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Coastal Blue Carbon Emissions of Salt Marsh Soils

Sydney Gray

Salt marshes and other coastal habitats are often overlooked for their potential in combating climate change and reducing carbon emissions. The objective of this study was to observe the variance in carbon flux between disturbed and undisturbed salt marsh soils when subjected to freezing and thawing cycles. Sediment samples were collected from both a natural and recovering site within a Mid-Atlantic salt marsh. The samples were incubated and pushed through freezing and thawing conditions, carbon emissions and temperatures of the soil being monitored throughout each thaw. The data suggested that there is a positive correlation between soil disturbance and soil respiration in conjunction with rising temperatures. These findings suggest that disturbances could convert salt marshes from effective carbon sinks to sources of carbon emissions, not only reversing the positive contributions of blue carbon ecosystems, but amplifying the issue of climate change.

Keywords: salt marsh, carbon flux, soil respiration, climate change, wetlands, freeze/thaw

Coastal Blue Carbon Emissions of Salt Marsh Soils

Coastal habitats are arguably some of the most productive ecosystems in the world. Not only do they offer services such as mitigating the damage of storms and filtering pollutants, but they are also an overlooked opportunity for the reduction of carbon emissions with the prevalent threat of global climate change (Gedan et al., 2011, p. 229). They have been coined "blue carbon" ecosystems for their coastal location and contributions to the sequestration and storage of carbon from the atmosphere into plants and soil (Pidgeon et al. 2019, para. 1). According to the Blue Carbon Initiative, an organization devoted to educating people on this overlooked topic, these ecosystems make up only 2% of total ocean area, yet account for nearly 50% of carbon storage in ocean sediments. As a result, their effects on the environment and the impact humans have exerted on these ecosystems have been the subject of many research studies. However, there is a lack of understanding in a few subject areas regarding blue carbon ecosystems. While there are several nutrient productivity studies taking place in the New England region of the United States, there is currently less literature on the Mid-Atlantic region, which is a dissimilar environment. In fact, according to Campbell (2020), the Chesapeake region is characterized by higher rates of sea level rise and sediment disturbances (para. 3). Disturbances and restoration have been a huge topic in past salt marsh research studies, due to the threat of carbon dioxide release from disturbed ecosystems. In one such study, McFarland (2016) measured the concentration of phosphorus, nitrogen, and carbon in natural versus restored blue carbon ecosystems, as well as converted farmland, finding the highest nutrient concentrations in restored marshes (p. 267). The impact of disturbances to these ecosystems in conjunction with rising temperatures associated with climate change is unknown. There is little to no research on the relationship between extreme temperature conditions and carbon storage within these ecosystems, particularly in salt marshes recovering from disturbances. This is principal in understanding recovering salt marsh productivity and resilience under different environmental conditions resulting from climate change.

Literature Review

Productivity and Nutrient Dynamics

Firstly, productivity and nutrient dynamics of these ecosystems dominate current literature. This focus of research helps us to understand the overall impact of blue carbon ecosystems as carbon sinks, beginning with the basic components. For instance, Nixon (1973) conducted a study of energy flow and biomass throughout trophic levels of a New England salt marsh over the course of a year (p. 463). The study compared the nutrient dynamics and biomass of plants like Spartina alterniflora and S. patens, as well as shrimp, fish, birds, plankton, sediments, etc. Furthermore, Greller (2010) compared the productivity, biomass, and biotic interactions of several common salt marsh plants in Long Island, New York (p. 105). These studies represent a pattern of literature measuring the smaller components involved in salt marsh productivity, such as abiotic and biotic relationships.

In addition, much of the current literature surrounding the carbon dynamics of coastal ecosystems focuses on long-term sediment storage. Understandably so, as Trevathan-Tackett (2015) affirmed the fact that as opposed to plants, sediments have the ability to store both allochthonous carbon, carbon that is sequestered from an external source, and autochthonous carbon, organic material from the ecosystem itself (p. 3043). This emphasizes the importance of soil activity in the abilities of salt marshes to sequester and store carbon. In a similar study, Samper-Villarreal (2016) measured the impact of various environmental factors on carbon uptake in seagrass sediments, including the turbidity of the water. It was determined that higher carbon uptake was associated with higher levels of turbidity (Samper-Villarreal et al., 2016, p. 943). Studies on the mechanisms of sequestration and nutrient dynamics offer a broad perspective on the significance of blue carbon ecosystems.

Soil Respiration in the Face of Freezing and Thawing Cycles

Furthermore, there are many existing studies on the effects of freeze and thaw on soil respiration and carbon release for other types of ecosystems. For instance, Wang (2015) conducted an incubation study investigating the effect of freezing and thawing cycles on the respiration of light and dark cyanobacterial crusts. Medium, mild, and severe freezing and thawing cycles were successively applied to the soil samples to test the change in the total carbon and nitrogen content of the soils (p. 265). It was determined that the light cyanobacterial crusts were more sensitive to the successive cycles than the dark cyanobacterial crusts (p. 267). However, in general, both crust types saw a decrease in carbon and nitrogen concentrations throughout the repeated freeze and thaw (p. 263). The repeated cycles led to the release of carbon and nitrogen from the soil samples at an increased rate. Likewise, Meyer (2018) observed soil respiration and sensitivity to temperature in soils from grasslands, croplands, and forestlands in order to investigate the potential of mid-infrared spectroscopy on large scale carbon modeling. This study observed higher rates of soil respiration in grasslands and croplands.

Disturbances and Recovery

As discussed previously, another popular subject of research is the recovery of marshes after disturbances. Disturbances and damage to these ecosystems can be attributed to a number of factors, including human development, "temperature increase, accelerating eutrophication, consumer-driven salt marsh die-off, and sea level rise" (Gedan et al., 2011, p. 229). For instance, Coverdale (2014) called attention to the problem of increased crab burrowing, an indirect impact of human activity, and how it led to the retreating of a Cape-Cod tidal marsh and the release of a high amount of previously sequestered carbon back into the atmosphere (para. 18). This is especially detrimental to the environment because it reverses the contributions of salt marshes in storing carbon. In fact, according to The Blue Carbon Initiative, disturbed coastal ecosystems account for nearly "1.02 billion tons of carbon dioxide" released back into the atmosphere every year. Instead of acting as effective carbon sinks, previously disturbed ecosystems have become a source of carbon emissions.

Moreover, Macreadie (2015) established a connection between carbon release and disturbances to seagrass ecosystems. Through carbon dating and the measurement of carbon stocks in the soil, disturbed seagrass ecosystems were proven to emit high amounts of carbon that had been built up over thousands of years (p. 3). In another study on seagrass ecosystems, it was pointed out that habitat loss attributed to disturbances from human development caused the release of "between 0.05 to 0.33 Pg CO2 yr-1 back into the atmosphere" (Greiner et al., 2013, para. 5). This makes disturbed blue carbon ecosystems dangerous sources of carbon dioxide release, as this is a rate comparable to the fossil fuel emissions of several small countries (Greiner et al., 2013, para. 5). This further emphasizes the need for a better understanding of the effects of blue carbon ecosystem disturbances, and how climate change can worsen these effects.

Despite the many existing productivity studies taking place in the New England region, there is a lack of information available on Mid-Atlantic salt marshes. Regarding disturbances and recovery, there are many studies that observe the effects of sea-level rise and rising temperatures. However, there seems to be a lack of understanding of the effects of freezing and thawing cycles on salt marsh ecosystems. This raised the question: To what extent does the carbon flux vary between disturbed and undisturbed soil samples from a Mid-Atlantic salt marsh when subjected to freezing and thawing cycles? The objective of this study was to assess the variances in the rate of CO2 emissions when recovering and natural salt marsh sediments from the same Mid-Atlantic marsh were exposed to freezing and thawing conditions, using an incubation study. This allowed for the experimental manipulation of salt marsh soil samples and a look at disturbed soils under extreme conditions.

Methods

Methodologically, this study utilized an incubation experiment. Incubation studies are ideal for climate change research, as they allow the researcher to manipulate and control the environment of the samples to test desired factors. Wang (2015) carried out a controlled incubation experiment to observe the effects of freezing and thawing cycles on total carbon and nitrogen content in cyanobacterial soil crusts, in an attempt to "simulate natural temperature changes in one of the temperate regions of northern China," (p. 263); similarly, this study aimed to simulate freeze and thaw events in the Mid-Atlantic region of the United States.

Study Area and Sampling

In order to be able to sample in a marsh, an advisor's permit was applied and the study was approved by the Independent Review Board of a public school in Delaware. Soil samples were collected from two regions of the St. Jones Reserve, a 5,119 acre estuarine research reserve on the St. Jones River in Dover, Delaware. Two shallow samples were taken from a natural area of the marsh, and the other two from an area that had recently faced a disturbance. This particular region had been oversampled in the recent past, leaving the mud churned up and the plant life damaged, whereas the natural region was practically untouched. It was critical to sample from within the same salt marsh for both the disturbed and undisturbed sediments in order to ensure soil homogeneity, which is essential in a project aiming to measure soil respiration. In fact, Wang (2015) evaluated the similarity of soil microstructure in order to ensure homogeneity (p. 265). The St. Jones Reserve offered a recovering and a natural region within close proximity, allowing for samples with little to no variation in salinity, nutrients, or vegetation.

Validity

All samples were collected from the same marsh within a distance of approximately ten meters. This increased internal validity, as it allowed for less variation in soil components, such as salinity, nutrients, sedimentary components, and heterotrophic components. External validity was ensured by maintaining water content and plant material in the soils throughout the study in order to reflect soil respiration in a natural environment. Samples were not sieved or dried in order to prevent any further disturbance and ensure that the experimental results would be comparable to the real world (Herbst, 2016, para. 1). In fact, Herbst (2016) critiqued sieving due to its impact on the relationship between water content and soil carbon dioxide emissions in studies on the effects of climate change (para. 1). Lastly, the results of the incubation study were representative of soil respiration in a salt marsh during freeze and thaw events.

Procedures

Soil samples were separated into four, 2000 mL plastic chambers; an experimental disturbed chamber, an experimental undisturbed chamber, a control disturbed chamber, and a control undisturbed chamber. The experimental undisturbed soil was referred to as the Natural group, while the experimental disturbed soil was called the Recovering group. Approximately 500 mL of soil was placed in each chamber. After being separated into these airtight containers, the soils were stored at room temperature in the dark until the start of the experiment (Wang, 2015, p. 265). On the first day of the treatment, all chambers remained in indirect sunlight at room temperature, or approximately 22°C. CO2 levels and the soil temperature for each batch were recorded every hour over the course of six hours. A Vernier CO2 gas sensor was placed in each chamber and hooked up to a LabQuest, which monitored soil respiration over time, digitally storing the CO2 emissions in parts per million (ppm) every thirty minutes.

When the 6 hours ended, experimental batches were placed in a freezer for sixteen hours (Wang, 2015, p. 265) at a temperature of -18°C (Meyer, 2016, para. 11). The next morning, the soils were removed from the fridge and allowed to thaw at 22°C for another six hours, during which the CO2 levels were recorded every thirty minutes and soil temperatures every hour.

The final cycle consisted of sixteen hours in the freezer at -18°C and a following twenty-four hours of thawing. During this interval, CO2 levels and soil temperatures were recorded every two hours. Each data set was then downloaded from the LabQuest and recorded in a spreadsheet for analysis. The spreadsheets were used to make line graphs. A line of best fit was fit to these graphs and a linear regression was calculated. A steeper slope suggested a faster rate of soil respiration. The temperatures of the soils in relation to CO2 levels were charted and graphed separately.

Control

Throughout cycles one and two, a recovering chamber and a natural chamber were kept at room temperature. These soils maintained a temperature of 21°C. Carbon levels were monitored and recorded over the same intervals as the experimental batches.

Results

The experimental undisturbed soil was referred to as the Natural group, while the experimental disturbed soil was called the Recovering group.

Control

Throughout cycles one and two, a recovering chamber and a natural chamber were kept at room temperature. These soils maintained a temperature of 21°C. Carbon levels were monitored and recorded over the same intervals as the experimental batches.

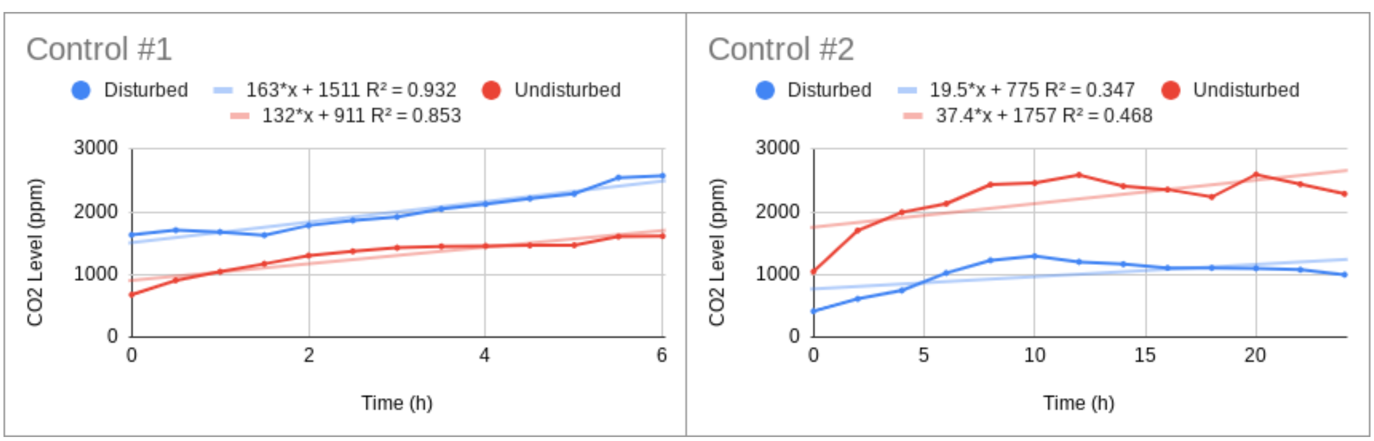

Figure 1: Carbon levels of control chambers during both cycle #1 and #2

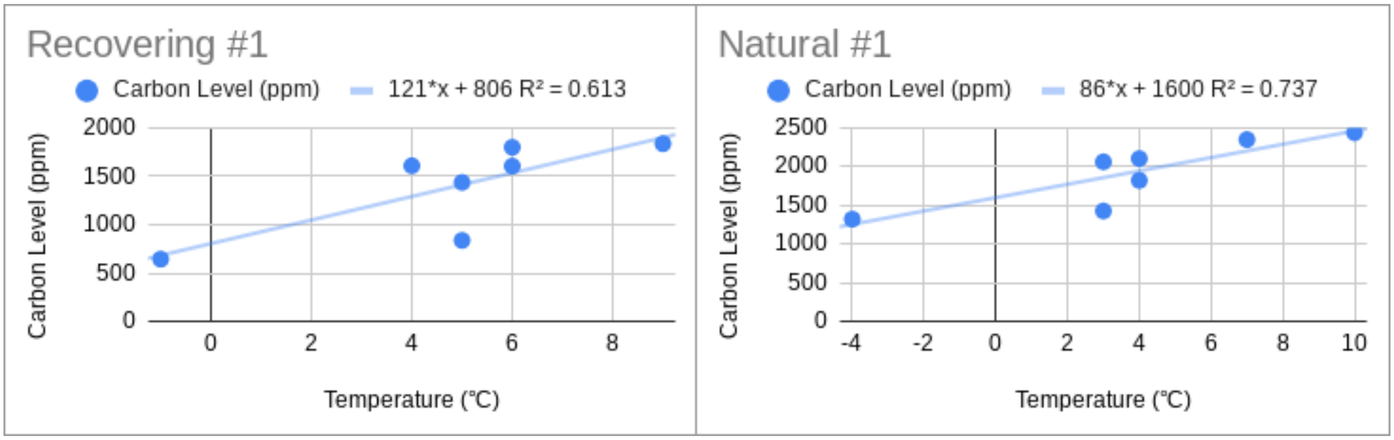

Figure 2: Influence of temperature on the release of carbon dioxide in cycle #1

As depicted in Figure 1, carbon levels increased over time for both the recovering and the natural soils. In the first cycle, the disturbed soil released more carbon overall, and the trendlines fit the data well, with 93.2% for the recovering chamber and 85.3% for the natural chamber. In the second cycle, undisturbed soils released higher amounts of carbon dioxide. The trendlines did not fit the data, with 46.8% for the recovering chamber and 34.7% for the natural chamber. This can be attributed to the extended amount of thaw time and the two hour intervals, as carbon flux is typically measured in smaller intervals.

Cycle One

As shown in Figure 2, carbon levels in the Recovering soil chamber had increased by approximately 121 ppm each time temperature was recorded (every hour). The coefficient of determination shows that the trendline fit the data by 61.3%, meaning the trendline was able to describe 61.3% of the data. Similarly to the recovering soil, natural soil respiration also increased with temperature, at a rate of approximately 86 ppm per hour. The trendline fit the data by 73.7%.

As time went on, the carbon levels in each chamber increased. The trendline fit the recovering soil data by 84.9% and had a steeper slope than that of the undisturbed soil, as the carbon level increased by 208 ppm per hour. The carbon level in the natural chamber increased by 198 ppm per hour, as demonstrated in Figure 3. The trendline fit 95.1% of the data for the natural chamber.

According to Figure 4, the undisturbed soil saw higher overall carbon levels throughout the first cycle.

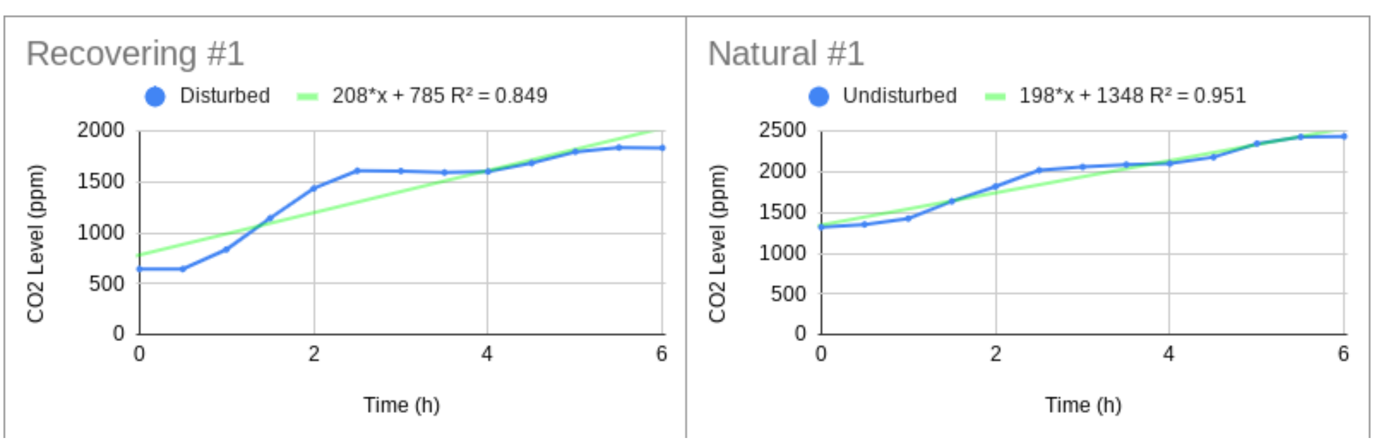

Figure 3: Carbon levels relative to time in cycle #1

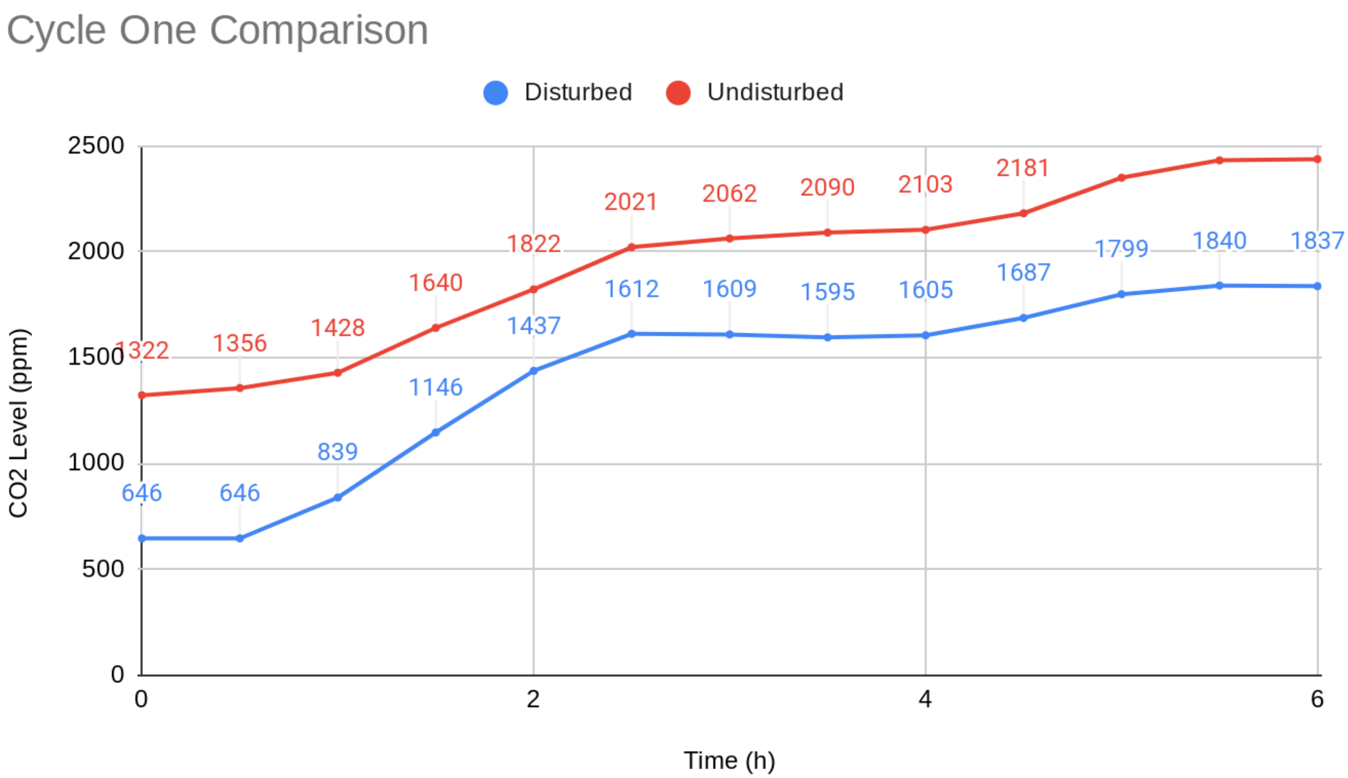

Figure 4: Comparison of carbon levels for disturbed and undisturbed soils in cycle #1

However, disturbed soil had a higher rate of soil respiration, emitting approximately 208 ppm of carbon per hour compared to 198 ppm per hour (Figure 3).

Cycle Two

Throughout cycle #2, carbon levels in the recovering chamber increased by approximately 53.9 ppm each time temperature was recorded, and the trendline described 84.5% of the data. Likewise, carbon levels in the natural chamber had a positive correlation with temperature rise, increasing by 47.8 ppm. The coefficient of determination for this chamber was 70.7%.

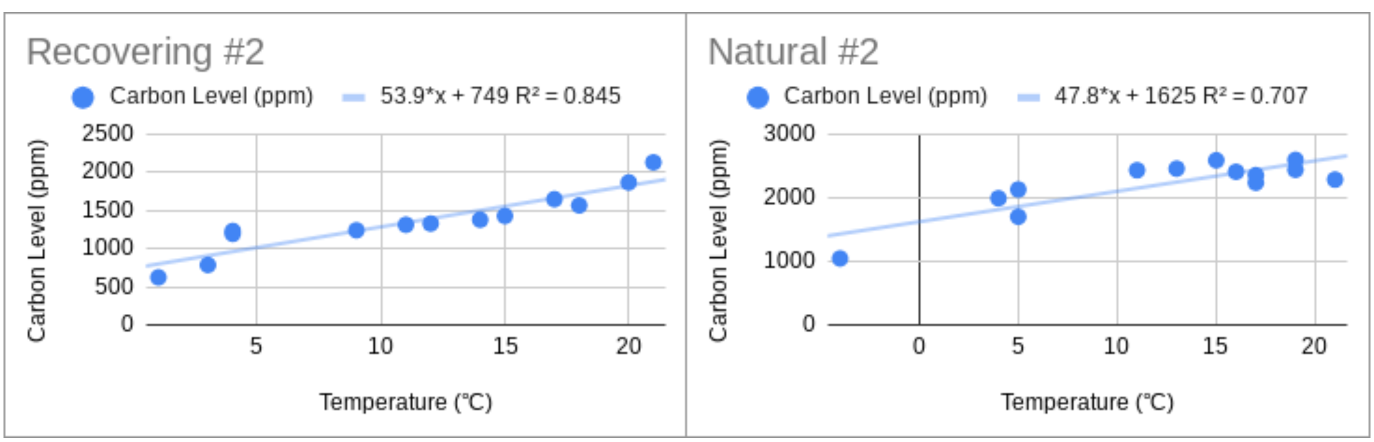

Figure 5: Influence of temperature on the release of carbon dioxide in cycle #2

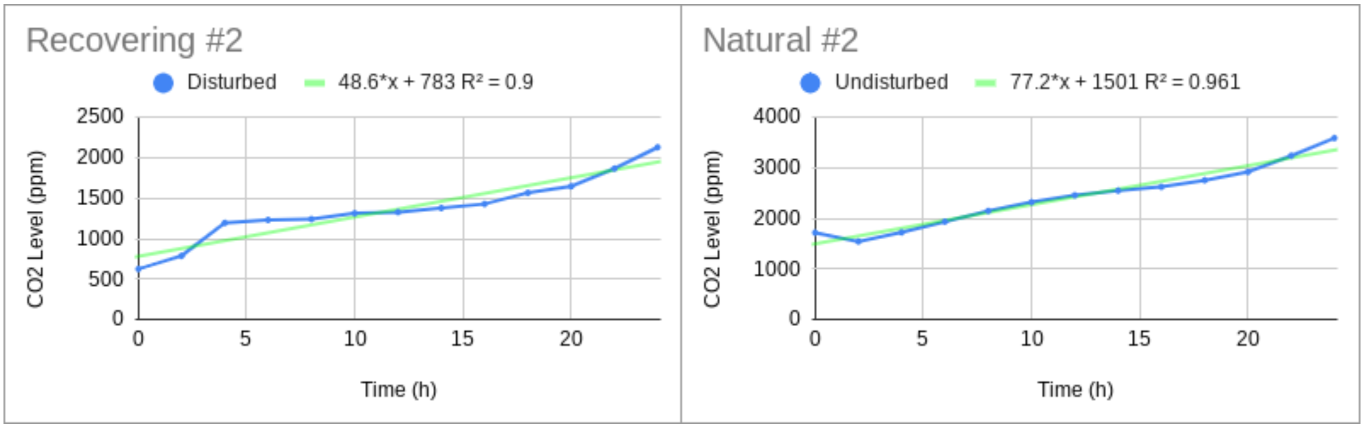

Figure 6: Carbon levels relative to time in cycle #2

Carbon dioxide levels increased by 77.2 ppm per hour in the natural chamber, while the recovering chamber saw an increase of 48.6 ppm per hour, as conveyed Figure 6. The coefficient of determination was 90% for the recovering chamber and 96.1 % in the natural chamber.

Figure 7 demonstrates that the undisturbed soil emitted more carbon dioxide overall throughout cycle #2, and the rate of soil respiration was higher than that of the disturbed soil (Figure 5).

In summary, carbon levels increased with time in the control chambers as well as all chambers in cycles #1 and #2. The relationship between temperature and soil respiration was positive for both disturbed and undisturbed soil in both cycles. Undisturbed soil re-

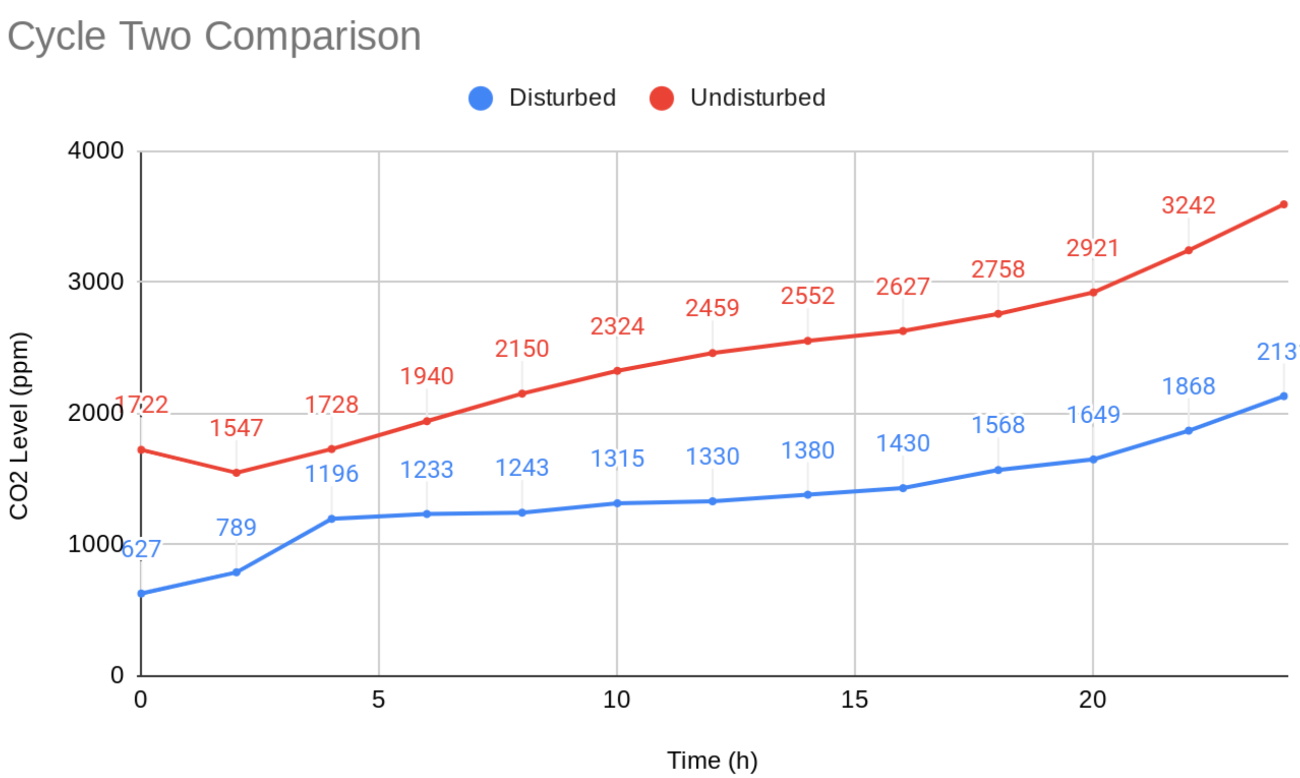

Figure 7: Comparison of carbon levels for disturbed and undisturbed soils in cycle #2

leased more carbon dioxide overall in both cycles, however, the rate of soil respiration was higher in disturbed soil in the first cycle.

Discussion

To review, this study aimed to answer the question, "to what extent does the carbon flux vary between disturbed and undisturbed salt marsh soils when subjected to freezing and thawing cycles?" In order to evaluate this, disturbed and undisturbed sediments were collected from the same marsh and subjected to freezing and thawing in an incubation experiment. The change in carbon emissions for each group was monitored over the course of the thaw. The results suggested that the rate of soil respiration is higher in soils recovering from a disturbance, while the natural soils released a higher overall amount of carbon dioxide at a lower rate. This implies a relationship between disturbances to salt marshes and the release of sequestered carbon during freeze/thaw events.

Meaning of the Results in the Context of the Study

To analyze the results more in depth, an evaluation of the relationship between temperature and carbon emissions was necessary. In general, increasing temperatures lead to an increasing rate of soil respiration, and therefore, a higher amount of carbon dioxide release. This is an idea expressed in many studies, such as Meyer (2018) and Kim (2012), and is further supported by the results of this study. The rate of soil respiration increased with increasing temperatures for both disturbed and undisturbed soils. Within the first cycle, the natural sample saw an 86 ppm increase for each degree Celsius increment. For the sample recovering from a disturbance, per degree Celsius increase, the carbon levels rose by 121 ppm. This indicates that disturbed soils release carbon more rapidly than untouched soils as temperatures increase. These results contradict the findings of a 2017 study by Persico et al., which discovered higher rates of soil respiration in undisturbed soils, as opposed to soil that had faced a disturbance caused by feral hog grazing. While the results of Cycle 2 reflect the same relationship between temperature and carbon release, the undisturbed soil saw a higher rate of respiration in relation to time. However, due to the extended amount of time between each recording, Cycle 2 did not offer an accurate representation of carbon flux. Carbon flux is typically measured in intervals of no more than thirty minutes, and carbon levels in Cycle 2 were measured every two hours, making the data more unreliable than the findings of Cycle 1.

Furthermore, over the course of the six hour thaw in Cycle 1, both soils demonstrated an increase in carbon release over thirty minute intervals. Disturbed soils had a higher rate of respiration, releasing 208 ppm of carbon per hour, as opposed to the undisturbed soil chamber, which saw a 198 ppm increase in carbon levels per hour. This phenomenon was also observed in a similar study, Macreadie (2015), which determined that a disturbed blue carbon ecosystem released 72% of carbon storage throughout 50 years after the disturbance. The undisturbed soils saw a lower rate of respiration. However, the undisturbed soil chamber contained the most carbon throughout the experiment overall. According to the data, the natural soil began the thaw with carbon levels at 1348 ppm, while the recovering chamber started at 785 ppm. There are a few possible explanations for this occurrence. As discussed in Persico (2017), these relatively high measurements of carbon levels in undisturbed chambers could be attributed to "enhanced benthic diatom biomass and microbial turnover" (p. 65). Fundamentally, the plant matter and organic content of the undisturbed soil was likely higher than the disturbed soil initially.

Implications, Limitations, and Future Research

Not only does this study insinuate a relationship between salt marsh disturbance and the rate of soil respiration, but it also has more profound implications regarding the contributions of blue carbon ecosystems in either combating or amplifying climate change. The study fills the gap of knowledge in understanding the effects of freezing and thawing cycles on salt marsh soil respiration in the Mid-Atlantic region of the United States. While there were existing studies that observed freeze and thaw in other ecosystems, this study helps to demonstrate the correlation in blue carbon ecosystems. This may allow for a better understanding of the consequences of freeze/thaw events on the abilities of wetlands to sequester and store carbon. However, a field experiment on freeze/thaw events and the impact of disturbances on soil respiration is needed to effectively expand on the findings of this study and broaden the understanding, as an incubation study can only represent the natural ecosystem to a certain extent.

While this study suggests a relationship between soil disturbance and respiration, alternative explanations could explain the higher rate of soil respiration in recovering soil. Variations in soil moisture, salinity, nutrients, and heterotrophic components could be attributed to these results. For example, although the disturbed and undisturbed samples were collected within very close proximity to each other, the sites were dominated by different plant species: a larger population of Spartina alterniflora occupied the disturbed area, and a larger population of Spartina patens occupied the undisturbed area. According to Greller (2010), a study on the carbon dynamics and ecology of a salt marsh, S. alterniflora had higher productivity levels than S. patens, with a net ecosystem production of 827 units compared to 503.4 units. This could explain the higher rate of carbon release in disturbed soil, especially due to the fact that samples were not sieved and organic matter was maintained. While sampling from the same marsh may have minimized the effects of these other factors, it is possible that they had an effect on the rates of soil respiration.

The major limitations of this study begin with the dilemma of sample collection, as soil sampling fundamentally disrupts the natural system. Therefore, it could be argued that both the recovering and natural soils had been disturbed in the research process. In addition, this experiment does not take into account other factors of climate change or environmental factors characteristic to winter on the Mid-Atlantic coastline, including increased rates of sea-level rise. Due to the lack of access to a laboratory during the COVID-19 pandemic, this study was conducted using a freezer and the room of a house, and therefore, the conditions do not reflect the natural conditions of the soils in a Mid-Atlantic salt marsh. A lack of appropriate equipment and a limited amount of time prevented a field experiment from being conducted in conjunction with the incubation study, which would have been beneficial to verifying the results.

In regards to future research related to this topic, a field experiment is imperative to fully understanding the scope of the issue. As mentioned previously, sample collection disrupts the soils, and therefore, an incubation experiment may not offer a clear representation of soil respiration in a natural environment. Furthermore, a potential future study could investigate the impact of different types of disturbances, as there are several that could potentially pose a threat to stored carbon stocks and soil respiration, including crab burrowing and human activity. Lastly, another significant factor for future consideration is the impact of disturbances on carbon emissions based on the severity of the disturbance. Both Persico (2017) and Coverdale (2014) suggest that the severity of the disturbance has an effect on the severity of the respiration rate, which would add to the understanding of recovering salt marsh productivity.

The abilities of blue carbon ecosystems to sequester and store carbon are known, but how do disturbances impact this effort to combat climate change? This study hints that disturbances to these ecosystems and rising temperatures could be extremely detrimental to the environment, converting salt marshes from effective carbon sinks to sources of carbon emissions. According to Coverdale (2014), wetland disturbances heavily contribute to the release of stored carbon back into the atmosphere. In fact, "three decades of salt marsh die-off, resulting from an indirect human impact, reversed centuries of carbon sequestration…". Based on the findings of this study, the rising temperatures that have resulted from climate change likely amplify this problem, due to the apparent increased carbon release of recovering soils in the face of freezing and thawing cycles. It is a detrimental positive feedback loop that may not be halted until these ecosystems are protected from disturbances and restored.

Conclusion

The results of this study confirmed the hypothesis that disturbed soils would have a higher rate of respiration in conjunction with rising temperatures. However, the higher levels of carbon in the undisturbed chamber were unexpected. Prior to this study, there was a lack of existing literature on the freezing and thawing of wetland ecosystems, as well as salt marsh productivity for the Mid-Atlantic region. This study fills the gap in understanding for both of these concepts, and it adds to the discussion of disturbances to blue carbon ecosystems and their implications towards climate change. The results of this study suggest that due to soil disturbances, wetlands that once served as effective carbon sinks face the threat of becoming sources of carbon emissions. The application of freezing and thawing cycles attempted to mirror extreme temperature changes within these ecosystems, and point to a growing threat that could alter the abilities of salt marshes to sequester and store carbon. Only until we can grasp these complex relationships can we know how to improve the state of our blue carbon ecosystems so that they can continue to serve as effective carbon sinks.

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