Hawaiian Dune Plant Tolerance to Simulated Coastal Flooding

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By

Devyn Montesinos

Thesis Advisor

Kasey Barton

I certify that I have read this thesis and that, in my opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

THESIS ADVISOR

Kasey Barton Digitally signed by Kasey Barton
Date: 2022.05.13 08:53:04 +02'00'

Dr. Kasey Barton

School of Life Sciences

For my parents Noelle Labang Montesinos and Vincent Montesinos whose sacrifices allowed me to pursue my education, and for their unyielding love and support.

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ABSTRACT

Background and Aims Climate change models project a combination of rising sea levels and increased storm frequency and intensity. Low-lying coastal dune plants will be subjected to a higher frequency of intense coastal flooding, oceanic storm surge events, as well as reduced rainfall in Hawai‘i, leading to a greater accumulation of substrate salts. Salinity stress negatively affects plants directly via ion toxicity and indirectly via osmotic stress associated with water limitation, leading to reduced photosynthesis and growth, and potentially plant death. The goal of this research is to investigate the survival and recovery of native and non-native Hawaiian coastal dune plants to simulated seawater flooding for insights into the resilience of dune ecosystems to changing climates and increasing salinity.

Methods A greenhouse experiment was conducted to test photosynthetic and growth responses to simulated seawater inundation in four plant species common in Hawai‘i's coastal dune communities: native *Gossypium tomentosum* and *Waltheria indica*, and non-native *Bidens pilosa* and *Prosopis pallida.* Photosynthetic function was assessed for leaf chlorophyll content and stomatal conductance rates, and growth responses were assessed for survival, plant height, and total biomass.

Key Results It was detected that there was considerable variation among species in the responses of growth and photosynthesis to seawater inundation. Freshwater inundation did not negatively affect plant growth or photosynthetic traits, indicating that the principal effect of immersion in seawater was due to salinity stress. The least tolerant species were the native *W. indica* and non-native *B. pilosa*. The most tolerant species was the invasive *P. pallida*. Intermediate salinity tolerance was observed in *G. tomentosum* seedlings, which were unable to fully tolerate seawater inundation but demonstrated strong recovery in photosynthetic traits.

Conclusion Coastal dune plants vary in their salinity tolerance, which will likely lead to changes in dune community composition under climate change. Conservation of sensitive species will require mitigation of high salinity. Restoration efforts may benefit by prioritizing tolerant species for successful establishment under elevated salinity. These results emphasize the complex and multi-strategy approach that will be required to protect coastal dune ecosystems that include species with considerable variability in tolerance to changing climatic conditions.

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1.0 INTRODUCTION

1.1 Climate Change Impacts

Coastal ecosystems are at risk of intense seawater flooding events due to anthropogenic climate change and sea level rise. Although coastal ecosystems are generally stressful to plants, with high solar radiation, strong winds, and frequent exposure to salt spray and waves, global climate change is predicted to increase these threats by subjecting low-lying coastal dune plants to a higher frequency of extreme weather events, including seawater flooding and reduced rainfall, which leads to a greater accumulation of substrate salts (IPCC, 2022). The increased likelihood of storm surge events combined with the impacts of sea-level rise will result in the increased frequency of saltwater inundation to low-lying coastal vegetation (Hanley et al., 2017; White et al., 2014). Threats to coastal plants have cascading effects on associated coastal biodiversity and ecosystem services. For example, coastal regions provide nesting sites for seabirds, contain vital floral resources for bees, are the critical habitat for many plant and animal species, protect the shoreline from beach erosion, and buffer coastal urban areas and agroecosystems from erosion and wave events (White et al., 2014; Feagin et al., 2005). Protecting coastal ecosystems and their foundation dune plants from climate change is thus a conservation priority, which will benefit from information about the resilience of coastal dune plants to changing and increasing salinity concentrations.

1.2 Salinity Stress

Despite regular exposure to saline conditions, increasingly frequent and severe storm surges in combination with sea-level rise and reduced precipitation are likely to lead to greater salinity stress for coastal plants than they encountered under historical conditions. Soil salinity stress negatively affects plants via direct toxicity as well as osmotic stress. Direct toxicity occurs within cells when accumulated salt ions disrupt membrane stability, protein structure, and ion transport dynamics (Isayenkov, 2019). Osmotic stress results from high concentrations of salts in the soil, which reduces soil water potential and constrains water uptake by roots (Munns et al., 2008; Ansari, 2015). Plants commonly respond to salt-induced water stress by closing stomata, thereby limiting transpiration, but also constraining CO_2 uptake (Munns et al., 2008). Osmotic stress from high salinity can also limit leaf expansion due to reduced turgor pressure (Ma et al., 2020). The consequences of these physiological responses to high salinity are reductions in plant growth, even in coastal dune plant species that are expected to be relatively tolerant to salinity exposure (Ma et al., 2020). Furthermore, plants exposed to coastal flooding will also experience oxygen limitation due to the lack of gas exchange to roots (Kozlowski, 1997), so that inundation stress is likely to be greater than salinity stress alone.

1.3 Salinity Tolerance Mechanisms

Plant species vary considerably in salinity tolerance, ranging from high tolerance in halophytes that have evolved mechanisms to sequester or avoid high levels of salt ions, to low tolerance in glycophytes that are not adapted to tolerate salinity (Munns et al., 2008). Strategies of salinity tolerance include mechanisms associated with osmotic stress tolerance and traits that limit salt ion uptake or minimize the cellular toxicity via sequestration (Ansari, 2015; Munns and Tester, 2008). Osmotic stress tolerance resembles drought tolerance and is characterized by traits that enable plants to maintain water balance and function despite water limitation, and can include stomatal closure, low root water potential to facilitate water uptake, high root-shoot ratios, water storage via succulence, and tolerance of fluctuating leaf water potentials (Acosta-Motos et al., 2017). Salinity tolerance varies not only among species, but also within species, with regard to plant age and ontogeny, environmental conditions, irrigation management, soil fertility, and the intensity of other stresses to the plant (Bezona et al., 2009; Lum and Barton 2020). Stage-dependent variation in salinity tolerance could influence population dynamics in complex ways, for example by reducing seed germination or seedling establishment, highlighting salinity tolerance in early life history stages as a research priority.

1.4 Seedling Recruitment

Previous studies have identified early life stages to be particularly sensitive to salinity stress in coastal dune plants (Lum and Barton, 2020; Alpha et.,1996). While it is generally recognized that stress tolerance is limited in early stages, causing seedlings to have higher mortality rates than other life stages (Beckman et al., 2011), these dynamics are likely to be exacerbated by climate change. Seedling recruitment is essential for population stability, with population declines and extirpation occurring in the absence of recruitment (Chesser and Brewer, 2011). Climate change may thus drive plant population declines through specific suppression of seedling recruitment, although this remains relatively unexplored for coastal dune plants experiencing elevated salinity.

1.5 Risk to Low-Lying Coastal Regions

Anthropogenic climate change impacts will disproportionately affect low-lying coastal regions, including many islands. Global sea-level rose approximately 5.4 cm from 1993 to 2011 at a rate of 3.2 mm/yr, although the rise was not uniform globally (Lim and Fletcher, 2012). While many small island nations in the Pacific are particularly vulnerable to sea level rise and increases in coastal flooding (IPCC 2022), some islands have thus far experienced relatively moderate sea level rise. For example, the Hawaiian Islands have experienced 1.5 mm/yr rise in sea level over the past century (Lim and Fletcher, 2012). Despite this modest rate, short-term fluctuations in coastal sea level have been turbulent across Hawaiian Islands, leading to more frequent and increasingly severe episodic flooding (Lim and Fletcher, 2012). With low-lying islands only a few meters above sea level, the rising scale and intensity of sea level rise, saltwater intrusion, and overall coastal destruction mean that the future of coastal ecosystems is highly uncertain (Hassan and Cliff, 2019). Moreover, the effects of increasing sea level and storm surges on Hawaiʻi's coastal ecosystems remain unclear. Salinity tolerance has been previously examined in a couple of Hawaiʻi's coastal dune plant species, all of which were found to be sensitive to salinity, identifying them to be glycophytes (Lum and Barton, 2020; Goldstein et al., 1996; Alpha et al., 1996). Additional research is needed to characterize salinity tolerance across a greater diversity of coastal dune species and with respect to different types of salinity stress. In particular, previous studies have tested salt spray and sustained seawater exposure in the substrate, but plant responses to inundation treatments that mimic flooding are lacking. By uncovering coastal dune plant resilience to salinity and inundation, we can contribute to Hawaiian ecosystem management and conservation efforts in the near future.

1.6 My Aims

To investigate tolerance to seawater flooding in coastal dune plants, I conducted a controlled experiment to test the physiological and growth responses of seedlings to short-term simulated seawater inundation. To determine whether inundation affects plants via salt ion effects or flooding per se, I also tested responses to freshwater inundations. The focal species included two native (*Waltheria indica* and *Gossypium tomentosum*) and two non-native (*Bidens pilosa* and *Prosopis pallida*) species that are common in Hawaiʻi's coastal dune habitats. Metrics of plant growth and survival indicate the extent of seedling salinity tolerance to seawater inundation, while photosynthetic trait analyses shed light on the underlying mechanisms by which salinity tolerance is achieved. For example, plants that are able to tolerate osmotic stress without jeopardizing photosynthetic rates may do so by increasing chlorophyll content and maintaining stomatal conductance under saline conditions (Lum and Barton, 2020). I predict that these coastal plant species will be tolerant to a short-term seawater inundation, as a consequence of their adaptation to the coastal dune environment. I further predict that they will achieve this tolerance by maintaining stomatal conductance and chlorophyll content in the inundated plants compared to control plants that were not inundated. I expect to observe no differences between the seawater vs. freshwater inundation treatment groups. Due to their prevalence in coastal habitats, I predict invasive plants to have similar tolerance and salinity responses as the native species tested. This experiment will provide the first tests of Hawaiian plant responses to simulated seawater inundation, providing important insights into the potential resilience of coastal dune plants to sea level rise and increased storm surges under climate change.

2.0 METHODS

2.1 Species Type

I investigated seawater flooding effects on four common and widespread coastal dune plant species (Table 1) at the University of Hawaiʻi at Mānoa Pope Greenhouses. *Gossypium tomentosum* (Malvaceae), maʻo in Hawaiian, is an endemic shrub. *Waltheria indica* (Malvaceae), ʻuhaloa in Hawaiian, is an indigenous shrub that can be found throughout the tropics (Wagner et al., 1990). *Bidens pilosa L.* (Asteraceae) is a herb that originates from tropical Central America; however, because of its high reproductive potential and ability to thrive in a diversity of environments, it is established throughout the world (Arthur et al., 2012). *Prosopis pallida* (Fabaceae), kiawe in Hawaiian, is considered an invasive noxious weed that originates from the coast of northwest South America (Gallaher et al., 2010). Seeds were scarified to promote germination and germinated under ambient greenhouse conditions. At the two-leaf stage, seedlings were transplanted into 1-gallon pots filled with equal parts by volume Promix nursery mix, black cinder, and sand. Seedlings were grown for two weeks before treatments were initiated.

Table 1 : Species included in the inundation experiments.

Species	**Hawaiian / Common Names**	**Plant Family**	**Nativity**	**Growth Form**	**Lifespan**	**Mature Height (m)**	**Seed Collection Location**	**Seed Collection Date**
Gossypium tomentosum	Maʻo	Malva-ceae	Native	Shrub	≥ 5years	1-2.5	Kanaha Beach, Kahului, Maui	February 2021
Waltheria indica	ʻUhaloa	Malva-ceae	Native	Shrub	≤ 5 years	0.5-3	Maui Nui Botanical Garden grounds, Kahului, Maui	October 2020
Prosopis pallida	Kiawe	Fabace-ae	Non-native	Thorny Tree	≤100 years	8-20	Kenolio Beach, North Kihei, Maui	October 2020
Bidens pilosa L.	Hairy beggartick	Astera-ceae	Non-native	Perennia l Herb	5-6 years	0.3-1	Pu'u Maohe, Kanaio, Maui	October 2020

2.2 Salinity Solution

Experimental salinity solutions were developed from Instant Ocean marine salts using 170g per 4000 ml to create a 34 ppt salinity solution. This concentration was confirmed with the YSI Pro30 Conductivity/TDS/Salinity/Temperature Meter. Generally, seawater has concentrations ranging from 33 - 38 ppt with a global average of 35 ppt (Grossman et al., 2005). Plants were watered daily with tap-water, except during the inundation treatments.

2.3 Procedure

Seedlings were randomly assigned to three treatment groups at the time of transplant: seawater inundation, freshwater inundation, and control. The seawater inundation groups were immersed to just below the top of the pots in large plastic tubs filled with the 34 ppt Instant Ocean solution for 12 hours, two weeks following transplant. The freshwater inundation groups were similarly immersed for 12 hours in large plastic tubs, but filled with freshwater from the tap. Control groups were not inundated. Immediately after the inundation plants were randomly arranged back on the benches to allow for free drainage and prevention of cross contamination between treatment groups. To allow time to re-grow, plants were harvested three weeks following the inundation treatments. During the 3 recovery weeks, plants were watered daily with freshwater while growing under ambient greenhouse conditions. Target sample sizes included 10 replicate seedlings per treatment group per species, producing a total sample size of N = 120 plants (4 species x 3 treatment groups x 10 replicates). However, mortality from transplant shock in *G. tomentosum* reduced the total sample size to N = 115 plants.

Species trials were conducted across two temporal blocks. The first block (March 2021) included *B. pilosa*, and the second block (April 2021) included the other three species. Climate seasonality is minimal in Mānoa (Giambelluca et al. 2014), and so climatic conditions were similar across both blocks. Photosynthetic traits were measured weekly, starting one day before inundations, including leaf chlorophyll content and stomatal conductance rates. Stomatal conductance (mmol m^{-2} s^{-1}) was measured with an SC-1 steady-state leaf porometer (Decagon Devices, Pullman, WA, USA). A chlorophyll meter (SPAD-502 Plus, Konica Minolta Inc. Japan) was used to measure chlorophyll content (index scale -9.9 to 199.9). Plant performance metrics such as plant height were measured weekly, and total dry biomass was harvested after the 3 ½ week recovery period. At the harvest, roots and shoots were separated, oven-dried for 7 days, and then weighed for biomass. Biomass data are missing for *B. pilosa* due to technical error.

2.4 Analysis Methods

Tolerance was assessed by analyzing the effects of treatment on height and growth using analysis of variance (ANOVA). A full model was used to test the effects of treatment, species, and their interaction on height and growth. To better understand how treatment effects differed among species, I subsequently analyzed each species individually. Because chlorophyll content and stomatal conductance were measured repeatedly within individual plants, these were analyzed individually within each species using repeated measures ANOVA models that included treatment and time as main explanatory variables

3.0 RESULTS

3.1 Survival and Growth

Survival rates varied considerably across species in the seawater treatment, indicating variation in salinity tolerance (Table 2). Specifically, no mortality was observed in *P. pallida*, indicating full salinity tolerance with respect to survival, while 100% mortality was observed in *B. pilosa*, indicating no salinity tolerance at all by this fitness metric. The two native species had intermediate tolerance, as evidenced by 60-70% survival (Table 2). Across all species, no mortality occurred in control or freshwater conditions, revealing that flooding alone does not drive mortality and suggesting that high salinity is responsible for the low survival in seawater inundation groups.

Table 2. Survival of seedlings in three treatment groups across species.

Species	% Survival Control	% Survival Seawater	% Survival Freshwater
G. tomentosum	100%	60%	100%
W. indica	100%	70%	100%
B. pilosa	100%	0%	100%
P. pallida	100%	100%	100%

Plant growth was significantly affected by inundation, and these effects varied among species for both height ($F_{4,76}$ = 45.239, $P < 0.0001$) and total biomass ($F_{6,132}$ = 30.988, $P < 0.0001$). Examining the species individually, variable effects of freshwater and seawater inundation were detected for the four focal species (Table 3). In general, freshwater inundation did not negatively affect plant growth, and *W. indica* even appeared to grow better following the freshwater inundation compared to control watering conditions (Figure 1). In contrast, seawater inundation significantly reduced plant height and total biomass for all species, although the magnitude of growth reduction varied among species. Moderate reductions in growth were detected for *P. pallida* and *G. tomentosum*, while *B. pilosa* and *W. indica* suffered dramatic reductions in growth following the seawater inundation (Figure 1). Overall with respect to growth, *W. indica* appears to be the least tolerant to seawater inundation while *P. pallida* appears to be the most tolerant (Figure 1).

Table 3. Inundation treatment effects on total plant biomass (g) and shoot height (cm). Significant effects are denoted as: * (*P* < 0.05), ** (*P* < 0.01), *** (*P* < 0.0001).

SPECIES	BIOMASS	HEIGHT
Bidens pilosa	N/A	$F_{2,56} = 134.38^{***}$
Gossypium tomentosum	$F_{2,22}=6.36^{**}$	$F_{2,22}=2.97$
Prosopis pallida	$F_{2,27}=10.11^{***}$	$F_{2,27}=.0931$
Waltheria indica	$F_{2,27}=389.11^{***}$	$F_{2,27}=354.8^{***}$

A)

B)

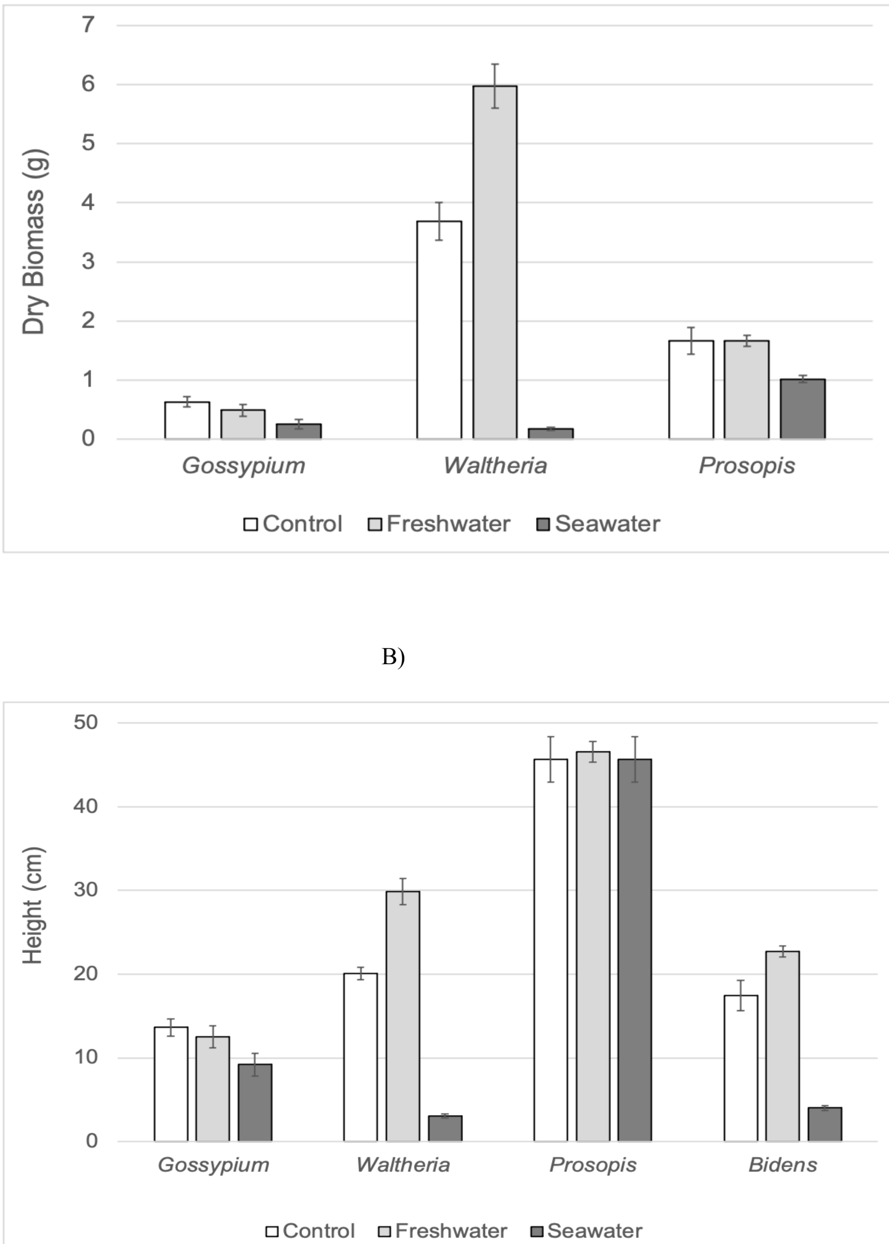

Figure 1. The effect of treatments (Control, Freshwater, Seawater) on dry biomass (A) and height (B) separated by species. Means and +/- 1 standard error.

3.2 Photosynthetic Traits

Across all species, photosynthetic traits were significantly affected by inundation, and these effects varied among species for both stomatal conductance and leaf chlorophyll content (Tables 4, 5). The effects of inundation on photosynthetic traits were also variable over time, leading to significant interactions for most species (Tables 4, 5), reflecting different patterns of adjustment to the inundation effects. Specifically, all species responded to inundation by reducing stomatal conductance in sampling periods immediately following the inundation treatments (Figure 2). While *G. tomentosum* and *P. pallida* recovered stomatal conductance within the experimental time period, indicating recovery, *W. indica* and *B. pilosa* persisted with dramatically reduced stomatal conductance even three weeks following the inundation (Figure 2). Similar temporal patterns were detected for leaf chlorophyll content, confirming recovery to seawater inundation for *G. tomentosum* and *P. pallida*, but not *W. indica* and *B. pilosa*. In contrast, freshwater inundation had minimal effects on stomatal conductance or chlorophyll content (Figure 2). In fact, freshwater inundation led to increased stomatal conductance at some point in all species except *G. tomentosum*, suggesting control plants may have experienced minor water limitation (Figure 2).

Table 4. Inundation, time, and inundation-time interaction effects on stomatal conductance. Significant effects are denoted as: * (*P* < 0.05), ** (*P* < 0.01), *** (*P* < 0.0001).

SPECIES	INUNDATION	TIME	INUNDATION*TIME
Bidens pilosa	$F_{2,56.5} = 56.99^{***}$	$F_{4,40.3} = 1.30$	$F_{6,38.4} = 15.01^{***}$
Gossypium tomentosum	$F_{2,24.4} = 19.43^{***}$	$F_{4,21.4} = 31.67^{***}$	$F_{8,26.5} = 1.682$
Prosopis pallida	$F_{2,50.1} = 17.52^{***}$	$F_{4,47.8} = 17.85^{***}$	$F_{8,47.8} = 3.084^{**}$
Waltheria indica	$F_{2,27.6} = 413.2^{***}$	$F_{4,27.5} = 227.6^{***}$	$F_{8,29.0} = 56.48^{***}$

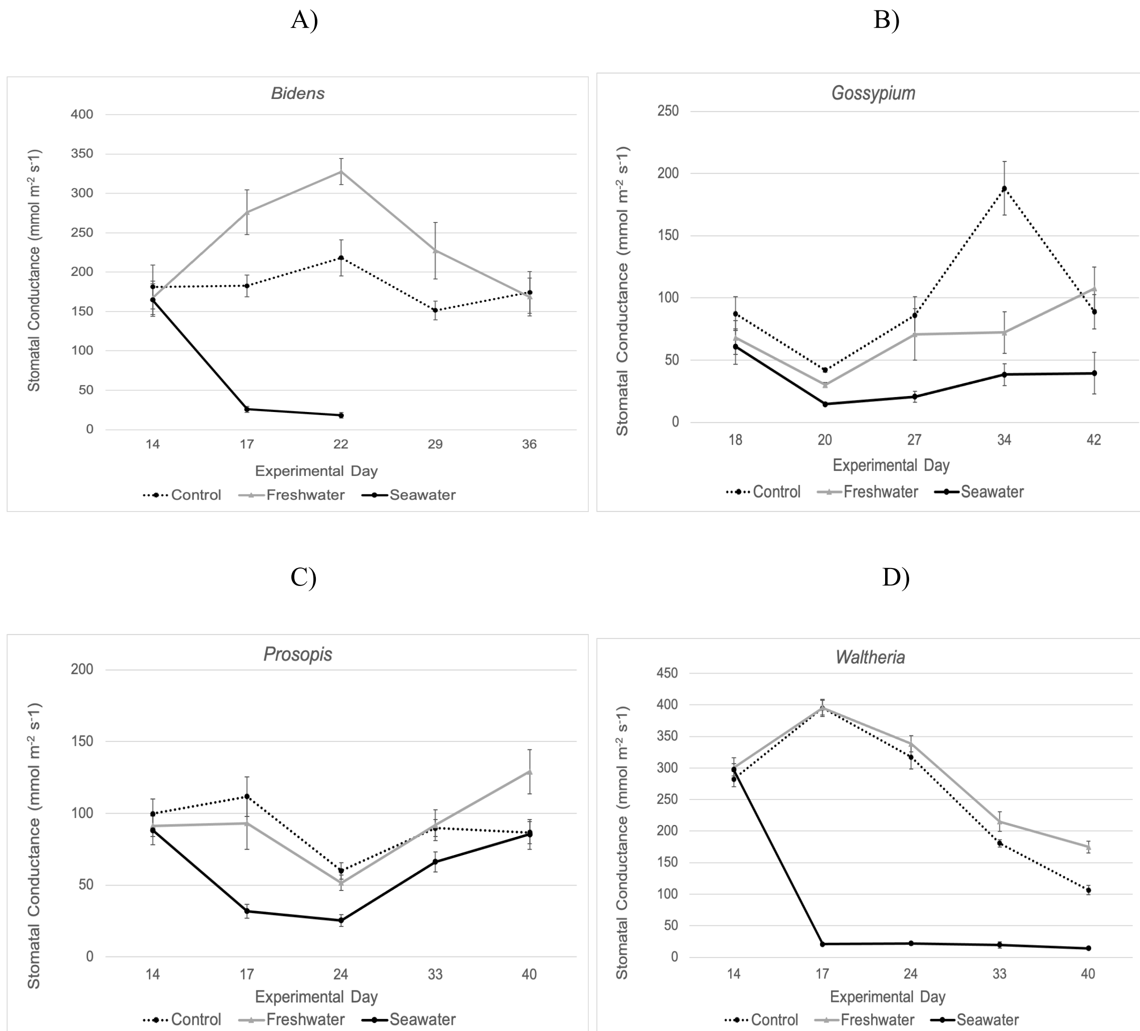

Figure 2. Temporal patterns in stomatal conductance for the three treatment groups. The inundation treatment occurred on day 15, and traits were measured on a weekly basis for 3 ½ weeks until plants were harvested. Means and +/- 1 standard error.

Table 5. Inundation, time, and inundation-time interaction effects on leaf chlorophyll content. Significant effects are denoted as: * ($P < 0.05$), ** ($P < 0.01$), *** ($P < 0.0001$).

SPECIES	INUNDATION	TIME	INUNDATION*TIME
Bidens pilosa	$F_{2,49.8} = 27.85^{***}$	$F_{4,37.6} = 3.340^{*}$	$F_{6,37.9} = 12.46^{***}$
Gossypium tomentosum	$F_{2,20.1} = 6.597^{**}$	$F_{4,20.5} = 3.517^{*}$	$F_{8,20.5} = 2.733^{*}$
Prosopis pallida	$F_{2,27.0} = 5.883^{**}$	$F_{4,27.0} = 16.54^{***}$	$F_{8,27.0} = 3.580^{**}$
Waltheria indica	$F_{2,25.6} = 150.1^{***}$	$F_{4,25.6} = 26.80^{***}$	$F_{8,25.4} = 42.48^{***}$

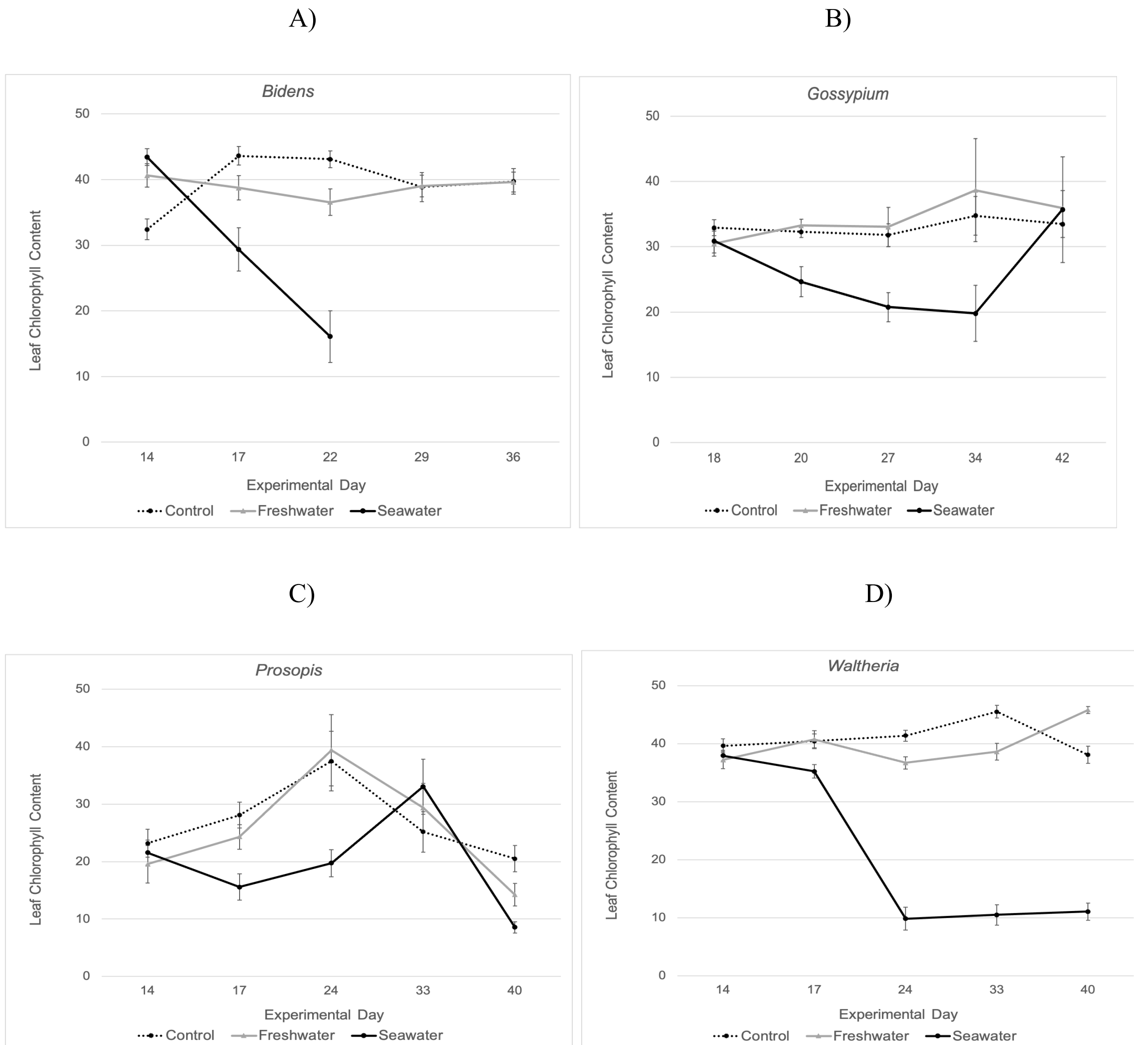

Figure 3. Temporal patterns in leaf chlorophyll content for the three treatment groups. The inundation treatment occurred on 15, and traits were measured on a weekly basis for 3 ½ weeks until plants were harvested. Means and +/- 1 standard error.

4.0 DISCUSSION

4.1 Main Findings

Using an experimental approach, limited tolerance to seawater flooding was observed in coastal dune plants. However, species varied considerably in their responses of growth and photosynthesis to seawater inundation, revealing complexity within coastal dune communities in their responses to sea level rise. Interestingly, freshwater inundation did not negatively affect plant growth or photosynthetic traits, revealing that the principal effects of immersion in seawater were due to salinity stress. Considering all performance metrics, the second least tolerant species was the native *W. indica*, while the most tolerant species was the invasive *P. pallida*. Although *G. tomentosum* seedlings were unable to fully tolerate seawater inundation, they demonstrated strong recovery in photosynthetic traits, suggesting that they have intermediate tolerance to salinity. Since non-native *B. pilosa* was the only species recorded to have all replicates experience plant death by seawater inundation and no signs of recovery, I can conclude that this species is extremely sensitive and has little to no tolerance to salinity.

4.2 Risks to Coastal Ecosystems

The persistence and stability of plant populations of low lying coastal dune ecosystems are critical. Coastal ecosystems are both economically and ecologically important, providing protection against the sea for urban areas, stabilizing shorelines, and offering sustenance and shelter to species that specialize in these habitats (White et al., 2014; Feagin et al., 2005). In addition, coastal dune ecosystems contribute to groundwater recharge and assist in the retention of freshwater as a buffer against saltwater intrusion (Martínez and Psuty, 2004). Specifically in Hawaiʻi, these coastal dune ecosystems attract millions of tourists each year, provide nesting habitats for seabirds and floral resources for native bees, and are vital for cultural practices and resources. Anthropogenic activities impose serious threats to the stability and persistence of coastal ecosystems, through construction, trampling, high traffic, invasive species introductions, and climate change. Climate change projections forecast greater frequencies and intensities of storm surges, sea level rise, an increased likelihood of drought conditions, all of which will contribute to an increase in salinity of coastal habitats.

4.3 Hawaiian Species Case Studies

In Hawaiʻi, relatively little is known about the salinity tolerance of coastal plants, which limits predictions about the persistence and resilience of coastal vegetation to climate change. Experimental approaches testing coastal plant responses to elevated salinity will inform management efforts to conserve these critical ecosystems. While several studies have examined salinity tolerance using persistent treatments of elevated salinity (Morais et al., 2012; Hamed et al., 2014; Alpha et al., 1996; Handley et al., 2020; Barett, 2003), relatively few studies have mimicked coastal flooding and seawater in Hawaiʻi, and these have all applied chronic salinity treatments (Lum and Barton, 2020; Alpha et al., 1996; Goldstein et al., 1996). For example, a study testing high salinity watering treatments on native Hawaiian coastal plant species *Jacquemontia sandwicensis* (Convolvulaceae) and *Sida fallax* (Malvaceae) demonstrated reduced ecophysiological performance, growth, and reproduction under increased salinity, revealing these species to be glycophytes (Lum and Barton, 2020). Other research on *Scaevola sericea* (Goodeniaceae) similarly reported negative effects of salinity on growth, using salt spray and substrate salinity treatments (Goldstein et al., 1996; Alpha et al., 1996). Synthesizing across these experiments, it seems that all types of elevated salinity, chronic substrate application, salt spray, and seawater inundation, negatively affect the growth and performance of native coastal dune plants in Hawaiʻi. Moreover, elevated salinity was observed to suppress gas exchange, leading to reduced photosynthesis and transpiration (Goldstein et al., 1996, Lum and Barton, 2020), consistent with the patterns observed here in response to seawater inundation. Thus, reduced growth under salinity is at least in part, driven by reduced photosynthesis via stomatal regulation.

4.4 Global Case Studies

With rising concerns about the impact of rising sea levels and storm surge events on coastal ecosystems, salinity tolerance of coastal plants is a global concern. In the United Kingdom, coastal grasses experienced reduced photosynthesis, growth, and flowering potential in response to a short-duration seawater soil flooding (Hanley et al., 2017). In addition, among 29 common sand dune species in New Zealand, root sensitivity to salinity was found to play a critical role in whole-plant salinity tolerance (Sykes and Wilson, 1989). Clearly, additional research is needed specifically testing coastal dune plant tolerance to seawater inundation to determine the generality of these responses.

4.5 Native vs. Invasive

Invasive species are a major cause of biodiversity loss in coastal ecosystems (Makowski and Finkl, 2018), and knowing whether climate change will enhance or constrain invasive species success is a major priority for conservation of coastal ecosystems. If invasive species are more salt tolerant than native species, they may benefit from sea level rise, contributing to native plant displacement. While my species pool does not allow for robust contrast of salinity tolerance in native vs. invasive species because only 2 species of each were tested, there was no indication that invasive species were more salt tolerant than native species. In fact, invasive species emerged as the most (*P. pallida*) and least (*B. pallida*) tolerant to salinity, with native species demonstrating intermediate tolerance. These results suggest that salinity tolerance may be idiosyncratic among invasive species, and that examination of additional species will identify those most likely to spread under sea level rise.

5.0 CONCLUSION

Current climate change projections highlight the urgent need for information about species resilience to salinity stress in coastal dune ecosystems. By identifying those species that are most sensitive and will require careful monitoring and management, as well as those species that are most tolerant and will require relatively little management, this study can inform management and conservation of Hawai‘i’s coastal dune plant communities. Species variability in salinity tolerance may also contribute to restoration plans, by highlighting robust species that may be most successful in outplantings.

Consideration of the experimental conditions reveal several potential limitations to these results. First, time was limited, leading to relatively few species tested over short durations. Running longer experiments may alter conclusions if, for example, some species are able to tolerate salinity better over longer time spans. Second, the use of Instant Ocean solution rather than real seawater might not fully inform us about responses of plants to actual coastal flooding. However, a previous salinity inundation study reported no detectable difference in plant responses to inundation by Instant Ocean solutions vs. seawater (Hanley et al., 2020), providing some justification for our methods. Lastly, this experiment isolates the effects of inundation on coastal plant performance. While such controlled experimental conditions are robust for quantifying plant responses to specific environmental treatments, it is difficult to know how well they relate to the greater complexity of conditions in natural habitats where coastal flooding occurs. Climate change is a complex, multidimensional process, and in reality, plants are not only coping with salinity effects but simultaneously with heat and drought stress (IPCC

2022), as well as biotic interactions. Future research directions could expand on these methods to provide additional insights, including treating plants with longer inundation treatments and longer recovery periods, testing across ontogeny, as well as additional environmental treatments. Testing a broader diversity of native and invasive species will provide stronger evidence for whether salinity tolerance differs between native and invasive species in Hawaiʻi's coastal dune ecosystems. Moreover, more in-depth plant growth metrics and photosynthetic traits that would allow for a better understanding of the underlying mechanisms of salinity tolerance in coastal dune plants. These future research directions will improve our understanding of coastal dune ecology and potential resilience under climate change, providing insights into the future of these critical ecosystems and enhancing their conservation.

LITERATURE CITED

Acosta-Motos, J. R., Ortuño, M. F., Bernal-Vicente, A., Diaz-Vivancos, P., Sanchez-Blanco, M. J., & Hernandez, J. A. (2017). Plant responses to salt stress: adaptive mechanisms. Agronomy, 7(1), 18.

Alpha, C. G., Drake, D. R., & Goldstein, G. (1996). Morphological and physiological responses of Scaevola sericea (Goodeniaceae) seedlings to salt spray and substrate salinity. American journal of botany, 83(1), 86-92.

Ansari, Zuby G., 2015. Salinity Stress Tolerance in Plants Master Seminar [PowerPoint Slides]. SlideShare. https://www.slideshare.net/ZubyGoharAnsari1/salinity-stress-tolerance-in-plants-master-seminar

Arthur, G. D., Naidoo, K. K., & Coopoosamy, R. M. (2012). Bidens pilosa L.: Agricultural and pharmaceutical importance. Journal of Medicinal Plants Research, 6(17), 3282-3281.

Barrett-Lennard, E.G. (2003). The interaction between waterlogging and salinity in higher plants: causes, consequences, and implications. Plant and soil, 253(1), 35-54

Beckman, N. G., & Rogers, H. S. (2013). Consequences of seed dispersal for plant recruitment in tropical forests: interactions within the seedscape. *Biotropica*, *45*(6), 666-681.

Ben Hamed, K., Chibani, F., Abdelly, C., & Magne, C. (2014). Growth, sodium uptake and antioxidant responses of coastal plants differing in their ecological status under increasing salinity. Biologia, 69(2), 193-201.

Bernstein, L., Bosch, P., Canziani, O., Chen, Z., Christ, R., & Riahi, K. (2008). IPCC, 2007: climate change 2007: synthesis report.

Bezona, Norman, et al. "Salt and Wind Tolerance of Landscape Plants for Hawai'i." (2009).

Chesser, J. D., & Brewer, J. S. (2011). Factors influencing seedling recruitment in a critically endangered pitcher plant, Sarracenia rubra ssp. alabamensis. Endangered Species Research, 13(3), 245-252.

Feagin, Rusty A., Douglas J. Sherman, and William E. Grant. "Coastal erosion, global sea‐level rise, and the loss of sand dune plant habitats." Frontiers in Ecology and the Environment 3.7 (2005): 359-364.

Gallaher, T., & Merlin, M. (2010). Biology and impacts of Pacific island invasive species. 6. Prosopis pallida and Prosopis juliflora (Algarroba, Mesquite, Kiawe)(Fabaceae). Pacific Science, 64(4), 489-526.

Goldstein, G., et al. "Growth and photosynthetic responses of Scaevola sericea, a Hawaiian coastal shrub, to substrate salinity and salt spray." International journal of plant sciences 157.2 (1996): 171-179.

Giambelluca, T.W., X. Shuai, M.L. Barnes, R.J. Alliss, R.J. Longman, T. Miura, Q. Chen, A.G. Frazier, R.G. Mudd, L. Cuo, and A.D. Businger. 2014. Evapotranspiration of Hawaiʻi. Final report submitted to the U.S. Army Corps of Engineers—Honolulu District, and the Commission on Water Resource Management, State of Hawaiʻi.

Grossman, B. G., Yongphiphatwong, T., & Sokol, M. (2005). In situ device for salinity measurements (chloride detection) of ocean surface. Optics & Laser Technology, 37(3), 217-223.

Hanley, Mick E., et al. "A pinch of salt: response of coastal grassland plants to simulated seawater inundation treatments." Annals of Botany 125.2 (2020): 265-276.

Hanley, Mick E., et al. "Differential responses of three coastal grassland species to seawater flooding." Journal of Plant Ecology 10.2 (2017): 322-330.

Hassan, H. R., and Cliff, V. (2019). For Small Island Nations, Climate Change is not a Threat. It's already here, World Economic Forum, [online] Available at:

https://www.weforum.org/agenda/2019/09/island-nations-maldives-climate-change/ [Accessed 30 Dec. 2019].

IPCC, 2022: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. In Press.

Isayenkov, S. V., & Maathuis, F. J. (2019). Plant salinity stress: many unanswered questions remain. Frontiers in plant science, 10, 80.

Kozlowski, T. T. (1997). Responses of woody plants to flooding and salinity. Tree physiology, 17(7), 490-490.

Lim, Siang-Chyn, and Chip Fletcher. “Sea Level Rise.” Sea Level Rise Hawaii, University of Hawai'i at Mānoa: School of Ocean and Earth Science and Technology , 5 Jan. 2012, http://www.soest.hawaii.edu/coasts/sealevel/#_ftn10.

Lum, Tiffany D., and Kasey E. Barton. “Ontogenetic variation in salinity tolerance and ecophysiology of coastal dune plants.” Annals of Botany 125.2(2020): 301-314

Ma, Y., Dias, M. C., & Freitas, H. (2020). Drought and salinity stress responses and microbe-induced tolerance in plants. Frontiers in Plant Science, 11, 1750.

Makowski, C., & Finkl, C. W. (Eds.). (2018). Impacts of Invasive Species on Coastal Environments: Coasts in Crisis (Vol. 29). Springer

Martínez, M. L., & Psuty, N. P. (2004). Coastal dunes. Springer Verlag.

Morais, M. C., Panuccio, M. R., Muscolo, A., & Freitas, H. (2012). Salt tolerance traits increase the invasive success of Acacia longifolia in Portuguese coastal dunes. Plant Physiology and Biochemistry, 55, 60-65.

Munns, Rana, and Mark Tester. “Mechanisms of salinity tolerance”. Annu. Rev. Plant Biol. 59 (2008): 651-681.

Sykes, M. T., & Wilson, J. B. (1989). The effect of salinity on the growth of some New Zealand sand dune species. Acta Botanica Neerlandica, 38(2), 173-182.

Wagner, W. L., Herbst, D. R., & Sohmer, S. H. (1990). *Manual of the flowering plants of Hawai'i*. University of Hawaii Press.

White, Anissia C., et al. "Variable response of three Trifolium repens ecotypes to soil flooding by seawater." Annals of Botany 114.2 (2014): 347-355.