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Thesis of
Jordan Page

Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science
Marine Science

Nova Southeastern University
Halmos College of Arts and Sciences

December 2022

Approved:
Thesis Committee

Committee Chair: Tyler Cyronak

Committee Member: Timothy Swain

Committee Member: Dorothy Renegar

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NOVA SOUTHEASTERN UNIVERSITY
HALMOS COLLEGE OF ARTS AND SCIENCES

Spatial Variability of Greenhouse Gases in Blue Carbon Mangrove Ecosystems

By
Jordan Page

Submitted to the Faculty of Halmos College of Arts and Sciences in partial fulfillment of the requirements for the degree of Master of Science

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Approved Thesis Committee:

Tyler Cyronak

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Dorothy Renegar

Abstract

Blue carbon ecosystems, including mangrove forests, play a vital role in the global carbon cycle through their carbon sequestration and storage capabilities. Mangrove trees remove CO_2 from the atmosphere and store it within these ecosystems. Buildup of organic matter also contributes to high production of methane that is eventually released to adjacent coastal systems and to the atmosphere through air sea gas exchange. It is necessary to investigate environmental conditions that drive greenhouse gas fluctuations to understand how they will change due to climate change and ocean acidification impacts. The goal of this study is to investigate the spatial variability of Greenhouse gas concentrations throughout different areas of a mangrove system and identify environmental changes that coincide with greenhouse gas fluxes. Continuous surveys were conducted throughout two different sites of a mangrove forest in Hollywood, Florida to measure CO_2, CH_4, dissolved oxygen, temperature, and salinity. CO_2 and CH_4 fluxes were positively correlated in both survey locations, emphasizing that both greenhouse gasses are driven by similar factors. Dissolved oxygen showed a strong negative correlation with CO_2 and CH_4 in both sites, indicating oxygen depletion due to high primary productivity rates. Surface water temperatures and salinity had a positive relationship with both greenhouse gases, indicating longer water residency times are associated with increased water temperatures and greenhouse gas concentrations. Potential factors such temperature, salinity, and dissolved oxygen can be used to further investigate the spatial variability of greenhouse gas concentrations throughout mangrove systems.

Keywords Mangrove forest - Blue carbon ecosystems - Carbon dioxide - Methane - Climate change - Ocean acidification

Acknowledgements

I would like to express my deepest appreciation to Tyler Cyronak for advising this project and being a mentor to me during this journey. Your endeavors to help modify my project anytime complications arose, and time dedicated towards editing my results allowed me to be successful. I am also grateful for the other members of my committee- Dorothy Renegar and Timothy Swain. Thank you for the time you took to edit my writing and discuss your feedback on the project. I'd also like to acknowledge my fellow lab members that helped me in the field and encouraged me along the way.

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Introduction

Mangrove forests line coasts around the world, providing shoreline protection with stable roots, aquatic nurseries, and valuable resources for the surrounding environment and local communities. The values and resources mangrove forests support are extensive, contributing billions of dollars worldwide to local economies (Mendez, 2020). Mangrove forests play a valuable role in the global carbon cycle due to their carbon sequestration and storage capabilities (Friess et al., 2020). They are known as natural carbon sinks due to their ability to sequester and store CO_2 from the atmosphere for extended periods of time (Ray, 2017). Recent investigations have revealed how vast mangrove sequestration is compared to terrestrial forests (Friess et al., 2020). It has been reported that mangrove forests are capable of sequestering ~10 times more carbon than terrestrial forests (Santos, 2021), and bury roughly 14% of the total organic carbon sequestered per year globally (Alongi, 2020). This has increased interest in "blue carbon" research, carbon sequestered from the atmosphere within marine ecosystems.

As greenhouse gas (GHG) emissions continue to increase, research has reported that CO_2 emissions from fossil fuel combustion contributes about 78% of total GHG emissions (Ray, 2017). To help offset these emissions, environmental policy makers have started to develop plans to help reach carbon neutrality through offset projects. There has been recent importance placed on global carbon budgets, proposed by Bouillon (Bouillon, 2008) due to climate change effects. Carbon budgets highlight that 50% of mangrove primary production is not accounted for (Bouillon, 2008). The two main issues that have led to short comings in carbon budgets are limited information and complex biological processes that occur within wetland environments (Bouillon, 2008). This emphasizes the value of accurate global carbon budgets to fully understand storage capabilities of blue carbon systems. To create accurate carbon budgets, carbon sequestration and transportation must continue to be investigated in local blue carbon ecosystems.

Mangrove trees thrive in intertidal areas of the coast where conditions are constantly changing due to tidal fluctuations (Adam and Lovelock, 2010). As the tide rises and falls throughout the day, solutes within the water are laterally transported in and out of the system (Adam and Lovelock, 2010). This affects greenhouse gasses and dissolved oxygen as water infiltrates the sediment as well as outwelled to surrounding water bodies. The circulation of tidal water replenishes oxygen within the first few millimeters of sediment. Deeper below the surface, a buildup of organic matter creates muddy sediment with anoxic conditions due to the depletion of oxygen. The vast buildup of organic matter that makes mangrove forests major carbon sinks is due to high levels of primary productivity (Gu, 2022). High primary productivity fosters an environment for various biological processes to occur within blue carbon ecosystems (Gu, 2022).

The same qualities that make mangrove forests an ideal environment for carbon sequestration to occur are what make it ideal for methanogenesis: rich organic matter and anoxic conditions (Al-Haj, 2020). Methanogenesis usually only occurs in anoxic environments where the redox potential of sediment must dip below -150 mv (Dutta, 2013). When these specific conditions are met, methane gas is dissolved within sediment porewater and ultimately discharged to the surface, infiltrating adjacent surface water systems (Dutta, 2013). Wetland ecosystems, including mangroves, are considered one of the largest natural sources of atmospheric CH_4 (Rosentreter, 2021). It is important to consider CH_4 emissions when quantifying greenhouse gas emissions in blue carbon ecosystems since CH_4 is a major GHG with higher global warming potential (GWP) than CO_2 (Dutta, 2013). Although methane has a higher GWP, it has a lower residency time than CO_2 so its impacts decrease relatively quickly compared to CO_2 (Rosentreter, 2021).

Seasonal and daily tidal cycles cause short term changes in environmental conditions such as salinity, temperature, water depth, and dissolved oxygen levels (Dubac, 2019). Mangrove systems experience extremely variable conditions from tidal fluctuations that affect the presence of greenhouse gasses within the system (Taillerdat, 2018). High tidal ranges significantly increase the magnitude of seawater circulation. At high tide, water comes into the system and infiltrates the sediment. Then during low tide, the saturated porewater is discharged to adjacent water bodies through tidal pumping (Alongi, 2020).

Tidal pumping from groundwater is also considered a major source of carbon emissions to surrounding coastal waters (Cabral, 2021). Greenhouse gasses can be stored underground through submarine groundwater and eventually can be discharged to surface waters (Macklin, 2014). When greenhouse gasses are emitted in coastal areas, the increased surface water concentrations influence biological processes occurring within the system. Groundwater discharge links dissolved material, such as GHG's, in intertidal sediments to surface waters and eventually the global ocean (Macklin, 2014). Groundwater discharge hotspots can be traced by observing variable changes in GHG concentrations within mangrove forests.

Carbon loading and respiration rates that occur in mangrove ecosystems influences the uptake of dissolved oxygen during tidal flooding. High respiration rates result in anoxic conditions that lead to high oxygen demands within the forest (Mattone, 2017). This results in significant oxygen depletion as tidal water floods the forest (Mattone, 2017). Dissolved oxygen (DO) levels tend to vary throughout different parts of the forest due to the spatial variability of mangrove systems. Past literature suggests DO levels tend to be higher near tidal sources and gradually decrease moving farther into the forest due to biological activity utilizing the oxygen (Mattone, 2017). It is also known that water temperature and salinity influence the dissolution of oxygen (Prabu, 2007). Waters that exhibit lower surface temperatures hold more dissolved oxygen than warmer waters (Prabu, 2007). As salinity levels increase, the number of non-polar oxygen molecules in the water decreases due to natural bonding with water molecules (Prabu, 2007).

Salinity and surface water temperatures both factor into the ability of water to dissolve carbon dioxide and oxygen (Prabu, 2007). Therefore, it is necessary to understand salinity and temperature variations within mangrove ecosystems to reveal drivers of GHG fluxes. Surface water temperatures are highly influenced by solar radiation and influx of water from other sources such as precipitation, groundwater, and tidal flooding (Prabu, 2007). Higher levels of precipitation lead to decreased water temperatures. Changes in salinity can be due to an influx of water from precipitation or tidal variations (Prabu, 2007). This can also infer a positive relationship between surface water temperatures and salinity. Observing changes in these environmental conditions is necessary to accurately reveal patterns in GHG fluctuations.

The complexity of mangrove ecosystems makes it difficult to gain a complete understanding of carbon dynamics and GHG transportation. Understanding the spatial variability of greenhouse gases is important to properly preserve these ecosystems from degradation. If mangrove carbon stocks are disturbed, large amounts of stored carbon and other GHG's will be emitted to surface waters and ultimately contribute to ocean acidification and climate change (Friess, 2020). Tidal changes and outwelling transport these emitted GHG's to adjacent coastal systems and eventually the open ocean or atmosphere through air-sea gas exchange (Friess, 2020).

Experimental Question

This project focuses on measuring greenhouse gas concentrations in mangrove forests to investigate their drivers and spatial variation. The spatial variability of GHG's within a blue carbon mangrove forest were observed through continuous surveys, connecting concentration measurements with coordinate points to create semi-quantitative maps. I also performed correlation analyses to understand the relationships between environmental parameters. Investigating the main factors that drive GHG fluctuations in mangrove forests provides information about the role these systems play in the global carbon cycle.

Materials and Methods

Survey Sites

Two mangrove forest locations were used in Hollywood Florida to carry out continuous surveys. West Lake and Whiskey Creek were both chosen to give more insight into different spatial variations that occur within these two mangrove systems. The local climate of Hollywood Florida is humid with warm temperatures and frequent rainstorms. The most dominant mangrove species in both West Lake and Whiskey Creek are Red mangroves (*Rhizophora mangle*), Black mangroves (*Avicennia Germinans*), and White mangroves (*Laguncularia racemosa*). These survey locations give a broader view of how concentrations change throughout different areas of a mangrove forest. To reveal spatial variability of GHG concentration within the system, surveys were conducted throughout narrow passages, tidal creeks, and along the shoreline of large water bodies.

The first survey was conducted in West Lake, a tidally influenced mangrove forest located Hollywood Florida. West Lake Park (26°02’40.67” N, 80°07’24.08” W) is situated on the western side of the Intracoastal Waterway (IC). This dense forest covers about 4.6 km^2 with mangroves skirting the shorelines on both sides of West Lake. Figure 1 displays the extent of the lake and surrounding ecosystem. The white marker at the southern edge of the lake pinpoints the main inlet that directly connects the IC and West Lake.

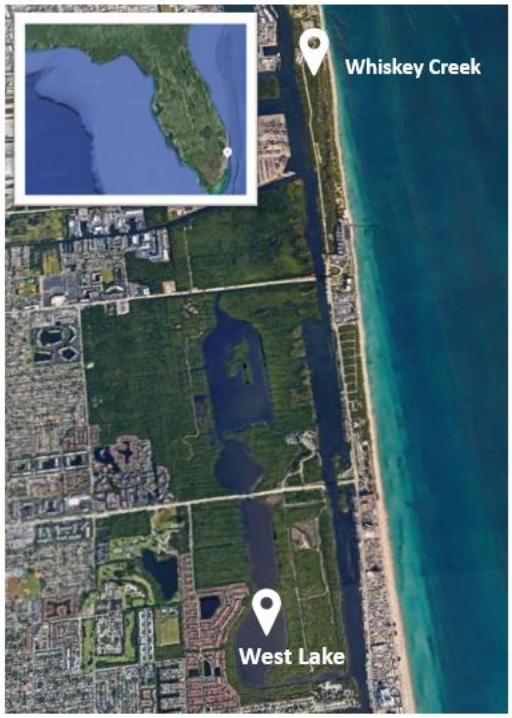

Figure 1- Satellite map of mangrove forest in Hollywood, Florida that extends from West Lake Park to Dr. Von Mizell-Eula Johnson state park where Whiskey Creek is located. The top left satellite image pinpoints where the mangrove forest located.

Surveys were conducted using the route highlighted in red on Figure 2. Surveys in West Lake started at the kayak launch and ran along the shoreline of the entire lake ending at the same launch location.

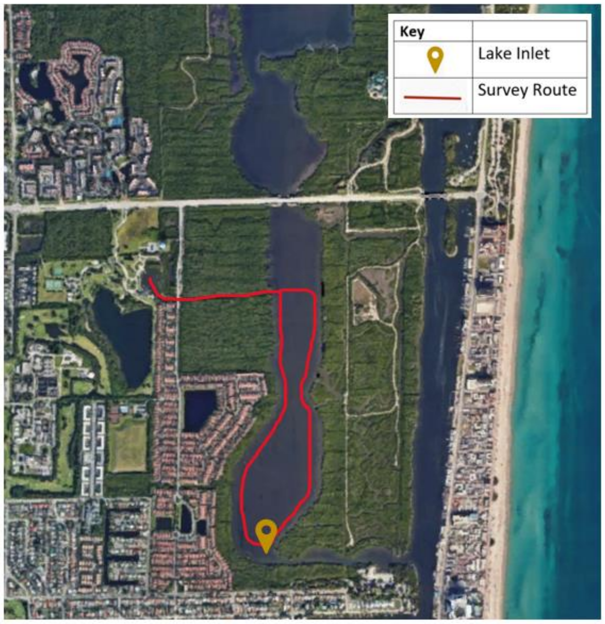

Figure 2 -Satellite map of West Lake displaying survey route and lake inlet to the Intercoastal Waterway

Surveys were also conducted at Whiskey Creek (26° 4'56.26"N, 80° 6'46.52"W), located in Dr. Von Mizell-Eula Johnson state park (Figure 3). Whiskey Creek is a narrow saltwater creek dominated by the same mangrove species as West Lake. The mangrove forest covers about 0.73 km^2 on the barrier island between the Atlantic Ocean and Intracoastal Waterway. The mouth of the creek drains from the Intracoastal, runs parallel to the coast, then connects back to the IC. The northern inlet near the boat dock, where the surveys began, is marked on Figure 3 along with the survey route highlighted in red. Each survey started at the northern inlet of the creek and continued down the main pathway. The inlets that connect to the IC are also in the same vicinity as Port Everglades, where the Intracoastal connects to the Atlantic Ocean.

Figure 3 - Satellite map of Whiskey Creek displaying survey route and creek inlet to the Intracoastal Waterway.

Data Collection

Continuous surveys took place in West Lake and Whiskey Creek to gather spatial data on local mangrove forests and create semi-quantitative maps. A kayak with the necessary equipment attached was launched from the shore at the beginning of each survey returning to the same location. Greenhouse gasses were detected throughout continuous water surveys using multiple instruments set up in a line. All the instruments were connected in a closed air loop using vinyl tubing. A pump on the side of the kayak pumped water into the closed chamber of a RAD AQUA shower head air-sea gas exchanger. The RAD AQUA shower exchanged dissolved gasses from the surface water into a closed air loop. The humidity of the air loop was kept under 10% using Drierite desiccants. The air also passed through a LiCOR 7810 (CO_2/CH_3/H_2O) infrared analyzer using vinyl tubing with a nylon filter (0.2µm) at the inlet. The LiCOR 7810 is an infrared gas analyzer that measures CO_2 and CH_4 by determining the absorption of an emitted infrared light source through the air sampled in each survey. A Garmin etrex10 GPS was used on each survey to connect the time stamp and location of GHG measurements. This allowed the connection of coordinates with a time series to pinpoint concentrations at different locations. A YSI ProSolo handheld multiparameter meter was also on board the kayak with the sensor attached to the side of the boat. This was used to measure temperature, salinity, and dissolved oxygen. Inaccurate salinity measurements from the 7/28 Whiskey Creek survey were removed due to the conductivity sensor and vent hole on the side of the probe not being completely submerged in the water.

Figure 4- Instruments used in surveys set up in a line connected through a closed air loop using vinyl tubing. Instruments were secured to the kayak with sensors and air pump secured on the side of the boat.

Data Analysis

Statistical analyses were conducted using Rstudio. Linear regressions and correlation tests were performed to investigate relationships between different chemical parameters and understand how GHG concentrations fluctuated with changes in environmental conditions. The results from these tests, such as p-values, were used to verify the significance of each relationship. For correlation tests, p-values < 0.01 were considered statistically significant. Concentration maps were also created in R to reveal the spatial variability of GHGs during each survey route. This was done by connecting concentration measurements with coordinate points to graphically display measurements along the survey route.

Results

Whiskey Creek

Whiskey Creek surveys took place during the summer, when the air is warm and humid in south Florida. Air temperature during the 7/15 Whiskey Creek survey averaged 25°C, while the 7/28 Whiskey Creek survey averaged 31°C. The 7/15 Whiskey Creek survey occurred during the fall of high tide. High tide peaked at 10:58 am and the survey began at 12 pm EST (U.S. Department of Commerce, 2020). The 7/28 Whiskey Creek survey occurred during outgoing tide. High tide peaked at 9am and the survey began at 11am EST (U.S. Department of Commerce, 2020). The average surface water temperature during the 7/15 Whiskey Creek survey was 31.8 °C with a maximum of 32.2 °C, and minimum of 31.5 °C (Table 1). The average surface water temperature during the 7/28 Whiskey Creek survey was 31.4°C with a maximum of 31.8 °C and minimum of 31 °C (Table 1). Changes in surface water temperatures displayed similar patterns to dissolved oxygen levels along the Whiskey Creek survey route (Figures 5 and 6).

Table 1- The minimum, maximum, mean, and range of salinity, temperature, DO%, CO_2, and CH_4 measurements throughout each survey

	Salinity (psu)	Surface Water Temperature ° C	DO%	CO_2 (ppm)	CH_4 (ppb)
Min	31.5	31.5	91.6	449.5	7316.7
Max	31.8	32.2	117.8	493.6	8721.9
Mean	31.7	31.8	107.7	469.1	8156.8
Range	0.3	0.7	26.2	44.1	1405.1
Min	-	31	63	409.3	3261.3
Max	-	31.	102	463.6	5955.8
Mean	-	31.4	87.8	439.3	4877.1
Range	-	0.8	39	54.2	2694.4
Min	29.5	24.5	56	832.5	5725.2
Max	32.4	25.6	97.8	1727.8	26863.3
Mean	32.1	25.0	78.0	1132.9	11224.4
Range	2.9	1.1	41.8	895.3	21138.1

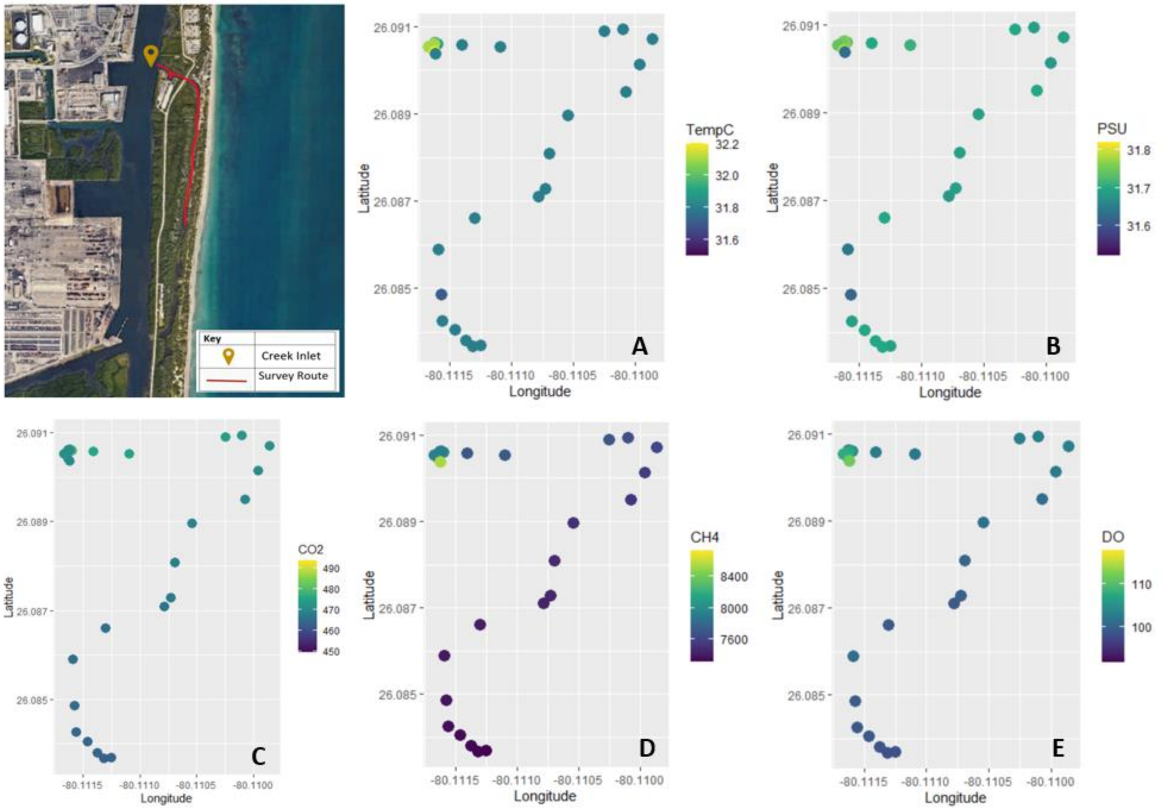

Figure 5- Satellite map of Whiskey Creek survye route along with concentration maps created using time series measurements during 7/15/22 survey. A) Surface water temperatures (°C) B) Salinity (psu) C) CO_2 (ppm) D) CH_4 (ppb) E) Dissolved Oxygen% . Severe wather conditions forced this survey to be shortened resulting in less corrdinate points.

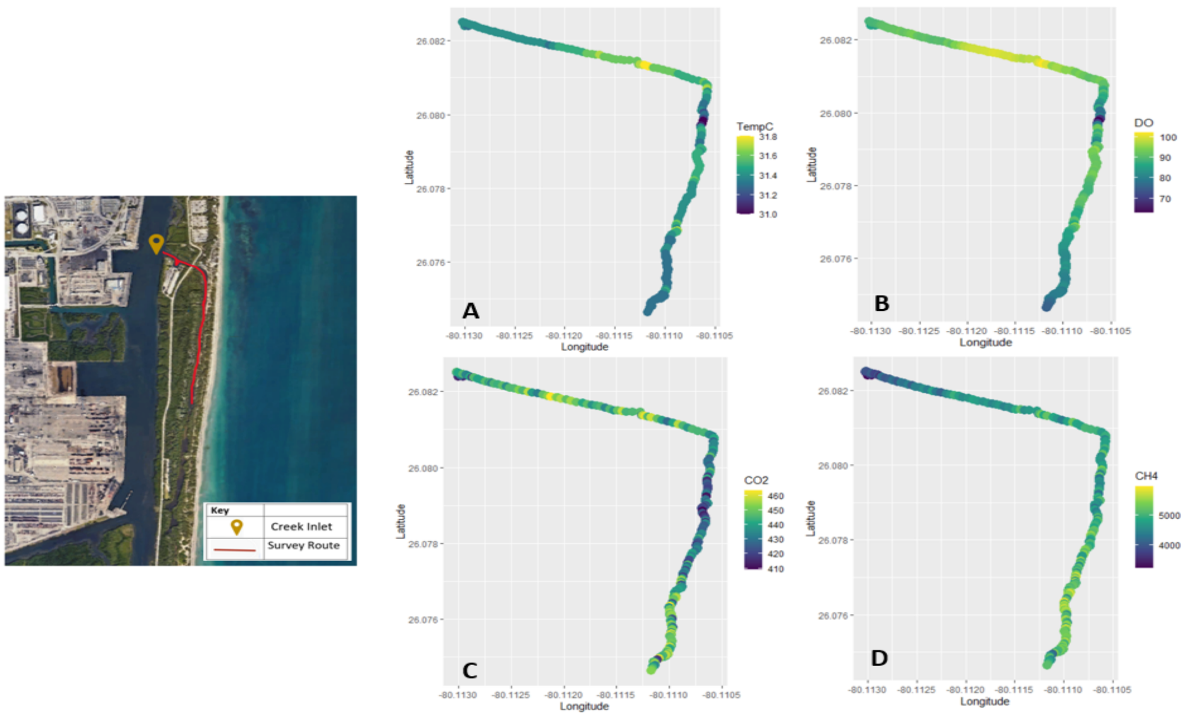

Figure 6- Satellite map of Whiskey Creek survey route along with concentration maps created using time series measurements during 7/28/22 survey. A) Surface water temperatures (°C) B) Dissolved Oxygen% C) CO_2 (ppm) D) CH_4 (ppb).

To investigate temperature as a potential factor that influences GHG concentrations, linear regressions and correlation tests were performed between surface water temperatures and both CO_2 and CH_4. There was a positive, but not significant ($p > 0.01$) correlation between CO_2 concentrations and temperature during 7/15 survey (Figure 7A). Temperature and CH_4 during the 7/15 survey (Figure 7B) showed a positive and significant relationship ($p < 0.01$). During the survey conducted on 7/28 there was a negative correlation between temperature and both CO_2 and CH_4 (Figure 7C and 7D). Correlation test for temperature and CO_2 during 7/28 survey resulted in an insignificant relationship ($p > 0.01$), while temperature and CH_4 resulted in a significant relationship ($p < 0.01$).

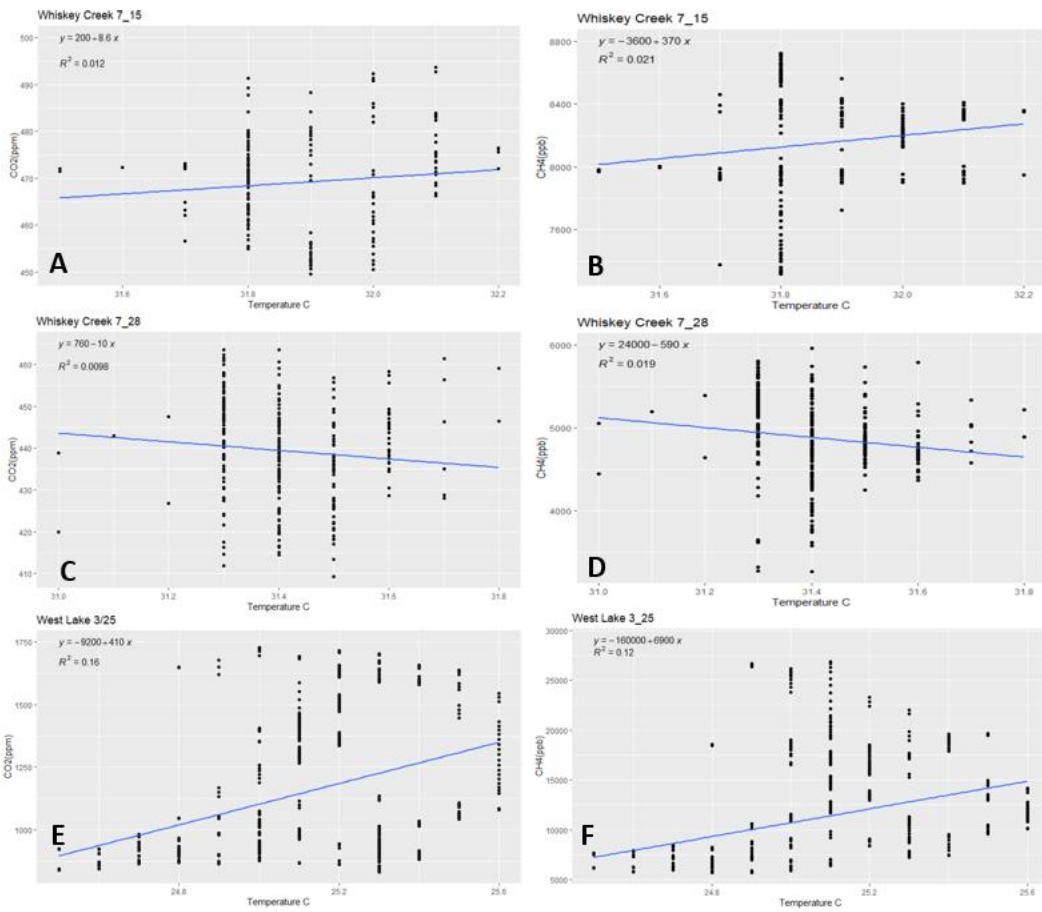

Figure 7- Correlation analyses of surface water temperatures (°C) with CO_2 (ppm) and CH_4 (ppb) during each survey A) Temperature vs CO_2 for 7/15 Whiskey Creek B) Temperature vs CH_4 for 7/15 Whiskey Creek C) Temperature vs CO_2 for 7/28 Whiskey Creek D) Temperature vs CH_4 for 7/28 Whiskey Creek E) Temperature vs CO_2 for 3/25 West Lake F) Temperature vs CH_4 for 3/25 West Lake.

Correlation analyses were also conducted between dissolved oxygen and both GHG's to examine the relationship between GHG concentrations and DO. Linear regressions for DO and CO_2 during the 7/15 survey (Figure 8A) resulted in a significant negative relationship ($p < 0.01$). CH_4 resulted in a positive correlation with DO for 7/15 survey (Figure 4B) with a significant p value ($p < 0.01$). Linear regressions for DO against CO_2 and CH_4 during 7/28 survey (Figures 8C and 8D) both resulted in significant negative relationships ($p < 0.01$). Elevated dissolved oxygen levels were observed in the same areas of lower GHG levels (Figures 5 and 6). The highest DO levels were recorded within the wider and deeper areas of the water column. As the main pathway continues to narrow moving deeper into the creek, DO levels began to decrease. Percent DO ranged between 91.6% and 117.8% throughout 7/15 survey and ranged between 63% and 102% throughout the 7/28 survey in Whiskey Creek (Table 1).

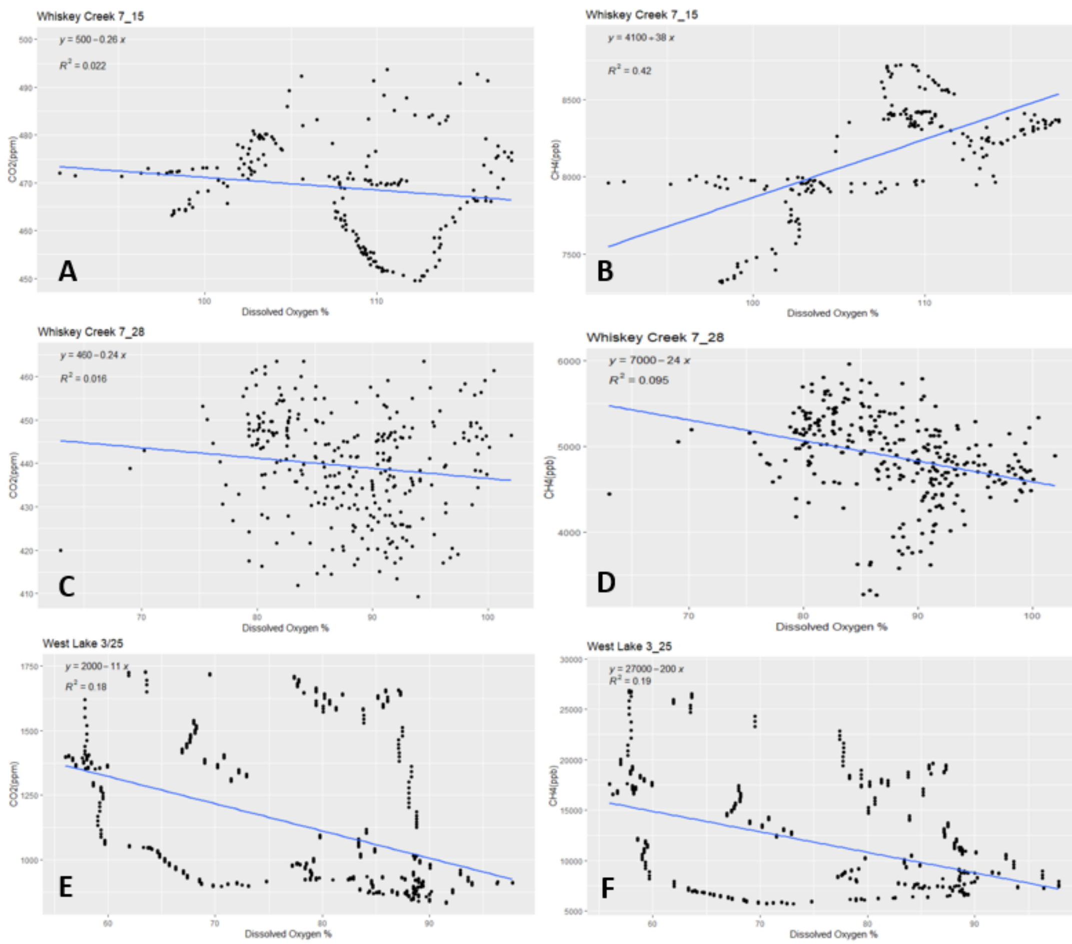

Figure 8- Correlation analyses of Dissolved Oxygen% with CO_2 (ppm) and CH_4 (ppb) during each survey A) DO% vs CO_2 for 7/15 Whiskey Creek B) DO% vs CH_4 for 7/15 Whiskey Creek C) DO% vs CO_2 for 7/28 Whiskey Creek D) DO% vs CH_4 for 7/28 Whiskey Creek E) DO% vs CO_2 for 3/25 West Lake F) DO% vs CH_4 for 3/25 West Lake.

CO_2 measurements were lowest near the creek inlet and gradually increased moving deeper into the creek and farther from the Intercoastal (IC) inlet (Figures 5C and 6C). CO_2 concentrations during 7/15 survey ranged between 449 ppm to 493 ppm (Table 1). CO_2 concentrations for 7/28 survey reached a minimum of 409 ppm and maximum of 463 ppm (Table 1). CH_4 concentrations in Whiskey Creek displayed similar distributions to carbon dioxide (Figures 5D and 6D). The lowest CH_4 measurements during 7/15 survey were recorded closest to the creek inlet (minimum =7316 ppb), and gradually increased deeper into the creek reaching a maximum of 8721 ppb (Table 1). CH_4 concentrations for 7/28 survey reached a maximum of 5955 ppb and a minimum of 3261 ppb (Table 1). Carbon dioxide and methane concentrations displayed a significant positive relationship during the 7/28 Whiskey Creek survey ($p < 0.01$) (Figure 9B), while data from 7/15 survey (Figure 9A) revealed a negative relationship ($p < 0.01$).

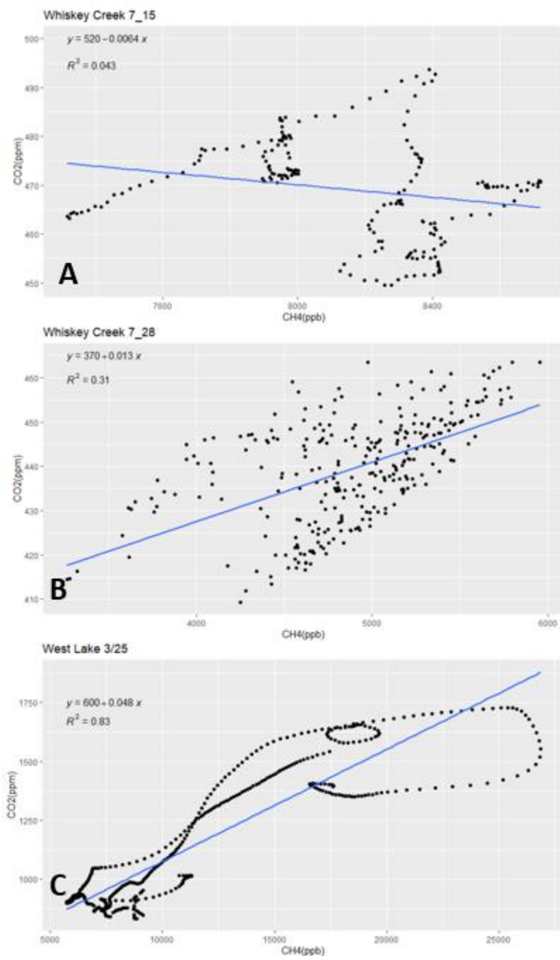

Figure 9- Correlation analyses of CH_4 (ppb) vs CO_2 (ppm) for each survey. A) CH_4 vs CO_2 during 7/15 Whiskey Creek survey B) CH_4 vs CO_2 during 7/28 survey for Whiskey Creek C) CH_4 vs CO_2 during 3/25 West Lake survey.

Average salinity recorded during 7/15 survey in Whiskey Creek was 31.7 psu (Table 1). The maximum salinity recorded during 7/15 survey was 31.8 psu and a minimum of 31.5 psu (Table 1). Linear regressions between salinity and CO_2 for 7/15 survey (Figure 10A) displayed an insignificant positive relationship ($p > 0.01$). Salinity was significantly negatively correlated with CH_4 during the 7/15 survey (Figure 10B), indicating CH_4 increased in areas of lower salinity ($p < 0.01$). The relationship between surface water temperatures and salinity was further investigated as well. Correlation analysis for salinity and temperature during the 7/15 survey (Figure 11A) resulted in a significant positive relationship ($p < 0.01$).

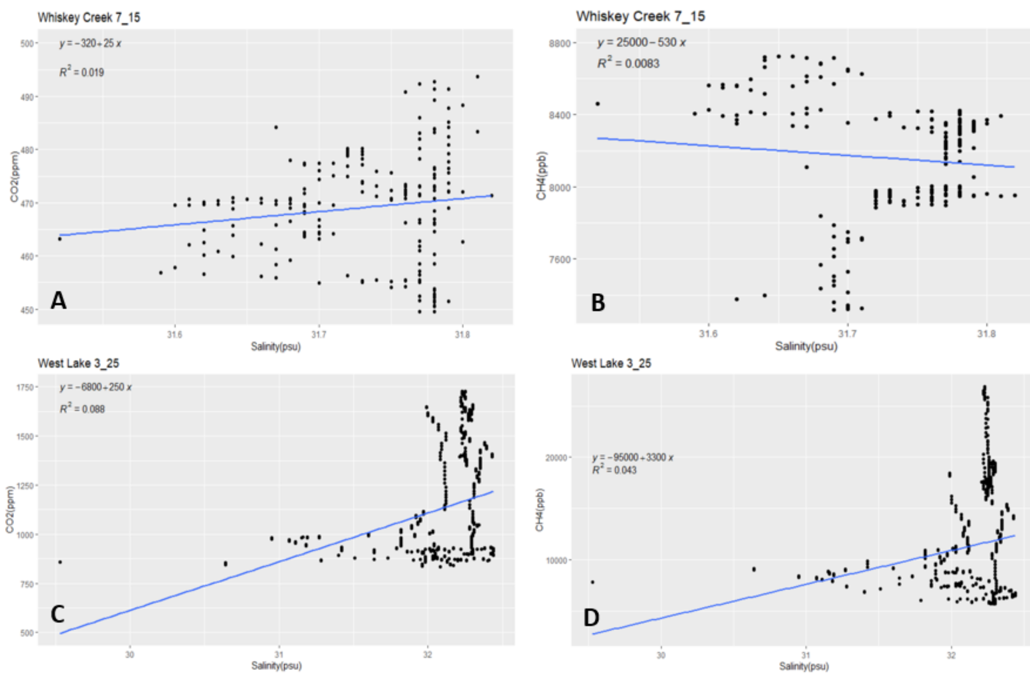

Figure 10- Correlation analyses of Salinity (psu) with CO_2 (ppm) and CH_4 (ppb) during each survey A) Salinity vs CO_2 for 7/15 Whiskey Creek B) Salinity vs CH_4 for 7/15 Whiskey Creek C) Salinity vs CO_2 for 3/25 West Lake D) Salinity vs CH_4 for 3/25 West Lake.

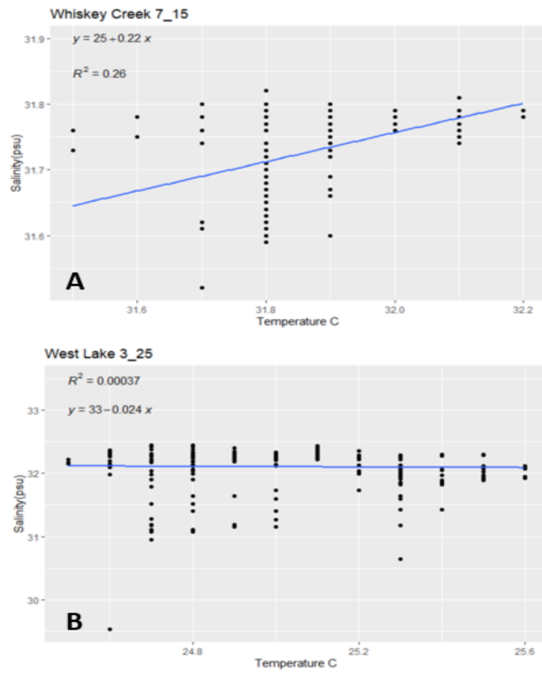

Figure 11- Correlation analyses for surface water temperature (°C) and salinity (psu) for each survey. A) Temperature vs salinity for 7/15 Whiskey Creek B) Temperature vs salinity for 3/25 West Lake

West Lake

The survey conducted in West Lake took place on 3/25, during the dry and cooler season of south Florida. The West Lake survey began near 11am EST during a rising high tide. High tide eventually peaked to 2.18 ft by 3pm (U.S. Department of Commerce, 2020). Air temperature during the time of the survey was 23 °C. The average surface water temperature throughout 3/25 West Lake survey was 25.2 °C (Table 1). All recorded temperatures ranged between 24 – 26 °C (Table 1). Surface water temperatures were highest along the western edge of the lake and slowly decreased moving towards the eastern shoreline (Figure 12A). Linear regressions of surface water temperartures with both CO_2 and CH_4 (Figures 7E and 7F) displayed significant positive relationships for 3/25 West Lake survey ($p < 0.01$).

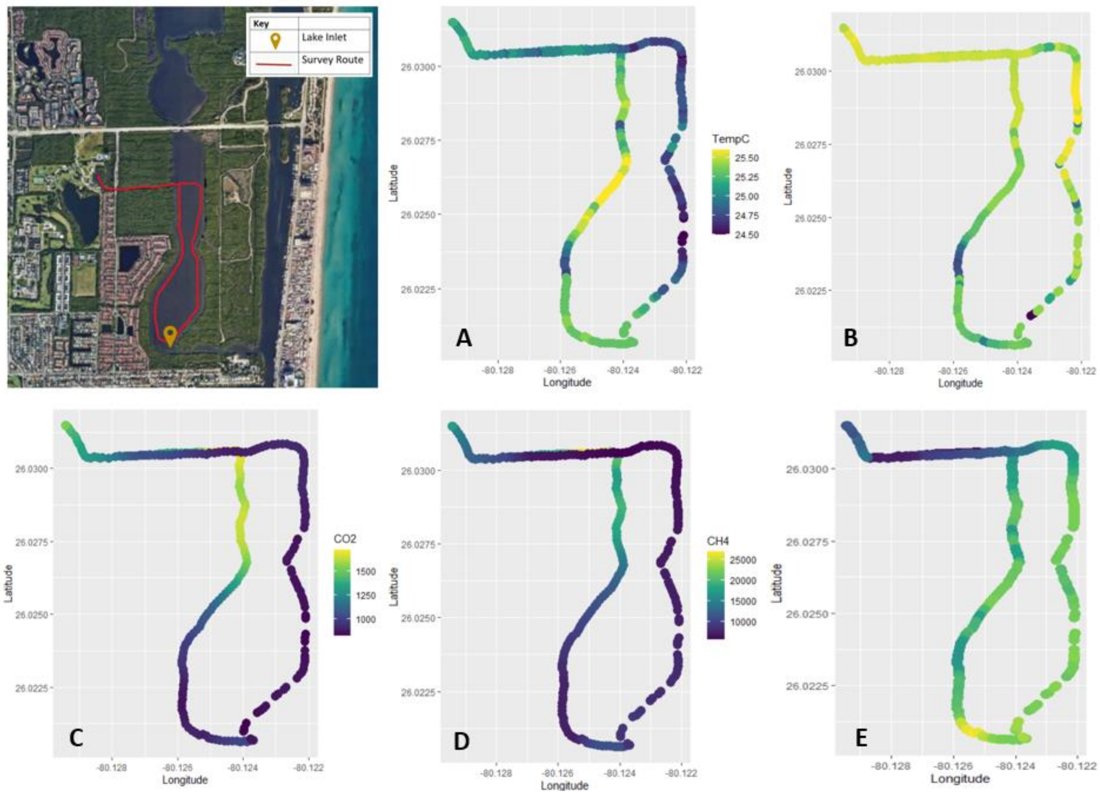

Figure 12- Satellite map of West Lake survey route along with concentration maps created using time series measurements during 3/25/22 survey. A) Surface water temperatures (°C) B) Salinity (psu) C) CO_2 (ppm) D) CH_4 (ppb) E) Dissolved Oxygen%

The highest dissolved oxygen levels were along the eastern shoreline of West Lake closest to IC inlet (Figure 12E). Dissolved oxygen displayed higher concentrations in areas of West Lake with lower GHG concentrations. DO percentages ranged between 56% and 97% throughout 3/25 West Lake survey (Table 1). DO and CO_2 throughout 3/25 West Lake survey (Figure 8E) displayed a significant negative relationship ($p < 0.01$). CH_4 and DO (Figure 8F) resulted in a significant negative realtionship as well ($p < 0.01$).

Narrow mangrove passages had higher GHG concentrations compared to the wide open extent of West Lake (Figure 12C and 12D). Along the edge of the lake, the western shoreline had higher CO_2 and CH_4 concentrations while the eastern shoreline near the IC inlet had lower GHG concentrations (Figures 12C and 12D). CO_2 concentrations reached a maximum of 1727 ppm and a minimum of 832 ppm during 3/25 survey (Table 1). CH_4 concentrations during 3/25 survey ranged between 5725 ppb and 26863 ppb (Table 1). There was a significant positive relationship between CH_4 and CO_2 during 3/25 survey in West Lake ($p < 0.01$) (Figure 9C). Areas of the mangrove forest where CO_2 concentrations increased or decreased, CH_4 did as well.

Average salinity observed in West Lake was 32.1 psu with a maximum of 32.4 psu and minimum of 29.5 psu (Table 1). Salinity remained above 30 psu for majority of the survey route on 3/25 (Figure 8B). There was a significant positive relationship between salinity and both GHG's during the 3/25 survey (CO_2: $p < 0.01$, CH_4: $p < 0.01$) (Figures 10C and 10D). Surface water temperatures and salinity throughout 3/25 survey (Figure 11B) displayed no correlation ($p > 0.01$).

Comparing Survey Sites

Surface water temperatures in West Lake were significantly lower than Whiskey Creek due to the difference in season (Table 1). Whiskey Creek survey took place during the summer, so surface water temperatures were higher. The survey that took place in Whiskey Creek during the summer revealed the maximum of percent dissolved oxygen being 117.8%. The maximum of percent DO in West Lake was 97.8% and all measurements remained within a 41.8 range (Table 1). Salinity in Whiskey Creek remained within a range of 0.3 throughout the entire 7/15 survey while there was a larger range in salinity in West Lake (2.9). Boxplots (Figure 13) allow for the comparison of chemical parameters measured in Whiskey Creek and West Lake. Overall, there were higher and more variable CO_2 and CH_4 concentrations in West Lake compared to Whiskey Creek (Figure 13A). Surface water temperatures (Figure 13E) remained within a small range of values throughout all surveys in both sites. There were significant differences in mean temperatures between survey dates due to seasonal temperature changes. Salinity was within a small range for both survey sites as well, although there was no salinity data available for one of the Whiskey Creek surveys (Figure 13C).

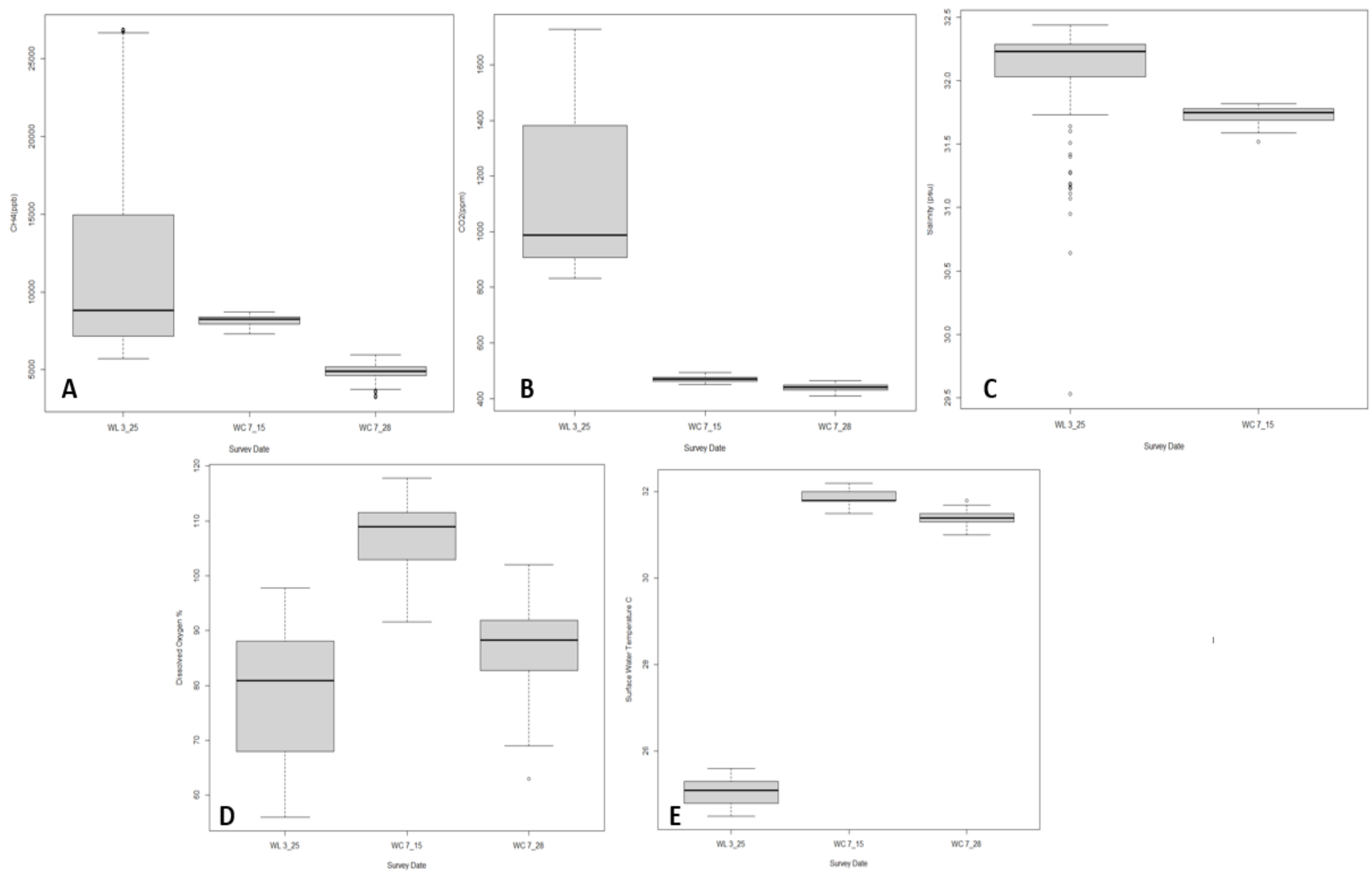

Figure 13- Boxplots of chemical parameters recorded for each survey to reveal spatial variability of West Lake and Whiskey Creek. A) CH_4 (ppb) B) CO_2 (ppm) C) Salinity (psu) D) Dissolved Oxygen % E) Surface water temperatures (^oC)

Discussion

The main goal of this project was to assess the spatial variability of greenhouse gasses in blue carbon mangrove systems and create semi-quantitative maps for GHG concentrations and other seawater properties. Continuous surveys within West Lake and Whiskey Creek mangrove forests revealed the spatial variation of CO_2 and CH_4 concentrations throughout different locations of the forest. Semi-quantitative maps were also created for dissolved oxygen, salinity, and surface water temperatures to investigate environmental conditions associated with GHG concentrations. Surveys were conducted at both mangrove sites to give more insight into different spatial variations that occur within these two urban mangrove systems. The structure of mangrove forests can be significantly different throughout different parts of the system, which leads to unequal changes throughout the forest as well. Therefore, it was interesting to investigate how GHG concentrations in a wide-open lake compared to a narrower tidal creek. It is also necessary to consider how concentrations change based on vicinity from the coast. West Lake is located on the western landward side of the Intercoastal waterway while Whiskey Creek runs along the eastern side of the IC through a barrier island between the IC and Atlantic Ocean (Figure 1).

Surface water temperatures play an important role in the environmental conditions of coastal ecosystems. Positive correlations between surface water temperature and both GHG's during 7/15 Whiskey Creek survey and 3/25 West Lake survey emphasizes that areas with higher temperatures within the forest have higher GHG concentrations. Tidal fluctuations affect water residency times throughout the mangrove forest and changes in temperature may reflect the amount of time water has spent in the system (Aspinwall, 2021). In these systems, it is likely that higher surface water temperatures can indicate higher water residency times within the mangroves, especially during the warmer summer months (Rangel, 2021). This increases the amount of time for GHG concentrations to increase due to other biogeochemical pathways. While temperature may reflect residence times of water masses, changes in seasonal temperatures may directly impact rates of productivity occurring within mangrove forests (Aspinwall, 2021). Photosynthesis and respiration regulate plant growth and ecosystem carbon storage, which can be differentially impacted by temperature with increased temperatures favoring higher respiration rates (Aspinwall, 2021). Surface water temperatures also had a significant positive relationship with salinity during 7/15 Whiskey Creek survey, which could mean elevated salinity due to evaporation was also associated with high temperatures. Respiration rates of mangroves are expected to increase with increasing salinity due to the metabolic demands associated with salt removal (Aspinwall, 2021). Depending on the time of year, increased temperatures and salinity may be an indication of higher GHG concentrations in these areas (Arden, 2018).

As tides flood the forest, GHG concentrations within the system change as well. Greenhouse gas concentrations increased moving farther from the intercoastal and deeper into the forest. The highest CO_2 and CH_4 measurements for both Whiskey Creek surveys were recorded within the narrowest parts of the creek moving farther away from IC inlet. CO_2 and CH_4 concentrations increased along the shorelines of West Lake moving farther away from the IC inlet as well. This suggests that areas of the forest with longer water residency times have higher GHG concentrations. Past studies have revealed that CO_2 concentrations were higher in vegetated areas deeper in the forest because of increased soil respiration (Wang, 2015). Microbes present in vegetated areas could stimulate CH_4 production as well (Wang, 2015). Peak CO_2 and CH_4 levels were also measured along the western shoreline of West Lake. Previous research and the current experiment suggest that GHG's are being produced within the system since concentrations increase moving deeper into the mangrove forest. There was a significant positive correlation between CO_2 and CH_4 during 7/28 Whiskey Creek survey and 3/25 West Lake survey. The correlation test for CO_2 vs, CH_4 on 7/15 in Whiskey Creek resulted in a significant p value indicating there is a significant relationship occurring, but due to the low R^2 reported, it could be a different relationship than what's graphed by the linear regression. It is expected for GHG concentrations to be lower near tidal sources and open water bodies compared to narrow passages within the mangroves due to the prevalence of more anoxic conditions (Call, 2015). This relationship was also observed in Whiskey Creek and West Lake surveys as GHG concentrations increase moving deeper into narrow passages of the forest that experience anoxic conditions from organic matter buildup. Yang et al., (2018) reported hourly average CO_2 concentrations within mangrove study sites ranged between 406 and 478 ppm. This range is similar to CO_2 concentrations recorded during 7/28 Whiskey Creek survey (min: 409 ppm, max: 763 ppm). CO_2 concentrations recorded during 7/15 Whiskey Creek and 3/25 West Lake surveys were significantly higher. Highest CO_2 concentrations were recorded in West Lake compared to Whiskey Creek. This suggests shorter water residency times in Whiskey Creek since the site is closer to the Port Everglades inlet from Atlantic Ocean, although the short surveys in Whiskey Creek likely played a role in the data.

Areas of the mangrove forest with larger exchange with the intracoastal displayed lower GHG levels, but high DO levels. Mangrove forests are associated with high respiration rates, so areas deeper within the forest with longer water residency times continue to utilize oxygen within the water column. Areas of the forest closer to the intracoastal inlet do not deplete oxygen as rapidly due to shorter water residency times and potentially less respiration (Mattone, 2017). This is likely due to the transport of dissolved oxygen into the mangroves during tidal flooding. The significant negative relationship between DO and both GHG's throughout West Lake and Whiskey Creek was observed in past studies as well. It has been suggested that correlations between DO and CO_2 could be a result of photosynthetic organisms that convert CO_2 into carbohydrates and increases oxygen levels in the water column (Li, 2021). Linear regression for DO and CH_4 during the 7/15 survey in Whiskey Creek strayed from this trend and I observed a positive relationship. This could be due to the tidal phase during the time the survey took place. The 7/15 survey occurred during the fall of high tide and began an hour after the peak of high tide. Since tidal flooding recently occurred, DO levels may have been higher during 7/15 survey compared to the 7/28 and 3/25 surveys that occurred at different tidal phases.

Conclusion

Continuous surveys measuring CO_2 and CH_4 revealed the spatial variability of greenhouse gases in two different south Florida mangrove forests. Surveys were conducted in West Lake and Whiskey Creek to observe fluctuations between a tidal creek, narrow passages within the forest, and wide-open lake. Environmental conditions were also monitored to understand changes in GHG concentrations and potential factors that drive these spatial fluctuations throughout the system. It is necessary to quantify changes in GHG concentrations to understand the role these ecosystems will play in climate change. As these ecosystems continue to be destroyed through land degradation, sequestered greenhouse gasses stored belowground are emitted to adjacent water bodies and back into the atmosphere. Results revealed a positive correlation between CO_2 and CH_4 concentrations throughout both survey sites, indicating both greenhouse gases are influenced by similar factors. West Lake observed significantly higher greenhouse gas concentrations due to longer water residency times compared to Whiskey Creek. A negative correlation was observed between dissolved oxygen and both greenhouse gases measured throughout all surveys, indicating low oxygen environments may be a source of the GHGs. Mangrove ecosystems are known to be diverse with variable conditions, so different parts of the system are not equally affected by environmental changes. Investigating spatial distributions and potential drivers can reveal important insights into the variability of greenhouse gasses and other seawater parameters in mangroves and other coastal ecosystems.

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