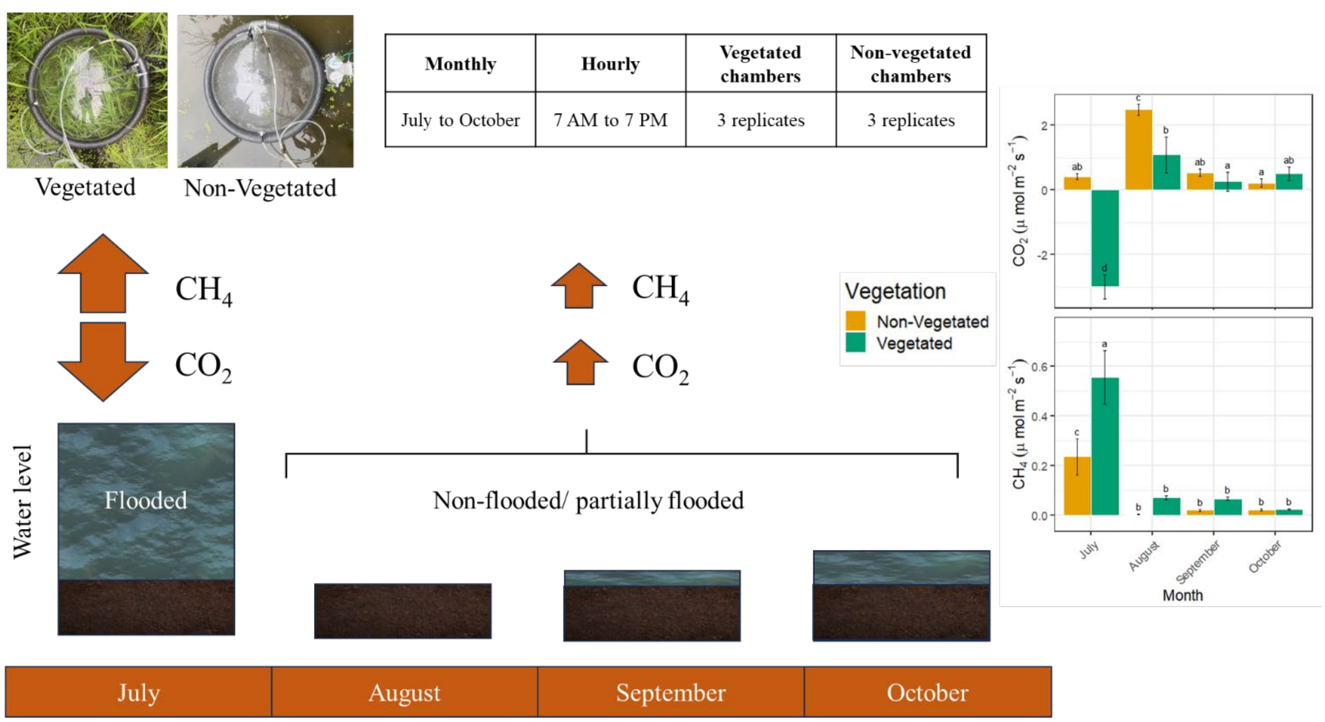
Changes in inundation drive carbon dioxide and methane fluxes in a temperate wetland

Erin Hassett[1], Gil Bohrer[2], Lauren Kinsman-Costello[3], Yvette Onyango[2], Talia Pope[3], Chelsea Smith[3], Justine Missik[2], Erin Eberhard[3], Jorge Villa[4], Steven E. McMurray[5], Tim Morin[1]

[1]SUNY College of Environmental Science and Forestry, Syracuse, NY
[2]Ohio State University, Columbus, OH
[3]Kent State University, Akron, OH
[4]University of Louisiana at Lafayette, Lafayette, LA
[5]Old Woman Creek NERR, Huron, OH

Keywords: greenhouse gases, inundation, biogeochemistry, Lake Erie

Graphic Abstract



Abstract

Wetlands cycle carbon by being net sinks for carbon dioxide (CO_2) and net sources of methane (CH_4). Daily and seasonal temporal patterns, dissolved oxygen (DO) availability, inundation status (flooded or dry/partially flooded), water depth, and vegetation can affect the magnitude of carbon uptake or emissions, but the extent and interactive effects of these variables on carbon gas fluxes are poorly understood. We characterized the linkages between carbon fluxes and these environmental and temporal drivers at the Old Woman Creek National Estuarine Research Reserve (OWC), OH. We measured diurnal gas flux patterns in an upstream side channel (called the cove) using chamber measurements at six sites (three vegetated and three non-vegetated). We sampled hourly from 7 AM to 7 PM and monthly from July to October 2022. DO concentrations and water levels were measured monthly. Water inundation status had the most influential effect on carbon fluxes with flooded conditions supporting higher CH_4 fluxes (0.39 µmol CH_4 m^{-2} s^{-1}; -1.23 µmol CO_2 m^{-2} s^{-1}) and drier conditions supporting higher CO_2 fluxes (0.03 µmol CH_4 m^{-2} s^{-1}; 0.86 µmol CO_2 m^{-2} s^{-1}). When flooded, the wetland was a net CO_2 sink; however, it became a source for both CH_4 and CO_2 when water levels were low. We compared chamber-based gas fluxes from the cove in flooded (July) and dry (August) months to fluxes measured with an eddy covariance tower whose footprint covers flooded portions of the wetland. The diurnal pattern of carbon fluxes at the tower did not vary with changing water levels but remained a CO_2 sink and a CH_4 source even when the cove where we performed the chamber measurements dried out. These results emphasize the role of inundation status on wetland carbon cycling and highlight the importance of fluctuating hydrologic patterns, especially hydrologic drawdowns, under changing climatic conditions.

1. Introduction

Carbon dioxide (CO_2) and methane (CH_4) are potent greenhouse gases whose concentrations are increasing in the atmosphere, contributing to climate change[1]. Natural wetlands are the largest natural source of atmospheric CH_4, contributing 30% of the total global emissions[2], although they only make up 5-8% of land on Earth (7 million km^2) [3,4]. Conversely, wetlands take in large quantities of CO_2, much of which is converted into biomass that ends up stored in wetland sediments, to the extent that 20-30% of global soil organic carbon resides in wetlands[5]. Given this dichotomous functioning, wetlands are often considered both atmospheric carbon sinks and net positive warming sources due to these greenhouse gases[6]. While the directionality of wetland greenhouse gas fluxes is generally understood, the timing and environmental conditions that affect the variability of CO_2 and CH_4 fluxes are still uncertain.

Wetland carbon cycling processes include the uptake and release of carbon by plants, soil microbial biogeochemical processing, and fluid dynamic transport. A large fraction of wetland carbon uptake occurs via photosynthesis[4], and a portion of this carbon is introduced to the soil through detritus accumulation in the sediments and via rhizodeposition[7], constituting a relevant energy source to aerobic and anaerobic microbial metabolic processes, including respiration and methanogenesis[8]. In the presence of oxygen (if available in the sediments), soil carbon can then be mineralized and emitted back to the atmosphere through autotrophic or heterotrophic respiratory metabolic processes[9,10], and CH_4 can be consumed via methanotrophy[11]. If oxygen is not available, CH_4 can be formed via methanogenesis, after which it is emitted to the atmosphere through diffusive concentration gradients in the sediments and water column[12,13], plant transport through aerenchyma and xylem[14,15], and ebullition from sediments[16].

Diurnal and seasonal CO_2 and CH_4 flux patterns covary with and are driven by environmental conditions[6,17]. Temperature and its effects on respiration rates are associated with gas production and fluxes[12,17–20]. Similarly, wetland vegetation experiences regular seasonal cycles (phenology) of growth and senescence, and diurnal dynamics of physiological processes (photosynthesis only occurs with light) control the overall uptake and emission of carbon by plants[21]. As such, CO_2 fluxes are often higher during the afternoon and when plants are at their peak growth, before senescence begins[22]. Likewise, CH_4 flux patterns vary diurnally, often increasing with daytime temperatures and decreasing at night when temperatures are cooler; however, interactive effects with water availability make these trends less certain as drier conditions may also increase CH_4 fluxes as night [23].

Wetland water levels are an additional environmental driver of CO_2 and CH_4 flux variability but, in most non-tidal sites, they do not covary in predictable ways with diurnal cycles[24]. In permanently flooded wetlands, the water elevation, which defines the depth of standing water over wetland soil, affects the rate and direction of carbon emissions. Specifically, there is a higher reduction potential in soil when the water level is high and more oxidizing conditions when the water level is low[25]. Since the rate of oxygen diffusion in water is slower than air[26], a lower water level decreases both the conductance length and time necessary for gas transport between the atmosphere and soil. This allows for more rapid oxygen diffusion into the sediments which facilitates aerobic respiration that leads to the oxidization of dissolved organic carbon and CH_4 to CO_2[27]. Under low water levels, the magnitude of CO_2 emissions tends to be higher and CH_4 emissions lower[18,28]. As water levels rise, CH_4 flux rates may increase[23]. Because wetlands may have varying water levels over the season, they may subsequently alter between being sinks and sources of carbon. Wetlands that transition between wet and dry states have been shown to have greater CH_4 fluxes compared to those that are permanently flooded[29].

At seasonal to interannual time scales, water levels influence vegetation, and the presence or absence of vegetation alters belowground carbon and oxygen inputs as well as transport rates of CH_4 from the soil to the atmosphere. Wetlands support spatially heterogeneous vegetation communities as dominant plant taxa may vary with water depths, and different species adapt to different surface water elevations or water table depths[18]. Vegetated areas tend to uptake more CO_2 during photosynthesis and subsequent rhizodeposition[7,9,10,15] but emit more CH_4 due to aerenchyma transport and root carbon supply. However, the ability of plants to transport carbon is also largely affected by water availability[30]. Thus, it is essential to characterize and quantify the effects that water depth and vegetation presence have on wetland carbon fluxes. Because wetland fluxes are highly heterogenous across space and time, in large part due to the spatiotemporal heterogeneity of water levels and vegetation presence, wetland carbon fluxes are challenging to observe and predict.

In this study, we sought to address this knowledge gap by determining how water levels, wetland inundation status, and the presence of vegetation affect wetland carbon cycling. We used *in situ* chamber observations of daily and seasonal CO_2 and CH_4 fluxes in a temperate freshwater marsh at locations with vegetated and non-vegetated surface coverage and during times with contrasting water levels and flooded or dry/partially flooded soils. We supplemented our chamber-based measurements with nearby continuous observations of wetland meteorological and hydrologic conditions to determine the environmental controls on those fluxes. We predicted that increasing water depths and vegetation presence will increase CH_4 fluxes. Conversely, we predicted that decreasing water depths will increase CO_2 emissions while vegetation presence will increase CO_2 uptake.

2. Methods

2.1 Site location

Old Woman Creek (OWC) National Estuarine Research Reserve (NERR) is a freshwater, estuarine marsh located along the southwest coast of Lake Erie in Huron, OH (Figure 1A; 41°22'39.0"N 82°30'30.5"W). The marsh is intermittently separated from Lake Erie by a narrow, sandy barrier beach that periodically erodes, forming a hydrological connection with the lake until the barrier reforms (Figure 1A). The surface of the marsh is dominated by floating leaf vegetation (i.e., *Nelumbo lutea* [yellow lotus] and *Nymphaea odorata* [water lily]), interspaced by open water (but see Ju and Bohrer[31] for a longer-term view of the vegetation cover composition in the site). An eddy covariance tower is positioned near the center of the northern basin of the wetland (Figure 1A). Much of the work carried out for this study took place in a cove formed at the spill of a tributary creek (Figure 1A-B). In 2022 when the study was conducted, the vegetation in the cove was dominated by *Elymus spp.* and *Lemna spp.*, with roughly 60% of the cove being covered by vegetation and 40% being unvegetated. Throughout the study, fluctuations of water levels caused the cove to experience a period of complete inundation, followed by drying and minimal rewetting, while the main wetland basin remained inundated throughout.

2.2 Data collection

2.2.1 Chamber flux measurement methodology

CO_2 and CH_4 fluxes were measured monthly from July to October across six sites: three vegetated areas and three non-vegetated areas (Figure 1B). Sites were chosen based on vegetation presence and vigor as well as boardwalk accessibility so that the sites would remain as undisturbed as possible for sampling. To measure CO_2 and CH_4 fluxes, we used a portable gas analyzer (Gas Scouter G4301, Picarro Inc., Santa Clara, CA) and the non-steady state headspace chamber approach. The chamber was a clear, acrylic, half dome with a float attached to the outside for floating on the water surface, and the design formed a closed loop, routing through the laser. The chamber had inflow and outflow ports connected to the gas analyzer via 1/8 in inner diameter bev-a-line tubing that recirculates the air. The chamber volume was 0.025 m^3, and the chamber footprint area was 0.164 m^2. An infrared digital thermometer was used to measure chamber temperature at the start and end of each measurement period, and a small electronic fan was used to circulate gas in the chamber to avoid stratification resulting from surface emissions. The barometric pressure was recorded using a watch (Casio SGW-300H). Each measurement was carried out for two minutes, and the two-minute interval began after the chamber was placed on the water surface and carbon concentrations stabilized. The carbon concentrations were recorded at a frequency of ~1 Hz. Data were collected hourly from 7 AM to 7 PM for each monthly measurement campaign. All hours of data collection were in the daylight except 7 AM and 7 PM in October.

2.2.2 Chamber flux analysis

We processed the flux chamber measurements by calculating the accumulation or removal rate of CO_2 or CH_4 in the headspace of the chamber over each individual measurement period. Wetland CH_4 fluxes are often strongly affected by ebullition[16]. To account for the effect of bubbles in each measurement period we used the approach developed by Villa et al[16] (Appendix A). In brief, all 2-minute CH_4 concentration measurements were plotted using MATLAB R2020b (MathWorks, Natick, MA) and visually assessed. Measurements qualitatively determined to lack ebullition (i.e., no sudden jumps in concentration between two subsequent points) were used to calculate a bubble threshold (i.e., the maximum difference in CH_4 concentration between two points in the absence of bubbles). Any instantaneous increase in CH_4 between two 1 Hz measurement points above this threshold in other chambers was considered a bubble, and the concentration increase due to this bubble was subtracted from the concentration-time series following the bubble occurrence time. We then fitted the concertation time series without the bubbles to the Hutchinson-Mosier one-dimensional exponential decay fit[16,32] model to determine the diffusive fluxes for each site (Appendix A). The contribution of ebullition was calculated by adding all the above-threshold concentration jumps during the 2-minute observation period and was added to the diffusive flux. The bubble thresholds were 0.59 ppm s^{-1} in July, 0.078 ppm s^{-1} in August and September, and 0.05 ppm s^{-1} in October. We attribute seasonal differences in the diffusive rate as the reasoning for why the threshold varied by month, possibly including the effects of temperature and water depth fluctuations. Final fluxes for CO_2 and CH_4 were averaged hourly across the three replicates in vegetated and non-vegetated sites to establish estimates for fluxes at a point in time. All flux calculations were performed using MATLAB R2020b (MathWorks, Natick, MA) using code provided by Villa et al[16].

2.2.3 Environmental driver measurements

Measurements of water elevation were obtained from the NERR database (http://cdmo.baruch.sc.edu/) at the OWC sampling location on State Route 6 (SR6; 41°22'57.00

N, 82°30'52.00 W; station ID OWCWMWQ; variable ‘Depth’) (Figure 1A). Because SR6 data were measured in the main channel of the wetland, we used a ground-elevation offset (i.e., 0.97 m) to relate the SR6 water depth to the depth at the chamber measurement locations in the cove. Water depth was converted from numerical to categorical (dry/partially flooded or flooded, Table 1) for statistical analyses.

Dissolved oxygen (DO) concentrations were measured using a Fibox 4 transmitter (PreSens, Regensburg, Germany), PSt3 oxygen dipping probe fiber optic cable (PreSens, Regensburg, Germany), and a Pt100 temperature sensor (PreSens, Regensburg, Germany). At least one DO measurement was taken monthly from July to October at the location of one non-vegetated chamber, and measurements were taken 1 cm beneath the soil surface (Figure 1B, Table 1). Because the DO measurements were not taken at the same time as each chamber measurement, the DO reading that was closest to the date of chamber sampling was recorded (Table 1). The largest temporal offset between the chamber flux measurements and the DO measurements was five days in October.

2.2.4 Eddy covariance tower carbon flux measurements

To evaluate whether cove drying and wetting was the dominant driver of differences between CO_2 and CH_4 in the cove during our measurement period, we compared our diurnal chamber measurements to data collected from an eddy covariance tower whose footprint extent included only flooded parts of the wetland (Figure 1A). Eddy covariance data were obtained from AmeriFlux (site-ID: US-OWC[33]).

Although eddy covariance data were available for most half hours throughout the summer, we specifically used the observed CO_2 and CH_4 fluxes during seven days around each monthly chamber measurement time (Table 1) and during the 12 hours of sampling from 7 AM to 7 PM. We compared the mean diurnal temporal pattern of these seven-day periods with the fluxes observed in our chamber measurements. The 95th percentile of the variation in half-hourly eddy covariance data around the weekly mean diurnal pattern was used to estimate the diurnal uncertainty.

2.3 Statistical analyses of chambers

We used type-3 ANOVA tests[34] to determine if the effects of seasonality (date of sampling converted to day of year [DOY]: 187, 230, 257, 285), DO concentration, water depth, inundation status (completely flooded or dry/partially flooded), time interval (collapsed from hourly into categorical variables: morning [7 AM to 11 AM], afternoon [12 PM to 3 PM], and evening [4 PM to 7 PM]), and vegetation presence (vegetated or unvegetated) on CO_2 and CH_4 fluxes were significant. All variable effects were assumed as fixed effects. DO concentration, water depth, and DOY were correlated (with one DO and water depth measurement recorded per DOY) and thus were modeled separately as one of four (including inundation status) alternative models (Table 2). Each of the four alternative models also included interactions with vegetation and diurnal time interval. Among all significant models, the model with the lowest root mean squared error (RMSE) was assumed to indicate the most direct variable to explain carbon fluxes. For each model, the triple interaction terms were included in the test, and we used the R package emmeans[35] for post-hoc testing to identify which groups were significantly different from each other at alpha = 0.05. All statistical comparisons were performed in R (R Core Team 2021, Vienna, Austria).

3 Results

3.1 *Seasonal and diurnal cycles of fluxes and conditions*

From July to October, 294 total chambers were collected with 146 chambers collected in open water and 148 collected in vegetation. There were 64 chamber collections in July (33 open and 31 vegetated), 78 in August (39 in open and 39 in vegetated), 75 in September (36 in open and 39 in vegetated), and 77 in October (38 in open and 39 in vegetated).

On average, the cove acted as a net CO_2 source with an average flux of 0.4 µmol m^{-2} s^{-1} (range= -8 to 6.2 µmol m^{-2} s^{-1}). A net uptake of CO_2 (negative flux) was measured only in July in vegetated locations (Figure 2A). During all other months, the wetland was a net source of CO_2 in both vegetated and unvegetated areas, though, in some months and most times of day, vegetated patches had a significantly lower net CO_2 flux rate (Figure 2A-B). Net CO_2 uptake was observed in vegetated patches in the afternoon, but during the morning and evening, regardless of vegetation and month, the net CO_2 fluxes were positive (Figure 2B).

The cove was also a net source of CH_4 with an average flux of 0.11 µmol m^{-2} s^{-1} (range= -0.2 to 3.5 µmol m^{-2} s^{-1}). CH_4 fluxes were higher in July than in other months in both vegetated and non-vegetated patches, and during July, they were highest in vegetated patches (Figure 2C). There were no significant differences in CH_4 fluxes among all other months and vegetation status (vegetated or non-vegetated; Figure 2C). Time of day (diurnal time interval) affected CH_4 fluxes but only with vegetation interactions as there were greater fluxes in earlier hours compared to the evening with plant presence (Figure 2D).

Water depth in the cove and inundation status changed during the observation period, with the highest water depths occurring in July (0.23 m; fully flooded) and the lowest in August, September, and October (-0.15, 0.1, and 0.02 m, respectively; or dry/partially flooded). Changes in water depths affected oxygen concentrations. Specifically, when water depths were low from

August to October, DO concentrations were higher, and when water depths were higher in July, DO concentrations were lower (Table 1).

From a series of linear models predicting CO_2 and CH_4 flux rates from different combinations of temporally covarying environmental conditions, the model including inundation status as a factor provided the best prediction of both carbon fluxes (Table 2). Post-hoc pairwise comparison tests for Model 4 demonstrated that significant drivers of CO_2 flux were inundation status, time interval, vegetation presence, inundation status × vegetation, and time interval × vegetation ($P < 0.05$; Table 3). Comparatively, all predictor variables except inundation status × time interval affected CH_4 fluxes, including time interval alone ($P = 0.048$; Table 3).

When water levels were at their highest in July, CO_2 fluxes were at their lowest, and CH_4 fluxes were at their highest. When the cove dried out in August and partially reflooded in September and October, CO_2 fluxes then increased while CH_4 fluxes decreased (Figure 3). Though DO concentration was a weaker predictor of carbon fluxes compared to inundation status (Table 2), when DO concentrations were at their lowest in July, coinciding with the highest water levels, CO_2 fluxes were at their lowest, and CH_4 fluxes were at their highest. Conversely, when DO concentrations were higher, CO_2 fluxes were higher, and CH_4 fluxes were lower (Figure 3).

3.2 Comparison of diurnal carbon fluxes between chamber and eddy covariance tower

We compared the diurnal profile from the eddy covariance tower whose footprint measures the flux from the main basin of the wetland, which was flooded throughout the observation period, to those measured in the cove by the chambers (flooded in July but dry in August). We observed that the measured tower fluxes indicated that the main basin of the wetland was a CO_2 source both before and after the cove dried. Conversely, we observed a functional shift in the cove from being a CO_2 sink to a source over the same time span (Figure 4A-B). Thus, the cove had higher CH_4 fluxes when flooded in July and lower fluxes when dry in August, while the CH_4 fluxes measured by the tower were similar levels over both months, with neither month showing a strong diurnal trend (Figure 4C-D).

4 Discussion

Inundation status (flooded or dry/partially flooded) was the most tightly correlated driver of carbon gas fluxes at OWC, when compared to DOY, water level, and DO concentration. Inundation status was also the most likely to be selected due to having fewer possible states (wet or dry as opposed to four different continuous variable states available to the other three variables). It's selection here suggests that the binary flooded or dry/partially flooded status of the wetland has an even stronger effect than might otherwise be inferred from the four tested models. This signifies that the presence or absence of an above-soil water table, and therefore the switching of states due to hydrologic drawdown or reflooding, better explains carbon fluxes compared to varying water depths. This finding is supported by other studies which found that once soils were already inundated, subsequent changes in water level did not explain CH_4 flux as effectively as a dry vs flooded soil status[19,36,37].

Even though DOY and DO concentrations did not drive carbon fluxes as strongly as water inundation status, they were still correlated with flux patterns. We interpret our results to indicate that this correlation is due to the covariance with inundation status. Similar to other studies[18,38,39], we found that when water levels were low, leading to a smaller water barrier between the atmosphere and sediment, there was more DO in surface sediments. Consequently, there were greater CO_2 and less CH_4 fluxes from August to October, the months with the lowest water levels. Conversely, when water levels were high in July, there was less DO in surface sediments and a greater CH_4 flux since more anoxic soils increase methanogenesis and decrease rates of CH_4 oxidization by microbes[18,38]. The role of inundation status on carbon fluxes is supported by the fact that when the main channel remained flooded during July and August, CO_2 and CH_4 fluxes were relatively constant in that area.

Changes in water levels and inundation are shaped by variation in river inflow rate and by the coastal wetland's barrier beach naturally breaking and reforming, facilitating the movement of wetland water to and from Lake Erie. During our sampling period, the barrier beach opened on 26 July and closed again 14 August (Appendix B). When opened, water from the wetland drained into Lake Erie, lowering water levels throughout the wetland and causing drying in the cove. As such, this barrier presence or absence highly dictated hydrologic drawdown and subsequent greenhouse gas emission potential in the wetland.

In addition to inundation status, carbon fluxes were also correlated with time of day and the presence or absence of vegetation. The diurnal effects on CO_2 fluxes were anticipated because plants uptake CO_2 during photosynthesis, and CO_2 fluxes grow more negative during times of greater photosynthetic activity[20], particularly in the mid-day when radiation is at its peak. In contrast, the flux of CH_4 lacked strong diurnal patterns and was consistently emitted to the atmosphere regardless of time of day, which has been similarly observed in a previous study[21]. Wetlands typically have large amounts of organic matter in submerged, anoxic environments, and it was expected that the wetland would always be a net source of CH_4 to the atmosphere. While some diurnal variation in CH_4 fluxes has been previously shown with higher fluxes during the daytime[17,40], the relationship between time of day and CH_4 fluxes is weaker than that for CO_2. While there were no consistent temporal effects across day, we did find strong spatial variation of CH_4 fluxes where vegetated sites emitted more CH_4 than unvegetated ones. This is likely due to plant aerenchyma functioning as a conduit for CH_4 transport from sediments to the atmosphere[14,15] and the production of CH_4 from decaying plant material in anaerobic sediments[41]. Prior studies have also shown that different plant species and functional types can mediate CH_4 transport at different rates.[21] Importantly, since the barrier beach between the wetland and Lake Erie drove inundation status in the wetland, it may also have affected plant productivity if plants became water limited[42]. This may have been the case in July when the wetland was flooded and the vegetated sites were CO_2 sinks, compared to August to October when vegetated sites were net positive sources of CO_2 and CH_4.

Limitations and Considerations

While our study shows the influence of water depth and inundation on carbon fluxes, we acknowledge that there are temporal considerations that we were not able to characterize. For instance, we collected data monthly from July to October and hourly for 12 hours. By mainly collecting data during the day, we were only able to calculate carbon fluxes during photosynthetic periods and during warmer day temperatures. However, wetlands emit CH_4 and CO_2 during the night, and cooler temperatures decrease the rate of microbial activity and methanogenesis[20]. Thus, relationships between CO_2 and CH_4 fluxes with the covarying site conditions remain unexplored, and microbial activity, which was not examined in this study, should be assessed in the future via integration of genomic, transcriptomic, and proteomic methods to understand its effects on carbon fluxes. Moreover, studying fluxes over the year to obtain comprehensive seasonal variation would improve our understanding of carbon flux processes. Specifically, prior research showed that CH_4 fluxes varied over growing and non-growing seasons, and higher soil and water temperatures increased flux rates, likely due to faster microbial processes[17,20,43].

Nevertheless, we believe our results have implications for wetland carbon fluxes. Particularly, as climate change alters precipitation patterns, sometimes reducing it, hydrologic drawdown may occur, leading to the decline of the areal extent and wetted perimeter of wetlands and thus causing peripheral drying[39]. With hydrologic drawdowns, we would anticipate a loss in carbon sequestration potential[44] and a decrease in CH_4 emissions from the newly dried-out soil at wetland boundaries. However, when water elevation decreases, the wetland edges may dry while the interior of the wetland may remain flooded and, subsequently, may not respond to drivers in a similar fashion. Furthermore, longer durations of inundation increase CH_4 emissions[19], and the mass and shape of wetland vegetation and plant aerenchyma size, which is affected by water regime, can affect the capacity of plants to transport carbon[41,45]. Hydrologic drawdowns may also support macrophyte colonization, which would increase CO_2 uptake[18]. Eventually, consistent wetland drying may permit terrestrial vegetation to seed and grow in an area that was once uninhabitable for upland species[18].

5 Conclusion

Water inundation status is a master driver of net wetland greenhouse gas emission and sequestration potential, with flooded soils leading to more CH_4 emissions and drier soils supporting greater CO_2 emissions. When soil conditions are dry, CO_2 fluxes increase due to oxygen exposure, and CH_4 fluxes decrease. However, areas with vegetation have higher rates of

CH_4 emissions due to plant-facilitated gas transport. Regardless of the fluctuating changes in water level, the wetland was a net source for both CO_2 and CH_4 during the study. As climate change alters precipitation patterns and inundation regimes, patterns of carbon emissions from wetlands will continue to change.

Abbreviations

CH_4- methane

CO_2- carbon dioxide

DO- dissolved oxygen

SR6- State Route 6

OWC- Old Woman Creek

NERR- National Estuarine Research Reserve

Acknowledgements

We would like to acknowledge the help of John Carnevali and Shelby Martin who were essential in assisting the collection of chamber measurement data. We would also like to thank Janice Kearns and the OWC staff for use of their facilities and accommodating us as we carried out the research. This research was funded by the Department of Energy and Division of Biological and Environmental Research, awards number DE-SC0022191, DE-SC0023084 and DE-SC0021067. Funding for US-OWC AmeriFlux core site was provided by the U.S. Department of Energy's Office of Science.

Data Availability

Eddy covariance and meteorological data are available through AmeriFlux:

Site ID: US-OWC.

Site info: https://ameriflux.lbl.gov/sites/siteinfo/US-OWC

Data: https://doi.org/10.17190/AMF/1418679.https://doi.org/10.17190/AMF/1418679.

Additional meteorological and water elevation data for Old Woman Creek are available through the NERR data interface: https://cdmo.baruch.sc.edu/. Data for chamber measurements and DO are available through the ESS-DIVE repository: https://data.ess-dive.lbl.gov/datasets/doi:10.15485/2229438. Codes are available through the public Github repository: https://github.com/erhasset/Old-Woman-Creek-Soil-Respiration

References

1. Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. (2021) doi:10.1017/9781009157896.
2. Zhang, Z. et al. Emerging role of wetland methane emissions in driving 21st century climate change. Proceedings of the National Academy of Sciences **114**, 9647–9652 (2017).
3. Mitsch, W. J. & Gosselink, J. G. Wetlands. (Wiley, 2007).
4. Mitsch, W. J. et al. Wetlands, carbon, and climate change. Landscape Ecol **28**, 583–597 (2013).
5. Lal, R. Carbon sequestration. Philosophical Transactions of the Royal Society B: Biological Sciences **363**, 815–830 (2008).
6. Morin, T. H. et al. Environmental drivers of methane fluxes from an urban temperate wetland park. Journal of Geophysical Research: Biogeosciences **119**, 2188–2208 (2014).
7. Gougoulias, C., Clark, J. M. & Shaw, L. J. The role of soil microbes in the global carbon cycle: tracking the below-ground microbial processing of plant-derived carbon for

manipulating carbon dynamics in agricultural systems. J Sci Food Agric **94**, 2362–2371 (2014).

8. Hatala, J. A., Detto, M. & Baldocchi, D. D. Gross ecosystem photosynthesis causes a diurnal pattern in methane emission from rice. Geophysical Research Letters **39**, (2012).
9. Hanson, P. J., Edwards, N. T., Garten, C. T. & Andrews, J. A. Separating root and soil microbial contributions to soil respiration: A review of methods and observations. Biogeochemistry **48**, 115–146 (2000).
10. Lak, Z. A., Sandén, H., Mayer, M. & Rewald, B. Specific root respiration of three plant species as influenced by storage time and conditions. Plant Soil **453**, 615–626 (2020).
11. Bridgham, S. D., Cadillo-Quiroz, H., Keller, J. K. & Zhuang, Q. Methane emissions from wetlands: biogeochemical, microbial, and modeling perspectives from local to global scales. Global Change Biology **19**, 1325–1346 (2013).
12. Torres-Alvarado, R., Ramírez-Vives, F., Fernández, F. J. & Barriga-Sosa, I. Methanogenesis and methane oxidation in wetlands: Implications in the global carbon cycle. Hidrobiológica **15**, 327–349 (2005).
13. Morin, T. H. et al. Carbon dioxide emissions from an oligotrophic temperate lake: An eddy covariance approach. Ecological Engineering **114**, 25–33 (2018).
14. Whalen, S. c. Biogeochemistry of methane exchange between natural wetlands and the atmosphere. Environmental Engineering Science **22**, 73–94 (2005).
15. Brix, H., Sorrell>, B. K. & Orr, P. T. Internal pressurization and convective gas flow in some emergent freshwater macrophytes. Limnology and Oceanography **37**, 1420–1433 (1992).

16. Villa, J. A. et al. Ebullition dominates methane fluxes from the water surface across different ecohydrological patches in a temperate freshwater marsh at the end of the growing season. Science of The Total Environment **767**, 144498 (2021).

17. Morin, T. H. et al. The seasonal and diurnal dynamics of methane flux at a created urban wetland. Ecological Engineering **72**, 74–83 (2014).

18. Morin, T. H. et al. Water level changes in Lake Erie drive 21st century CO2 and CH4 fluxes from a coastal temperate wetland. Science of the Total Environment **821**, 153087 (2022).

19. Hondula, K. L., Jones, C. N. & Palmer, M. A. Effects of seasonal inundation on methane fluxes from forested freshwater wetlands. Environ. Res. Lett. **16**, 084016 (2021).

20. Tsai, C.-P., Huang, C.-M., Yuan, C.-S. & Yang, L. Seasonal and diurnal variations of greenhouse gas emissions from a saline mangrove constructed wetland by using an in situ continuous GHG monitoring system. Environ Sci Pollut Res **27**, 15824–15834 (2020).

21. Villa, J. A. et al. Plant-mediated methane transport in emergent and floating-leaved species of a temperate freshwater mineral-soil wetland. Limnology and Oceanography **65**, 1635–1650 (2020).

22. Joshi, B. B. et al. Seasonal and diurnal variations of carbon dioxide and energy fluxes over three land cover types of Nepal. Theor Appl Climatol **139**, 415–430 (2020).

23. Bansal, S., Tangen, B. & Finocchiaro, R. Diurnal Patterns of Methane Flux from a Seasonal Wetland: Mechanisms and Methodology. Wetlands **38**, 933–943 (2018).

24. Villa, J. A. et al. Relationships between methane and carbon dioxide fluxes in a temperate cattail-dominated freshwater wetland. Journal of Geophysical Research: Biogeosciences **124**, 2076–2089 (2019).

25. Wang, J., Bogena, H. R., Vereecken, H. & Brüggemann, N. Characterizing redox potential effects on greenhouse gas emissions induced by water-level changes. Vadose Zone Journal **17**, 170152 (2018).

26. Chapman, S. K., Hayes, M. A., Kelly, B. & Langley, J. A. Exploring the oxygen sensitivity of wetland soil carbon mineralization. Biol Lett **15**, 20180407 (2019).

27. Elberling, B. et al. Linking soil O2, CO2, and CH4 concentrations in a wetland soil: implications for CO2 and CH4 fluxes. Environ. Sci. Technol **45**, 3393–3399 (2011).

28. Askaer, L., Elberling, B., Friborg, T., Jørgensen, C. J. & Hansen, B. U. Plant-mediated CH4 transport and C gas dynamics quantified in-situ in a Phalaris arundinacea-dominant wetland. Plant Soil **343**, 287–301 (2011).

29. Bansal, S., Tangen, B. & Finocchiaro, R. Temperature and Hydrology Affect Methane Emissions from Prairie Pothole Wetlands. Wetlands **36**, 371–381 (2016).

30. Riutta, T., Korrensalo, A., Laine, A. M., Laine, J. & Tuittila, E.-S. Interacting effects of vegetation components and water level on methane dynamics in a boreal fen. Biogeosciences **17**, 727–740 (2020).

31. Ju, Y. & Bohrer, G. Classification of wetland vegetation based on NDVI time series from the HLS dataset. Remote Sensing **14**, 2107 (2022).

32. Hutchinson, G. L. & Mosier, A. R. Improved soil cover method for field measurement of nitrous oxide fluxes. Soil Science Society of America Journal **45**, 311–316 (1981).

33. AmeriFlux BASE US-OWC Old Woman Creek. AmeriFlux https://ameriflux.lbl.gov/doi/AmeriFlux/US-OWC/.

34. Arnhold, E. Package in the R environment for analysis of variance and complementary analyses. Braz. J. Vet. Res. Anim. Sci. **50**, 488–492 (2013).

35. Russell V. Lenth, Ben Bolker, Paul Buerkner, Iago Giné-Vázquez, Maxime Herve, Maarten Jung, Jonathon Love, Fernando Miguez, Hannes Riebl, Henrik Singmann. R package emmeans: Estimated marginal means.

36. Morin, T. H. Advances in the eddy covariance approach to CH4 monitoring over two and a half decades. Journal of Geophysical Research: Biogeosciences **124**, 453–460 (2019).

37. Knox, S. H. et al. FLUXNET-CH4 synthesis activity: objectives, oobservations, and future directions. Bulletin of the American Meteorological Society **100**, 2607–2632 (2019).

38. Schrier-Uijl, A. P., Veraart, A. J., Leffelaar, P. A., Berendse, F. & Veenendaal, E. M. Release of CO2 and CH4 from lakes and drainage ditches in temperate wetlands. Biogeochemistry **102**, 265–279 (2011).

39. Altor, A. E. & Mitsch, W. J. Pulsing hydrology, methane emissions and carbon dioxide fluxes in created marshes: A 2-year ecosystem study. Wetlands **28**, 423–438 (2008).

40. Rey-Sanchez, A. C., Morin, T. H., Stefanik, K. C., Wrighton, K. & Bohrer, G. Determining total emissions and environmental drivers of methane flux in a Lake Erie estuarine marsh. Ecological Engineering **114**, 7–15 (2018).

41. Wassmann, R. & Aulakh, M. S. The role of rice plants in regulating mechanisms of methane missions. Biol Fertil Soils **31**, 20–29 (2000).

42. Chivers, M. R., Turetsky, M. R., Waddington, J. M., Harden, J. W. & McGuire, A. D. Effects of experimental water table and temperature manipulations on ecosystem CO2 fluxes in an Alaskan rich fen. Ecosystems **12**, 1329–1342 (2009).

43. Sha, C. et al. Methane emissions from freshwater riverine wetlands. Ecological Engineering **37**, 16–24 (2011).

44. Hopkinson, C. S., Cai, W.-J. & Hu, X. Carbon sequestration in wetland dominated coastal systems—a global sink of rapidly diminishing magnitude. Current Opinion in Environmental Sustainability **4**, 186–194 (2012).

45. Suralta, R. R. & Yamauchi, A. Root growth, aerenchyma development, and oxygen transport in rice genotypes subjected to drought and waterlogging. Environmental and Experimental Botany **64**, 75–82 (2008).

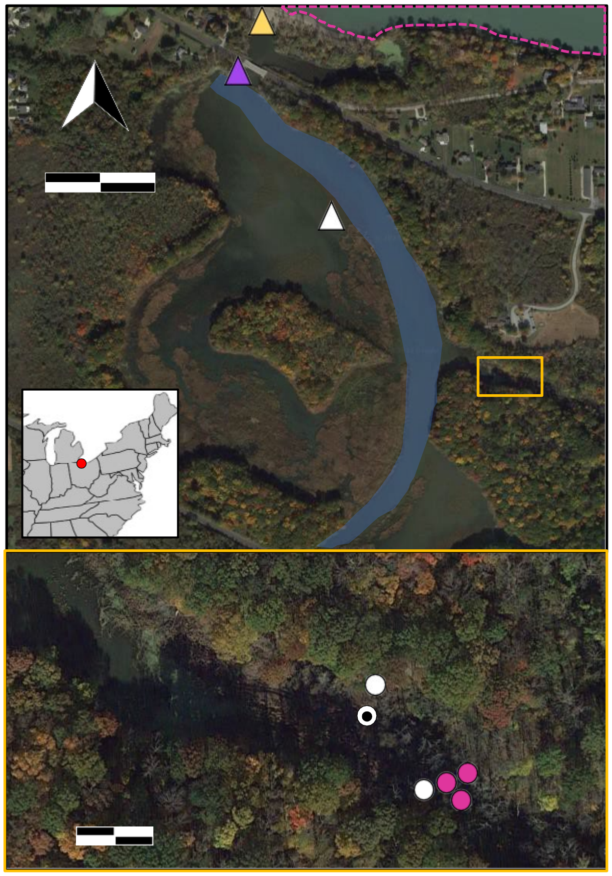


Figure 1. Old Woman Creek National Estuarine Research Reserve. A) (top) The location of OWC estuary in Ohio, USA and the main channel (shaded blue area), highlighting the cove (yellow box), the beach barrier (yellow triangle) that separates Lake Erie (delineated by dashed pink line) from OWC, the eddy covariance tower location (white triangle), and the water depth sampling location (purple triangle). B) (bottom) Sampling sites in the cove showing vegetated (pink circles) and non-vegetated (white circles) chamber locations. Monthly DO concentration measurements were taken at one of the open water chamber sites (black dot within white circle).

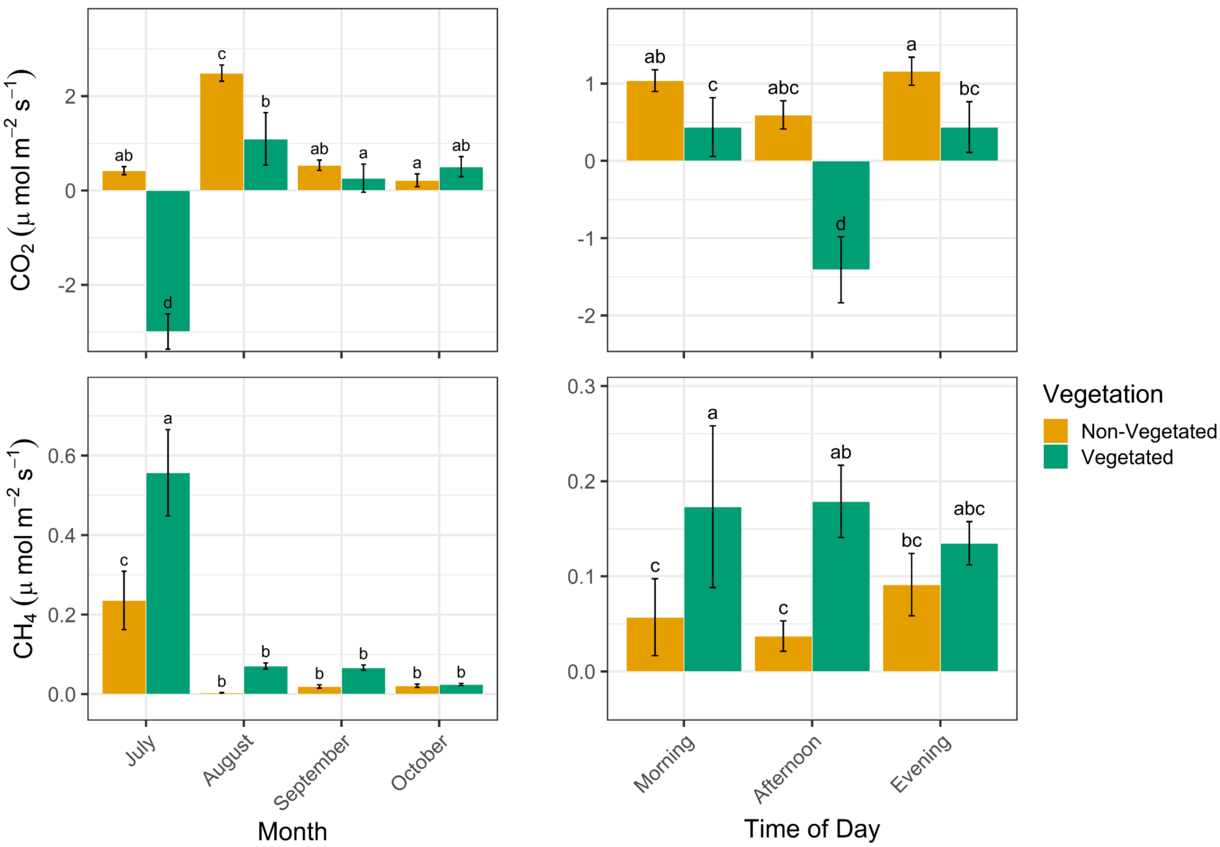


Figure 2. Interactive effects of month, vegetation status, and time interval on CO_2 and CH_4 fluxes. A) The effect of month and vegetation on CO_2 flux. B) The effect of time interval and vegetation on CO_2 flux. C) The effect of month and vegetation on CH_4 flux. D) The effect of time interval and vegetation on CH_4 flux. Letters denote linear model significance from type-3 ANOVA at P <0.05. Bars represent the standard error of the data.

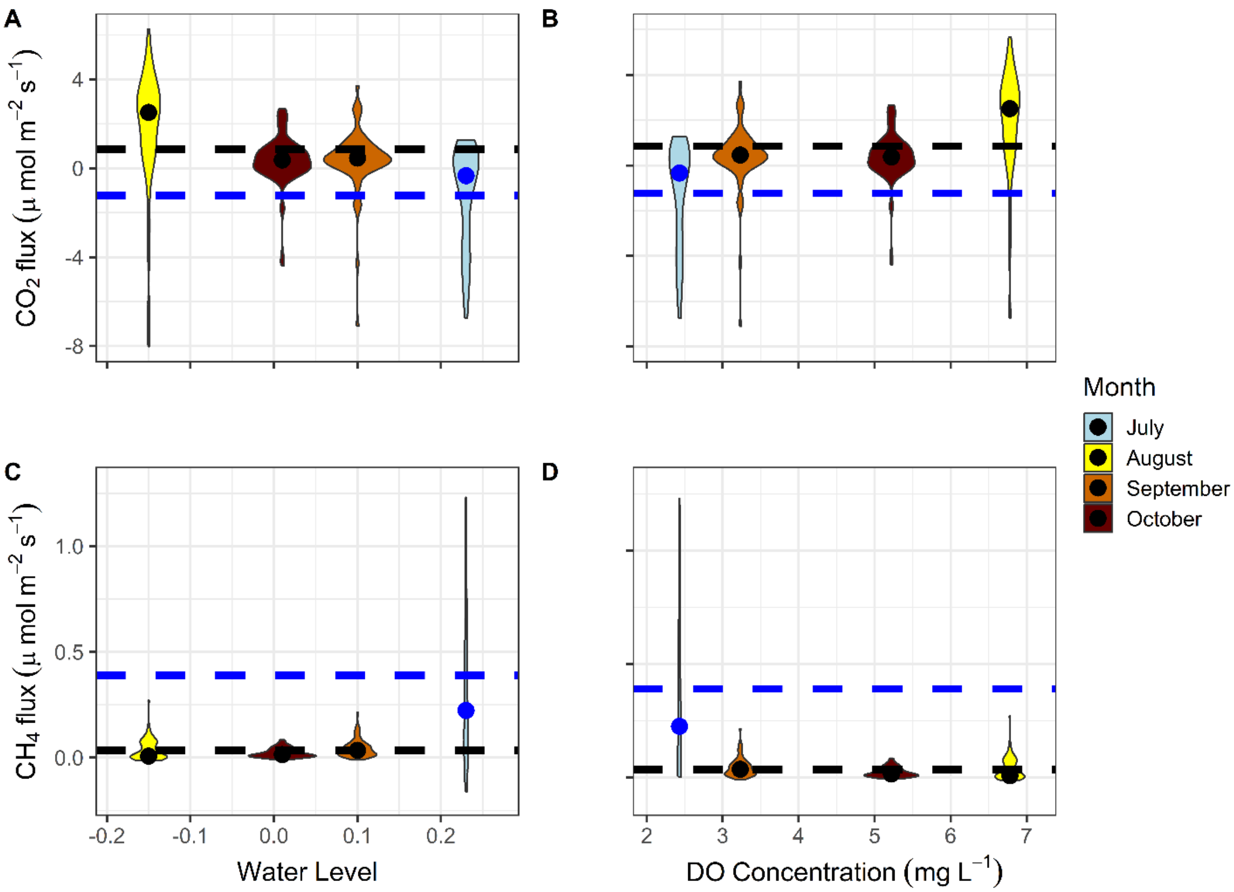


Figure 3. Water level and DO concentration effects on carbon flux. The violin plots show the spread of carbon flux data points at each water level and DO concentration. Blue violins (and blue dot marking the medians) represent when the cove was completely flooded (July only) while all other violins (and black dots marking the medians) represent when the cove was dry/partially flooded. The black dashed line shows the mean carbon flux (CO_2 and CH_4 in upper and lower panels, respectively) during the dry/partially flooded months, while the blue dashed line shows the mean carbon flux during the flooded month of July.

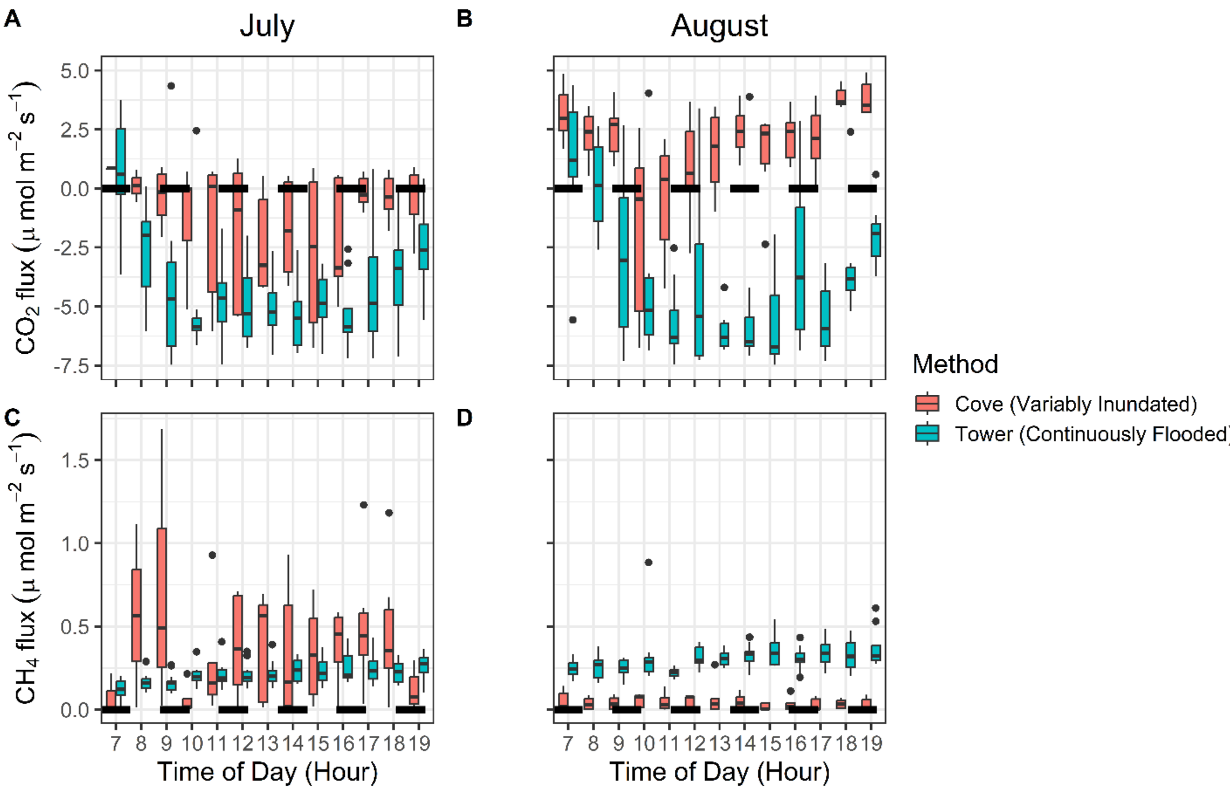


Figure 4. Comparison of carbon fluxes from chamber measurements (pink) in the cove and eddy covariance tower measurements (blue) in the flooded open water channel from 7 AM to 7 PM. The black dashed line indicates carbon fluxes at 0 μmol m^{-2} s^{-1}. A) CO_2 flux measurements in July. B) CO_2 flux measurements in August. C) CH_4 flux measurements in July. B) CH_4 flux measurements in August. Box and whisker plots represent quartiles of the data. For chamber measurements, n=64 in July and n=78 in August for both CO_2 and CH_4. For the tower measurements, n=18 in July and August for both CO_2 and CH_4.