BIOTIC AND ABIOTIC FACTORS MEDIATING COASTAL ELEVATION

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Abstract

Humans impact Southern Louisiana marshes through pollution and global change that causes severe weather events and sea level rise. In addition to destroying habitat, these factors put marshes at risk of erosion. Increased nutrients, such as from pollution, can alter plant biomass allocation above- or belowground. Marsh grasses can also mitigate erosion and promote buildup of sediments through accretion. This study aims to determine whether changes in nutrient levels in marshes alter biomass allocation to a degree that impacts land elevation by limiting erosion and/or promoting accretion. This study includes analyses of: impacts of nutrient levels on the biomass allocation of marsh grasses, the correlation between biomass allocation and land elevation/inundation risk, and models of indirect correlations between nutrient levels and marsh elevation, mediated by plant biomass. Marshes with higher N tended to have lower above- and belowground biomass (AGB and BGB, respectively); higher P was correlated to lower AGB. It is likely that nutrient levels are so high that they are stressful to the grasses, causing lower biomass. Higher BGB in marshes correlated to lower submergence risk; higher AGB in marshes generally correlated to lower land elevation. These results are varied, likely because of geographic location and other confounding variables. Higher nutrients indirectly correlated to lower elevation and lower elevation change, while high nutrients also correlated to decreased submergence risk and increased projected elevation. Further field and/or greenhouse experiments are necessary to understand how increased nutrients in marshes can impact land elevation through biotic means.

Acknowledgements

I would like to thank the entire Tulane EEB community for their kindness and support, inspiring me to pursue this field. In particular, I want to thank Emily Farrer and Renata Durães Ribeiro, as well as Nicole Gasparini, for acting as my readers through this process. I especially appreciate Dr. Farrer and Dr. Jelagat Cheruiyot for being personal mentors to me. Carolyn Schroeder was integral to this project and I can’t thank her enough for the hours spent at her desk helping with coding.

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Introduction

Coastal land loss in Southern Louisiana is becoming an ever more urgent issue to address and prevent. Sea level rise, severe weather events such as hurricanes, and destruction of marsh habitat are several root causes that lead to erosion and eventually complete inundation of land. Conservatively, Louisiana is projected to lose approximately 5000 km^2 of land by the year 2100, with more extreme estimates closer to 13,000 km^2 (Blum & Roberts, 2009). Sea level rise caused by climate change threatens to inundate low-lying land on Louisiana's coasts, including marshes; as marshes erode and flood, formerly inland areas are put at greater risk of sea level rise and hurricane damages such as storm surges because marshes buffer inland areas from these threats (Howes et al., 2010). Marshes also distance economically valuable inland areas such as New Orleans, LA, Mobile, AL, and Biloxi, MS from open ocean, decreasing the severity and impacts of hurricanes in these places. Global change also increases the frequency and severity of storms, particularly hurricanes, making marshes even more essential.

Anthropogenic changes including channelization of the Mississippi River's path alter the amount and location of sediment deposits at the delta of the river (Chamberlain et al., 2018; Blum & Roberts, 2009). Some estimates state that modern sediment loads are only 27-34% of historic levels (Blum & Roberts, 2009). Accretion is the accumulation of sediment and organic matter on an existing surface; because of anthropogenic alterations to the Mississippi River that prevent periodic flooding and deposition (i.e. levees), areas that previously relied on sediment deposits to maintain their elevation consequently experience decreased deposition, and likely decreased accretion rates. Decreased accretion, especially when paired with increased rates of sea level rise, extreme weather events, subsidence, and erosion, increases the relative severity of sea level rise and the potential for a given area to become permanently submerged.

In addition to increasing land elevation, deposited sediments carry agricultural and industrial pollutants with nutrients such as nitrogen (N) and phosphorous (P), which are necessary for plant growth. Because of the widespread use of fertilizers in the Mississippi River watershed, large volumes of these nutrients are deposited at the delta of the River. These nutrients largely remain in the Gulf of Mexico, though some nutrients reach coastal and inland marshes via disturbances such as waves and storms, as well as through diffusion and local pollution. The increased nutrient load in these marshes may play a role in the growth patterns of marsh grasses.

Marsh grasses such as *Spartina alterniflora* are considered ecosystem engineers because they can play an active role in altering the ecosystem structure and function, while simultaneously adapting to changes in their environment. Studies show that *S. alterniflora* and other marsh grasses respond to changes in nutrient concentrations by altering their biomass allocation in greenhouse and field experiments, meaning that they may preferentially grow above- or belowground in response to environmental conditions. Increased N concentration in soil has been shown to facilitate the growth of aboveground biomass (AGB) in *S. alterniflora* (Darby & Turner, 2008a). Marsh grass stem density and regrowth efficiency also increased with N (Darby & Turner 2008a, Vivanco et al., 2015). However, the benefits of N decrease as N levels increase, such that after a certain point N no longer increases plant AGB (Vivanco et al., 2015). Other nutrients may interact with N to increase effects on marsh grasses. Darby & Turner (2008a) found that increased N in combination with increased P and/or iron (Fe) increased the AGB more than N addition alone. These results were consistent across a salinity gradient and between several marsh types (Vivanco et al., 2015), suggesting transferability to other grass species because the dominant species of marshes typically varies depending on salinity.

There is strong evidence that adding N as well as P and/or Fe to soil decreases the total BGB in *S. alterniflora*, however, addition of N alone does not have significant impacts on BGB (Darby & Turner, 2008a). In some cases, nutrient levels are so high that they constitute a stressor for marsh grasses; such was the case in Hollis & Turner's (2021) greenhouse experiment involving *Spartina patens*, where increased levels of N and P caused lower tensile root strength because the existing BGB was more porous than it would have been in a lower-nutrient environment. Deegan et al. (2012) found similar results, where increasing nutrients decreased belowground biomass (BGB), likely because the plants allocated more energy aboveground. There is little support that total BGB differs significantly when N alone is increased (Vivanco et al., 2015; Darby & Turner, 2008a).

Despite evidence that nutrient concentration can alter plant growth, published literature predominantly studies greenhouse and manipulated field experiments. In contrast, little research has been done to determine the effects of nutrients on plant growth patterns in non-manipulated, natural settings. Additionally, few (if any) studies have tested the impacts of the addition of various levels of P alone on marsh grasses. These gaps in the literature should be addressed in order to predict the effects of agricultural and industrial pollution in the Mississippi River, as well as understand the differences in functionality of marshes with different nutrient concentrations in order to determine which marshes may be more resistant to sea level rise.

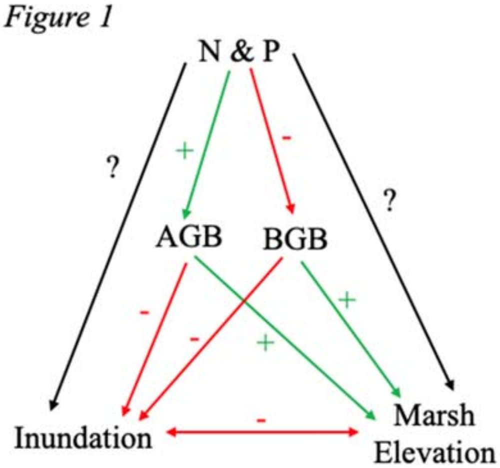
Marsh grasses can potentially impact land elevation by trapping sediments in their stems, thereby promoting accretion, as well as by preventing erosion by trapping sediments in their root systems. The level to which plants can promote accretion is dependent on their stem density, with denser stands often trapping more sediment (Bernik et al., 2018). Additionally, root systems are better able to mitigate marsh erosion if the tensile root strength, or the "structural integrity" of the root, is greater (Hollis & Turner, 2021). Plants also increase the volume of organic matter below the soil surface, increasing land elevation (Vivanco et al., 2015). The impacts of plant biomass allocation on land elevation are not widely studied, especially on a large-scale, landscape level, and therefore further research is needed to understand how plants influence marsh elevation.

The loss of coastal marshes constitutes a loss of a wetland that provides habitat, ecosystem services, and intrinsic value as an ecosystem. Projections estimate that up to one third of coastal wetlands will be lost to sea level rise alone by 2100 (Howes et al., 2010), and between one quarter and one half of tidal marshes have already been lost (Deegan et al., 2012). Marshes provide habitat for many species of birds, mammals, aquatic animals, plants and microorganisms; loss of habitat may cause these species to experience endangerment or extinction. Marshes are important to protect inland areas from storm surges, they act as carbon sinks, and offer hurricane protection by increasing the distance of inland areas from open water (Howes et al., 2010). The key to protecting Southern Louisiana from sea level rise and global change is protecting coastal marshes. In order to effectively do so, it is necessary to understand the potential for pollution to alter land elevation, either directly or indirectly, by impacting plant biomass allocation. It is also crucial to understand any differences in marsh functionality and ecosystem structure caused by various nutrient levels, and how these differences impact marshes' vulnerability to sea level rise.

The goal of this study is to determine whether nutrients (N and P), mediated by plant biomass, can indirectly or directly impact marsh elevation and inundation (Figure 1). In order to do this, the impacts of N and P concentrations on the biomass allocation of grasses were studied. This information can be used to draw conclusions about the impacts of different nutrient levels on marsh grasses. The relationships between plant biomass and elevation and inundation were also studied. Greater BGB can prevent erosion by strengthening existing soil, and marshes with greater AGB can trap more sediment in their stems, promoting accretion.

Based on results from the literature, I predict that marshes with greater N and/or P concentrations will have lower BGB and greater AGB than relatively nutrient-poor marshes. I also predict that marshes with high BGB will have higher elevation and lower inundation risk because of the abundance of roots to secure the soil, preventing erosion and allowing sediment to accumulate. Finally, I predict that marshes with greater AGB will also have higher elevation and lower inundation risk because more AGB likely correlates to higher stem density, and deposited sediment is more likely to be trapped in denser stands of marsh grasses, leading to increased accretion. Because of complex interactions

Figure 1



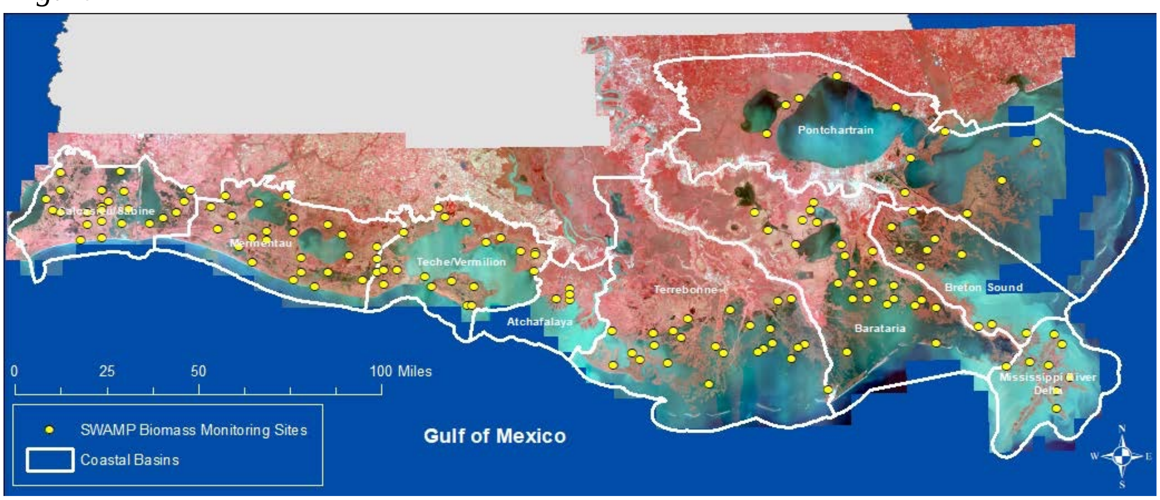
Concept map of the predicted results of the analyses, as well as the main question/goal of the study: how does nutrient concentration indirectly effect coastal marsh elevation and inundation?

between the variables, further research of the indirect and direct impacts of nutrient concentration on elevation and inundation risk must be done (Figure 1).

Methods

This study consists of a literature review and analysis in RStudio. The data was downloaded from the Coastwide Reference Monitoring System (CRMS), which consists of approximately 390 sites (Figure 2). All sites are located in southern Louisiana wetlands and have been measured for a number of biotic and abiotic variables, including nutrient concentrations, plant biomass, and land elevation. Data was downloaded for 68 sites for 2016-2017; only sites with data for all necessary variables were used, and the years studied were limited by the absence of N data for all years except 2016-17.

Figure 2

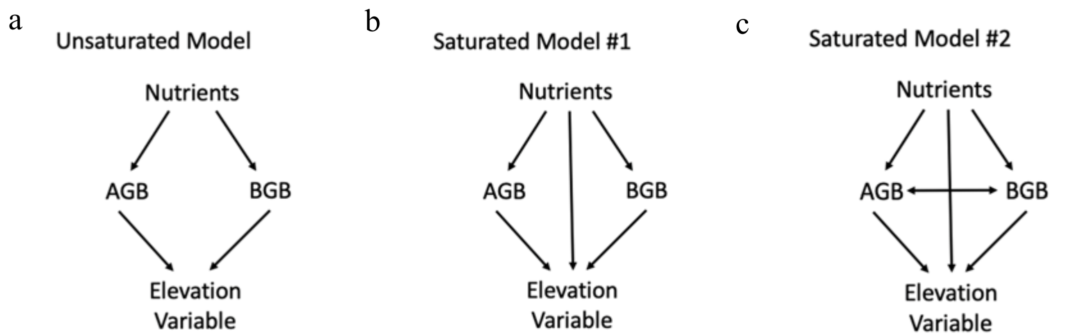


Map depicting sites in the CRMS monitoring network and Louisiana's nine coastal basins (Folse et al., 2020). 68 of the sites depicted were used for this study.

The study is split into three parts: nutrient analysis, elevation analysis, and a structural equation model section that synthesizes the trends of the former two analyses. The nutrient analysis studies the relationships between nutrient concentration and biomass allocation. The nutrients studied are N (measured in g/kg) and P (measured in mg/kg); values were obtained based on their concentrations in the soil. Biomass was quantified by measuring the dry masses (in g/m^2) of live, dead, and total AGB and BGB for the dominant species at each site (Folse et al., 2020). Elevation and inundation risk analyses study the relationships between biomass allocation, elevation, and inundation risk. The variables used for the elevation analysis include current marsh elevation (cm above sea level (NAVD88)), surface elevation change (cm/year, calculated from the date of site establishment to the most recent sample), projected elevation (cm; projected to five years after the most recent sample using a linear regression where the slope equals elevation change rate in cm/yr), and submergence vulnerability index (SVI; a calculated score between 0-100, where lower values indicate a greater risk of inundation (see Appendix 1)). SVI acts as a proxy for inundation risk, as there was inadequate data for inundation. These variables were analyzed against the biomass variables listed previously. The data was collected and measured by the Coastal Protection and Restoration Authority of Louisiana using the methods explained in Folse et al. (2020).

Data was analyzed with RStudio using ggplot2, lavaan, and semPlot packages. Graphs were created using linear regressions (geom_smooth). The significances of the pairwise linear relationships were analyzed using Anova ($p<0.05$). Structural equation models (SEMs) were used to determine whether there were any significant indirect or direct relationships between nutrient (N and P) concentrations and elevation and inundation risk variables ($p>.05$). For SEMs, I followed the procedures outlined by Grace (2017). I compared the unsaturated model (Figure 3a) to two saturated models (Figures 3b & 3c) to determine whether any statistically significant differences were present between the models. After determining no significant differences between the three models, I proceeded to use the unsaturated model for all analyses. This procedure was repeated for N and P; live, dead, and total AGB and BGB; and each elevation variable.

Figure 3



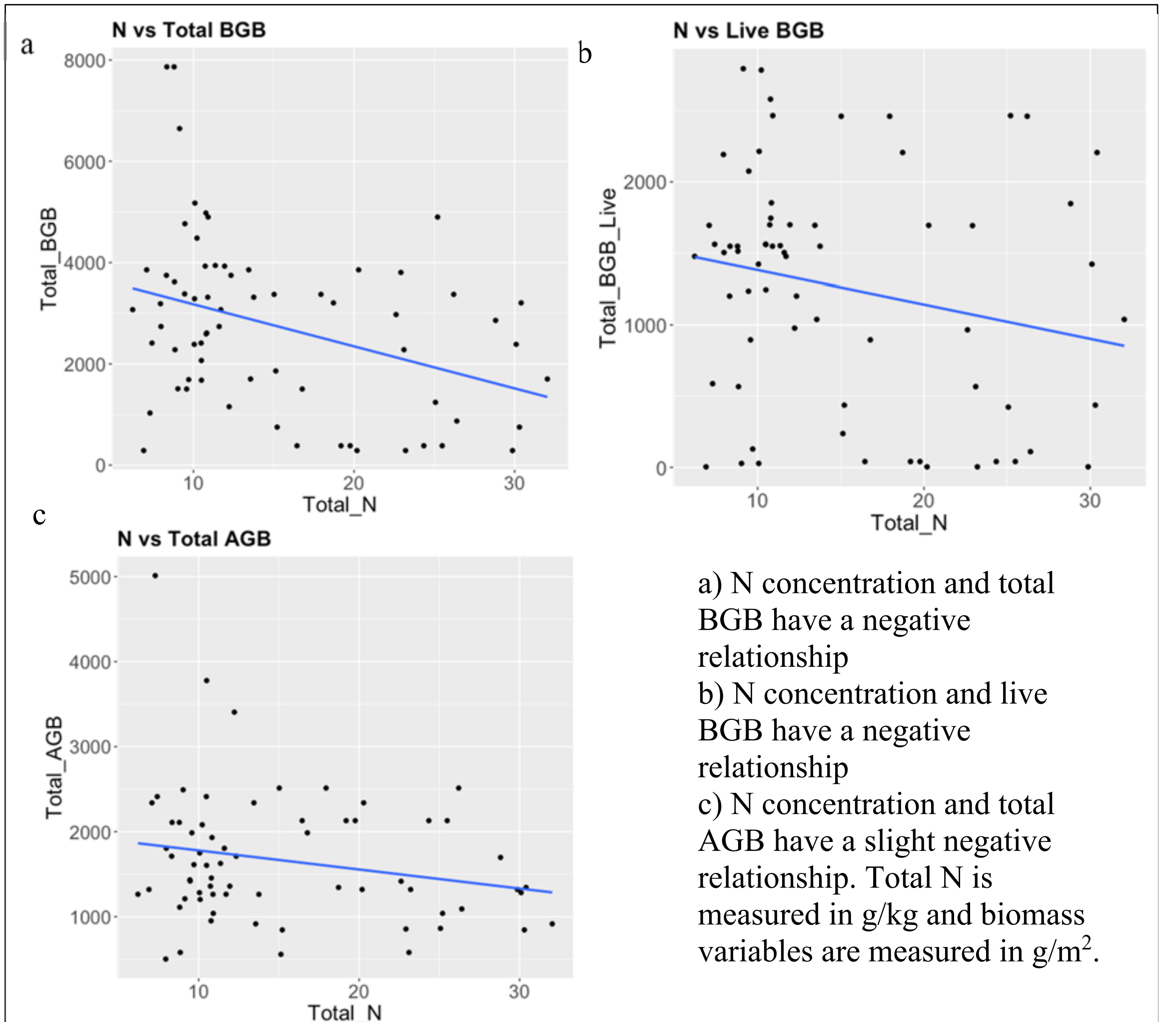
a) Unsaturated SEM b) Saturated SEM #1 (improvement upon the unsaturated SEM) c) Saturated SEM #2 (improvement upon saturated SEM #1)

Results

Nitrogen

Nitrogen had a strong negative correlation with total BGB (p=.0030, F=9.53, df=2; Figure 4a). N concentration had a nearly significant negative correlation with live BGB (p=.084, F=3.08, df=2; Figure 4b) and total AGB (p=.082, F=3.12, df=2; Figure 4c). Dead BGB, dead AGB, and live AGB did not have significant relationships with N.

Figure 4

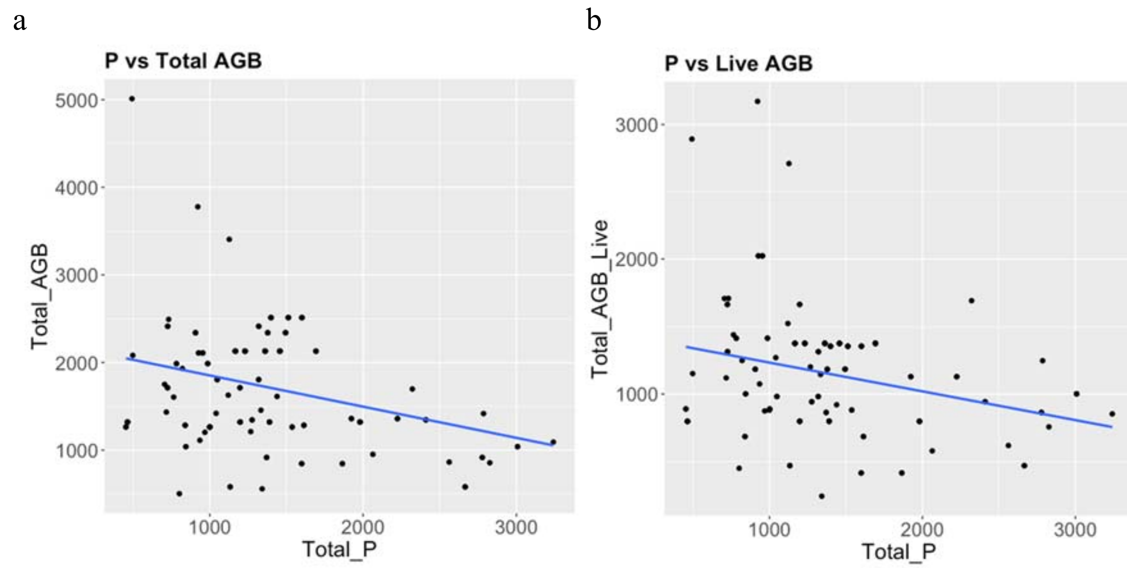


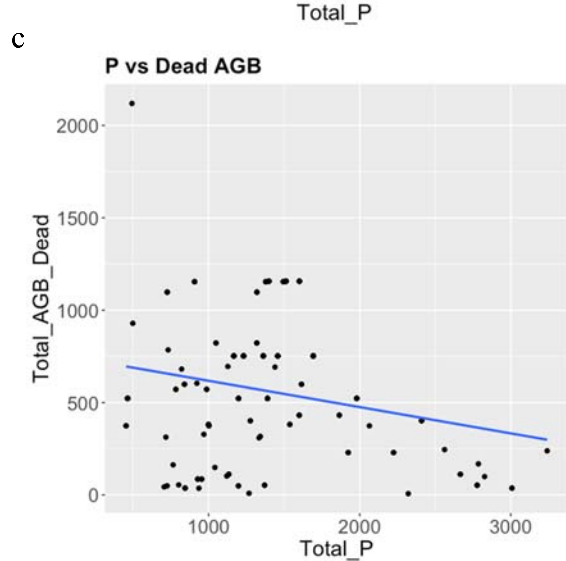
a) N concentration and total BGB have a negative relationship
b) N concentration and live BGB have a negative relationship
c) N concentration and total AGB have a slight negative relationship. Total N is measured in g/kg and biomass variables are measured in g/m^2.

Phosphorous

The concentration of P in soil had a significant negative correlation to total AGB (p=0.0020, F=10.34, df=2; Figure 5a), live AGB (p=0.0078, F=7.55, df=2; Figure 5b), and dead AGB (p=0.026, F=5.18, df=2, Figure 5c). There were no significant relationships between P and any BGB measurements. Additionally, N and P had a very strong positive relationship (p=3.35e-5, F=18.41, df=2).

Figure 5





a) P concentration (mg/kg) versus total AGB (g/m^2)
b) P concentration (mg/kg) versus live AGB (g/m^2)
c) P concentration (mg/kg) versus dead AGB (g/m^2).

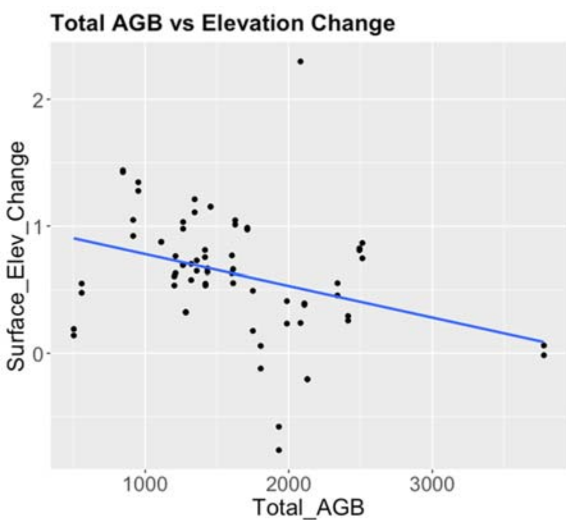
Marsh Elevation

Marsh elevation was split into three categories: current elevation, surface elevation change, and projected surface elevation. The current marsh elevation did not have any significant correlations with biomass variables.

Surface elevation change had a significant negative correlation with total AGB ($p=.0064$, $F=7.93$, $df=2$; Figure 6) and live AGB ($p=0.033$, $F=4.76$, $df=2$). Additionally, surface elevation change had a nearly significant negative correlation with dead AGB ($p=.074$, $F=3.31$, $df=2$). In the majority of cases, elevation was changing positively (i.e., increasing), but to a lesser degree as AGB values increased. There were no significant or near-significant relationships between surface elevation change and any BGB measurements.

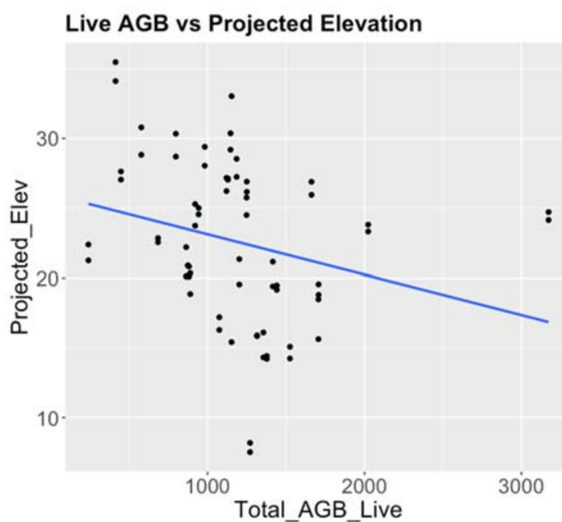
The projected surface elevation had a significant negative relationship with live AGB ($p=.033$, $F=4.73$, $df=2$; Figure 7). The correlation between projected surface

Figure 6



Total AGB (g/m^2) versus marsh surface elevation change (cm).

Figure 7



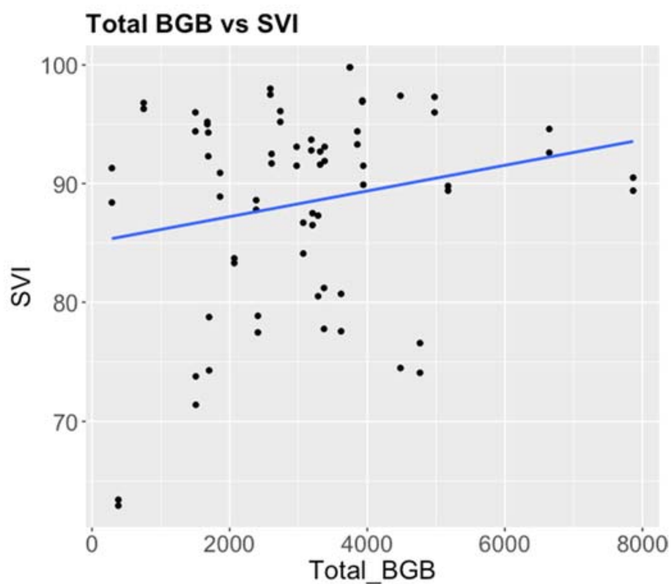
Live AGB (g/m^2) versus projected land surface elevation (cm).

elevation and total AGB was negative and nearly significant (p=0.118, F=2.50, df=2). There were no significant or near-significant relationships between projected surface elevation and dead AGB or any BGB measurements.

Submergence Vulnerability Index

Submergence Vulnerability Index (SVI) is a calculated measure that accounts for land elevation and water levels; a higher SVI value indicates a lower risk of inundation. SVI had a nearly significant positive relationship with total BGB (p= 0.0951, F=2.867, df=2; Figure 8), indicating that high BGB is correlated to lower submergence risk in marshes. There were no significant or near-significant relationships between SVI and live BGB, dead BGB, or any AGB measurements.

Figure 8

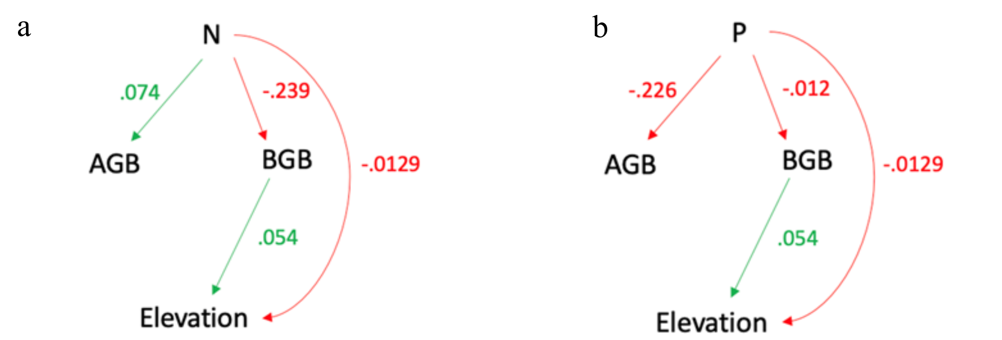


Total BGB (g/m^2) versus SVI. Larger x-values indicate a lower risk of flooding and inundation.

Structural Equation Models

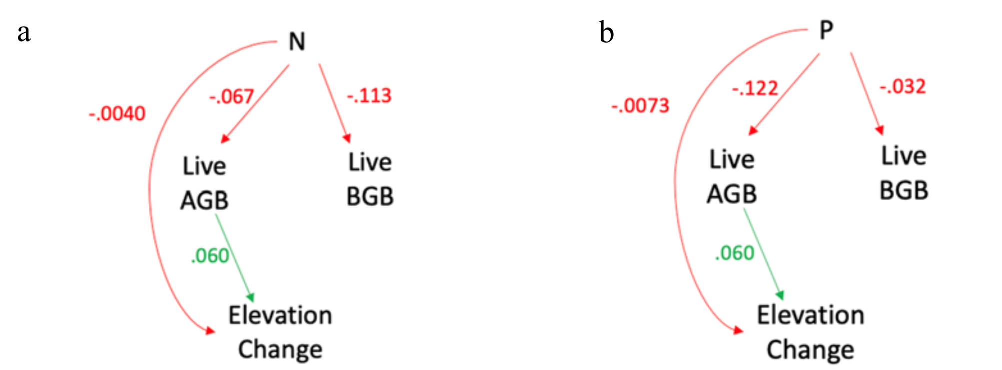
All structural equation models (SEMs) presented have a good model fit (i.e. they had non-significant chi-squared values, indicating no significant discrepancy between the models and the data), meaning that the variables in the models have a significant impact on each other. SEMs found indirect effects of both N and P on current marsh elevation, both mediated by total BGB. Specifically, N and P had negative indirect effects on current marsh elevation; increased N and P decrease BGB, which increases current marsh elevation (Figure 9). There were also negative indirect effects of N and P on elevation change, both mediated by live AGB (Figure 10). Models also found indirect effects of N and P on projected surface elevation, both mediated by live BGB (Figure 11). There were indirect relationships between N and P and SVI, both mediated by live AGB (Figure 12), meaning that higher nutrients correlated to lower inundation risk.

Figure 9



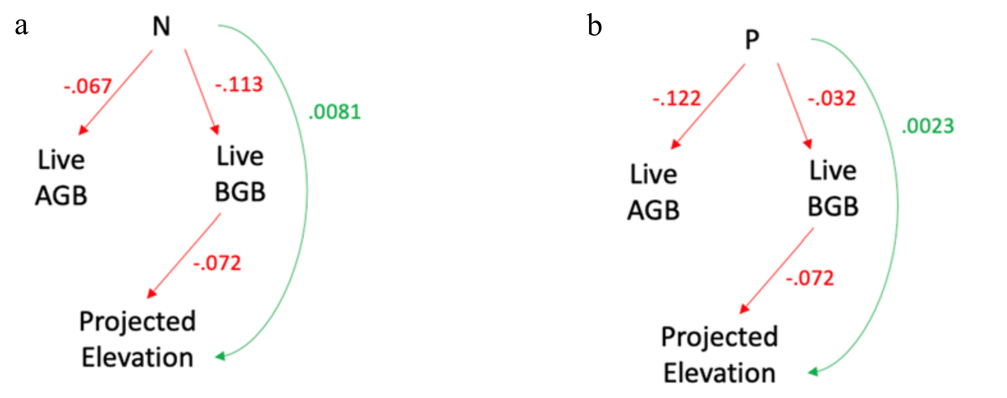
SEMs showing the indirect effects of a) N and b) P on elevation, mediated by total BGB. Red arrows and negative numbers indicate a negative correlation, and green arrows and positive numbers indicate a positive correlation. Curved arrows indicate indirect effects of nutrient levels on elevation. Only significant relationships are shown in the diagrams.

Figure 10



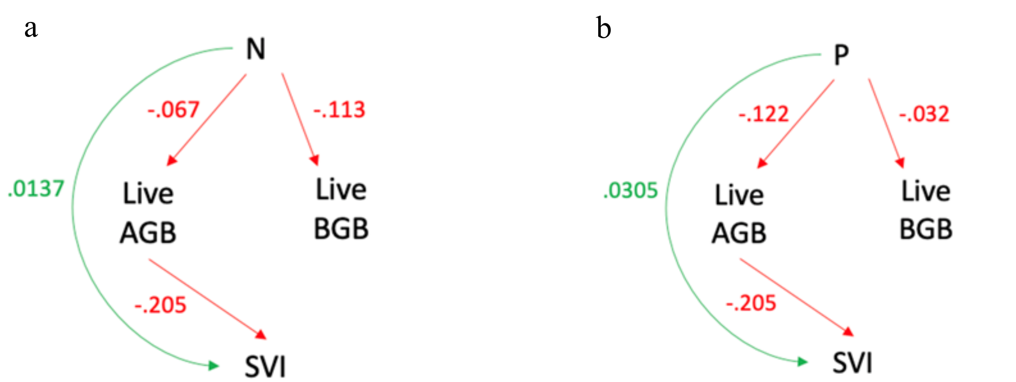
SEMs showing the indirect effects of a) N and b) P on elevation change, mediated by live AGB. Red arrows and negative numbers indicate a negative correlation, and green arrows and positive numbers indicate a positive correlation. Curved arrows indicate indirect effects of nutrient levels on elevation change. Only significant relationships are shown in the diagrams.

Figure 11



SEMs showing the indirect effects of a) N and b) P on projected elevation, mediated by live BGB. Red arrows and negative numbers indicate a negative correlation, and green arrows and positive numbers indicate a positive correlation. Curved arrows indicate indirect effects of nutrient levels on projected elevation. Only significant relationships are shown in the diagrams.

Figure 12



SEMs showing the indirect effects of a) N and b) P on SVI, mediated by live AGB. Red arrows and negative numbers indicate a negative correlation, and green arrows and positive numbers indicate a positive correlation. Curved arrows indicate indirect effects of nutrient levels on SVI. Only significant relationships are shown in the diagrams.

Discussion

SEMs

Structural equation models found weak yet significant indirect relationships between nutrient concentration and elevation variables. Generally, SEMs should be considered the most accurate results, as they provide a more complete picture of existing correlations compared to linear regressions. The SEMs yield different results than linear regressions because SEMs elucidate patterns differently than pairwise linear regressions, leading to discrepancies in the relationships.

Nutrient concentrations indirectly decreased marsh elevation and are correlated to decreased or negative elevation change: these relationships were mediated by BGB and live AGB, respectively. This offers some support for my hypotheses, and is logical because high nutrient marshes tend to have lower overall BGB and AGB, which correlate to lower elevation and elevation change. Higher levels of N and P decrease tensile root strength and alter the biomass allocation of plants, leading to the decreased AGB and BGB (Hollis & Turner, 2021). Increased nutrients may directly impact land elevation by increasing the rates of decomposition of organic matter, leading to settling as the average particle size decreases (Deegan et al., 2012).

On the other hand, nutrients have an indirect positive effect on projected elevation and SVI, mediated by live BGB and live AGB, respectively. The relationship between nutrient levels and projected elevation is uncertain. In the SEMs, live BGB mediates this relationship despite there being no significant linear relationship between BGB variables and projected elevation; in fact, live BGB has an insignificant, slightly positive relationship with projected elevation change. SEMs of projected elevation likely yielded different results than those of current elevation and elevation change because projected elevation is based on both the current elevation and elevation change, which are independent of each other. Projected elevation and current elevation are strongly correlated; the difference between these SEMs is accounted for because different biomass variables mediate the indirect relationships. Projected elevation and surface elevation change are less strongly correlated, so it is probable that current elevation impacts projected elevation more so than surface elevation change, accounting for the different indirect relationships with nutrients. Projected elevation is slightly greater than current elevation for most sites, though it is possible that sea levels will increase more than the marsh elevation, leading to inundation despite the increase in elevation. Further analysis of these relationships is required to fully understand this discrepancy.

SVI has an indirect positive relationship with nutrient levels, mediated by live AGB, meaning that areas with more nutrients tend to be at lower risk of inundation. This contradicts findings that high nutrient areas tend to have lower elevation. SVI is a calculated measure that accounts for both water level and land elevation, adding a previously unconsidered variable (water level) to the relationship. Both marsh elevation and water level are measured relative to sea level, therefore it is possible for water level to exceed the marsh elevation, leading to inundation. Further geographic analysis of water levels across South Louisiana is needed to understand the cause of this correlation.

Nutrient-Biomass Regressions

The analyses for N and P partially supported my hypothesis that greater N and P concentrations in the soil are correlated to lower BGB. Greater N concentration correlated to lower BGB and lower AGB; greater P concentrations correlated to lower

AGB only. Excessive nutrients (such as from agricultural pollutants) can constitute a stressor for grasses, leading to lower tensile root strength and BGB (Hollis & Turner, 2021). Higher nutrients, particularly nitrate ions, interact with the organic carbon that makes up plants' roots and potentially alter respiration pathways, reducing overall biomass, especially belowground (Hollis & Turner, 2021). Vivanco et al. (2015) found a neutral response of BGB to increases in N in California marshes, and a leveling off of total biomass as N increased. It is possible that the concentration of N in the study sites surpassed the threshold to yield a neutral response, and instead became stressful and decreased both BGB and AGB. It is unknown how the nutrient levels in the CRMS sites compare to those in prior experiments because of the differences in methodologies to apply, and units used to measure, existing and/or added nutrients. The lack of significant correlations between P and BGB measurements indicate that P concentration may play little role in BGB volume, which does not support my original hypothesis. However, this finding corroborates existing literature, which found no significant differences in BGB for different nutrient additions, including P, so long as N concentrations were not elevated (Darby & Turner, 2008a).

I also hypothesized that greater N and P concentrations would correlate to greater AGB. Contrary to my hypothesis, high N and P levels correlated to lower AGB. Studies have shown that when plants are in high N environments, they devote more energy to producing AGB (Darby & Turner, 2008a; Deegan et al., 2015). This is partially because they do not need to allocate their energy belowground to forage for nutrients, and partially because there are ample nutrients from which to construct the molecules necessary for growth (Darby & Turner, 2008a). However, after N reaches a certain level it no longer benefits the plants, causing AGB to level off and eventually decline as excessive nutrients become a stressor (Vivanco et al., 2015; Hollis & Turner, 2021). It is likely that excessive nutrients present in marshes act as a stressor, inhibiting aboveground growth. It is also possible that other confounding variables are impacting AGB more than N or P levels; Darby & Turner (2008b) found statistically significant differences in AGB year to year, which could mean the negative correlation is due to chance or other unmeasured or unconsidered variables that vary year to year. It is probable that factors aside from nutrient levels impact biomass allocation due to the lack of controls in place.

Interestingly, P concentration was also negatively correlated to total, live, and dead AGB. Darby & Turner's (2008a) field experiment found that the addition of P alone does not increase AGB, but addition of both N and P increases AGB compared to control plots. Frost et al. (2009) concur this result, finding that addition of N and addition of both N and P increases AGB, while adding P alone does not. Marshes are often N-limited, therefore it is expected that P will have a relatively weak or nonexistent impact on biomass concentration compared to N (Darby & Turner, 2008c).

Biomass-Elevation Regressions

There was some support for the hypothesis that BGB correlates to higher marsh elevation. SVI was positively correlated to BGB, indicating that sites with greater BGB were at lower risk of inundation, according to CPRA's calculations. Greater BGB in marshes may play a role in mitigating inundation risk; alternatively, BGB allocation could be adaptive for different elevations and inundation regimes (Kirwan & Guntenspergen, 2012). The hypothesized mechanism by which BGB would increase elevation is by decreasing erosion by physically blocking the soil with their roots and rhizomes. The tensile strength of roots and rhizomes plays a role in whether increased BGB actually decreases erosion; stands with greater tensile root strength were found to be more effective at stabilizing soil and reducing erosion in models based on data from Hurricane Katrina (Howes et al., 2010). This analysis and dataset do not measure tensile root strength, necessitating further experiments to determine a relationship in the field. The lack of correlations between BGB and other elevation measurements suggest that BGB may help protect against submergence but does not necessarily alter marsh elevation.

Analyses largely did not support the hypothesis that greater AGB correlates to higher marsh elevation and decreased inundation frequency or severity. The negative correlation between surface elevation change and total and dead AGB shows that sites with greater AGB tend to be subsiding or not changing, and sites with less AGB tend to be increasing in elevation. A similar trend is found with AGB and projected surface elevation. These findings directly contradict my hypothesis and the findings of Vivanco et al. (2015), who assert that marshes with greater AGB, and often greater stem density and/or thickness, can trap more sediment than low-AGB areas, leading to accretion. The stem density was not measured for this dataset, and it is likely that sites with greater AGB do not always the highest stem density. Deegan et al. (2012) found that increased nutrient loads tended to increase AGB by increasing grass height rather than stem thickness or density, explaining why increased AGB does not necessarily increase land elevation. It is also possible that marsh grasses are better adapted to low-elevation areas and establish populations with more AGB here. Further geographic and biological research would be necessary to determine the cause of this correlation.

Conclusions & Implications

Overall, this study found mixed support for my hypotheses. Higher N and P levels tended to reduce biomass, suggesting that the nutrient levels are so high that they become stressful to the plants, reducing their AGB and BGB (Hollis & Turner, 2021). Therefore, it is important to limit agricultural and industrial runoff into the Mississippi River watershed in order to relieve marsh grasses of this stressor.

BGB reduced submergence risk, while AGB correlated negatively with marsh elevation variables, providing mixed support for my hypothesis. It is likely that geographic or other confounding variables in addition to biomass allocation play a role in determining elevation. Tensile root strength and stem density play major roles in erosion control and sediment accretion, respectively, however these metrics were not included in the datasets (Howes et al., 2010). Low stem density may allow sediment to travel through the marshes and into open water, while stem density that is too high may impede water and sediment movement through marshes. Further analysis of growth patterns is necessary to understand plants' role in elevation control. Alternatively, differences in elevation cause differences in plant biomass, with biomass decreasing above and below a certain optimal elevation (Kirwan & Guntenspergen, 2012). One must consider that marsh grasses adapt depending on their environment in addition to altering the environment themselves. Further research into why marshes vary in elevation is necessary to fully understand these relationships.

Mixed evidence was found for the indirect effects of nutrient concentrations on marsh elevation. Higher nutrient levels correlated to higher projected elevation and lower submergence risk, while also correlating to lower current elevation and elevation change.

N and P each had similar impacts on marsh elevation, indicating that nutrients in general impact marshes, rather than just one of the specific elements studied. The biotic variable mediating these relationships was not consistent, meaning that neither AGB nor BGB plays a dominant role in determining or otherwise correlating to marsh elevation. It is likely that geographic and other confounding variables influenced these results, and further research is necessary to fully understand the mechanisms by which abiotic factors influence marsh grasses, and the direct and indirect effects that these patterns have on marsh elevation.

Further Research

Because of the mixed and occasionally contradictory evidence found in this study, further research is necessary to confirm any potential correlations between nutrients, biomass allocation, and elevation. Because this is a correlative study, causation is unknown; this is especially important to consider for *Spartina*- and *Phragmites*-dominated marshes because these genera are ecosystem engineers, meaning that in addition to the plants being shaped by their environment, the grasses also shape the environment itself. Mapping the CRMS sites and studying the same variables used in this study spatially will provide further insight into the causes of the correlations found in this study. For example, does the distance of a marsh from the current mouth of the River affect the elevation? Specifically, mapping elevation data to determine if marsh grasses preferentially settle in low or high elevation areas would also provide valuable insight. Determining the tensile root strength and/or the root:rhizome ratio of marsh grasses will help determine why BGB does not necessarily increase elevation.

The inconclusiveness of P analyses in particular beg further analysis; to my knowledge, no studies have explicitly compared the effects of the addition of different levels of P on biomass allocation of marsh grasses such as *S. alterniflora* or *S. patens*. It is also unknown at which point excessive N and P become stressful for the plants. Further geographic, field, and/or greenhouse studies will help determine the reasons for these correlations.

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Appendix

1. The SVI model assesses the submergence vulnerability of a site based on the 5-year projection of its relative position within the hydrologic frame. Both wetland surface elevation and water levels (based on at least 5 years of data) are projected 5 years into the future. Wetland elevation is projected using surface elevation change rates, and water levels are projected using eustatic sea-level rise rates. The position of the projected wetland relative to the distribution of projected water levels determines the SVI score. A site is scored (0-100) according to the position of the future wetland elevation within the distribution of future water levels using the following equation: $P_n = 100/N * (n-1/2)$ where n is the rank of the projected wetland elevation within the projected distribution of water levels, that contains N total observations. Sites with more frequent flooding receive lower scores and are considered more vulnerable to submergence, whereas sites that are flooded less frequently receive higher scores and are considered less vulnerable to submergence.