Diel Variability of CO₂ Emissions From Northern Lakes

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Abstract. Lakes are generally supersaturated in carbon dioxide (CO₂) and emitters of CO₂ to the atmosphere. However, estimates of CO₂ flux (F_CO₂) from lakes are seldom based on direct flux measurements and usually do not account for nighttime emissions, yielding risk of biased assessments. Here, we present direct F_CO₂ measurements from automated floating chambers collected every 2–3 hr and spanning 115 24 hr periods in three boreal lakes during summer stratification and before and after autumn mixing in the most eutrophic lake of these. We observed 40%–67% higher mean F_CO₂ in daytime during periods of surface water CO₂ supersaturation in all lakes. Day-night differences in wind speed were correlated with the day-night F_CO₂ differences in the two larger lakes, but in the smallest and most wind-sheltered lake peaks of F_CO₂ coincided with low-winds at night. During stratification in the eutrophic lake, CO₂ was near equilibrium and diel variability of F_CO₂ insignificant, but after autumn mixing F_CO₂ was high with distinct diel variability making this lake a net CO₂ source on an annual basis. We found that extrapolating daytime measurements to 24 hr periods overestimated F_CO₂ by up to 30%, whereas extrapolating measurements from the stratified period to annual rates in the eutrophic lake underestimated F_CO₂ by 86%. This shows the importance of accounting for diel and seasonal variability in lake CO₂ emission estimates.

Plain Language Summary. Considerable carbon cycling occurs within lakes, and carbon inputs from the catchment can be processed internally, stored in sediment and biomass or transported downstream. Additionally, carbon is exchanged with the atmosphere, resulting in lake uptake or atmospheric emission of carbon dioxide. Carbon dioxide exchanges from lakes have globally significant implications, but may be highly variable in time in ways that are not yet accounted for in emission estimates. Here, we estimated carbon dioxide exchange during multiple days and nights in three lakes with different nutrient levels during summer and autumn. For the most nutrient rich lake we also covered the period of water column mixing in autumn, which constitutes a critical time for carbon exchange. When carbon dioxide emission exceeded uptake, we found 40%–67% higher average exchange rates during daytime than nighttime. In contrast, the most nutrient rich lake experienced clear day-night differences only after autumn mixing, when carbon dioxide emissions increased. We found that only using daytime measurements overestimated carbon dioxide emissions by up to 30%, and not accounting for autumn mixing underestimated carbon dioxide emissions by 86%. This shows the importance of accounting for day-night and seasonal variability in lake carbon dioxide emission estimates.

1. Introduction

Lakes have been estimated to emit 0.32–0.64 Pg C year⁻¹ as CO₂ to the atmosphere (Aufdenkampe et al., 2011; Cole et al., 2007; Holgersson & Raymond, 2016; Raymond et al., 2013; Tranvik et al., 2009). This is of the same order of magnitude as the CO₂ emissions from land use change, or the carbon transport from continents to the ocean (Ciais et al., 2013), making CO₂ emissions from lakes important in the global carbon cycle. Lakes are concentrated in boreal regions, which contain roughly 30% of global lakes (Dongwing et al., 2006; Verpoorter et al., 2014), and together with the arctic region contribute 17% of global lake CO₂ emissions (Aufdenkampe et al., 2011). Potential climate change effects in boreal lakes, including increased runoff (Larsen et al., 2011; Weyhenmeyer et al., 2015) and increased carbon mineralization rates (Bergström
et al., 2010; Gudasz et al., 2010; Marotta et al., 2009), may lead to higher lake CO$_2$ emissions as more carbon is fluxed to and processed within these lakes.

CO$_2$ fluxes across the water surface ($F$$_{CO2}$) in lakes is controlled by the difference in CO$_2$ concentration between the surface water (here expressed as partial pressure, pCO$_{2aq}$) and atmosphere, and the gas transfer velocity ($k$) across the air-water boundary layer. Both pCO$_{2aq}$ and $k$ depend on processes that can have diel fluctuations. Primary production (PP) consumes CO$_2$, reducing pCO$_{2aq}$ during daytime, and respiration (R) at night can increase pCO$_{2aq}$. Temperature declines, frequently occurring at night, facilitate convection which generates near-surface turbulence enhancing $k$ and bringing CO$_2$-rich water from depths to the surface (Czikowsky et al., 2018; Heiskanen et al., 2014; Liu et al., 2016; MacIntyre et al., 2010). Furthermore, winds may influence both $k$ and pCO$_{2aq}$ by influencing surface water turbulence, sediment pore water exchange or upwelling (Crill et al., 1988; Czikowsky et al., 2018; Heiskanen et al., 2014). When winds are similar both day and night, enhanced fluxes from the increased concentrations will usually occur at night (Liu et al., 2016); in contrast, when winds are higher in the day, the enhanced fluxes will usually occur in the day (Czikowsky et al., 2018).

Despite the many factors that have potential to influence diel variability of pCO$_{2aq}$ and $k$ and thereby also $F$$_{CO2}$, most estimates of $F$$_{CO2}$ rely on daytime sampling of pCO$_{2aq}$ or flux measurements, and it remains common to extrapolate such measurements to full 24 hr $F$$_{CO2}$. In cases where both daytime and nighttime fluxes have been estimated, observations have usually been made within one or a few 24 hr periods in single systems (Natchimuthu et al., 2014; Reis & Barbosa, 2014; Xiao et al., 2014), whereas studies covering diel variability over longer periods during seasonal stratification and mixing in lakes are rare (e.g., Amaral et al., 2020; Spafford & Risk, 2018). Hence, more extensive studies of diel variability in $F$$_{CO2}$ are needed, where lakes are examined for multiple days across seasons.

Monitoring of direct $F$$_{CO2}$ at high temporal resolution and for periods of weeks or months is almost exclusively made using eddy covariance (EC) (Franz et al., 2016; Jammet et al., 2017; Jonsson et al., 2008; Liu et al., 2016; Mammarella et al., 2015; Podgrajsek et al., 2015; Shao et al., 2015), which covers larger areas than flux chambers but depend on assumptions of homogeneous surface roughness and air movement (Aubinet et al., 2003). Additional challenges with EC remain for the large number of small boreal lakes. These lakes are often wind sheltered by surrounding trees, resulting in heterogeneous air movements across the lakes and in difficulties to separate $F$$_{CO2}$ originating from the lakes with those originating from surrounding land (Kenny et al., 2017; Sahle et al., 2013). Hence, supplementary studies of temporal variability using flux chambers would be beneficial to assess diel $F$$_{CO2}$ variability of well-defined areas in boreal lakes.

Here, we present measurements of diel variability in $F$$_{CO2}$ and the influence of potential factors influencing the fluxes in three contrasting boreal lakes, using high temporal resolution measurements with automated flux chambers (Thanh Duc et al., 2020). We measured $F$$_{CO2}$ at multiple locations in each lake, generating in total 3,361 $F$$_{CO2}$ observations over 121 24-hr periods. Measurements were made during periods of stratification in all three lakes as well as during autumn mixing in the most eutrophic lake, where we investigated the role of diel variability before and after mixing. Additionally, we compare our results with previous research and assess the importance of diel variability and autumn mixing in estimates of annual CO$_2$ emission.

2. Methods

2.1. Studied Lakes

Three lakes were studied (Figure 1; Table S1). Venäsjön (VEN; 58°27′22.61″N, 16°11′11.54″E) is a eutrophic lake (trophic state based on total phosphorous (Carlson, 1977)) situated in south-eastern Sweden in the transition between the temperate and boreal zones. It has mean and maximum depths of 5.4 and 10.5 m, respectively, and lake and catchment areas of ∼69 and ∼17,000 ha. The lake has a permanent inlet which drains farmland on its western side. Parsen (PRS; 58°20′25.7″N, 16°12′15.2″E) is a mesotrophic lake located in the same region as VEN, with mean and maximum depths of 3.4 and 8 m, respectively, and lake and catchment areas of ∼13 and ∼140 ha. It is surrounded by coniferous forest and the catchment includes agricultural land. Ljusvattenjärn (LIJ; 64°5′33.44″N, 18°56′6.45″E) is a humic, small (~1.7 ha) oligo-mesotrophic northern-boreal lake, containing two basins where the northern one has mean and maximum
depths of 5.7 and 9.7 m and the southern one has depths of 4.4 and 9.5 m. It has a catchment area of \( \sim 89 \) ha with coniferous forest.

### 2.2. Field Measurements

#### 2.2.1. \( F_{\text{CO}_2} \)

\( F_{\text{CO}_2} \) was measured during 2018 in VEN and PRS (June 14–September 25 and September 28–October 25, respectively) with automated flux chambers (AFCs). We have denoted the campaigns in VEN before and after autumn mixing (June 14–September 10 and September 12–September 25) as VEN\text{bef} and VEN\text{aft}, respectively, where the date of autumn mixing is based on observations of lake temperature, DIC and \( F_{\text{CO}_2} \), according to Text S1. In LJU, sampling of \( F_{\text{CO}_2} \) was done with AFCs during 2017 between July 11 and August 22. The AFCs were constructed as described by Thanh Duc et al. (2020), and consisted of floating chambers made of round, plastic buckets (8.6 L volume, 31 cm diameter) covered with alumina tape to minimize internal heating, and attached to a control box. The control box regulated a pump maintaining ventilation of the chamber every second or third hour to restart measurements. By pumping air into a rubber bladder attached to the chamber, the bladder was inflated which lifted one side of the chamber from the water and allowed
air to ventilate the chamber headspace. CO₂ concentration, temperature and humidity inside the chamber headspace were recorded each minute with a Senseair K33 ELG sensor located inside each chamber as described by Bastviken et al. (2015). Prior to being used in the AFCs, sensors were calibrated with nitrogen-gas according to manufacturer’s instructions (zero calibration). Fluxes were based on relative changes in CO₂ concentration, and were therefore not sensitive to moderate sensor drift or differences in absolute values among sensors. The AFCs transmitted data to a server located at the lakes, allowing for data retrieval without the need to visit the chambers.

AFCs were distributed to cover off-shore and near-shore parts of the lakes (Figure 1). Six, five, and four AFCs were used in VEN, PRS, and LJU, respectively. In VEN, the AFCs were concentrated in the western bay, and in PRS they were located in the northern bay. In LJU, the AFCs were divided equally between the two basins. Additional AFCs were deployed to cover the off-shore pelagic zone in LJU (not shown in Figure 1), but CO₂ measurements in these AFCs were malfunctioning during the sampling campaign. As a result, $F_{\text{CO}_2}$ in LJU may not be representative of the pelagic zone.

### 2.2.2. Weather

Meteorological data (atmospheric pressure and temperature, relative humidity, precipitation, wind speed, wind gust speed, and wind direction) were retrieved from Swedish Meteorological and Hydrological Institute (SMHI), through their meteorological analysis model MESAN, which combines a meteorological model and interpolations from existing weather stations using a technique called optimal interpolation to determine meteorological variables on a 2.5 × 2.5 km grid for hourly intervals (Häggmark et al., 2016). The MESAN model uses data measured at 10 m above the surface, and the closest weather stations used in the interpolations are located around 15, 21, and 25 km from VEN, PRS, and LJU, respectively. Wind speed is sampled as 10 min averages, and wind gust speed is defined as the maximum wind speed within a 2-s interval. Hourly averages of wind speed and wind gust speed data compared reasonably well with measurements from anemometers located at the lake center in PRS (September 27–December 6, 2018; $R^2_{\text{wind speed}} = 0.74–0.81$, $R^2_{\text{wind gust speed}} = 0.77–0.87$; Figure S1) and at the lake center of the northern basin in LJU (September 2–October 27, 2019; $R^2_{\text{wind speed}} = 0.65–0.78$, $R^2_{\text{wind gust speed}} = 0.77–0.87$; Figure S1). We did not have measurements to compare at VEN. Due to differences in magnitude between wind speed at 10 m height and at lake level (slope $R^2_{\text{wind speed}} = 0.45–0.67$, slope $R^2_{\text{wind gust speed}} = 0.39–0.46$; Figure S1), wind speed measurements have been z-normalized in all figures, and we refer to relative differences in wind speed and wind gust speed in the text. Values of photosynthetically active radiation (PAR) were retrieved from SMHI’s model STRÅNG, which uses input from MESAN to provide solar radiation estimates on a 2.5 × 2.5 km grid.

### 2.2.3. DIC

DIC was sampled from vertical profiles, including near the surface (≈0.1 m depth), at monthly intervals during the open water season in all lakes. The samples were collected at the deepest spot in the lakes with a maximum distance of 2 m between each sample. In VEN and PRS, additional surface water DIC samples were collected at 12 locations 2–3 times during the same week as the profile samples were collected. Surface water DIC was sampled by transferring 4 or 5 mL of water from ≈0.1 m depth to a 22 mL and N₂-filled vial holding 100 μL concentrated phosphoric acid, and samples were stored at 20°C until gas analysis. The sampling procedure for vertical profiles and surface water and the calculation of DIC concentration is described in Text S2.

### 2.2.4. CO₂ in Surface Water and Air

Samples of surface water CO₂ concentration (or its equivalent partial pressure; pCO₂aq) were collected manually each month in the open water season at seven locations in VEN and PRS. A headspace equilibration method was used where 105 mL surface water was equilibrated with 35 mL of air, and the equilibrated headspace was transferred to a dry vial and stored at 20°C until analysis. pCO₂aq was then calculated by accounting for extraction volumes and temperature. The sampling procedure and calculation of pCO₂aq is described in Text S3.

In LJU, surface pCO₂aq was measured manually at monthly intervals with a CO₂-sonde (Vaisala GMP222), calibrated for temperature and pressure according to Johnson et al. (2010) before the field campaign.
Automated sampling of surface pCO$_{2aq}$ was made every minute using CO$_2$ sensors (Senseair K33 ELG, Sweden) in chambers that were closed at all time (in contrast to AFCs which were ventilated regularly) and allowed to equilibrate with the water, as described by Bastviken et al. (2015). The equilibration time in the closed chamber is subject to a delay, which depends on the air-water transfer rate of CO$_2$. Due to the uncertainty of this delay, surface pCO$_{2aq}$ measured this way was averaged for whole daytime and nighttime periods rather than for shorter time periods with awareness that the delayed response will lead to underestimation of day-night differences. This delay in equilibration time prevented us from calculating pCO$_{2aq}$ from AFC concentration measurements, since equilibration was rarely reached within the 2-hr or 3-hr chamber closure times. Therefore, AFCs were only used for measuring $F_{CO_2}$.  

### 2.2.5. Surface Water pH

Surface water pH was derived indirectly from concentration of surface CO$_{2aq}$ and DIC in VEN and PRS, as described in Text S3.

### 2.2.6. Surface Water O$_2$

Dissolved surface water O$_2$ (DO) was measured in PRS and LJU using PME MiniDot loggers at 0.2 and 0.25 m depths, respectively. In PRS, sampling was made close to the deepest point and in LJU sampling was made at the deepest point of each basin.

### 2.2.7. Water Temperature

Temperature was measured manually and continuously in the surface water and at depth. Manual temperature measurements were collected at the deepest spot in the lakes, and at the deepest spot of each basin in LJU, at least every second meter in the water column. Measurements were made with multimeter-sondes (AP-5000 Aquaprobe in VEN and PRS and YSI ProODO in LJU) and were done monthly in VEN and PRS. In LJU, measurements were done once before and twice during and after the $F_{CO_2}$ sampling campaign.

In VEN, continuous temperature measurements were made at ~0.1 m and at four additional depths (1.5, 3, 4.5, and 5.5 m), in the middle of the western bay. HOBO U22-001 thermistors (Onset, USA) were used for all depth except at the water surface, where a light shielded RBRSolo$^2$ thermistor (RBR, Canada) was used. All thermistors were connected to a taut-line mooring. In PRS, continuous temperature measurements were made the same way as in VEN, but at different depths (0.1, 1, 2, 3, and 3.8 m) in the middle of the northern bay. In LJU, continuous temperature measurements were made at four depths (0.25, 2.5, 5, and 7.5 or 8 m) at the deepest point of the two respective basins, using PME MiniDot loggers.

### 2.2.8. Gas Analysis

Analysis of gas samples from VEN and PRS were made with a Agilent 7890A GC (Agilent Technologies, USA, equipped with a 1.8 m × 3.175 mm Porapak Q 80/100 column from Supelco, and a flame ionization detector) through automatic injection, with a 7697A headspace sampler (Agilent Technologies, USA) attached. Serially diluted certified high concentration standard (50,000 ± 1,000 ppm), and an independent certified standard of 1,985 ± 40 ppm were used for calibration. Before loading the GC for analysis, vial overpressure was removed by inserting a 0.5 mL hypodermic needle connected to a water-filled 60-mL syringe. This setup made it possible to account for potential gas leakage during storage. Analysis of samples in LJU was made with a Clarus 500 GC (Perkin Elmer, USA, equipped with a 30 m × 0.53 mm Elite-Q PLOT column from Perkin Elmer and a flame injection detector) through automatic injection, with a TurboMatrix 110 headspace sampler (Perkin Elmer, USA) attached. CO$_2$ standards of 410 and 9420 ppm were used for calibration.

### 2.3. Calculation of $F_{CO_2}$

Following retrieval of CO$_2$ data from the AFCs (in ppm) and prior to calculating $F_{CO_2}$, the data were filtered to account for humidity peaks, as described by Bastviken et al. (2015). Additional filtering was made to
account for sensor issues related to unlikely concentration shifts and vapor condensation inside the measurement cell, as described in Text S4.

For each period when the AFCs were closed (i.e., between periods of ventilating), linear regressions were made for different subsets of the CO\textsubscript{2} data. Slopes were calculated from the regressions that had highest \( R^2 \), as described in Text S4. Cases, when the \( R^2 \) of the highest slope was <0.9, were only considered if the RMSE was below 5 ppm in order to not discriminate against small fluxes, as \( R^2 \) decreases when the slope approaches zero. The slopes, corresponding to change in CO\textsubscript{2} mole fraction over time (ppm s\(^{-1}\)), were converted to mmol m\(^{-2}\) h\(^{-1}\) by applying the ideal gas law, dividing with the area of the chamber, \( A \) (m\(^2\)), and multiplying with \( 3.6 \times 10^3 \) as a conversion factor from second\(^{-1}\) to hour\(^{-1}\), see Equation 1. The total barometric pressure, \( P \) (atm) was derived from the MESAN model, whereas air temperature, \( T \) (K), was measured directly with the CO\textsubscript{2} sensor. Volume, \( V \) (m\(^3\)), represents the chamber headspace, and \( R \) is the ideal gas constant, \( 8.21 \times 10^{-2} \) (L atm K\(^{-1}\) mol\(^{-1}\)).

\[
F_{CO_2} = \frac{ppm}{t} \cdot \frac{PV}{RTA} \cdot 3.6 \times 10^3.
\]  
(1)

The concentration measurements that passed the filtering criteria mentioned above were used to derive 3,361 estimates of \( F_{CO_2} \). Of these estimates, 4.2\% were discarded in VEN\textsubscript{bft}, and <1\% in VEN\textsubscript{aft}, PRS, and LJU due to low \( R^2 \) and high RMSE, resulting in a total of 3,303 \( F_{CO_2} \) estimates that were used for analysis (\( n_{VENbf} = 1,150; n_{VENaf} = 446; n_{PRS} = 402; n_{LJU} = 1,305 \)).

### 2.4. Diel Variability of \( F_{CO_2} \)

We have defined daytime and nighttime from sunrise and sunset, where each 24 hr period started with a sunrise and ended with a sunrise the consecutive day. The length of daytime and nighttime varied between lakes due to differences in latitude and sampling times. In VEN, sunrise and sunset were (rounded to closest hour) between 04:00–07:00 and 19:00–22:00, in PRS between 07:00–08:00 and 17:00–19:00 and in LJU between 03:00–05:00 and 21:00–23:00, meaning that daytime periods made up 12–18, 10–12, and 16–20 hr for each 24 hr period in VEN, PRS, and LJU, respectively.

Daytime and nighttime \( F_{CO_2} \) were calculated as the collective average of all daytime and nighttime \( F_{CO_2} \) values over each 24 hr period, and these average daytime or nighttime fluxes for each 24 hr period were then averaged for all measurement days yielding a total daytime or nighttime average, respectively. Similarly, mean 24 hr \( F_{CO_2} \) was first calculated from all \( F_{CO_2} \) measurements within each 24 hr period, and then, these daily 24 hr means were averaged for all measurement days to calculate total 24 hr mean \( F_{CO_2} \). To calculate areal cumulative \( F_{CO_2} \), means of daytime and nighttime \( F_{CO_2} \) in each 24 hr period were multiplied with the fraction of the period belonging to daytime and nighttime, respectively. Areal cumulative \( F_{CO_2} \) was only calculated for 24 hr periods that contained measurements from both daytime and nighttime. Ratios of day:night \( F_{CO_2} \) (daytime \( F_{CO_2} \) divided by nighttime \( F_{CO_2} \)) were calculated for each 24 hr period. Day-night differences in \( F_{CO_2} \) (daytime \( F_{CO_2} \) minus nighttime \( F_{CO_2} \)) were also calculated as alternative indicators of diel variability to the ratios. Equivalent day:night ratios or day-night differences were generated for the environmental variables to test their relationships with \( F_{CO_2} \).

### 2.5. Extrapolation to Open-Water \( F_{CO_2} \)

We estimated annual \( F_{CO_2} \) in VEN, where we sampled \( F_{CO_2} \) during both the seasonally stratified period and the period of autumn mixing. Diel variability was first accounted for within the seasonally stratified and mixed periods, respectively. Measurements of 24 hr \( F_{CO_2} \) made within each specific sampling period (seasonally stratified or mixed) were extrapolated to the full open-water season. The ice-covered periods were estimated from observations during fieldwork and air temperature measurements and were not considered in the annual estimate (details in Text S1). Our estimate of 24 hr mean \( F_{CO_2} \) from measurements made during the seasonally stratified period was extrapolated to the whole period of seasonal stratification. Our estimate of 24 hr mean \( F_{CO_2} \) measured within the period of autumn mixing was extrapolated according to two different scenarios—(a) to the period of full lake mixing in autumn alone and (b) to the period of full lake mixing in autumn and spring (assuming similar patterns of \( F_{CO_2} \) in spring as in autumn), resulting in
an estimate of minimum and maximum contribution of $F_{CO_2}$ during the period of seasonal lake mixing. These scenarios may be conservative, as the spring mixing period itself has been found to contribute to the highest annual CO$_2$ evasion rates in arctic lakes (Kling et al., 1991), contributing up to more than half of annual $F_{CO_2}$ (Karlsson et al., 2013).

### 2.6. Comparison With Other Studies

We compared our estimates with other studies that included measurements of $F_{CO_2}$ during both days and nights (Table S2). Daytime and nighttime were defined differently between studies but were often based on sunrise and sunset, or metrics that followed diel patterns. In studies where multiple methods (floating chambers, eddy-covariance, or k-models) were used (Czikowsky et al., 2018; Erkkilä et al., 2018), we averaged daytime and nighttime results separately for each method and considered whether the lake was seasonally stratified or mixed.

### 2.7. Statistical Analysis

All calculations, data handling, plotting and statistical testing was made using Python 3.7. Reported $R^2$-values are modified according to the number of predictors in the model (adjusted $R^2$). $P$-values below 0.05 have been considered statistically significant to reject null-hypotheses.

To test for significant day to night differences, the two-tailed non-parametric Wilcoxon ranked-sum test was applied. Bi-variate and multiple regression analyses were made to distinguish factors related to diel variability of $F_{CO_2}$ and were carried out using Python package sklearn (sklearn.linear_model.LinearRegression), and $p$-values for regressions were derived using the two-tailed Spearman rank-order correlation (scipy.stats.spearmanr).

### 3. Results and Discussion

#### 3.1. CO$_2$ Exchange

$F_{CO_2}$ was continuously monitored for 1–2 months in each lake (Figure 2) together with additional measurements (DIC, pCO$_{2aq}$, pH, DO and temperature; measured the whole open-water season. See Section 2, Figures S2 and S3 for details). Autumn mixing occurred in VEN from September 11 to 13, resulting in an increase in $F_{CO_2}$ (Figure 2a), whereas PRS and LJU were partly stratified for the full sampling period and are regarded as stratified lakes.

All lakes were net sources of CO$_2$ to the atmosphere during the sampling campaigns based on the areal cumulative flux (Figure 3a), and mean (±1 SD) 24 hr $F_{CO_2}$ was estimated as 5.3 ± 17.1, 76 ± 26.2, 24.3 ± 11.4, and 9.9 ± 3.2 mmol m$^{-2}$ d$^{-1}$ in VEN$_{bef}$, VEN$_{at}$, PRS, and LJU, respectively. The rates are within the range of estimates from 96 inland waters (lakes, reservoirs, ponds) in Sweden, Norway and Finland, compiled by Natchimuthu et al. (2017) (range: 0.4 and 71.8 mmol m$^{-2}$ d$^{-1}$; mean: 21.7 mmol m$^{-2}$ d$^{-1}$). VEN$_{bef}$ was a sink if only considering measurements made in July and onwards, where net uptake of CO$_2$ was observed in more than half of the 24 hr periods (Figure 2). This is similar to what has been observed elsewhere, where CO$_2$ uptake occurred in the growth period in eutrophic lakes with high photosynthetic rates (Huotari et al., 2011; Natchimuthu et al., 2014; Shao et al., 2015). Apart from VEN$_{bef}$, we only observed occasional uptake of $F_{CO_2}$ during daytime from individual measurements (Figure 2). $F_{CO_2}$ was most variable in VEN, where we observed five-fold greater
areal cumulative CO$_2$ during the 13 days after autumn mixing than during 38 days of the stratification period (Figure 3a).

### 3.2. Diel Variability of CO$_2$

CO$_2$ during daytime (between sunrise and sunset) was higher than during nighttime (between sunset and sunrise) in VEN$_{\text{aft}}$, PRS, and LJU (Table 1; Wilcoxon signed-rank test, $p < 0.05$), but no corresponding difference was observed in VEN$_{\text{bef}}$ ($p = 0.15$). The lack of diel variability in VEN$_{\text{bef}}$ was likely due to its near-equilibrium levels of surface pCO$_2$$_{\text{aq}}$ (Figure S2a), which led to low variations in CO$_2$$_{\text{EF}}$. In contrast, VEN$_{\text{aft}}$ had the highest mean daytime and nighttime CO$_2$$_{\text{EF}}$, exceeding CO$_2$$_{\text{EF}}$ in VEN$_{\text{bef}}$ by roughly 18-fold and 11-fold for daytime and nighttime, respectively. Daytime exceeded nighttime mean CO$_2$$_{\text{EF}}$ by 67%, 55%, and 40% and was greater than nighttime CO$_2$$_{\text{EF}}$ in 12 of 13, 19 of 23, and 34 of 42 24-hr period in VEN$_{\text{aft}}$, PRS, and LJU, respectively (Figures 3b–3e). Differences observed in diel variability of CO$_2$$_{\text{EF}}$ between 24 hr periods were not related ($p > 0.59$) to changes in the length of daytime during sampling in each lake.

![Figure 3](image.png)

**Figure 3.** Diel variability and cumulative FCO$_2$. Areal cumulative FCO$_2$ for the respective sampling periods is displayed in panel (a). Panels (b)–(e) show mean daytime (green dots) and nighttime (blue dots) FCO$_2$ connected with same-colored lines to clarify change between 24 hr periods for (b) VEN$_{\text{aft}}$, with dashed horizontal line representing the separation between negative (below) and positive (above) mean FCO$_2$, (c) VEN$_{\text{aft}}$, (d) PRS, and (e) LJU. The range on y-axis (mean FCO$_2$) varies among the figures for clarity.

### Table 1

| Daytime FCO$_2$ | Nighttime FCO$_2$ |
|-----------------|-------------------|
|                 | Mean ± 1 SD | Med | Range     | Mean ± 1 SD | Med | Range     |
|                 | (mmol m$^{-2}$ h$^{-1}$) |     |           | (mmol m$^{-2}$ h$^{-1}$) |     |           |
| VEN$_{\text{bef}}$ | 0.22 ± 0.79 | 0.12 | −12.13–13.4 | 0.2 ± 0.62 | 0.06 | −1.79–7.82 |
| VEN$_{\text{aft}}$ | 3.92 ± 1.28 | 3.52 | −2.07–14.8  | 2.35 ± 1.2 | 2.14 | 0.49–11.19 |
| PRS             | 1.26 ± 0.54 | 1.11 | −0.9–5.78   | 0.81 ± 0.51 | 0.71 | 0.16–4.52  |
| LJU             | 0.44 ± 0.14 | 0.41 | −1.36–2.31  | 0.32 ± 0.17 | 0.27 | −0.37–2.14 |

| Stat.diff | n$_{24 \text{ hr}}$ | n$_{\text{obs}}$ |
|-----------|-------------------|-----------------|
| No        | 37                | 1,150           |
| Yes**     | 13                | 446             |
| Yes*      | 23                | 402             |
| Yes***    | 42                | 1,305           |

**Note.** Daytime and nighttime FCO$_2$ mean (±1 standard deviation), median (med) and range for the studied lakes including before and after autumn mixing in VEN, statistical difference (Stat.diff) between daytime and nighttime FCO$_2$ (Wilcoxon signed-rank test; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$), total number of 24 hr periods with diel FCO$_2$ measurements ($n_{24 \text{ hr}}$), and total number of FCO$_2$ measurements ($n_{\text{obs}}$).
$CO_{2}$ EF was the highest between mornings and late afternoons (08:00 hr–16:00 hr) most of the measurement days in the lakes when surface $pCO_{2aq}$ was supersaturated (e.g., VEN aft, PRS, and LJU), exceeding mean $CO_{2}$ EF during other hours by 48%–59% (Figure 4). However, the large variability for daytime and nighttime, and the fact that nighttime exceeded daytime $CO_{2}$ EF for some 24 hr periods (Figures 3b–3e), shows the importance of measurement periods covering multiple days (Jansen et al., 2020; Klaus et al., 2019; Natchimuthu et al., 2017; Wik et al., 2016) and nights.

3.3. Influence of Environmental Factors on Diel $F_{CO_{2}}$ Variability

$F_{CO_{2}}$ and incident PAR, wind speed, wind gusts, air temperature ($T_{a}$), and air-water temperature ratio ($T_r$) were all higher during daytime, except for in VEN bef where $F_{CO_{2}}$ did not have clear diel patterns (Figure 5). Continuous measurements of $pCO_{2aq}$, which were limited to LJU, did not show significant differences between daytime and nighttime ($p = 0.16$). Furthermore, we did not observe correlation between $F_{CO_{2}}$ and surface water DO in PRS and LJU. The mean day-night differences in surface water DO were low (0.05 and 0.07 mg L$^{-1}$) and corresponded to only 0.6% and 0.8% of variation from the 24 hr mean DO in PRS and LJU, respectively (Figure S6). In VEN, only occasional manual DO measurements were available, preventing direct comparisons between variability of diel $F_{CO_{2}}$ and diel DO. However, we observed that surface water DO in VEN went from being supersaturated 14 days before autumn mixing (105%; 9.8 mg L$^{-1}$) to unsaturated 16 days after autumn mixing (83%; 8.7 mg L$^{-1}$).

Bivariate linear regressions with the day-night differences for $F_{CO_{2}}$ ($\Delta F_{CO_{2}}$) and other variables measured at high enough resolution to resolve day-night differences, had strongest relationships with day-night differences in wind gust speed ($\Delta WGS$) and in wind speed ($\Delta WS$), particularly in wind-exposed VEN aft where

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4}
\caption{Daily variability of $F_{CO_{2}}$ in (a) VEN bef and VEN aft (in blue and red, respectively), (b) Parsen (PRS), and (c) Ljusvattentjärn (LJU). Lines denote mean $F_{CO_{2}}$ for the respective hourly intervals. Daytime and nighttime are represented by the color toning, where the lightest, the darkest, and neutral toning represents the hourly intervals that always belonged to daytime, always belonged to nighttime, and partly belonged to daytime and nighttime, respectively (rounded up to closest hour), reflecting differences in sunrise and sunset times during the sampling campaigns. The boxes indicate the distribution of $F_{CO_{2}}$, where the box itself represents the range of the middle 50% of measurements (IQR), the horizontal lines in each box show the median $F_{CO_{2}}$, the whiskers show the upper and lower quartile of data, and points represent outliers (>1.5 × IQR above the upper quartile and below and lower quartile). Some outliers have been removed for increased visibility. Figure with all outliers are displayed in Figure S4.}
\end{figure}
they explained 82% and 77% of $\Delta F_{CO2}$ variability (Figure S5). In PRS, the contribution from $\Delta WGS$ and $\Delta WS$ was lower, explaining 31% and 39% of $\Delta F_{CO2}$ variability. In LJU, only $\Delta WGS$ was significant, explaining 28% of $\Delta F_{CO2}$ variability. Adding additional variables to $\Delta WS$ and $\Delta WGS$ did not increase model performance except for in PRS, where addition of wind direction to the $\Delta WS$ model increased the degree of explanation of $\Delta F_{CO2}$ variability by 10%. The fact that wind gust speed was more relevant than wind speed for explaining diel $F_{CO2}$ patterns in VEN and LJU is interesting, since $F_{CO2}$ is usually modeled from wind speed rather than wind gust speed (Cole & Caraco, 1998; Heiskanen et al., 2014; Wanninkhof, 1992). Possibly, wind gusts were important for transferring kinetic energy to the water, thereby influencing water turbulence, and consequently $k$ and $F_{CO2}$, more than average wind speed.

For 24 hr periods where the day:night $F_{CO2}$ ratio ($R_{F_{CO2}}$) was above 1 (i.e., higher during day), this coincided with periods of day:night WS ratio ($R_{WS}$) above 1 in 100%, 84% and 88% (or 12 of 12, 16 of 19, and 30 of 34) of the cases in VEN, PRS and LJU, respectively. The same analysis but for $R_{F_{CO2}}$ below 1 showed a degree of coincidence with $R_{WS}$ below 1 in 100%, 75% and 50% (or 1 of 1, 3 of 4, and 4 of 8) of the cases. This may imply a smaller influence from direct wind effects to drive $F_{CO2}$ during nights than during days in stratified PRS and LJU, but the few 24 hr periods observed where $R_{WS}$ was below 1 makes it difficult to draw clear conclusions.

Figure 5. Twenty Four hours variability of environmental variables in (a) VEN, (b) VEN, (c) Parsen (PRS), and (d) Ljusvattentjärn (LJU). The diagrams display distribution of z-normalized hourly data of wind speed (WS), wind gust speed (WGS), air temperature (T), PAR, air:water temperature ratio (Tr) dissolved oxygen (DO), and mean $F_{CO2}$. White and dark gray areas denote daytime and nighttime measurements and light-gray areas denote the time period belonging to daytime or nighttime depending on the 24 hr period sampled, and thus reflect differences in sunrise and sunset times during the sampling campaigns.

Although fluxes were typically higher in the daytime in agreement with wind speeds being, on average, higher in the day (Figure 5), in LJU we found several peaks in $F_{CO2}$ during nighttime. These peaks were limited to local sampling locations and thereby more likely caused by upwelling of CO$_2$ than by convection, which would cause mixed layer deepening over much of the lake. One of these peaks (July 19 and 20; A1 in Figure 6) may have been caused by upwelling following changing wind directions from north-western to southern winds, and the enhanced mixing to at least 3 m depth. Two other peaks (July 25–27; A2 in Figure 6) coincided with a shift in nighttime wind direction from northern to southern winds, that is, shifting winds at nighttime from opposite to similar direction as winds during daytime. $F_{CO2}$ increases were distinct in A2 even though daytime winds were below the measurement period average, and temperature stratification was less pronounced than during A1. Observed peaks in A1 and A2 resulted in a 5%–15% increase
in sampling location mean $F_{\text{CO}_2}$. It is noteworthy that such a small lake displays pronounced and local spatial variability in near-shore $F_{\text{CO}_2}$. Our observations at LJU also correspond to observations in a similar lake under light to moderate winds (MacIntyre et al., 2021). That relations between $\Delta F_{\text{CO}_2}$ and day-night differences of other environmental factors was less clear in LJU than in VEN, and PRS is compatible with the hypothesis that upwelling events may blur, otherwise, wind-driven patterns of diel $F_{\text{CO}_2}$ in small and wind-sheltered boreal lakes.

Changes in DO and pCO$_{2\text{aq}}$ can be used to interpret alterations in the balance between respiration (R) and primary productivity (PP), where the former consumes O$_2$ and produces CO$_2$ and the latter consumes CO$_2$ and produces O$_2$. The unsaturated surface water DO observed in VEN$_{\text{at}}$ and the small day-night DO variability in PRS and LJU indicate higher R than PP, and the higher daytime than nighttime $F_{\text{CO}_2}$ in these lakes implies that PP had limited influence on $F_{\text{CO}_2}$. However, the observed DO supersaturation in VEN$_{\text{at}}$ is in accordance with the near-equilibrium pCO$_{2\text{aq}}$ levels, showing that PP was higher and could explain the low or even negative daytime $F_{\text{CO}_2}$ observed there. Decreased PP relative to R may also lead to lower pH, and mean pH did decline from 7.9 to 7.5 between sampling occasions half a month before and after mixing, respectively ($n = 28$; Figure S2a). Decreased PP following lake mixing is logical due to shorter daylight time and deeper mixing, reducing the mean light exposure in the mixed surface water layer. The lack of clear diel $F_{\text{CO}_2}$ variability in VEN$_{\text{at}}$ may imply that PP, when being large enough to deplete pCO$_{2\text{aq}}$ to levels of near-atmospheric equilibrium, can reduce diel variability in $F_{\text{CO}_2}$ compared to situations when surface waters are highly supersaturated with CO$_2$.

### 3.4. Change in DIC After Autumn Mixing

The onset of autumn mixing in VEN mixed DIC from deeper to shallower waters (Figure S3a) and can explain higher $F_{\text{CO}_2}$ in VEN$_{\text{at}}$, in line with previous findings (Huotari et al., 2011; López Bellido et al., 2009; Riera et al., 1999; Striegl & Michmerhuizen, 1998). The increase in $F_{\text{CO}_2}$ after mixing implies loss of DIC in terms of CO$_2$, release to the atmosphere, but we found that total amount of lake DIC increased by 3% half a month after compared to before autumn mixing (Figure S7). This was unexpected, especially as we calculated (according to Text S5) this half month of post-mixing $F_{\text{CO}_2}$ to amount to 25% of the total DIC amount.

![Figure 6. Temporal variability in LJU at different sampling locations. (a) Extract of $F_{\text{CO}_2}$ from locations specified in the insert window (colored points) connected with lines for increased visibility, where thicker green and orange lines belong to locations where we observed peaks of $F_{\text{CO}_2}$. (b) Values of z-normalized wind speed (black dashed line), water temperature at 0.25 and 2.5 m depth (blue lines), and 24-hr mean wind direction during daytime (green arrow) and nighttime (blue arrow). A1 and A2 (yellow colored areas) denote periods with peaks in local $F_{\text{CO}_2}$. Gray areas denote nighttime.](image-url)
The DIC necessary to support both losses through emission and the increased DIC amount after autumn mixing seems to have been compensated by either DIC formation from in-lake net $R$, DIC input from the catchment or lateral exchange of DIC from littoral regions of the lake. We did observe increased precipitation during late summer and autumn in VEN (Figure 2), which may have resulted in DIC input from the catchment (Ojala et al., 2011). It is also known that mixing can reduce light for primary producers, favoring $R$ over PP (Rööm et al., 2014; Staehr & Sand-Jensen, 2007), which could contribute to the increase in DIC. The effect of this shift in metabolism on surface $pCO_2$ is usually difficult to separate from the effect of deep water CO$_2$ mixing to surface waters, as they occur simultaneously (Hanson et al., 2016). Nevertheless, here we find that DIC alterations after autumn mixing cannot be explained by autumn mixing alone, and that shifts in metabolism or DIC export from catchments to lakes may increase $F_{CO_2}$ on an annual basis despite summertime surface water CO$_2$ depletion by primary productivity (Maberly et al., 2013). The increase in DIC amount after autumn mixing in VEN and the supersaturation of pCO$_2$ during most of the measurement periods thereafter (Figure S2a), implies that $F_{CO_2}$ may be elevated for weeks to months after autumn mixing in eutrophic systems. Such systems often have high alkalinity and a pH above 6.5 (Balmer & Downing, 2011), resulting in a large pool of HCO$_3^−$ serving as a reservoir from which CO$_2$ is formed following losses by emission (Stumm & Morgan, 1996). In eutrophic lakes, upwelling of DIC-rich deep water may therefore contribute to a disproportionately high share of the annual $F_{CO_2}$ (Riera et al., 1999; Striegl & Michmerhuizen, 1998), as in VEN illustrated by the larger cumulative $F_{CO_2}$ after than before autumn mixing (Figure 3e).

### 3.5. Comparison With Other Studies

We compared our results on diel variability with 29 published estimates of diel $F_{CO_2}$ within 16 studies, covering 11 lakes, 1 reservoir and 4 ponds (Table S2). Higher daytime $F_{CO_2}$ was observed in 12 cases whereas nighttime $F_{CO_2}$ was higher in 14 cases. Two systems had no clear difference between daytime and nighttime $F_{CO_2}$, and in one system daytime and nighttime $F_{CO_2}$ had different direction (i.e., influx at daytime and outflux at nighttime). Day:night $F_{CO_2}$ ratios could be calculated for 23 of the estimates (Figure 7), allowing for comparisons between methods and seasonally stratified and mixed systems. For easier interpretation, only estimates where daytime and nighttime $F_{CO_2}$ were of the same direction have been compared (i.e., data from all systems except one).

Day:night $F_{CO_2}$ ratios were higher for measurements made using floating chambers (FCs) or models compared to when EC was used (1.26 ± 1.18; range 0.042–3.2, and 0.89 ± 0.4; range 0.34–1.57, respectively). For estimates derived using FCs and models ($n = 17$), higher mean day:night $F_{CO_2}$ ratio have been reported in 10 cases (five mixed system, four stratified systems, and one full-year estimate). In contrast, estimates made using EC ($n = 12$) report higher nighttime mean $F_{CO_2}$ in all but two cases (one mixed system and one full-year estimate). This difference implies there may be systematic methodological differences that need to be accounted for. Disagreements between methods have been observed previously (Anderson et al., 1999; Czikowsky et al., 2018; Erkkiiliä et al., 2018; Eugster, 2003), and EC results may have been affected by differences in footprint size and location and/or in lateral air transport patterns between daytime and nighttime (Kenny et al., 2017; Sahlée et al., 2013). Nevertheless, studies reporting diel $F_{CO_2}$ variability are relatively rare, and it is possible that differences reported here reflect natural variability. More studies on diel flux variability are needed to evaluate potential methodological differences.

We found lower mean day:night $F_{CO_2}$ ratios for stratified ($n = 8$) than mixed ($n = 7$) systems (1.08 ± 0.59; range 0.34–2.14, and 1.43 ± 0.35; range 0.75–1.91). This compares well with day:night $F_{CO_2}$ ratios in seasonally stratified VEN$_{be}$ and mixed VEN$_{sh}$ (1.08 and 1.67). Day:night $F_{CO_2}$ ratios in PRS and LJU (1.5 and 1.4) were also within the range of other studies (Figure 7). It should be noted that eutrophic systems are overrepresented in these studies, and few may have the high DOC and pCO$_2$ levels that are common in northern lakes globally (see Table S2). The difference in diel variability between mixed and stratified systems demonstrates the importance of sampling both before and after seasonal mixing events to account for $F_{CO_2}$ variability on an annual scale.
3.6. Importance of Mixing and Diel Variability for Total Open-Water $F_{CO_2}$

We extrapolated our measurements of 24 hr mean $F_{CO_2}$ in VEN during periods of seasonal stratification and mixing to the full open-water period (see Methods). This yielded a cumulative $F_{CO_2}$ of 0.03 kg CO$_2$m$^{-2}$ from the stratification period. For the mixing period, cumulative $F_{CO_2}$ was 0.31–0.39 kg CO$_2$m$^{-2}$, with the lowest value assuming negligible $F_{CO_2}$ at spring mixing and the highest value assuming similar 24 hr mean $F_{CO_2}$ at spring mixing as during autumn mixing. Hence, $F_{CO_2}$ from the stratified period of eutrophic VEN contributed only around 7%–9% of the total open-water period $F_{CO_2}$ despite the lake being stratified for 52% of the open-water season. Using only measurements from the stratified period to upscale to the full open-water period as has been done elsewhere (Balmer & Downing, 2011; Lazzarino et al., 2009), would in the case of VEN underestimate $F_{CO_2}$ by 83%–86%. This supports results elsewhere, where summertime extrapolations of $F_{CO_2}$ from undersaturated eutrophic lakes to the annual scale underestimated emissions by more than 100%, compared to a mean underestimation of 21% in supersaturated lakes (Ducharme-Riel et al., 2015). These findings illustrate the importance of considering multiple seasons when estimating open-water $F_{CO_2}$ despite the lake being stratified for 52% of the open-water season. Using only measurements from the stratified period to upscale to the full open-water period as has been done elsewhere (Balmer & Downing, 2011; Lazzarino et al., 2009), would in the case of VEN underestimate $F_{CO_2}$ by 83%–86%. This supports results elsewhere, where summertime extrapolations of $F_{CO_2}$ from undersaturated eutrophic lakes to the annual scale underestimated emissions by more than 100%, compared to a mean underestimation of 21% in supersaturated lakes (Ducharme-Riel et al., 2015). These findings illustrate the importance of considering multiple seasons when estimating open-water $F_{CO_2}$ for eutrophic lakes. Clearly, in spite of daytime CO$_2$ uptake during stratification, eutrophic lakes can be large net CO$_2$ sources over the full open-water period. Calculating open-water $F_{CO_2}$ in VEN by accounting for seasonally stratified and mixed periods as above, but only using daytime measurements (between sunrise and sunset) or measurements made between the morning and late afternoon (08:00–16:00), overestimates total fluxes by 21%–22% and 28%–30%, respectively. Hence, it may be crucial to account for both seasonal mixing and the diel patterns when estimating long-term $F_{CO_2}$.

From our results of diel variability in $F_{CO_2}$ in VEN$_{alt}$, PRS, and LJU (Table 1), we suggest a 1.5 times higher mean $F_{CO_2}$ from 0800 to 1600 than over the rest of the 24 hr period. From this, we derived a conversion factor (CF$_{24 hr}$) of 0.83 to convert $F_{CO_2}$ obtained from morning to late afternoon hours to full 24 hr estimates.
Our results indicate that diel $F_{\text{CO}_2}$ variability can be expected in boreal lakes except when surface $pCO_{2aq}$ is close to equilibrium with the atmosphere and generates small fluxes. In all cases where we observed day-night differences in $F_{\text{CO}_2}$, the pattern was similar, with daytime exceeding nighttime $F_{\text{CO}_2}$ by 40%–67% and with peaks in $F_{\text{CO}_2}$ observed between mornings and late afternoons (08:00–16:00), when sampling campaigns are generally conducted. We found that extrapolating such peak measurements to open-water periods may overestimate $F_{\text{CO}_2}$ with 28%–30%, demonstrating the importance of accounting for diel variability when calculating annual $F_{\text{CO}_2}$.

Day-night variability in wind speed explained 77% and 39% of the day-night $F_{\text{CO}_2}$ variability in two of our lakes. In the smallest and most wind-sheltered lake, individual local peaks of $F_{\text{CO}_2}$ were observed at nighttime when winds were low indicating complex and local $F_{\text{CO}_2}$ variability, possibly induced by convection or upwelling. Additional work is needed to address such within-lake spatial variability of $F_{\text{CO}_2}$.

In the eutrophic lake, an increase in diel $F_{\text{CO}_2}$ variability coincided with high and sustained $F_{\text{CO}_2}$ following post-autumn mixing which represented a more important part of the open-water $F_{\text{CO}_2}$ than the lower and variable fluxes observed during the longer stratified period. This raises concerns that $F_{\text{CO}_2}$ measurements in eutrophic lakes may not be representative of the annual flux and that eutrophic lakes, despite being net CO$_2$ sinks during summer, may in fact be considerable CO$_2$ sources over the whole open-water period.

For future sampling campaigns, we suggest that measurements are conducted during multiple days and nights in ways that include both seasonal stratification and mixing periods and different wind conditions to properly estimate $F_{\text{CO}_2}$ from lakes.

### 4. Conclusions

The large variability in diel $F_{\text{CO}_2}$ across studies (Figure 7) means that this conversion factor is not applicable for the full spectrum of boreal lakes. Instead, it can serve as a way to facilitate comparisons with future studies. Such a conversion factor was recently proposed for methane (Sieczko et al., 2020) and represents an attempt to account for diel variability if diel data are missing.

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### Data Availability Statement

Source data for figures and tables referred to in the text are provided through the institutional repository DIVA (https://doi.org/10.48360/BN1M-1287).

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

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$$CF_{24h} = \frac{F_{\text{CO}_2 16h} + F_{\text{CO}_2 16h}}{2} = \frac{\left(\frac{F_{\text{CO}_2 16h} + F_{\text{CO}_2 16h}}{2}\right) / \left[F_{\text{CO}_2 16h} / F_{\text{CO}_2 16h}\right]}{2} = 1 + \left(\frac{1/1.5}{2}\right) = 0.83 \tag{2}$$

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