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LETTER

Diel variation in CO_2 flux is substantial in many lakes

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Scientific Significance Statement

Lakes act as both sources and sinks of carbon dioxide (CO_2), with the magnitude and direction of this flux determined by characteristics of the waterbody and its surrounding catchment, as well as weather and sunlight. Despite an increasing awareness of diel (over 24 h) variation in the flux of CO_2 from aquatic ecosystems, comparable in situ data from lakes around the

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world are limited. Here we present, for the first time, an international assessment of diel CO_2 fluxes, and show that diel variation can be grouped into three recognizable patterns linked to the productivity of lakes. Our findings suggest that the time of day greatly influences CO_2 fluxes in lakes, with resulting implications for scaling up single daytime measurements to values relevant to global carbon budgets.

Abstract

Lakes play a significant role in the global carbon cycle, acting as sources and sinks of carbon dioxide (CO_2). In situ measurements of CO_2 flux (FCO_2) from lakes have generally been collected during daylight, despite indications of significant diel variability. This introduces bias when scaling up to whole-lake annual aquatic carbon budgets. We conducted an international sampling program to ascertain the extent of diel variation in FCO_2 across lakes. We sampled 21 lakes over 41 campaigns and measured FCO_2 at 4-h intervals over a full diel cycle. Rates of FCO_2 ranged from -3.16 to 4.39 mmol m^{-2} h^{-1}. Integrated over a day, FCO_2 ranged from -381.68 to 878.49 mg C m^{-2} d^{-1} (mean = 76.54) across campaigns. We identified three characteristic diel patterns in FCO_2 related to trophic status and show that for half of the campaigns, daily flux estimates were biased by > 50% if based on a single (daytime) measurement.

Lakes play an important yet uncertain role in the global carbon cycle (Cole et al. 2007) by transporting and processing terrestrial carbon along the land–ocean aquatic continuum (Engel et al. 2018), storing large amounts in sediment (Henry et al. 2024), and exchanging carbon dioxide (CO_2) and methane (CH_4) with the atmosphere (Holgerson and Raymond 2016). Gas flux across the air–water interface is a function of the transfer velocity (k), and the difference in partial pressure (pCO_2) between the surface water and the atmosphere (Cole et al. 2010). The combination of these two variables determines the direction (in or out of the lake, i.e., influx and efflux) and magnitude of the gas flux. Both k and pCO_2 are controlled by biophysical drivers which vary spatially and temporally, resulting in potentially large variations in CO_2 flux (FCO_2) (Vachon et al. 2017; Rudberg et al. 2024). While considerable work has been done on FCO_2 spatial variation across and within lakes (e.g., Rocher-Ros et al. 2017) and temporal variation at annual and seasonal time scales (Denfeld et al. 2018; Reed et al. 2018; Ngochera and Bootsma 2020), less is known about variation in FCO_2 over diel timescales. This variation has been recognized as a large source of uncertainty when upscaling CO_2 fluxes from inland waters into global budgets (Xu et al. 2019; Ran et al. 2022; Lauerwald et al. 2023).

There is a strong theoretical basis for expecting FCO_2 diel variability to be substantial, as the primary drivers of pCO_2 and k have diel patterns (e.g., sunlight, temperature, wind speed). For example, lakes with high primary production from photosynthesizing algae or macrophytes will uptake large amounts of CO_2 in the day, resulting in lower (even negative) daytime FCO_2 (Wang et al. 2024). The transfer velocity (k) is determined by wind speed, convection, and other drivers of turbulent mixing (Crusius and Wanninkhof 2003; Podgrajsek et al. 2015; Czikowsky et al. 2018) that vary in relative importance over diel (Imberger 1985) and seasonal cycles (Read et al. 2012). Hence, the interaction of k and pCO_2 is likely to produce complex patterns in FCO_2 that will be moderated by the characteristics of individual waterbodies.

Several methods are used to collect measurements of FCO_2 from lakes (Lauerwald et al. 2023). Eddy covariance (EC) systems capture data at fine temporal resolution (Eugster et al. 2003; Liu et al. 2016; Golub et al. 2023) but they measure flux over a relatively large spatial footprint (> 1 ha) and may be too coarse for smaller lakes or large ones with significant spatial heterogeneity. There is also a clear unresolved issue between lake-surface and atmosphere FCO_2 measurements (Baldocchi et al. 2020). Modeling of flux using a gas transfer velocity (k) and the concentration gradient of the gas in the air and surface water is also common (e.g., Yang et al. 2019), but determining k is often challenging (Dugan et al. 2016). Chamber measurements provide direct estimates at a local scale (m^2) and are suitable for understanding the mechanisms driving fluxes from smaller lakes (Bastviken et al. 2022). However, carrying out chamber measurements on lakes is logistically difficult, particularly in the nighttime, resulting in a large bias towards daytime measurements. Where chambers have been used to measure FCO_2 from aquatic ecosystems, it has tended to be for detailed studies at a small number of sites (e.g., Ojala et al. 2011; Natchimuthu et al. 2017).

Several studies have documented significant diel variability in FCO_2 in streams and rivers (Attermeyer et al. 2021; Gómez-Gener et al. 2021; Woodrow et al. 2024), and in lakes where EC data are available (Shao et al. 2015; Spank et al. 2020; Golub et al. 2023; Hounshell et al. 2023) but it is surprisingly hard to find direct measurements of FCO_2 from lakes overnight. A recent review of data availability describing FCO_2 over diel cycles found 29 published estimates from lakes, ponds, and one reservoir (Rudberg et al. 2021), with an almost equal split between higher daytime or higher nighttime FCO_2. Higher nighttime FCO_2 has been recorded in several eutrophic waterbodies (Ran et al. 2022; Zhang et al. 2022; Rulík et al. 2023; Zhao et al. 2024), with some researchers advocating the use of a night/day ratio to correct the bias introduced by daytime sampling alone (Wang et al. 2024).

The aim of this work was to characterize diel FCO_2 variability across a broad range of lakes, using a standardized approach. We measured FCO_2 over a diel cycle in 21 lakes, using low-cost CO_2 sensors and floating chambers. We hypothesized that FCO_2 would have high diel variability in lakes with high productivity and diel variability in turbulence drivers, particularly nocturnal heat loss and afternoon wind peaks. We used our data to calculate an integrated daily carbon flux for each study lake, and we compared these integrated fluxes to daily fluxes extrapolated from a single midday FCO_2 to estimate temporal up-scaling bias.

Methods

Study sites

We recruited researchers through the Global Lake Ecological Observatory Network to conduct a field campaign comprising in-situ flux measurements every 4 h over one diel cycle ($\sim$ 28 h) using floating chambers and directly measured pCO_2 over several minutes. We encouraged the use of inexpensive in-situ sensors (i.e., SensAir, *see* Bastviken et al. 2015), which enabled research groups with limited funding to participate. In some cases, participants used sensors that they already had, for example, a Gasmet Dx-4030 spectrometer (Rõõm et al. 2022) or Los Gatos GHG analyzer (McClure et al. 2020).

We measured FCO_2 in 21 lakes between November 2016 and October 2018 (Fig. 1). Lakes varied in terms of surface area, depth, trophic status, seasonality of ice-cover and mixing regime, among other characteristics (Table 1). Diel sampling was done once in 12 lakes and was repeated on non-consecutive days twice in 5 lakes, 3 times in 5 lakes, and 4 times in 1 lake, resulting in 41 campaigns. Over half ($n = 23$) of the campaigns were conducted in summer, eight were in spring and autumn, and two were in winter. Two sampling locations were used at two lakes (Pallasjärvi and Mendota) which were spatially different enough to warrant separate consideration, leading to 23 flux measurement sites in total.

Flux measurement

Campaigns lasted between 17 and 28 h and consisted of six or seven sampling periods spaced approximately every 4 h. Chambers were fitted with foam collars and had an average volume of 12 L (range 7–31 L). The surface area of the water enclosed averaged 0.11 m^2 (range 0.06–0.28). We vented the chambers, placed them on the water surface and allowed them to drift for at least 5 min. The FCO_2 measurement was replicated in most cases, either using multiple chambers at the same time, or consecutive deployments of the same chamber. In most cases, sensors were calibrated using N_2 gas and the

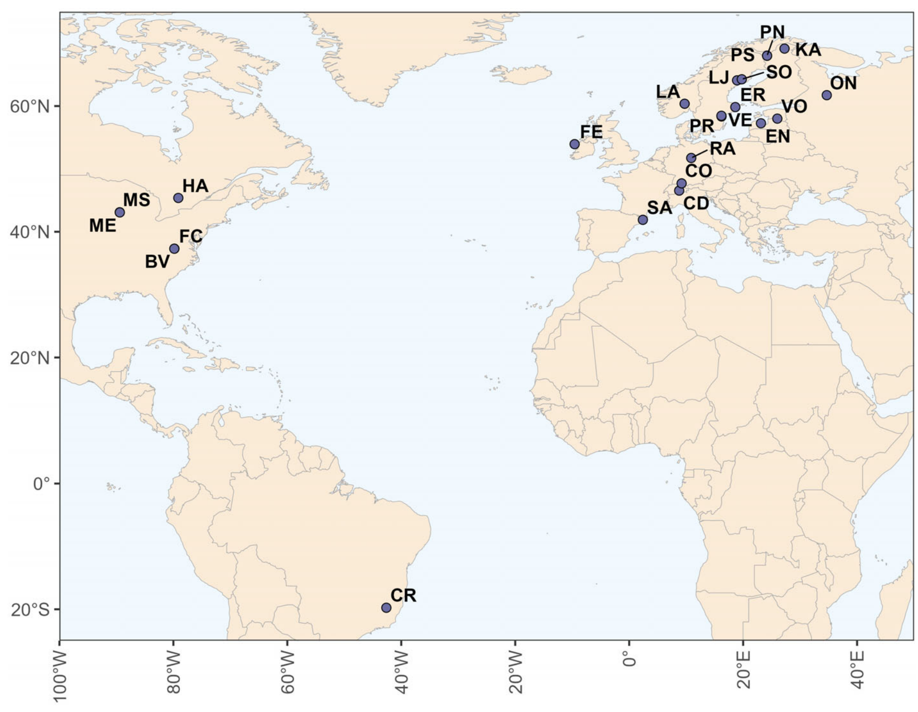

Fig. 1. Location of our study sites. Lake name abbreviations can be found in Table 1.

Table 1. Characteristics of lakes included in this study.

Lake	Code	Lat	Long	Mean depth (m)	Max depth (m)	Surface area (km^2)	Altitude (m)	Fetch (m)	Catchment area (km^2)	Mixing regime	Humic	Trophic status
Beaverdam reservoir	BV	37.31	−79.81	6	13.4	0.39	509	28	4.11	Di	No	Meso
Cadagno	CD	46.55	8.77	9.7	21	0.26	1920	120	2.51	Mero	No	Meso
Carioca	CR	−19.75	−42.61	4.76	11.8	0.14	268	110	0.72	Mono	No	Eu
Constance	CO	47.69	9.20	90	253	536	395	NA	11,500	Mono	No	Oligo
Engure	EN	57.25	23.12	0.4	2.1	41.3	3	200	644	Poly	No	Eu
Erken	ER	59.83	18.62	9	20.65	24.2	11.1	25	141	Di	Yes	Meso
Falling Creek reservoir	FC	37.30	−79.84	4	9.3	0.12	591	30	3.68	Di	No	Meso
Feeagh	FE	53.93	−9.57	14.5	45	3.92	20	500	85	Mono	Yes	Oligo
Harp	HA	45.38	−79.13	10	35	0.7	350	500	4.71	Di	No	Oligo
Kaamanen	KA	69.13	27.26	0.7	0.7	0.019	153.3	30	0.24	Poly	Yes	Oligo
Langtjern	LA	60.36	9.73	2	12	0.23	516	50	4.8	Di	Yes	Oligo
Ljusvattentjärn	LJ	64.09	18.93	5.2	9.7	0.02	252	129	0.24	Di	Yes	Oligo
Mendota	ME	43.10	−89.42	12.7	25.3	39.9	259	3000	562	Di	No	Eu
Mendota shore	MS	43.08	−89.40	3	3	39.9	259	10	562	Di	No	Eu
Onego	ON	61.73	34.67	30	127	9720	33	700	51,540	Di	Yes	Meso
Pallasjärvi North	PN	68.01	24.21	4	5	0.48	267	145	105.2	Di	No	Oligo
Pallasjärvi South	PS	68.00	24.20	1.5	2	0.18	267	82	105.2	Di	No	Oligo
Parsen	PR	58.34	16.20	3.4	8	0.13	72	345	1.82	Di	No	Meso
Rappbode	RA	51.74	10.89	28.6	89	3.95	423	200	274	Di	No	Meso
Sau Reservoir	SA	41.98	2.38	29	65	5.8	425	3065	1680	Mono	No	Eu
Stortjärn	SO	64.26	19.76	2.7	6.7	0.04	299	60	0.65	Di	Yes	Meso
Venasjön	VE	58.45	16.19	5.4	10.5	0.68	47	95	170	Di	No	Eu
Võrtsjärv	VO	58.28	26.03	2.8	6	270	34	230	3374	Poly	Yes	Eu

"zero calibration" method per Bastviken et al. (2015) although this was not possible at some remote locations. At sites where relative humidity was high, an appropriate correction was made. Flux rates were calculated following eq. 1 in Rudberg et al. (2021).

In addition to FCO_2, we collated lake (Table 1) and campaign (Supporting Information Table S1) metadata to use as explanatory variables for our analyses. We measured water temperatures and pCO_2 of the surface water and gathered meteorological data from the nearest weather station to calculate the mixing depth (Z_{mix}) and turbulent velocity scales for wind shear (u*), and convection (w*) following Imberger (1985). Photosynthetically active radiation was converted to total shortwave radiation following Read et al. (2011). Campaign-specific partial pressure of CO_2 in the atmosphere was downloaded from the Copernicus Atmosphere Monitoring Service (2021).

Statistical methods

All results were based on the mean flux from replicates within each sampling time period of every diel campaign (de Eyto et al. 2025). We removed outliers within each sampling period before averaging, based on the interquartile range criterion. We binned measurements across 11 time periods to allow for comparison of diel cycles across campaigns with varying start times (Supporting Information Table S2). Day and night sampling periods were determined using the R package "geosphere" (Hijmans et al. 2016). For lakes at northern latitudes, we also used shortwave radiation (< 50 W m^{-2}) to determine nighttime.

We used longitudinal *k*-means clustering to determine common diel flux patterns across campaigns. In brief, this analysis tests for different temporal trajectories or "shapes" from repeated measurements, and optimal clusters of similar shapes are selected based on variance ratio criteria (Genolini and Falissard 2010). Importantly, this algorithm does not have linearity or distribution assumptions, so trajectories or "shapes" of repeated measurements can take many forms. Within each campaign, flux data were scaled as *z*-scores to have equal mean and variation. This reduced bias in the cluster analysis that might be skewed by very high or low flux values and allowed the cluster analysis to identify common patterns in diel fluxes, irrespective of measurement differences between campaigns that might have impacted the flux magnitude. We tested for 2–9 possible clusters with 20 redraws using the "kml" package (Genolini et al. 2015) in R. The optimal number of clusters was selected as that with the highest average Calinski–Harabatz quality value across redraws. Each campaign was assigned a cluster based on the results of the optimal clustering algorithm.

We then used a classification tree analysis to assess the characteristics and conditions associated with each cluster, using the "rpart" package (Therneau and Atkinson 2013). We included 18 predictor variables of cluster in the classification tree (Supporting Information Table S3), selected by reducing cross-correlation with analogous variables (i.e., selecting for $|\text{Pearson } r| < 0.75$). The resulting classification tree was pruned by selecting the model with the fewest nodes and a cross-validated error rate within ± 1 standard error of the model with the overall lowest cross-validated error.

Finally, we calculated the area under each diel flux curve using trapezoidal integration in the R package "pracma" (Borchers 2023). This allowed us to calculate daily flux (mg C m^{-2} d^{-1}) for each campaign, based on FCO_2 integrated across 4-h time periods ($dFCO_{2int}$). We compared this to extrapolations based on multiplying the midday flux rate by 24 ($dFCO_{2mid}$) as is often used in upscaling, to examine potential bias introduced by using a single daytime FCO_2.

Results

Our complete dataset comprised 41 diel campaigns and 992 individual flux chamber measurements across 23 sites. After averaging across replicates within sampling periods, the final dataset comprised 277 FCO_2 rates ranging from -3.16 to 4.39 mmol m^{-2} h^{-1} (mean = 0.29, median = 0.14) (Fig. 2A). We measured negative (influx) FCO_2 103 times and positive (efflux) 174 times. Mean FCO_2 per campaign ranged from -1.31 and 3.13 mmol m^{-2} h^{-1} and the standard deviation per campaign varied from 0.02 to 1.30 mmol m^{-2} h^{-1}. In other words, FCO_2 was very stable in some lakes over the diel cycle, while in others, there were large differences depending on the time of day the sample was taken. We recorded wholly negative FCO_2 in 11 campaigns, wholly positive FCO_2 in 19 campaigns with the remaining 11 campaigns switching between influx and efflux over the diel cycle. Humic lakes tended to have positive and larger FCO_2 compared to non-humic lakes which centered on neutral (Fig. 2B). Oligotrophic lakes displayed small, slightly positive effluxes while mesotrophic to eutrophic were highly variable (Fig. 2C). Autumn campaigns skewed towards efflux, while influxes, indicating demand for CO_2, were more likely in campaigns carried out during the growing season in mesotrophic to eutrophic lakes. The biggest seasonal difference was found in Lake Mendota where fluxes were entirely negative in the spring and positive in the autumn. We found that campaigns where the surface water pCO_2 was close to equilibrium with the atmosphere (398–410 ppm CO_2 at the time of sampling) corresponded with FCO_2 close to zero, low standard deviations in FCO_2 and switches between influx and efflux during the campaign (Supporting Information Fig. S1). Across all campaigns, there was no significant difference in FCO_2 measured between day and nighttime (Supporting Information Figs. S2, S3; Table S4) or between sampling periods (Supporting Information Fig. S4; Table S5).

We found that the optimal clustering algorithm for the patterns of diel flux resulted in three clusters (Fig. 3A). Campaigns in Cluster A ($n = 17$) had the highest fluxes in the late

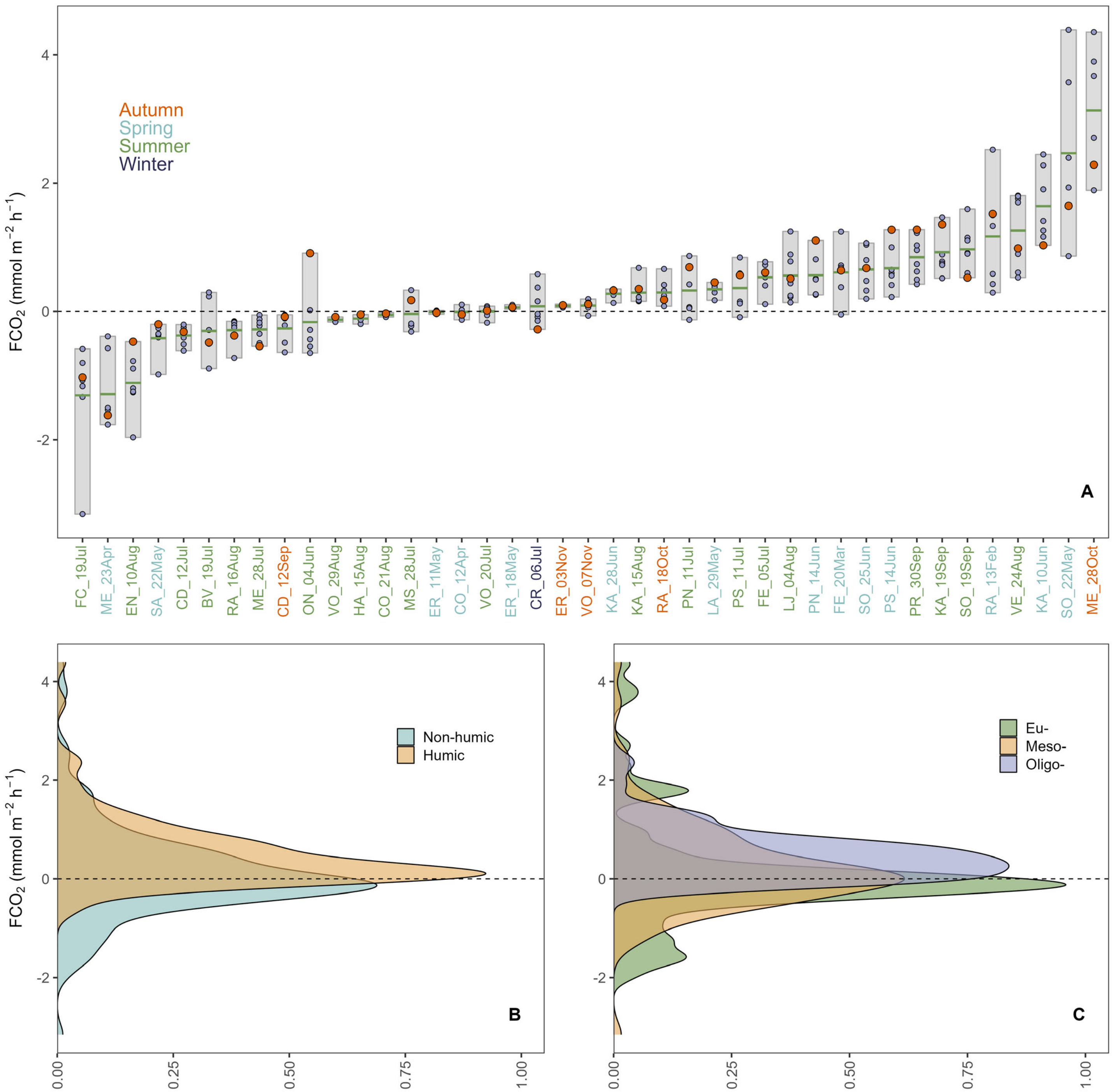

Fig. 2. CO_2 flux between water and air measured during 41 sampling campaigns (**A**). Each gray box represents the range of FCO_2 measured over a diel campaign. The horizontal line within each box indicates the mean FCO_2 per campaign, and green dots are FCO_2 measured at ~ 4 h intervals over a diel cycle. The orange dot is the midday value. Data below the dashed line are influxes (CO_2 into the lake), while those above the line are effluxes (CO_2 out of the lake) to the atmosphere. Campaigns are ordered left to right according to the mean FCO_2 per campaign. Density plots of 277 measurements of FCO_2, with study sites split according to non-humic/humic water (> 30 mg L^{-1} PtCO) (**B**), and by trophic status (**C**).

afternoon to evening, which decreased around midnight, and remained comparatively low during night into early morning, a pattern consistent with diurnal wind-driven efflux. Those in Cluster B ($n = 11$) had relatively low fluxes in the afternoon that increased in the evening until midnight, followed by relatively high flux rates during night and into early morning, a

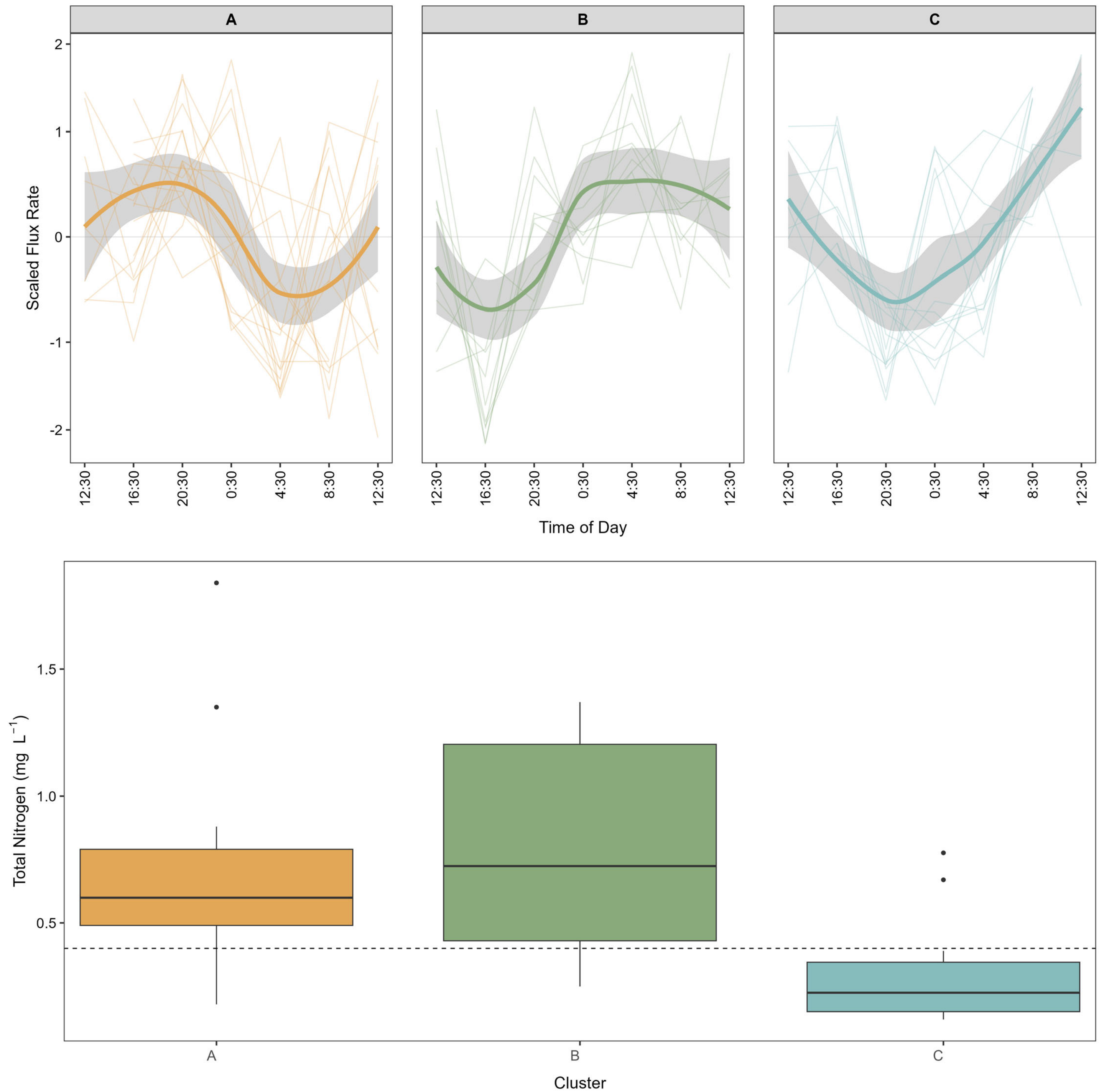

Fig. 3. Line plots (*top*) of the average diel flux pattern for each cluster identified from the scaled observed data using longitudinal *k*-means clustering. The heavy line is the average smoothed pattern within each cluster, with the gray area indicating the 95% confidence interval. Thin lines are the individual patterns for each campaign. Total nitrogen as a function of observed cluster results (*bottom*), driven by pruned regression tree results predicting clusters based on split on total nitrogen at 0.4 mg L^{-1} (horizontal dashed line). Lakes with total nitrogen (TN) < 0.4 mg L^{-1} were classified as Cluster C (blue; $n = 11$ campaigns, 82% correct classification). Lakes with TN ≥0.4 mg L^{-1} were classified as Cluster A (gold; $n = 30$ campaigns, 53% correct classification), though lakes in Cluster B (green) had a similar mean and range of TN values.

pattern consistent with high productivity and respiration. Finally, we found that campaigns in Cluster C ($n = 13$) had moderate but decreasing fluxes during the afternoon that were lowest around midnight, and increased in early morning and into afternoon (i.e., "U-shaped" from midday to midday).

The classification tree suggested total nitrogen was the key driver differentiating two of these three clusters. We note that total phosphorus was highly correlated with total nitrogen (TN) (Pearson $r = 0.84$) and using it in the classification analysis gives the same predicted cluster splits. Campaigns with total nitrogen < 0.4 mg L^{-1} were classified at Cluster C, representing generally oligotrophic systems with low primary productivity. Campaigns with total nitrogen ≥ 0.4 mg L^{-1} were classified as Cluster A or B, representing more productive systems (Fig. 3B). However, some campaigns with lower TN did cluster into A or B, resulting in a relatively high misclassification result of 47% (Supporting Information Fig. S5).

When integrated across sampling periods, $dFCO_{2int}$ for each campaign ranged from -381.68 to 878.49 mg C m^{-2} d^{-1} (mean = 76.54). In comparison, we found that extrapolated $dFCO_{2mid}$ ranged from -466.88 to 659.12 mg C m^{-2} d^{-1} (mean = 100.23). The absolute difference per campaign between these two calculations ($dFCO_{2int} - dFCO_{2mid}$) ranged from 0.21 to 314.89 mg C m^{-2} d^{-1}, with some differences being positive and some being negative (Fig. 4A) because midday fluxes were above and below the observation mean in lakes with diel variation (red dots in Fig. 2A). When the difference is expressed as a proportion of $dFCO_{2int}$, we found that using $dFCO_{2mid}$ to estimate daily flux resulted in a potential error of > 50% in 19 out of 41 campaigns (Fig. 4B). This bias

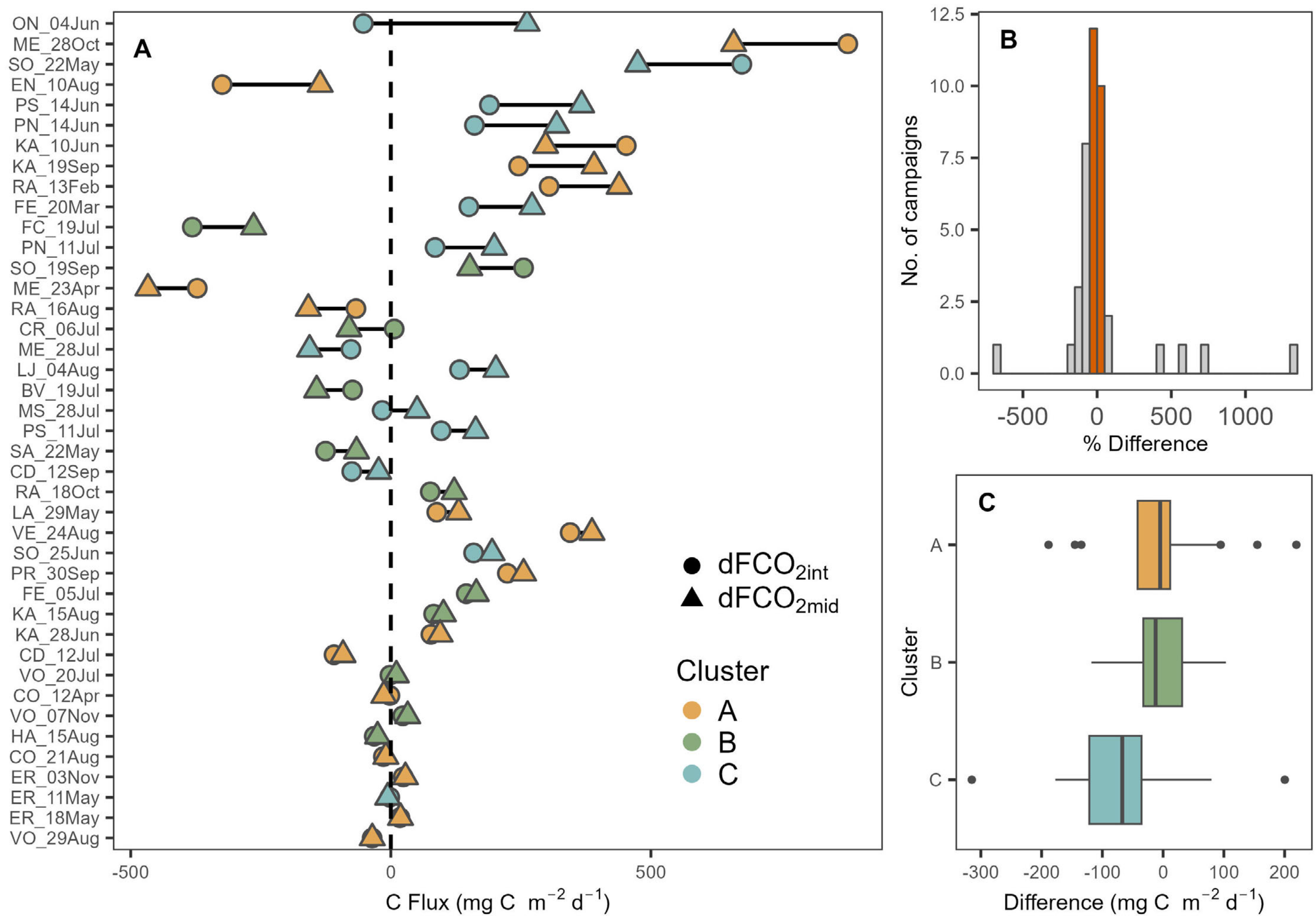

Fig. 4. Difference between CO_2 flux per day (mg C d^{-1}) for each campaign calculated by integrating across 6 measurements taken over 24 h ($dFCO_{2int}$) and by extrapolating from midday measurements ($dFCO_{2mid}$) (**A**). Data to the left of the dashed line are influxes, while those to the right are effluxes. Campaigns are ordered top to bottom by the difference ($dFCO_{2int} - dFCO_{2mid}$). Histogram of the differences expressed as the percentage of $dFCO_{2int}$, with campaigns where the difference was less than 50% indicated in orange (**B**). Difference in daily flux calculations within each cluster of campaigns shown in Fig. 3 (**C**).

was particularly obvious for campaigns which displayed the U-shaped curve exemplified by Cluster C (Fig. 3), where we typically measured more positive midday FCO_2 than in the nighttime. Thus, the use of $dFCO_{2mid}$ leads to an overestimate of daily flux, and a negative bias (Fig. 4C).

Discussion

The large range of estimated carbon fluxes from lakes (e.g., 1.99–3.58 PgC yr^{-1}; Del Sontro et al. 2018) can be partly attributed to uncertainties arising from poor spatial and temporal coverage of direct observations (Lauerwald et al. 2023). This work is an important contribution to understanding one source of temporal uncertainty, that is, diel variation in flux rates from lakes. The range of FCO_2 rates that we report (-3.16 to 4.39 mmol m^{-2} h^{-1}) is within previously reported ranges (Natchimuthu et al. 2017; Potter and Xu 2023). Many of our FCO_2 measurements were negative, indicating influx of CO_2, and for some campaigns, this occurred for a substantial part of the diel cycle. CO_2 flux in some lakes was highly variable over diel timescales, particularly in mesotrophic–eutrophic lakes during spring and summer, and in lakes which were supersaturated with CO_2. Supersaturation can happen during spring and autumn turnover in dimictic lakes (Brentrup et al. 2021) and shortly after ice-off (Denfeld et al. 2018) leading to high FCO_2 (López Bellido et al. 2009). This is apparent in two campaigns which occurred close to ice-off (SO_May22 and KA_Jun10) (Supporting Information Table S1). Although we initially planned to conduct sampling campaigns three times at each lake over a 12-month period to allow comparison across seasons, this proved difficult owing to weather and staffing constraints. As a result, we lacked statistical power to quantitatively examine diel FCO_2 variation across seasons.

Large diel variability in FCO_2 has been recorded at eutrophic lakes in temperate to subtropical climates, with higher effluxes at night and lower efflux (or even influx) during the day attributed to respiration and photosynthesis respectively (Ran et al. 2022; Potter and Xu 2023; Wang et al. 2024). The campaigns in our dataset that took place in productive lakes had more nuanced patterns, one with afternoon maxima and dawn minima (Cluster A), and the other with afternoon minima and dawn maxima (Cluster B). Theoretically, the pattern observed in Cluster A may be related to windier conditions in the afternoon leading to higher gas exchange and greater flux rates compared to calmer conditions at night. In contrast, the Cluster B pattern is similar to that described in Hounshell et al. (2023) and Liu et al. (2016), where daytime influxes were linked to higher primary productivity in the afternoon and nighttime effluxes to convective mixing distributing respired CO_2 to surface waters overnight. Cluster C, characterized by low nitrogen, had a pattern that aligned with solar radiation, with fluxes highest at midday and lowest around midnight. This pattern may reflect photomineralization of dissolved carbon at the lake surface, which can be considerable in boreal and northern temperate lakes with high dissolved organic carbon (Vachon et al. 2016).

We expected that the calculations of turbulent velocity scales for wind shear (u^*), and convection (w^*) might have been informative in determining the drivers of the patterns, particularly in Clusters A and B, but this was not the case. This may have been owing to insufficient resolution of turbulence parameters to adequately assess the linkage with FCO_2, or masking of diel patterns by the interactions of multiple drivers changing on diel and longer timescale. Further work to combine u^* and w^* estimates into gas transfer models (Podgrajsek et al. 2015; Erkkilä et al. 2018) may help to understand the underlying dynamics, but were beyond the scope of this paper.

The use of a diel variability factor (night/day ratio) to calculate daily average flux has been proposed recently (Wang et al. 2024), along with the use of a standardized time period of sampling, in order to make data comparable across studies (Potter and Xu 2023). While both these suggestions may work within subsets of lake types, our results show that the night/day ratio varied widely across our campaigns from -4.78 to 9.52 (Supporting Information Table S1; Fig. S6). We found no single time period within the diel cycle that universally represented the average diel FCO_2 (Supporting Information Fig. S7) across diel pattern clusters. We therefore caution against oversimplifcation of FCO_2 without careful consideration of diel variability. We suggest that a priori knowledge of surface pCO_2, either gained from predictive modeling using landscape features (Kortelainen et al. 2006; Valiente et al. 2022), remote sensing of related variables (Kutser et al. 2015) or targeted spot sampling, may be informative in identifying under- or supersaturated surface waters, enabling the design of appropriate sampling programs.

Our use of chambers equipped with relatively inexpensive sensors allowed the inclusion of many lakes which have not previously been sampled for FCO_2, and this is an obvious advantage of these systems (Hunt et al. 2017). These sensors have been successfully used in recent years in a number of sampling campaigns (e.g., Serikova et al. 2019; Baldocchi et al. 2020), and modifications are being deployed to counteract some of the known issues (e.g., humidity, Bastviken et al. 2020). We recommend using a similar protocol as described here to target understudied lakes in poorly monitored biomes (Lauerwald et al. 2023) and growing season in mesotrophic to eutrophic lakes to improve understanding of the scope of lakes for which diel variability is important to consider. Our geographically dispersed observations across varied lakes demonstrated significant bias in $dFCO_2$ in approximately half of all sampling campaigns if we do not consider the diel variation in flux rates. This underlines the importance of accounting for measurement biases when upscaling data from highly variable systems to global estimates.

Author Contributions

Angela Baldocchi, Alo Laas, Annalea Lohila, Anna Lupon, Amir Reza Shahabinia, Blaize A. Denfeld, Brian C. Doyle, Biel Obrador, Cayelan C. Carey, David Reed, David Rudberg, Elvira de Eyto, Eva-Ingrid Rõõm, Hannah E. Chmiel, Ilga Kokorite, Jānis Bikše, Jorge Encinas Fernández, James A. Rusak, Jan-Erik Thrane, Ludmila S. Brighenti, Mika Aurela, Matthias Koschorreck, Philipp S. Keller, Rafael Marcé, Ryan P. McClure, and Samuel Haverinen carried out fieldwork. Gesa A. Weyhenmeyer, R. Iestyn Woolway, Robyn L. Smyth, Hans Peter Grossart, Alo Laas, Heleen A. de Wit, Ankur R. Desai, Annalea Lohila, Anna Lupon, Blaize A. Denfeld, Brian C. Doyle, Cayelan C. Carey, Elvira de Eyto, Francois Clayer, Ludmila S. Brighenti, Matthias Koschorreck, Philipp S. Keller, Rafael Marcé, Ryan P. McClure, Steve Sadro, and David Bastviken conceived the research and designed the sampling methodology. Nathan Barros, Sarian Kosten, José Fernandes Bezerra-Neto, Francois Clayer, and Sari Juutinen contributed expertise and advice on analysis and provided ancillary data. Elvira de Eyto, Robyn L. Smyth, and Rachel M. Pilla collated the data, carried out the analysis and wrote the first draft of the manuscript.

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Data Availability Statement

Data are available in the Irish Marine Institute's data repository at https://www.doi.org/10/pqcm. The code used in the paper is available at https://github.com/edeeyto/DCFlux/.

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Supporting Information

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

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