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 $\mu mol\ m^{-2}\ s^{-1}$ in FI-VKa to 1.82 $\mu mol\ m^{-2}\ s^{-1}$ in DE-Zrk, whereas SEM for nighttime observations ranged from 0.200 $\mu mol\ m^{-2}\ s^{-1}$ in FI-VKa to 1.38 $\mu mol\ m^{-2}\ s^{-1}$ 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 $\mu mol\ m^{-2}\ s^{-1}$ to 0.932 $\mu mol\ m^{-2}\ s^{-1}$ (mean: 0.565 $\mu mol\ m^{-2}\ s^{-1}$), while the daytime SEM in CP ranged from 0.196 $\mu mol\ m^{-2}\ s^{-1}$ to 0.558 $\mu mol\ m^{-2}\ s^{-1}$ (mean: 0.382 $\mu mol\ m^{-2}\ s^{-1}$). The CO_2 flux uncertainty in DE-Zrk measured with CP was higher (mean: 1.76 $\mu mol\ m^{-2}\ s^{-1}$) 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 1^{st} and 99^{th} 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;	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.