pm - polymictic; WMm - warm monomictic; ESm - episodic summer mixing due to weak thermal stratification; SSm - strong summer stratication; EDm - episodically dimictic; EMm - episodically fall monomicitic or spring monomictic

8 Sensor type: OP – open path gas analyzer; CP – closed path gas analyzer.

Supplemental Table S2. Summary statistics of the literature-compiled mean daily, annual and inter-annual CO_2 fluxes derived from at least four samples per year**.**

Within-study flux variation is expressed as one standard deviation of the (published or calculated) mean. Numbers in brackets indicate the minimum and maximum flux values at given time scale

Source	Daily CO2 flux [mgC m	Annual CO2 flux [gC m	Inter-annual CO2 flux	Measurement Freque	Notes
Site-level discrete CO2 flux					
Brothers et al., 2012	1343±72	na	na	22 year-1	Estmain R., Ice-free season; Jun-Sep sampling; Boreal
Casper et al., 2000	480	na	na	13 year-1	Priest Pot; Ice-free season; May-Oct sampling
Chmiel et al., 2013	406	94	na	Two-year 6 years-1	L. Gäddtjärn; Ice-free season; Boreal
Cole and Caraco, 1998	109±29 (80-138)	40±11 (30-50)	na	Multi-year weekly	L. Mirror, Two methods of flux estimation;
Demarty et al., 2011	na	81±52 (21-137)	4 (Eastmain R.)	Space-resolved two-ye	One reservoir and two lakes; Ice and ice-free sampling; Boreal
Denfeld et al., 2018	na	30±37 (-11-152)	11 (4-23)	Multi-year 7-9 year-1	10 lakes; Ice-free season; Temperate
Einola et al., 2011	na	50±232 (18-86)	102 (4-19)	1-4 year-1 (5 lakes)2; 1	5 lakes; Ice-free season; Boreal
Eugster et al., 2003	191-102 (114-365)	na	na	8-602 year-1	L. Toolik; Convective and stratified periods; Four methods of flux estimation; Arctic
Finlay et al, 2019	341	61±24	7	Multi-year (37) weekly	Bufallo Pound Lake; Ice-free season; Great Plains;
Jonsson et al., 2008	180±45 (119-225)	na	na	6 summer-1 (2 methoc	L. Merasjarvi; Three methods of flux estimation; Summer; Boreal
Karlsson et al., 2013	na	9±14	na	7 year-1	Twelve lakes; May-Oct sampling
Kling et al., 1991	258±100 (150-420)	na	na	Multi-year mean 44-62	Two lakes and multi-lake (25) average; Arctic;
Kokic et al., 2015	500±100 (400-600)	na	na	5 year-1	L. Gäddtjärn and headwater lakes, Ice-free season; Jun-Nov sample; Boreal
Miettinen et al., 2015	542±13 (529-555)	84±5 (79-89)	5	14 year-1	Kuivajarvi; Ice-free season; Boreal;
Natchimuthu et al., 2017	549±193 (306-780)	1433	na	Space-resolved 89-129	Three lakes; Ice-free season; Jun-Oct sampling; Hemiboreal
Ojala et al., 2011	261±109 (151-401)	59±16 (41-82)	na	weekly	Two lakes, Two methods of flux estimation; Ice-free season; Boreal
Repo et al., 2007	328±136 (136-437)	na	na	6-7 year-1	Three lakes; Jul-Sep sampling; Subarctic
Riera et al., 1999	245±223 (5-549)	54-49 (1-120)	na	8-32 year-1	Four lakes; Ice-free season; Apr-Nov sampling; Temperate
Sobek et al. 2003	na	10±18	na	4 year-1	29 lakes; Ice-free season; Boreal
Stets et al., 2009	na	26±24 (2-49)	na	daily	Two lakes; Year-round integration; Mass-balance model; Temperate;
Striegl & Michmerhuizen 1998	na	49±47 (1-96)	na	21-25 year-1	Two lakes; Ice and ice-free season; Mar-Aug sampling; Temperate
Site-level, high-frequency, seasonal CO2 flux					
Franz et al., 201529	516	174	na	Year-round continuous	Zarnekow macrophyte reservoir; Footprint heterogeneity incorporated; Temperate; Eddy covariance
Huotari et al., 2009	na	37±7 (30-44)	7	Two-years continuous	L. Valkea-Kotinen; Ice-free season; Boreal
Huotari et al., 2011	na	77±10 (68-97)	10	Five-year continuous	L. Valkea-Kotinen; Ice-free season; Boreal, Eddy covariance
Lundin et al., 2015	na	24±16 (5-54)	na	Continuous	Six lakes; Ice-free season; Subarctic
Morales-Pinnieda et al, 2014	311±202 (96-601)	na	na	Continuous	Two reservoirs; Ice-free annually; May-Oct sampling; Two methods of flux estimation; Mediterranean
Pelletier et al., 2014	450±300	na	na	Two-year continuous	Pool in peatland; Ice-free with a brief under-ice period; May-Oct sampling; Boreal
Vachon et al., 2017	311±39 (272-350)	49±6 (43-56)	na	Continuous	Two lakes; Ice and ice-free season; Boreal
This study	450±354 (-78-1298)	95±49 (14-224)	22 (4-44)	Continuous	Nine lakes and three reservoirs, Ice-free season; Six climatic zones; Eddy covariance
	75±1006 (-890-1402)	16±151 (-39-632)	151	Continuous	Macrophyte reservoir DE-Zar, Ice-free season; Temperate; Eddy covariance
Regional upscaling (Process- or mass balance models) CO2 flux					
Cardille et al, 2009	na	119±18 (99-142)	na	daily time steps	Ice-free season; US Mid-west region; Different precipitation scenarios
Zwart et al., 2018	na	47±5 (41-53)	na	daily time steps	Ice-free season; US Mid-west region
	na	27±3 (24-31)	na	daily time steps	Year-round; US Mid-west region
McDonald et al., 2013	263±180 (-50-610)	96±66 (-18-223)	na	daily	Year-round; Continental US
Regional / global upscaling (Extrapolation-based models or space-resolved average) CO2 flux					
Alin and Johnson, 2007	na	52±26 (14-91)	na	variable	Large lakes, Latitudinal gradient, Global
Buffam et al., 2011	na	32 (25–39)	na	1 summer-1 (168 lakes	Ice-free season, Summer sampling; US Mid-west region;
Bogard & delGiorgio., 2016	232 (-187-979)	na	na	1 summer-1 (346 lakes	Boreal region
Deemer et al., 2016	451±86 (330-525)	na	na	variable	Reservoirs, Global summary statistics
Del Sontro et al., 2018	374±114 (242-563)	na	na	variable	Size area bins, Global summary statistics
Hastie et al., 2018	na	139 (54-257)	na	variable	Size area bins, Boreal region
Holgersson and Raymond, 2016	269±77 (138-423)	na	na	variable	Size area bins, Global summary statistics
Kankaala et al., 2013	na	77±43 (41-159)	na	weekly (17 lakes)	17 lakes; Ice-free season; Size area bins, Boreal region
Kortelainen et al., 2006	na	65±24 (37-102)	na	4 year-1	177 random lakes; Ice-free season; Size area bins; Boreal region
Rantakari & Kortelainen, 2005	138±12 (114-149)	24±32 (18-28)	32	3 year-1	37 lakes; Ice-free season; Boreal region
Raymond et al., 2013	na	148±146 (-1-537)	na	variable	Back-calculated from flux yield; Year-round integration; Northern Hemisphere excl. tropical region;
Weyhenmeyer et al., 2015	708 (128-2,620) 448 (	na	na	1 autumn-1 (5,118 lak	Ice-free season, Two methods of flux estimation; Boreal and hemiboreal region,

S4. Supplemental Figures

Supplemental Fig. S1. Seasonal patterns of CO_2 flux in three example lakes: a) FI-Van - a boreal lake, mesotrophic, mesohumic, deep, fall monomicitc with episodic summer mixing due to weak stratification, b) FI-VKa - a boreal lake, mesotrophic, mesohumic, shallow, fall monomictic, strong summer stratification, and c) DE-Zrk – a temperate eutrophic reservoir, shallow, cold polymictic with emergent macrophytes.