Title: Promoting success in thin layer sediment placement: effects of sediment grain size and amendments on salt marsh plant growth and greenhouse gas exchange

Running Head: Salt marsh sediment and biochar additions

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Author contributions

EBW, KBR designed the study; BPW, KLR conducted the study; BPW conducted the data analysis; ABG, TM conducted critical laboratory analysis; BPW, EBW wrote and edited the manuscript; BPW, EBW stewarded data and code.

Abstract

Thin layer sediment placement (TLP) is used to build elevation in marshes, counteracting effects of subsidence and sea level rise. However, TLP success may vary due to plant stress associated with reductions in nutrient availability and hydrologic flushing or through the creation of acid sulfate soils. This study examined the influence of sediment grain size and soil amendments on plant growth, soil and porewater characteristics, and greenhouse gas exchange for three key US salt marsh plants: *Spartina alterniflora* (synonym *Sporobolus alterniflorus), Spartina patens* (synonym *Sporobolus pumilus*), and *Salicornia pacifica.* We found that bioavailable nitrogen concentrations (measured as extractable NH_4^+-N) and porewater pH and salinity were inversely related to grain size, while soil redox was more reducing in finer sediments. This suggests that utilizing finer sediments in TLP projects will result in a more reduced environment with higher nutrient availability, while larger grain sized sediments will be better flushed and oxygenated. We further found that grain size had a significant effect on vegetation biomass allocation and rates of gas exchange, although these effects were species-specific. We found that soil amendments (biochar and compost) did not subsidize plant growth but were associated with increases in soil respiration and methane emissions. Biochar amendments were additionally ineffective in ameliorating acid sulfate conditions. This study uncovers complex interactions between sediment type and vegetation, emphasizing limitations of soil amendments. The

findings aid restoration project managers in making informed decisions regarding sediment type, target vegetation, and soil amendments for successful TLP projects.

Key words: salt marsh, sea level rise, particle size distribution, biochar, greenhouse gas, soil amendments, restoration, ecosystem

Implications for practice

- Utilization of coarse sediment in TLP projects may benefit salt marsh plants less tolerant of saline and reducing conditions, and will support lower soil carbon accumulation
- Conversely, utilization of fine sediment in TLP projects may benefit salt marsh plants that are halophytic or respond positively to added nutrients, and will support greater soil carbon accumulation

Introduction

Accelerated sea level rise (SLR) is a major threat to coastal salt marshes, as studies have suggested that increased rates of SLR have resulted in marsh vegetation die-off and expansion of tidal channels and ponds (Crosby et al. 2016; Davis et al. 2019; Watson et al. 2016). Analysis of aerial photographs and peat cores has shown that marsh vegetation can migrate upslope to compensate for marsh loss at lower elevations (Fagherazzi et al. 2019; Hussein 2009). However, barriers can preclude the marsh vegetation from migrating upslope, such as urban and agricultural development, species competition and steep topographic gradients (Fagherazzi et al. 2019; Schieder et al. 2018). As a result of fragmentation and coastal marsh losses, valuable ecosystem services and functions are at risk, including shoreline stabilization, flood mitigation, denitrification, and carbon sequestration (Gedan et al. 2011; Sutton-Grier et al. 2015; Temmerman et al. 2013). Without further action, these ecosystem services and functions will be degraded due to accelerated SLR.

Thin layer sediment placement (TLP) is a method of SLR adaptation that increases the elevation of the marsh platform through the application of sediment, as an effort to prevent over-inundation and extend the lifespan of the marsh (Oldenborg & Steinman 2019; Thorne et al. 2019; Wigand et al. 2017). Target sediment placement thickness varies greatly among restoration and enhancement projects, often ranging from less than 10 cm up to a meter (Raposa et al. 2023), depending on the restoration project's functional goals and the tidal range of the marsh, as a low tidal range marsh will experience a greater reduction in surface flooding for a commensurately thinner sediment placement. Additionally, thickness may vary depending on dredged sediment type, method of application, and grading equipment. For example, TLP projects in New Jersey had sediment slurries that sorted by grain size during application, resulting in thicker applications closer to the spray outlet where the larger grained sediments were more concentrated (NJDEP & TNC 2023). This can have significant effects on underlying vegetation and the subsequent recolonization of vegetation on the elevated marsh platform, as thinner applications are more likely to allow for vegetation breaking through the overlying sediment. Projects with thicker additions or with sediments that act as potential impediments for underlying vegetation to break through, such as those with heavy clay content, will be more reliant on ingrowth from the edges of the TLP area (Allison 1995; NJDEP & TNC 2023). Additionally, coarse sediment has a greater bulk density, and added weight from coarse sediments has in some cases caused mortality of target vegetation species (Jiang & Middleton 2011; Middleton & Jiang 2013).

Sediment composition is also a main driver of chemical properties, and as such will alter vegetation biomass allocation and cause changes in nutrient cycling. For instance, a significant reduction in *Spartina patens* stem production was found after dredged sediment addition in the study of Matzke & Elsey-Quirk (2018); however, there was also an increase in fine root production, demonstrating a shift in biomass allocation. Furthermore, soil type and texture has been suggested to shape species growth responses among common wetland species (Howard 2010). The results from these studies strongly suggest that there is an interactive effect between plant species and sediment texture that can be leveraged to plan TLP projects that meet restoration goals.

Incorporation of biochar and compost into TLP projects may offer a complementary method of enhancing plant recolonization. Biochar is a carbonaceous, porous material formed from anoxic combustion of organic feedstock material and is often used in agriculture and restoration projects to enhance soil fertility, denitrification, hydraulic flow, and carbon sequestration (El-Naggar et al. 2015; Ojeda et al. 2016; Yao et al. 2018). However, biochar characteristics may be dependent upon the feedstock and combustion parameters used to produce the biochar (Atkinson et al. 2010). Studies have shown greater long-term carbon sequestration of biochar made from high-lignin feedstocks combusted for longer periods (Tag et al. 2016). Biochar is often applied with compost, as some studies have suggested a synergistic effect on soil fertility (Sánchez-Monedero 2019). As compost provides a more bioavailable source of nutrients due to its low recalcitrance, biochar may ensure the released nutrients remain within the rhizosphere by adsorption to the biochar particle surface (Gong et al. 2019).

Additionally, studies have suggested using biochar as a means of ameliorating soil acidity through moderation of the soil pH, total alkalinity, and metal concentrations (Dai et al. 2017; Manickam et al. 2015; Novak et al. 2009). This benefit of biochar is particularly notable as many benthic sediments have high concentrations of iron sulfide, and oxygenation of these sediments can result in the formation of acid sulfate soils (Salisbury et al. 2017; Xu et al. 2018). Acid sulfate soils, characterized by a pH less than 4, have been shown to have phytotoxic effects on common salt marsh hydrophytes (Ingold & Havill 1984). Incorporation of biochar into dredge sediments may prevent acid sulfate formation by increasing the pH buffering capacity of soil through carbonate formation from the release and transformation of carboxylate groups on the biochar surface (Dai et al. 2017; Leng & Huang 2018; Manickam et al. 2015). Biochar incorporation could thus neutralize acidic soils and enhance plant recolonization. However, most biochar studies have been conducted in agricultural or otherwise non-hydric conditions, with few studies examining biochar properties in wetlands (e.g., Borchard et al. 2019; Wang et al. 2016). It is difficult to generalize the potential benefits of biochar in tidal wetland restorations as there are complicated interactions between sediment type and the emergent properties resulting from the feedstock and treatment of biochar, and how those properties may interact with hydric conditions (Cayuela et al. 2013; Leng & Huang 2018; Sun et al. 2016).

This study focuses on the three questions relative to TLP projects: (1) the effects of sediment textures typical of dredged material used in TLP projects on the growth of common salt marsh vegetation species, (2) the potential of biochar and compost to enhance plant growth, and (3) the use of biochar to ameliorate soil acidity. Salt marsh plants were grown in greenhouse mesocosms for a full growing season in sediments of varying texture with and without treatments of softwood-feedstock biochar and compost. As previous studies have demonstrated the species-specific sensitivity of hydrophytes to soil texture and water holding capacity (Howard 2010; Matzke & Elsey-Quirk 2018; Muench et al. 2019), we hypothesized that the propagated plants would have higher biomass in coarser sediments. We expected an exaggerated difference in the high marsh species *S. patens* and *S. pacifica,* which are less tolerant of extended inundation conditions, grown in coarse sediments relative to those grown in fine sediments. *S. alterniflora* is a low marsh species and thus was expected to be hardier in fine grained sediments, as it can tolerate longer periods of inundation (Gleason & Ziemen 1981). We further hypothesized that softwood biochar and compost additions would enhance plant growth (Roberts et al. 2015). Lastly, as biochar contains a high amount of surficial carboxylate groups, additions of biochar to sediments may increase the carbonate concentration of sediments through the cleavage of the carboxylates and conversion into carbonate ions, resulting in an increase in the buffering capacity of these sediments (Dai et al. 2017; Leng & Huang 2018; Manickam et al. 2015). Therefore, we hypothesized that softwood biochar would neutralize acidic soils. This study's overall aim was to determine which benthic sediment textures would be most beneficial to TLP restoration projects and whether soil amendments, including biochar and compost, could promote successful early plant recolonization.

Methods

Coastal marsh plant taxa, including *Spartina alterniflora* (synonym *Sporobolus alterniflorus)*, *Spartina patens* (synonym *Sporobolus pumilus*), and *Salicornia pacifica*, were obtained from restoration nurseries (Native West Nursery, San Diego, CA & Pinelands Nursery, Columbus, NJ and propagated during the 2018 growing season in a roof-top greenhouse in Philadelphia, PA (39.9539°, -75.1878°) in benthic sediments like those used in TLP projects (Raposa et al. 2023). *S. patens* and *S. alterniflora* were chosen as high and low marsh representatives (respectively) due to their high prevalence within eastern U.S. coastal salt marshes, while *S. pacifica* is a dominant low marsh species of the West Coast. Three experiments were performed to determine if: 1) sediment texture influences the success of restoration planting, 2) if biochar or compost additions facilitate vegetation growth in nutrient-poor dredge sediment, and 3) whether biochar ameliorates acidity caused by oxidation of sulfides in soils. Plants were tempered over two weeks to a final salinity of 20‰, using a mixture of water collected from Barnegat Bay, NJ (39.7483°, -74.1931°) and distilled water. Plants were exposed to ambient light conditions under 15% shade cloth, and the greenhouse was outfitted with several fans for temperature moderation.

Sediment texture effects on vegetation

Following a 3x4 factorial design replicated four times, three plant species were propagated in four types of homogenized sediments of contrasting textures (Table 1; Fig. S1-S2) over the course of a growing season (130 days; 22 June – 29 Oct 2018). To replicate the way plant plugs are planted in the field in restoration projects post sediment application, plugs (5cm x 5cm x 9cm) were obtained from restoration nurseries and those which were relatively homogenous in the amount of biomass present were planted into larger containers (10cm x 10cm x 24cm). Plants were exposed to simulated once-daily tides (MacTavish & Cohen 2014) where plants were flooded to a depth of 5 cm for four hours, and the soil was drained to 16.5 cm below the sediment surface for twenty hours. For reference, this inundation time (17%) corresponds to that considered 'regularly flooded' (Eleuterius and Eleuterius 1979), but is flooded less frequently than that observed for nine of ten Mid-Atlantic marshes which were found to have an average inundation time of 31% (Elsey-Quirk et al. 2022). Inundation times for Cape Cod marshes were found to be 15% in healthy marshes vs. 45% in fragmenting marshes (Smith et al. 2012).Sediment texture of soil source material was analyzed for all sediment types using a laser granulometer (LS 13-320, Beckman Coulter, Brea, CA) after pretreatment (Gray et al. 2010). Average particle size distributions were post-processed with Gradistat.v8 software (Blott & Pye 2001), including bin aggregation to texture classes and statistical description.

Photosynthesis, community respiration (CR), net ecosystem exchange (NEE), and CH_4 emissions were measured once from 20 to 29 July 2018 using an ultraportable greenhouse gas analyzer (ABB, San José, CA) in a 20L chamber. Measurements of NEE were collected during five minute incubations in a transparent chamber, and CR fluxes were determined by similar incubations with the chamber covered with black-out material. Photosynthesis was calculated as the sum of CR and NEE. The Ideal Gas Law ($PV = nRT$) was used to convert linear changes in CO_2 and CH_4 concentrations within the chamber during each incubation period to fluxes standardized to the surface area of the plant pots (Powell et al. 2020).

Porewater was sampled three times (17 August, 18 September, 24 October 2018), using a Rhizon sampler from a depth range of 0-5 cm. Porewater pH was measured using a benchtop Thermo Orion A111 pH meter, and porewater salinity was measured using a YSI pro30 conductivity and salinity meter. At the end of the growing season, aboveground and belowground biomass of the plants was determined by harvesting, washing, and drying the plant samples at 60 °C to a constant weight. Belowground root material was extracted by washing the container sediment over a 2 mm sieve. Soil redox (eH) was measured at a depth of 5 cm at harvest using a benchtop Oakton oxidation-reduction potential electrode. Sediment samples were collected at harvest and processed for KCl extractable ammonium-nitrogen (NH_4^+-N), with ammonium concentrations analyzed using the phenate method (EPA Method 350.1; APHA 2012). Saturated hydraulic conductivity (K_{sat}) was measured (for S1-4) using a Decagon KSAT (Decagon Services, Pullman, WA) using the falling head method.

We conducted short incubation experiments to assess the $\delta^{13}C$ of the CO_2 emitted from amended soils to help determine whether these emissions could be attributed to plant respiration (~$\delta^{13}C$=-16 to -12‰ for C4 grasses) vs. remineralization of the carbon in biochar or compost (~$\delta^{13}C$=-30 to -25‰ associated with C3 plant material) (O'Leary 1988; Smith & Epstein 1971). We sampled the headspace of the chamber containing plant at the beginning and end of 30-m incubations using 60 mL luer lock syringes outfitted with a stopcock, where the gas was evacuated and stored in 0.1 L Cali-5-bond gas pillows. Carbon dioxide was subsequently analyzed for $\delta^{13}CO_2$ using a benchtop Picarro (Santa Clara, CA, USA) G2201i isotope and gas concentration analyzer.

Biochar and Compost Treatments

S. alterniflora was grown in coarse sand presumed to have low nutrient levels, with the following soil amendments: softwood biochar (10% v/v), compost (10% v/v), and with both softwood biochar (10% v/v) and compost (10% v/v) to match a paired field study (Raposa et al., 2023). Biochar amendments were a commercially available softwood biochar (Blacklite Pure, Pacific Biochar, Santa Rosa, CA; produced from Douglas-Fir feedstock). Compost feedstock included manure, livestock products, aged pine bark, coir, and worm castings (Planting Mix Compost Blend, Organic Mechanics Soil Company, Modena, PA). Plants were propagated under identical conditions as the first experiment over a growing season (22 June – 29 Oct 2018), with 16 total units (n=4 per each treatment). Plant biomass, CO_2 and CH_4 emissions, porewater salinity and pH, KCl-extractable NH_4^+-N, and eH measures were conducted.

Additional samples of *S. pacifica* were grown in two types of benthic sediments prone to acidification (S6, S7) with and without a 10% (v/v) addition of softwood biochar and without tidal flooding. *S. pacifica* was propagated for 181 days; 22 June – 19 December 2018. Each treatment was replicated four to six times for a total of 22 experimental units. As described above, plant total biomass, porewater salinity and pH, KCl-extractable NH_4^+-N, and eH were measured. In additional porewater total alkalinity was measured (EPA Method 2320 B; APHA 2012).

Data Analysis

All statistical analyses were performed in R ver. 4.0.3 (R Core Team 2023). Correlation matrices were created to examine the dependency of measured variables. The relationship between sediment texture and edaphic parameters (eH, NH_4^+-N, K_{sat}, and porewater pH and salinity) was tested using a non-parametric Kruskal-Wallis test with Bonferroni-correction. Significant interactions ($p<0.05$) were followed by a post hoc non-parametric Dunn's Multiple Comparison Test.

Plant biomass and photosynthesis were modeled as a function of sediment texture-related parameters (eH, KCL extractable NH_4^+-N, soil hydraulic conductivity, and porewater pH and salinity) using partial least squares regression (PLSR) due to collinearity of predictors. Each variable was assessed for variable importance in projection (VIP), where VIP scores >1 represent high importance to the regression. Bonferroni-corrected one-way Analysis of Variance (ANOVA) tests were run to determine differences in sediment grain size effects on plant species' biomass and gas emissions, as well as to test if biochar and compost treatments on low-nutrient sediments significantly impact sediment eH, NH_4^+-N, porewater pH, and porewater salinity. In certain cases where normality or homoskedasticity assumptions could not be met, Kruskal-Wallis tests were conducted. Significant effects in the ANOVAs or Kruksal-Wallis tests were followed by a post hoc Tukey's Honestly Significant Difference test or Dunn's Multiple Comparison Tests, respectively. To determine the effects of biochar-treatments within non-tidal mesocosms on soil properties (e.g., porewater pH, salinity, eH, NH_4^+-N, and total alkalinity), Welch's Two Sample t-tests were run.

Results

Sediment texture effects on vegetation

Grain size analysis revealed that S1 had a median particle diameter (d_{50}) of 10.3 µm, while S2, S3, and S4 had median particle size diameters of 213, 451, and 523 µm, respectively (Table 1; Fig. 1). Measurements of K_{sat} showed greater hydraulic conductivity in coarser sediments (Table 2). Finer-grained sediments (S1 and S2) and coarser-grained sediments (S3 and S4) were further distinguished by significant differences in sediment eH, porewater pH and salinity (Table 2). S1 and S2 had lower sediment eH than S3 and S4 ($p < 0.001$). Porewaters were significantly more alkaline ($p < 0.001$) and 25-28% more saline ($p < 0.01$) for the finer grained sediments (S1, S2). Extractable NH_4^+-N had an inverse relationship with sediment d_{50}, with higher extractable NH_4^+-N in finer sediments.

Regression analyses demonstrated relationships between edaphic parameters and plant species responses (Fig. 2; Table S1-4). Aboveground biomass of *S. pacifica* and *S. patens* was positively correlated with redox (r=0.64, p<0.001; r=0.72, p<0.001, respectively) and K_{sat} (r=0.59, p<0.001; r=0.31, p=0.1). However, *S. alterniflora* aboveground biomass was negatively correlated with redox (r=-0.26, p=0.07) and K_{sat} (r=-0.56, p<0.001). Belowground biomass of the three plant species was found to be negatively correlated with K_{sat} (r=-0.50, p=0.01), such that there was greater belowground biomass in sediments with low K_{sat}. PLS regression suggested biomass and greenhouse gas exchange were also found to be significantly related to edaphic characteristics, including porewater pH, porewater salinity, K_{sat}, eH, and NH_4^+-N (Tables S5-10). Important predictors were K_{sat} for aboveground biomass (VIP=1.34), K_{sat}, porewater ammonium and pH (*VIP*=1.57, 1.06, and 1.02, respectively) for belowground biomass, and K_{sat}, and salinity for respiration (*VIP*=1.33, 0.99), and NEE (*VIP*=1.55, 1.49).

Responses of plant growth to treatments varied (Fig. 3; Table S11-S13). *S. pacifica* had little aboveground growth in S2, and *S. patens* displayed more of a threshold effect, with lower growth in the two finer sediments and greater growth in the two coarser sediments. There were no statistically significant differences among treatments for *S. patens* for either biomass or CO_2 exchange (Table S12). Generally, the coarsest sediments (S4) had the greatest respiration rates (Fig. 4; Tables S11-13), and also the greatest rates of carbon dioxide photosynthetic uptake for *S. pacifica* and *S. patens,* the less inundation tolerant taxa. Despite differences in CO_2 effluxes across species, emissions of CH_4 from all three plant species mesocosms were significantly higher in S2 sediments (Table S11-13). Of the three species, *S. pacifica* mesocosms produced the most CH_4 emissions, at a rate of 2,598 ± 1,107 μmol CH_4 m^{-2} hr^{-1}.

Biochar and Compost Treatments

Biochar and compost amendments had significant effects on some soil characteristics in the coarse, low-nutrient S5 sediment (Table 2). Biochar and compost amendments resulted in an average increase in extractable NH_4^+-N by 86% and an increase in average soil eH of 434% compared to unamended S5 sediments. Additionally, while the biochar treatment increased the pH and decreased the salinity of S5 porewater, the treatments with compost (both with and without the second addition of biochar) decreased pH and increased salinity. Although the biomass of *S. alterniflora* grown in S5 sediments was not statistically different between treatments (Fig. 5a), the greatest average biomass (for aboveground, belowground, and total biomass measurements) was found in plants grown in S5 without any soil amendments. Average total biomass measured 39% greater for plants grown without additives in comparison with plants grown with compost soil additives, 33% greater in comparison with plants grown with biochar additives, and 20% greater than plants grown with both biochar and compost additives.

Carbon dioxide efflux from *S. alterniflora* mesocosms reflected the trends of biomass measurements (Fig. 5b). Photosynthesis, CR, and NEE rates had no statistical differences among treatments. However, NEE was negative for unamended sediments and biochar amended sediments (-6.21±2.65 and -1.40±3.57 µmol CO_2 m^{-2} s^{-1}, respectively), while amendments with compost and compost with biochar resulted in positive emissions (3.08 ± 4.63 and 3.59 ± 5.43 µmol CO_2 m^{-2} s^{-1}, respectively). Emissions of CH_4 were highest from mesocosms that were treated with compost (Fig. 5c), where compost-only treatments (S5C) resulted in the statistically highest rate of emissions at 332 ± 82.9 µmol CH_4 m^{-2} hr^{-1}, compared to unamended soils which emitted 3.60 ± 3.20 µmol CH_4 m^{-2} hr^{-1}.

The $\delta^{13}C$ of CO_2 emitted from compost amended sediments was more negative than that emitted from biochar and unamended sediments (Fig. 5d). Increased sediment respiration from compost-amended sediments likely originated from compost decomposing, which had a more negative isotope ratio than the C4 plant *Spartina alterniflora*. In contrast, sediments not amended with compost emitted more positive $\delta^{13}C$ CO_2, suggesting origination from enhanced soil respiration rather than the remineralization of biochar. This suggests that biochar is stable in the soil, but enhances soil carbon decomposition.

Although two sediments were used to test if biochar could prevent development of acid sulfate soil conditions only one sediment (S6) acidified. Porewater pH of unamended S6 sediments was more acidic (3.46 ± 0.22) than biochar-amended sediments 4.06 ± 0.48 ($p < 0.05$) (Table 2; Table S15). Biochar additions were also associated with a +355 mV increase in eH in amended sediments. Biochar additions were associated with an increase in the total alkalinity of S7 sediments, which did not acidify, by 67% and an increase in eH and pH by 149% and 3%, respectively.

Discussion

The colonization and zonation of marsh vegetation is a direct response to varying environmental parameters, such as sediment type, salinity, hydrology, and elevation (Contreras-Cruzado et al. 2017; Moffett et al. 2010; Pennings & Callaway 1992). Sediment type is a strong driver of zonation as it encompasses a number of parameters that influence how a plant allocates biomass, assimilates water and nutrients, and respires (Akhtar et al. 2015; Howard 2010; Maricle & Lee 2007). Our studies confirmed that salt marsh vegetation is sensitive to edaphic properties related to grain size, and additionally that the response is species-specific.

Beneficial use of dredge material, such as in the case of TLP projects, is a progressively more common method of increasing marsh elevation in response to accelerating rates of SLR (Ganju 2019). Utilizing TLP for raising marsh elevations has been an overall effective method of increasing the resilience of valuable marsh habitats to climate change through enhancing elevation capital (NJDEP & TNC 2023), but dredge sediment has been shown to have mixed effects on wetland vegetation biomass (Grandy et al. 2018), resulting in variable rates of revegetation and subsequent sediment capture. Grandy et al. (2018) demonstrated that these shifts in growth rates may be due to species-specific interaction with the physical and chemical properties of sediment.

For example, we determined that coarser sediments resulted in higher K_{sat}, allowing for porewater flushing. This may benefit plants less tolerant of inundation or salinity, such as *S. patens* (Muench et al. 2019; Schile et al. 2011). However, these higher flushing rates may reduce the availability of nutrients around the root zone (Fisher & Acreman 2004). As in the case of constructed wetlands for water treatment, high retention rates are important as they allow for maximum nutrient absorption by marsh plants, and flushing the water too quickly results in a lack of assimilation of nutrients (Reinhardt et al. 2005). In line with this, the finest sediment in this study, S1, contained the highest concentration of extracted NH_4^+-N compared to the other sediments. This sediment also had the lowest K_{sat}, demonstrating a clear trade-off between K_{sat} and nutrient concentrations. This has important implications for designing TLP projects. Systems in which *S. alterniflora* is dominant may benefit from application of moderate grain sized sediments, as nutrients were not a significant driver of biomass for this species due to its ability to efficiently capture bioavailable nitrogen (Muench et al. 2019). Salt marshes dominated by *S. patens*, on the other hand, may benefit greatest from larger grain sediment applications. For species that grow best under high drainage and high nutrient availability, such as *S. pacifica,* choosing a sediment texture will involve tradeoffs. However, it should be noted that the design of this study limited plants to accessing nutrients only from the dredge sediment within the pots, while a field TLP project would consist of the dredge material as well as the original marsh platform below. This original sediment layer may act as an important source of pre-existing nutrient and carbon stock needed for enhanced growth, but it may also result in consistent saturation of lower sediment depths, depending on its composition and the thickness of placed sediments.

Grain size of sediments added in TLP projects had a significant impact on greenhouse gas emissions, which is an important consideration when designing a restoration project with climate change mitigation goals. Dredged material must be chosen carefully, as finer grained sediments are likely to contain a higher proportion of organic content. When removed from anoxic conditions and placed upon the marsh surface, these sediments oxidize and decompose, resulting in carbon mineralization and escalated CO_2 and CH_4 emissions, a similar process that occurs in de-watered aquatic sediments (Paranaíba et al. 2020). However, these increases are typically temporary, with microbial activity peaking within a few weeks (Luo et al. 2016).

Overall, our observations of NEE and CR were similar to those reported in the literature for salt marshes, although our variables had slightly greater spreads (e.g., NEE of -10 to +10 μmol m^{-2} s^{-1} vs. more typical values in the field of -2 to +2 μmol m^{-2} s^{-1}) (e.g., Martin and Moseman-Valtierra 2015; Emery et al., 2019; Powell et al., 2020). We found that finer grain sediments were associated with lower CO_2 emissions (measured as CR or NEE) than coarse-grained sediments. This is likely a result of the anoxic conditions found in the fine-grained sediments vs. vs. the more oxygenated conditions found in coarser sediments, which promotes carbon turnover. This result aligns with another study examining the effects of bioturbation and plant root oxygenation on greenhouse gas emissions, where it was demonstrated that more porous sediments resulted in overall higher CO_2 emissions (Gribsholt & Kristensen 2002). Sediments with a higher clay composition are better able to form soil particle aggregates, which act as a protective layer around smaller organic particulates (Kirk 2004).

However, we found extremely high emissions of methane from one sediment type (S2), that far exceeded (~1000 µmol m^{-2} hr^{-1}) typical observations in salt marshes of -5 + 10 µmol m^{-2} hr^{-1} (Martin and Moseman-Valtierra 2015; Emery et al., 2019; Powell et al., 2020), although these emissions levels are not uncommon for oligohaline tidal marshes (Martin and Moseman-Valtierra 2015). There was also a trend towards higher methane emissions (100 µmol m^{-2} hr^{-1}) in another fine sediment type for *S. pacifica.* This finding highlights the potential for benthic sediment placed in marshes to be a source of methane to the atmosphere, offsetting carbon sequestration benefits of marsh restoration.

Biochar has been touted as a method to increase carbon sequestration through multiple routes, including increasing the direct burial and sequestration of the recalcitrant carbon within the soil, enhanced plant biomass, suppression of CO_2, CH_4, and N_2O production, and adsorption of carbon to the biochar particle, (Agegnehu et al. 2015; Roberts et al. 2015; Yin et al. 2022). Compost and biochar amendments are used together to enhance plant growth (Agegnehu et al. 2015; Darby et al. 2016). Our study demonstrated that biochar amendments did not suppress greenhouse gas emissions, nor enhance growth. These results may suggest that the soil amendments primed the microbial community and enhanced decomposition.

We found no difference in the $\delta^{13}C$ of respired carbon between the biochar amended and control soils, suggesting that biochar may have primed microbial communities (Bernal et al. 2017).

Given that a key goal of biochar incorporation in restoration projects is carbon sequestration, our findings suggest that incorporation of amendments should be studied as part of the project design. We recommend any large-scale application of carbon-based amendments into a wetland environment should be preceded by a pilot study to test different biochar feedstock and dosage interactions with target plant species and sediment combinations. A more recalcitrant feedstock biochar may allow for increased carbon sequestration by reducing emissions due to its reduced bioavailability (Tag et al. 2016), while labile biochar feedstocks may be more bioavailable but provide an increased nutrient supply for vegetation. An increased dosage of biochar may additionally increase the potential nutrient load, but exacerbate emissions, depending on the feedstock as well as the particle size, where larger particle sizes will result in increased aeration of sediments. Because we did not see an effect on *S. alterniflora* with an addition of both biochar and compost, a larger dose may not be more effective for this species; however, other species may be more receptive to the increased carbon and nutrient load. We further suggest a multi-year effort to monitor any microbial or biogeochemical changes over time.

Biochar has been noted to contain alkaline functional groups, lending itself to increasing pH (Yuan et al. 2011) and reducing the formation of acid sulfate soils (Manickam et al. 2015). We found that biochar amendments did not prevent acidification, like the findings of Novak et al. (2018). However, biochar amendments did impact some sediment chemical properties, including eH, total alkalinity, and porewater pH. It is possible that softwood biochar could be utilized to increase the buffer capacity of the marsh system over time (Gunarathne et al. 2020). We hypothesize that given more time in a more reduced environment, the biochar would have created a more substantial buffer capacity within the mesocosms, providing a higher likelihood of preventing acidification of the sediments, such as during droughts.

Through our examination of sediments and soil amendments, we demonstrated the important trade-offs related to using specific sediment textures that must be considered before application of beneficial use of dredged material for TLP. Grain size was associated with multiple other sediment physicochemical properties and can be used to help predict the success of TLP projects. Additionally, we provided insight into the limitations of biochar and compost additions to enhance vegetation growth and prevent acid sulfate formation in dredge sediments, while also determining which sediment chemical properties are significantly affected by these amendments. This investigation highlights the necessity of performing smaller pilot studies with various combinations of sediments and vegetation before application to a natural landscape.

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Table 1. Sediment types used in greenhouse experiments. S6 is a 50/50 (% v/v) mixture of coarse sand and benthic mud. *Sediments were obtained from Graniterock A. R. Wilson Quarry, Aromas, CA 95004.

Sediment	sand (%)	silt (%)	clay (%)	Sample Sorting	Sediment Name	Collection Location(s)
S1	17.1	65.6	17.3	Polymodal, Very Poorly Sorted	Very Fine Sandy Medium Silt	39.5386°, -74.3253°
S2	65.6	29.6	4.8	Bimodal, Very Poorly Sorted	Very Coarse Silty Coarse Sand	39.7433°, -74.1183°
S3	96.7	2.7	0.6	Unimodal, Poorly Sorted	Poorly Sorted Coarse Sand	39.7700°, -74.1892°*
S4	94.8	4.0	1.2	Unimodal, Poorly Sorted	Poorly Sorted Medium Sand	39.6128°, -74.2628°
S5	99.8	0.1	0.1	Unimodal, Moderately Well Sorted	Moderately Well Sorted Coarse Sand	39.6511°, -74.1711°
S6	95.6	3.5	0.9	Unimodal, Poorly Sorted	Poorly Sorted Coarse Sand	41.3283°, -71.7614° & 39.7700°, -74.1892°
S7	76.2	20.2	3.6	Polymodal, Very Poorly Sorted	Very Coarse Silty Coarse Sand	41.3283°, -71.7614° & 41.5787°, -71.4542°

Table 2. Average sediment property measurements of all experimental treatments. Uncertainty (±) denotes one standard error. Abbreviations: eH = oxidation-reduction potential; K_{sat} = saturated hydraulic conductivity; and NH_4^+-N = ammonium – nitrogen.

Sediment	**eH (mV)**	**NH_4^+-N (μMol g_{dry}^{-1})**	**K_{sat} (cm s^{-1} at 10°C)**	**pH**	**salinity (‰)**
S1	-144 ± 5.34	1.62 ± 0.18	$5.60*10^{-5}$	8.09 ± 0.04	26.3 ± 0.53
S2	-152 ± 0.72	0.77 ± 0.10	$9.71*10^{-5}$	7.98 ± 0.02	26.0± 0.70
S3	18.0 ± 3.88	0.57 ± 0.11	$9.98*10^{-4}$	7.36 ± 0.08	24.2 ± 1.17
S4	29.6 ± 5.50	0.51 ± 0.13	0.03	7.58 ± 0.05	20.7 ± 0.31
S5	38.9 ± 5.13	0.29 ± 0.05	-	7.93 ± 0.02	19.9 ± 0.21
S5B	208 ± 125	0.54 ± 0.16	-	7.99 ± 0.04	19.3 ± 0.05
S5C	113 ± 56.8	0.47 ± 0.12	-	7.87 ± 0.04	20.1 ± 0.24
S5BC	184 ± 119	0.48 ± 0.11	-	7.85 ± 0.03	21.8 ± 0.34
S6	296 ± 1.87	2.70 ± 0.41	-	3.46 ± 0.22	47.4 ± 3.24
S7	651 ± 3.52	1.49 ± 0.20	-	4.06 ± 0.48	44.1 ± 3.21
S7B	47.6 ± 1.66	0.74 ± 0.17	-	7.58 ± 0.08	37.7 ± 1.52

Figure 1. Particle size distribution curves for sediments and mixtures utilized in this study. Sediment S1 had the lowest median particle diameter (d_{50}) of 10.3 µm, and S6 had the highest d_{50} of 883 µm. All other sediments' d_{50} ranged from 213 to 747 µm in the following order of increasing d_{50}: S2 < S7 < S4 < S5 < S3.

Figure 2. Correlation matrices of measured soil and plant characteristics for plants grown in different soil textures. Correlations are shown by r; regressions where p<0.05 were outlined in dashed lines; where p<0.001 are outlined in solid lines; regressions where p>0.05 are covered by an X (Table S1-S4).

Figure 3. Aboveground, belowground, and total biomass of three species of representative plant species (*S. alterniflora*, *S. pacifica*, and *S. patens*) grown in four sediments of varying texture. Sediments increase in saturated hydraulic conductivity from left to right. Error bars are ± standard error. Different letters denote statistically significant differences between treatments.

Figure 4. Average rates of net ecosystem exchange (NEE), photosynthesis, and community respiration (CR) of three representative plant species (*S. alterniflora*, *S. pacifica*, and *S. patens*) grown in four sediments of varying texture. Positive values represent emissions of greenhouse gases, and negative values represent carbon fixation. Sediments increase in saturated hydraulic conductivity from left to right. Error bars are ± SE. Note that methane emissions are represented as per hour and are displayed on a logarithmic scale. Different letters denote statistically significant differences between treatments.

Figure 5. Average biomass (a), CO_2 gas efflux (b), CH_4 gas efflux (c) of *S. alterniflora* grown in low nutrient beach sand (sediment type S5) with and without treatments of biochar (sediment type S5B), compost (sediment type S5C), or a combination of biochar and compost (sediment type S5BC). No significant differences were found in the biomass or CO_2 gas efflux across all treatments; however, significant differences were found in the methane emissions of mesocosms treated with compost ($p < 0.01$) but not the combination of biochar and compost (Table S14). Error bars are ± SE. Note that methane emissions are represented as per hour and are displayed on a logarithmic scale. (d) shows changes in $\delta^{13}C$ over time for CO_2 for incubations.Different letters denote statistically significant differences between treatments.

Figure 1.

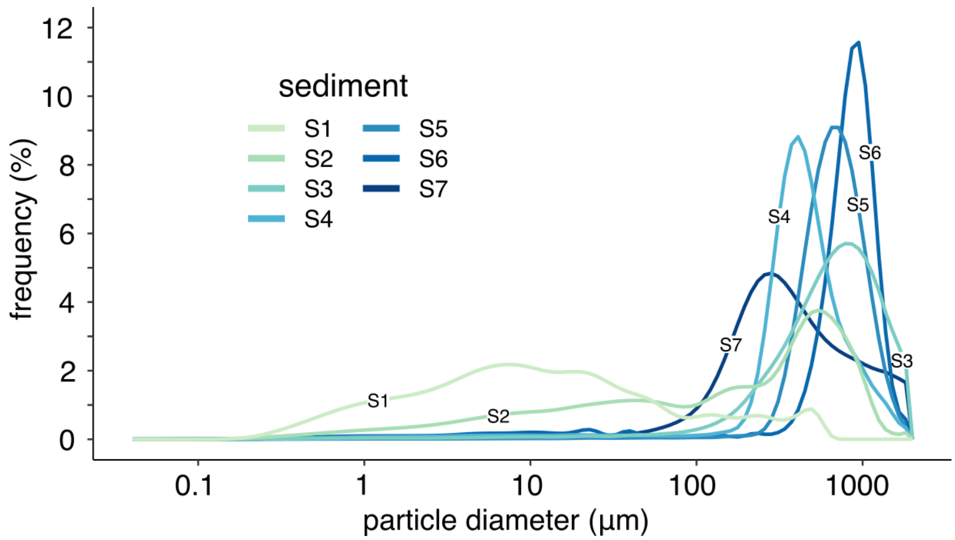
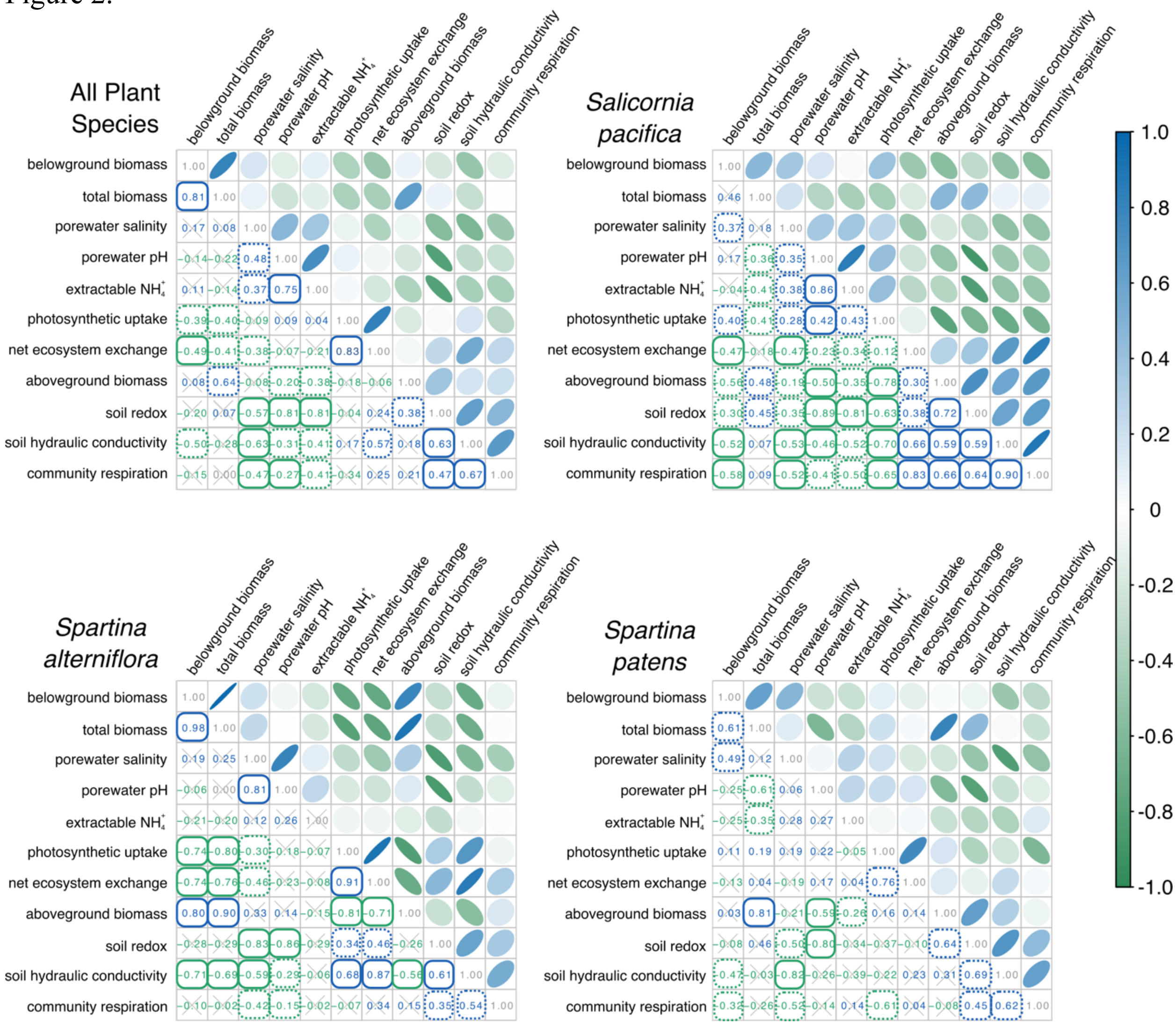
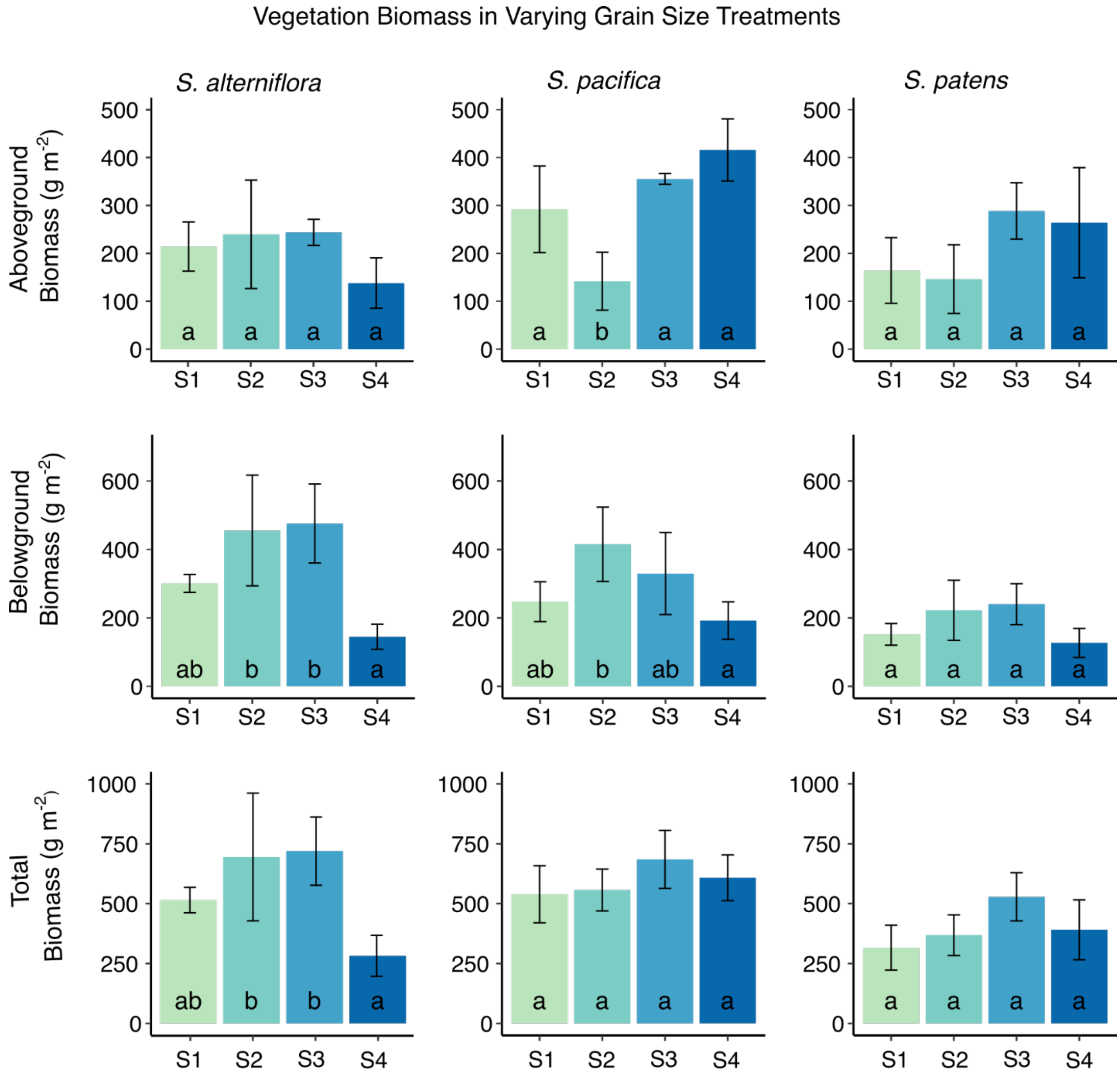

sediment
S1
S2
S3
S4
S5
S6
S7
frequency (%)
0
2
4
6
8
10
12
0.1
1
10
100
1000
particle diameter (µm)

Figure 2.



All Plant Species
Salicornia pacifica
Spartina alterniflora
Spartina patens
belowground biomass
total biomass
porewater salinity
porewater pH
extractable NH$_4^+$
photosynthetic uptake
net ecosystem exchange
aboveground biomass
soil redox
soil hydraulic conductivity
community respiration
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0

Figure 3.



Vegetation Biomass in Varying Grain Size Treatments
S. alterniflora
S. pacifica
S. patens
Aboveground Biomass (g m-2)
Belowground Biomass (g m-2)
Total Biomass (g m-2)
S1
S2
S3
S4

Figure 4.

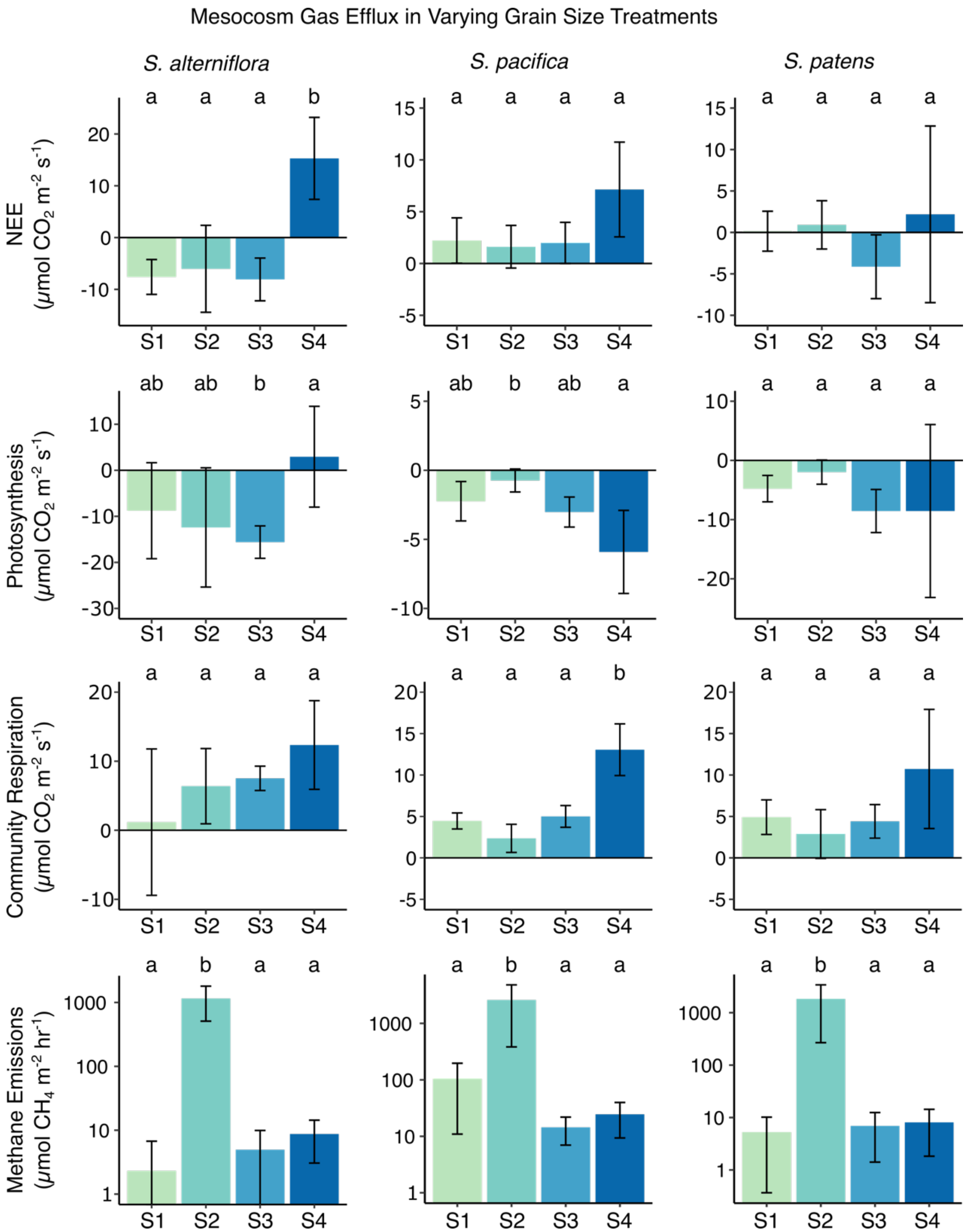
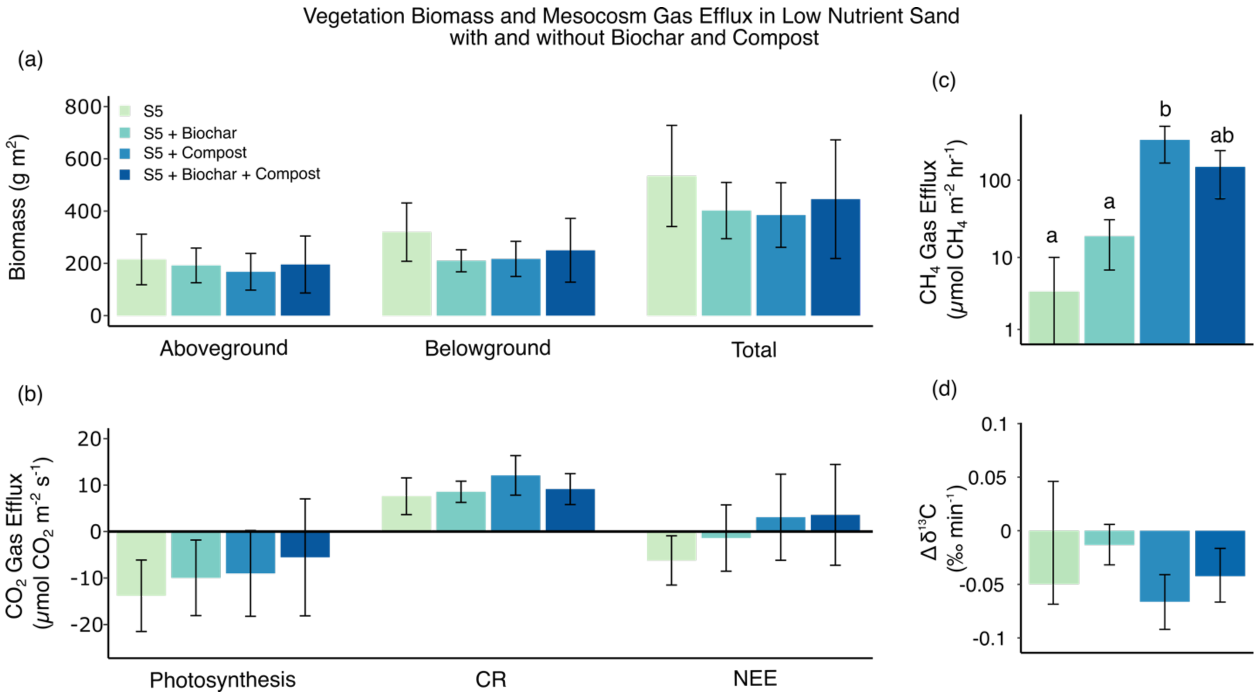

Mesocosm Gas Efflux in Varying Grain Size Treatments
S. alterniflora
S. pacifica
S. patens
NEE
(μmol CO2 m-2 s-1)
Photosynthesis
(μmol CO2 m-2 s-1)
Community Respiration
(μmol CO2 m-2 s-1)
Methane Emissions
(μmol CH4 m-2 hr-1)
S1
S2
S3
S4
a
b
ab

Figure 5.



Vegetation Biomass and Mesocosm Gas Efflux in Low Nutrient Sand
with and without Biochar and Compost
(a)
S5
S5 + Biochar
S5 + Compost
S5 + Biochar + Compost
Biomass (g m^{2})
800
600
400
200
0
Aboveground
Belowground
Total
(c)
CH$_4$ Gas Efflux
(μmol CH$_4$ m^{-2} hr^{-1})
100
10
1
a
a
b
ab
(b)
CO$_2$ Gas Efflux
(μmol CO$_2$ m^{-2} s^{-1})
20
10
0
-10
-20
Photosynthesis
CR
NEE
(d)
$\Delta\delta^{13}$C
(‰ min^{-1})
0.1
0.05
0
-0.05
-0.1