Carbon dioxide fluxes increase from day to night across European streams

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Globally, inland waters emit over 2 Pg of carbon per year as carbon dioxide, of which the majority originates from streams and rivers. Despite the global significance of fluvial carbon dioxide emissions, little is known about their diel dynamics. Here we present a large-scale assessment of day- and night-time carbon dioxide fluxes at the water-air interface across 34 European streams. We directly measured fluxes four times between October 2016 and July 2017 using drifting chambers. Median fluxes are 1.4 and 2.1 mmol m\(^{-2}\) h\(^{-1}\) at midday and midnight, respectively, with night fluxes exceeding those during the day by 39%. We attribute diel carbon dioxide flux variability mainly to changes in the water partial pressure of carbon dioxide. However, no consistent drivers could be identified across sites. Our findings highlight widespread day-night changes in fluvial carbon dioxide fluxes and suggest that the time of day greatly influences measured carbon dioxide fluxes across European streams.

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Inland waters are important sources of atmospheric carbon dioxide (CO₂) partially offsetting the terrestrial carbon sink¹⁻². Streams and rivers therein represent major CO₂ emitters³. Fluvial CO₂ fluxes are primarily controlled by the gas exchange velocity at the water-air interface (k) and the gradient between the water and atmospheric partial pressures of CO₂ (pCO₂)⁴. Both parameters are highly variable in space and time⁵,⁶, causing uncertainty in the magnitude of regional and global fluvial CO₂ emissions⁷.

The high spatiotemporal variability of k and water pCO₂ can be attributed to a complex interplay of underlying controls. While k in streams is mostly driven by water turbulence created by variations in flow and stream morphology⁸, the water pCO₂ is influenced by the degree of hydrological connectivity between the stream and the adjacent riparian soils⁹ as well as by in-stream processes (e.g., stream metabolism). The supply of CO₂ from external sources, such as soil water or groundwater, into streams, varies with reach and season¹⁰. Furthermore, seasonal and diel changes in stream pCO₂ are attributed to stream metabolism driven by temperature and solar radiation¹¹⁻¹³. Ecosystem respiration, a source of CO₂ in the stream, takes place throughout the whole day, and gross primary production, a sink of CO₂, occurs only during daylight. Temperature and solar radiation also directly influence water pCO₂, the former by changing the solubility of the gas and the latter due to photomineralization¹⁴. However, questions remain regarding the magnitude and relative drivers of seasonal and diel fluctuations of CO₂ fluxes in streams.

Presently, most fluvial CO₂ emission values are derived from k estimates based on water velocity and stream channel slope and on water pCO₂ values indirectly calculated from alkalinity, pH, and temperature³. This approach fails to capture the high spatiotemporal variability observed for k and pCO₂ and therefore can provide imprecise estimates of CO₂ fluxes¹⁵,¹⁶. Direct field observations provide the means to improve estimates and understanding of the drivers behind spatiotemporal variability, and thus the dynamics of CO₂ outgassing from running waters. However, besides mostly local studies that indirectly infer CO₂ fluxes from pCO₂ and k¹¹⁻¹²,¹⁷,¹⁸, no direct measurements exist that compare day-time and night-time CO₂ fluxes from streams on a larger spatial scale.

The aim of this study was to assess the magnitude and drivers of stream CO₂ flux variations between day and night across European streams. We hypothesized that CO₂ fluxes would differ between day and night due to diel variations in terrestrial inorganic carbon inputs, in situ metabolism, and temperature. As higher temperatures and solar radiation may drive differences in pCO₂, we expected a higher difference between day-time and night-time fluxes with warmer temperatures and at lower latitudes. Hence, we measured day-time and night-time fluxes of CO₂ at four different periods throughout one year from 34 streams (Strahler stream orders from 1 to 6) in 11 countries across Europe following a standardized procedure. CO₂ fluxes were measured starting at midday (11 a.m. Greenwich Mean Time (GMT)) and midnight (11 p.m. GMT) with drifting flux chambers equipped with CO₂ sensors as described in Bastviken et al.¹⁹. In the majority of the European streams, we found increased CO₂ fluxes at the water–air interface in the night compared to the day with a median increase of 0.5 mmol m⁻² h⁻¹. Most of the observed CO₂ flux variability was explained by changes in pCO₂ from day to night with more pronounced changes at lower latitudes.

### Results and discussion

**Magnitude of CO₂ flux variation from day to night.** Midday CO₂ fluxes at the water–air interface ranged from −2.7 (uptake) to 19.9 mmol m⁻² h⁻¹ (emission) (1.4 [0.5, 3.1]; median [interquartile range (IQR)]; n = 107) and midnight fluxes ranged from −0.3 to 25.6 mmol m⁻² h⁻¹ (2.1 [0.9, 3.7]; n = 107) (Fig. 1a; Supplementary Table S3). Our measured fluxes are comparable to other studies conducted in temperate and boreal streams that used chambers²⁰,²¹ or empirical models¹²,²²,²³, although they were in the lower range of the numbers modeled in a study in the USA²³ (Supplementary Fig. S2). The lower numbers might be due to the lack of tributary inflows, large woody debris, and strong hydraulic jumps in the selected stream sections (Supplementary Sampling manual).

To assess stream CO₂ flux variations between day and night, we computed the difference of night-time minus day-time fluxes for each stream and sampling period, where positive numbers indicate an increase from day to night and vice versa (Fig. 1b). Differences in CO₂ fluxes amounted to 0.5 mmol m⁻² h⁻¹ [0.1, 1.4] (n = 107) across all sites and sampling periods, which is equivalent to a relative increase of 39% [4%, 100%] (n = 101; n reduced due to exclusion of relative comparisons to zero flux at day-time) (Fig. 2). Altogether, these results point towards a high relevance of night-time CO₂ fluxes as reported earlier for single pre-alpine streams¹₂, stream networks¹³,¹⁷ or rivers¹⁸, and in a recent compilation of diel CO₂ data from 66 streams worldwide²⁴. A rough annual extrapolation of fluxes from our study sites (Supplementary Methods) shows that the inclusion of night-time fluxes increases annual estimates of site-specific stream CO₂ emissions by 16% [6%; 25%] (Supplementary Table S4). Hence, our measurements and the simplified extrapolation of our data emphasize the need to collect and integrate night-time CO₂ flux data into sampling protocols as well as regional upscaling efforts.

Looking into the individual comparisons, we found 83 increases in median CO₂ fluxes from day to night with seven comparisons where the stream even switched from a sink to a source of CO₂ to the atmosphere (Supplementary Table S3). However, we also found four comparisons where median CO₂ fluxes at day and night were the same and 20 decreases in the night (Supplementary Table S3). These results and also other studies¹³,²⁵,²⁶ suggest that the direction and strength of diel pCO₂ pattern can be largely variable across space and time.

### Diel CO₂ flux differences vary as a function of latitude and water temperature.

The diel differences in CO₂ fluxes were significantly negatively related to latitude (Table 1A), with substantial diel variation more likely at lower latitudes. Likewise, the interaction with latitude and the water temperature was significant (Table 1A), which might be explained by higher temperatures at lower latitudes during the sampling periods and higher solar radiation boosting in-stream primary production²⁷. This dataset is derived from only 34 streams distributed across different climate zones in Europe. However, to our knowledge, it is currently the largest study of its kind, using flux chambers to measure CO₂ fluxes, and compare those fluxes at day-time and night-time on such a spatial scale.

We found no significant differences in the magnitude of diel differences in CO₂ fluxes related to water temperature (Table 1A) using a linear mixed-effect model (LME). However, comparing the CO₂ fluxes at midday to midnight at the different sampling periods, we detected significant diel changes in CO₂ fluxes in October, January, and April (Fig. 1a). Contrary to our expectation that higher differences can be expected at higher temperatures, we did not detect significant changes from day to night in July (Fig. 1a), during which period the lowest changes in absolute numbers were recorded (0.3 mmol m⁻² h⁻¹; Fig. 1b). The highest differences of CO₂ fluxes from day to night were measured during April (1.1 mmol m⁻² h⁻¹), followed by January (0.5 mmol m⁻² h⁻¹).
and October (0.5 mmol m⁻² h⁻¹). Lower day-night changes in July could be explained by increased riparian shading reducing photosynthesis. For example, reduced in-stream photosynthesis in summer compared to spring has been shown for a subalpine stream network or a temperate forested headwater stream. However, comparing the canopy cover of the streams and the differences in CO₂ fluxes from day to night (Supplementary Fig. S3h) revealed no clear pattern. A probable alternate explanation is that CO₂ production via photomineralization during the day counteracted a decrease via CO₂ fixation by photosynthesis and diminished diel pCO₂ and ultimately CO₂ flux changes. This highlights the complex interplay between different light-dependent processes in streams influencing pCO₂ on a diel scale.

The importance of year-round measurements is highlighted by the January data set containing the second-highest diel CO₂ flux changes. European ice-free streams may be perceived “dormant” during these periods and representative CO₂ flux estimates are thus often missing. Our January data showed a magnitude of flux compared to the rest of the year across the European streams as well as high diel variability in CO₂ fluxes (Fig. 1). This may be attributed in part to the latitudinal coverage of our study as we included streams from the boreal to the Mediterranean. For example, the water temperatures of the Spanish streams were still relatively high in winter with around 2.8–9.5 °C during the day whereas Swedish streams showed these temperatures in October and April. A study in the coterminous US looking into stream pCO₂ variability also reports varying strengths of diel pCO₂ variability, dependent on the investigated stream and time. Hence, diel pCO₂ and CO₂ flux variability can be large in streams of the northern hemisphere, stressing the need to unravel the site-specific drivers of and mechanisms behind these diel changes.

**Fig. 1** Day-to-night changes of CO₂ fluxes at the water–air interface of the sampled European streams. Stream CO₂ fluxes (in mmol CO₂ m⁻² h⁻¹) at day-time (yellow) and night-time (blue) (a) and the calculated changes from night minus day (ΔCO₂ flux) (b) for all data and separately for each sampling period. In the sampling periods comparisons in (a), CO₂ fluxes for individual stream sites are indicated by red (day) and light blue (night) dots. The boxplots visualize the median of all stream sites (line), the first and third quartiles (hinges), the 1.5*inter-quartile ranges (whiskers), and the outliers outside the range of 1.5*inter-quartile ranges (black dots). On top of (a) are p values retrieved from paired comparisons of median CO₂ fluxes tested by Wilcoxon signed-rank tests and the sample size (n). Significant p values with p < 0.05 are in bold with an asterisk. The differences in the CO₂ fluxes (b) in mmol CO₂ m⁻² h⁻¹ from day to night are for October: 0.5 [0.1, 1.2]; January: 0.5 [0.3, 0.9]; April: 1.1 [0.1, 2.3]; July: 0.3 [−0.2, 1.1] (median [IQR]).

**Fig. 2** Relative changes in CO₂ fluxes from day to night for all data together and for each sampling period. A positive value indicates an increase in CO₂ fluxes during the night and vice versa (expressed as a %-change of the daytime values). Outliers (>1.5*IQR) were excluded for illustration purposes as the large relative variation in these fluxes was due to minor absolute variation in fluxes close to zero. The median relative changes were positive throughout all sampling periods, ranging from 32% [0.6%, 95%] in October, 38% [16%, 50%] in January, 60% [7%, 177%] in April, to 24% [−16%, 69%] in July (median [IQR]; n = 26, 21, 28, and 26, respectively).
The variabilities of gas exchange velocities have been reported for CO2, attributed to changes in water parameters that vary on a diel scale (Table 1B), whereas changes in the gas exchange velocity $k$ appeared less important. In fact, we did not measure significant variations in $k$ from day to night in our streams (Fig. 3; Supplementary Fig. S4b). Although diel variabilities of gas exchange velocities have been reported for CO2 and other gases$^{31,32}$, the majority of the investigated streams in this study did not show those changes. The pCO2 as a major driver of diel CO2 flux variability was also identified by a global compilation of high-frequency CO2 measurements$^{24}$. Consequently, if no major changes in physical drivers of gas exchanges occur that strongly affect the turbulence, such as heavy rain events, it is sufficient to focus on pCO2 for assessing diel flux changes at the water–air interface.

In a second step, we tested the influence of biogeochemical parameters that vary on a diel scale on water pCO2 day-to-night differences (Table 1C). This LME identified a link between the day-to-night changes in water pCO2 and water dissolved O2, with pCO2 generally increasing and O2 decreasing from day to night (Supplementary Fig. S4b, c). This potentially reflects a diel cycle of CO2 controlled by aquatic primary production and respiration (in-stream metabolism). Hence, even though in situ metabolism may play a minor role in determining the baseline pCO2 and flux in smaller streams (mostly controlled by terrestrial inputs$^{23}$), our results suggest that metabolism can be an important driver of the diel fluctuations in CO2 fluxes. Indeed, increased water pCO2 during the night has been attributed to a decrease in CO2 fixation by primary producers$^{13,18,24}$, although a recent study suggests that the adjacent groundwater can also show measurable but less pronounced diel pCO2 variations$^{33}$. Previous research suggests that in situ mineralization of CO2 should play a larger role in CO2 dynamics in larger streams because they are less influenced by external CO2 sources$^{23}$. Nevertheless, we did not find any trend in CO2 flux day-to-night differences with stream width or discharge as a proxy for size (Supplementary Fig. S3c, f) or with stream order (Supplementary Fig. S5) although other studies suggest change over a size gradient$^{33,34}$. Furthermore, the LME testing hydromorphological and catchment variables on pCO2 day-to-night differences (Table 1D) did not reveal significant relationships with either of these drivers. This could either be due to the fact that we missed the best proxy that determines day-to-night differences of pCO2 in European streams or that there are no common drivers among the investigated streams. Large diel variability of CO2 patterns within one Swedish stream$^{26}$ or among US headwater streams$^{25}$ have been described, which complicates the identification of general drivers. Hence, further research is needed to decipher the diel variability of the sources and dynamics of pCO2 in streams and to understand the environmental, hydromorphological, and catchment drivers before their importance on a regional or global scale can be assessed.

In-stream metabolism with photosynthetic CO2 fixation diminishing pCO2 during the day may explain the increase in CO2 fluxes from day to night, but cannot explain why in some instances we measured a lower CO2 flux at night. Potential explanations for a lower night flux might include: (i) higher atmospheric CO2 concentrations due to the absence of terrestrial CO2 fixation during night and therefore a lower water–atmosphere pCO2 gradient, (ii) photomineralization of

Table 1 Results of the linear mixed-effect models (LME).

| Response variable | Fixed effect | $\chi^2$ (1) | p  | Sign |
|-------------------|--------------|-------------|----|------|
| (A) Testing spatial and temporal hypotheses | CO2 flux | Latitude | 7.4207 | 0.006 | – |
| | | Temperature | 0.0168 | 0.897 | – |
| (B) Testing physical and biogeochemical drivers of CO2 flux changes | CO2 flux | Δ Water pCO2 | 4.9497 | 0.026 | + |
| | | Δ Conductivity | 0.5613 | 0.454 | + |
| (C) Testing biogeochemical drivers of pCO2 changes | pCO2 | Δ Water O2 concentration | 7.9879 | 0.005 | – |
| | | Δ pH | 0.0345 | 0.853 | – |
| (D) Testing catchment and hydromorphological drivers of pCO2 changes | pCO2 | Daylength | 1.7244 | 0.189 | – |
| | | Discharge | 3.4458 | 0.063 | + |
| | | % forest | 0.0950 | 0.758 | – |

*Heat flux calculated as water temperature ($T_w$) minus air temperature ($T_a$). (A) Marginal $R^2 = 0.12$, conditional $R^2 = 0.19$, sample size = 107. (B) Marginal $R^2 = 0.08$, conditional $R^2 = 0.10$, sample size = 77. (C) Marginal $R^2 = 0.13$, conditional $R^2 = 0.33$, sample size = 78. (D) Marginal $R^2 = 0.11$, conditional $R^2 = 0.13$, sample size = 68. The effects of latitude and water temperature during the day (A) and the effect of day-to-night differences of pCO2 and the gas transfer velocity ($Δ = -night minus day values$) (B) on the day-to-night difference of CO2 fluxes were tested. Furthermore, the effect of day-to-night differences of physical and biogeochemical parameters (C) and the effect of catchment and hydromorphological related parameters (D) on the day-to-night differences of pCO2 were evaluated. Stream ID was included as a random effect on the intercept. Significance of fixed effects were assessed with likelihood ratio tests with degrees of freedom evaluated. Stream ID was included as a random effect on the intercept. Significance of fixed effects were assessed with likelihood ratio tests with degrees of freedom evaluated. The slope direction (sign) of the effect is indicated with − or + when significant. Significant p values < 0.05 are in bold.

Fig. 3 Diel changes in CO2 fluxes (FCO2) and other physical and chemical parameters for October/January/April and July, respectively. The physical and chemical parameters comprise atmospheric CO2 (Air CO2), the differences of CO2 concentrations in the water minus the air (CO2 gradient), the water–air gas transfer velocity ($k$), the differences of temperatures in the water minus the air (Δ $T_w-T_a$), the water temperature (WT), the oxygen concentration in the water (O2), pH in the water, the partial pressure of CO2 in the water (pCO2), and conductivity (Cond). The arrows indicate significant increases (↑) or significant decreases (↓) from day to night and the line indicates no significant change (——) tested by a Wilcoxon signed-rank test (see Supplementary Fig. S4 for more information). The differences between the sampling periods October/January/April and July, respectively, detected in this European study are highlighted in red.
organic matter to CO₂ counteracting the CO₂ fixation by primary producers during day-time, and (iii) lower turbulence due to a decrease in stream discharge in the night. We found significant increases in atmospheric CO₂ close to the investigated streams at night. However, this was usually accompanied by concomitant increases in water pH and therefore did not translate into smaller CO₂ gradients between the water–air interface (Fig. 3; Supplementary Fig. S4b, e, i). Production of CO₂ due to photomineralization of dissolved organic carbon (DOC) could play a role in diel CO₂ dynamics in streams with high amounts of colored terrestrial organic matter. In the highly colored streams, diel CO₂ patterns can additionally be influenced by DOC shading diminishing benthic primary production. In October, we measured DOC concentrations in a subset of the investigated streams for another study where an agricultural stream in Sweden and peatland-dominated streams in Great Britain had high DOC concentrations (>10 mg L⁻¹) whereas the median DOC was much lower with 2.6 mg L⁻¹. Due to the limited data, we could not test the effect of DOC on pCO₂ changes and we can neither confirm nor exclude that photomineralization might play a role for diel pCO₂ and consequently CO₂ flux variability in the studied streams. We did find, nonetheless, that the majority of the streams where CO₂ fluxes were lower during the night also had a lower gas transfer velocity (kₘₙₐₓ), likely due to a slight decrease in stream discharge and therefore turbulence. Thus, while there was a general tendency of increased pCO₂ from day to night (only 4 out of 20 decreases in CO₂ fluxes from day to night showed a concomitant decrease in water pCO₂), individual streams at single time points seemed to experience diel fluctuations in discharge as described elsewhere. This can simultaneously reduce the gas exchange velocity of the stream and therefore cause lower nighttime CO₂ fluxes. In this study, we only measured stream discharge during the day, and therefore the importance of this mechanism remains to be confirmed.

Maximum CO₂ flux differences might be even higher—limitations of the study design. For organizational reasons, the sampling scheme of this collaborative study was standardized to fixed times of measurements for the day and the night. All teams across Europe started their measurements at 11:00 (midday) and 23:00 GMT (midnight) during each sampling period, which has consequences for the magnitude of the observed diel variability of the CO₂ fluxes. The largest diel differences in stream pCO₂ have generally been detected at the end of the day compared to the end of the night. In an agricultural Swedish stream, diel maximum and minimum CO₂ concentrations were reached at 04:00 and 16:00 (GMT), respectively, during spring and early summer periods (late April to early July) where diel dynamics were most pronounced. In these scenarios, sampling midday and midnight, as conducted in this study, would be close to those maxima and minima as they can be reached already earlier during the day (see Supplementary Fig. S6 in May). However, the maxima and minima of diel CO₂ dynamics in streams can vary largely (see Supplementary Fig. S6 in October, April, July). In another example of German streams, the times of minima and maxima differ between streams and times, and the fixed time points chosen in this study would miss the maximum differences that can be observed (see Supplementary Fig. S7 in August). Hence, our estimates could be conservative as we compared fixed time points at midday and midnight. In general, CO₂ flux measurements in streams are highly sensitive towards the time of the day because diel minimum and maximum of pCO₂ can vary largely from month to month but also from day to day. As we found that the diel variability of pCO₂ was the major driver of diel CO₂ fluxes, we recommend future studies that plan to measure CO₂ fluxes directly with the chamber method, to additionally monitor the diel variability of pCO₂ with loggers at a high temporal resolution. This approach will provide the opportunity to estimate if the measurements are done during peak times or not.

While our results provide a first insight into the drivers of day-night differences in CO₂ fluxes, the high uncertainty in the models as well as the sometimes opposing patterns—increases and decreases from day to night in different streams and sampling periods—point towards different drivers varying on a temporal and spatial scale. We recommend that future studies designs incorporate high-frequency CO₂ data together with biogeochemical variables from the stream (e.g., pH) and the atmosphere (e.g., CO₂ or temperature). Additionally, we recommend including radioactive or stable carbon isotope signatures to track potential sources of CO₂ and their changes in streams to better assess terrestrial–aquatic linkages. Linking temporal patterns of fluvial CO₂ fluxes with their drivers across large spatial scales is a path towards a more accurate understanding of their role in regional and global carbon cycles. Our results demonstrate that in many streams across Europe, night-time CO₂ fluxes exceeded day-time, representing an underestimation of global CO₂ emissions from inland waters if not considered. It is thus critical to account for the diel variability of fluvial CO₂ fluxes for accurate daily and annual estimates of CO₂ emissions from inland waters.

Methods

Sampling scheme. The project included 16 teams distributed across 11 European countries. Every team sampled one to three streams (Supplementary Table S1) every 3 months (October 2016/January 2017/April 2017/July 2017) within a time frame of 2 weeks throughout a whole year. These sampling periods roughly cover the seasons autumn/winter/spring/summer although, due to the large latitudinal coverage of the sampling sites, the seasons and their characteristics vary largely. In total, 34 stream sites (Supplementary Fig. S1) were visited each sampling period during the specified 2 weeks’ time frame except for 11 streams in January that were frozen during the sampling weeks (Supplementary Table S3).

CO₂ fluxes were measured once every sampling period with drifting flux chambers equipped with CO₂ sensors. This method has proven to be a reliable and least biased direct measurement of CO₂ fluxes at the water–air interface in streams. CO₂ concentrations in the chamber headspace were logged every 30 s over a period of 5–10 min during each run, and CO₂ fluxes were calculated based on the rate of change over time in pCO₂ in the chamber headspace. At each stream, we measured CO₂ fluxes with the flux chamber (five times), pCO₂ in the atmosphere and water with the CO₂ sensors in the flux chamber (details described in Supplementary Methods), pH, temperature, conductivity, and oxygen in the water with a multiprobe (Supplementary Table S2). These measurements were started at 11:00 and 23:00 (GMT) and lasted approximately two hours and are referred to as midday and midnight throughout this article. Stream width, depth, canopy cover, and discharge were determined during the day (see Supplementary Sampling manual for details). In addition, the following information was collected for each stream once during the study: stream order, climate zone, catchment area until the endpoint of the investigated stream site and the percentage of coverage of different land use classes in this catchment area, and predominant geology (Supplementary Table S1).

Calculations of CO₂ fluxes and gas transfer velocity. Flux rates were obtained from the linear slopes of the pCO₂ in the chamber headspace over time and flux was accepted if the coefficient of determination (R²) of the slope was at least 0.65. An exception was made in cases where the slope was close to zero and the pCO₂ in the atmosphere and water (measured at the same time) were at equilibrium. These fluxes were set to zero. Final flux rates F (mmol CO₂ m⁻² h⁻¹) were calculated according to Eq. (1):

\[ F = \frac{P}{RTA} \times S \times 10^{-3} \times 60 \times 60 \]  

\[ \text{where } \begin{align*} S &= \text{the slope (ppm s}^{-1}), \ P &= \text{the pCO₂ in the atmosphere (atm), } V &= \text{the volume (L) of the drifting chamber, } R &= \text{the gas constant (82.0562 mL atm K}^{-1} \text{ mol}^{-1}), \ T &= \text{the chamber air temperature (K)}, \ A &= \text{the bottom area of the chamber (m}^2), \ \text{and the last term is the conversion from seconds to hours.} \end{align*} \]

In this study, we followed the sign convention whereby positive values indicate a CO₂ flux from the stream to the atmosphere (source) and negative values indicate a flux from the atmosphere to the stream (sink). The magnitudes of variations between day-time and night-time measurements are additionally stated as percent increases, which
were computed by dividing the difference between the values at night minus day by the value at day and expressing the result as a percent change from day to night. We solved Eq. (1) to obtain the transfer velocity (\(t\)) as

\[ t = \frac{\Delta \text{CO}_2}{m \cdot \Delta \text{day}} \]

where \( \Delta \text{CO}_2 \) is the difference in concentration between day and night. If \( m \) is the slope of the regression line, and \( \Delta \text{day} \) is the difference in concentration between day and night, the transfer velocity \( t \) is given by

\[ t = \frac{\Delta \text{CO}_2}{m \cdot \Delta \text{day}} \]

We used Eq. (2) to estimate the transfer velocity for each site and sampling period, and with the data, \( t \) (Eq. (2)) was standardized to \( \text{lm} \) (Eq. (3)).

\[ t_{\text{std}} = \frac{1000}{t} \]

where \( t_{\text{std}} \) is the transfer velocity at site in situ temperature \( T \), Sc is the Schmidt number for \( T \) in \( \text{cm h}^{-1} \). The statistical analyses were performed with median values of three to five floating chamber runs per day and night, with the statistical programming language R (version 3.5.1). The statistical analysis included both fixed and random effects. The fixed effects with the data point per sampling period per stream) and available for streams. For the LMEs it included stream ID as a random effect representing a hydrodynamic rough water surface typical in streams the exponent of \( 0.5 \) was chosen.

### Statistical analyses

All statistical analyses were performed with median values of three to five floating chamber runs per day and night, respectively, using the statistical programming language R (version 3.5.1). The statistical analysis included both fixed and random effects. The fixed effects with the data point per sampling period per stream) and available for streams. For the LMEs it included stream ID as a random effect representing a hydrodynamic rough water surface typical in streams the exponent of \( 0.5 \) was chosen.

### Methods

The data that support the findings of this study are openly available in figshare at https://doi.org/10.6084/m9.figshare.12717188.

### Code availability

This manuscript includes no code.

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K.A. and P.B. conceived the study design, coordinated the project and contributed equally to this work; all authors collected and analyzed the field data and K.A. and P.B. gathered and performed the quality check of all data; K.A., P.B., and J.P.C.-R. co-wrote the paper with the help of M.K., G.H.N., and N.C. All authors (K.A., J.P.C.-R., T.F., A.P., S.C.-F., D.S., A.C.N., A.L.D., A.P.P., B.C.D., N.S., C.G.R., G.H.N., X.T., V.E., L.B.-F., T.B., J.A., A.D., G.B., S.F., N.C., E.D.E., F.F., J.-R.M., J.M., D.F., C.N., M.C., M.N., L.L., C.R., G.-Q., F.R., N.P., J.L., J.P., M.K., A.F., S.H.O., C.M.-L., A.B., J.A.F., P.I.G., L.A.K., M.R., P.B.) commented on the manuscript.

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