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Use of Floating Wetland Islands as a Method of Phytoremediation in Brackish Bodies of Water

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UNIVERSITY OF CALIFORNIA
SANTA BARBARA

Use of Floating Wetland Islands as a Method of
Phytoremediation in Brackish Bodies of Water

by

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Bachelor of Science
in
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ABSTRACT

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Around the world, fragile, coastal aquatic ecosystems are threatened by a range of factors, including pollution and eutrophication, which hinder their ability to provide ecosystem services such as water filtration, habitat, and coastal resilience to climate change. Elevated nutrient levels, the presence of pollutants, such as chemicals and heavy metals, and low levels of dissolved oxygen all negatively affect these ecosystems. Anthropogenic actions are at the root of the majority of these issues, resulting in severe damage, but also the knowledge that, with changes, this damage can be remediated and eventually entirely avoided. Damage to aquatic systems threatens both local and migratory organisms while simultaneously causing economic and societal damage as productivity levels fall and resilience to climate change is weakened. The importance of coastal lagoons in species conservation and resilience to climate change cannot be overstated, making the conservation and management of these ecosystems paramount.

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Chapter 1

INTRODUCTION AND OVERVIEW

Throughout the world, shallow coastal ecosystems –such as marshes, wetlands, and lagoons – play critical roles in global ecological function, regulating exchanges between terrestrial and oceanic systems and dictating the life histories of millions of organisms. One of these systems, coastal lagoons, typified as shallow, semi-enclosed coastal bodies of water, represents a particularly significant ecological zone facilitating the transition between terrestrial and marine systems. Coastal lagoons often feature differences in aquatic and pedological salinities, nutritional regimes, and ecosystem structure. Their periodic connectivity with the ocean through narrow inlets, whose passability can change depending on geomorphic factors and tidal regimes, contributes to exchange between these systems, resulting in productive zones that support a range of organisms, including humans. Unlike other coastal systems, the aquatic exchange between lagoons and oceans means coastal lagoons contain neither marine nor freshwater, instead being brackish or hypersaline. These unique characteristics make coastal lagoons, which represent around [13% of Earth's terrestrial land mass](#), some of the world's most productive environments. Their environmental characteristics cascade to support a range of ecosystem services, such as water filtration, groundwater recharge, flood control, and acting as habitat. Additionally, their presence on the landscape helps form a variety of other landscape types, including [salt marshes, seagrasses, and mangrove stands, all of which are important carbon sinks](#). Coastal lagoons also contribute to coastal resilience by buffering storm impacts and protecting against sea level rise (SLR). Despite their environmental, social, and economic value, however,

coastal lagoons are at risk of disappearing, as they are filled to make space for expanding human populations, are polluted, or are swallowed by rising ocean heights.

Throughout human history, coastlines have long been favored locations for the establishment of human settlements, including major urban centers. Proximity to the ocean allows for access to diverse resources, milder weather, and transportation. However, the development of human settlements along coastlines has caused and accelerated the destruction of the habitats that once drew people there, including coastal lagoons, which have become some of the fastest disappearing ecosystems around the world as they are particularly sensitive to threats of urbanization and eutrophication. Conservation and management efforts surrounding these fragile aquatic ecosystems aim to reduce their conversion into urban or agricultural land, and address pollution and eutrophication to protect ecosystem health and conserve the ecological roles they provide.

Strategies commonly implemented in the protection of coastal lagoons include the designation of protected zones, the diversion of toxic runoff, and the restoration of lagoons and the land surrounding them. Recent research, however, has indicated that phytoremediation, defined as the use of plants and their associated microbes for environmental cleanup by Pilon-Smits in 2005 (Pilon-Smits, 2005), could effectively treat damage in coastal aquatic ecosystems. Historically, this method has been implemented on freshwater systems, particularly urban rivers and lakes subject to high levels of anthropogenic disturbance. While the restoration and re-introduction of lagoons is resource-intensive and expensive, the installation of artificial floating wetland islands (FWIs) could be an effective, cost-efficient, and environmentally friendly

method to address excess nutrients and pollution in bodies of water (Chen et al., 2023), thus treating some of the threats coastal lagoons face on the spot.

FWIs are small, constructed ecosystems aimed at [replicating the nutrient removal and cycling of natural ecosystems](#) by structurally supporting hydroponic plants. These islands allow plants to grow in waters that are typically too deep for them, facilitating the spread of their roots into the water column where they take up nutrients. In addition to replicating nutrient cycling and enabling the removal of harmful substances, FWIs also provide habitat for local wildlife, including birds and aquatic life. Relatively easily constructed and installed, FWIs have been shown to rapidly positively impact the aquatic environment they are placed in, as hydroponic plants begin contributing to the removal of excess nutrients and pollutants. Global studies have shown significant improvement in eutrophic urban bodies of water where FWIs have been installed. These improvements include the removal of excess [nutrients, reduction in bacterial contamination, and the transformation of pollutants into less harmful compounds. Additionally, the floating islands have contributed to the return of local aquatic fauna, which find shelter and sustenance in and near them.](#) These results clearly indicate the potential FWIs have to improve environmental quality in degraded aquatic environments. However, much of current FWI research is concentrated on remediation in urban, freshwater ecosystems, resulting in uncertainty regarding their effectiveness on brackish waters, whose dynamics differ significantly from freshwater systems. Answering whether FWIs can be deployed in brackish systems might expand the field of phytoremediation while simultaneously advancing the protection and survival of shallow coastal lagoons and their ecosystem services.

Chapter 2

BACKGROUND AND CONTEXT

Shallow coastal lagoons are distributed globally, taking on different shapes and functions based on their local and regional morphologies. In the United States, these ecosystems are particularly prevalent in the Gulf States and on the East Coast, where they serve as habitat, fish hatcheries, and zones of recreation. While present in smaller numbers, coastal lagoons are also found along California's coast. Lagoons in the state are critical for both local and migratory birds, including the Snowy Plover, a federally threatened species. The ecosystem services and the impact coastal lagoons have on the survival of other organisms make understanding how they function, how they are affected by anthropogenic action, and how they can be protected paramount. To understand whether FWIs may help protect brackish, coastal lagoons, the following study was designed and conducted.

The preservation of coastal systems has and will continue to play a key role in the well-being and survival of many species, including our own. This study will focus on the implementation of FWIs on the University of Santa Barbara's Campus Lagoon, a brackish lagoon with a history of minor environmental issues. Located along California's Central Coast, approximately two hours northwest of Los Angeles, the University of California Santa Barbara (UCSB) is situated in a region known for its agriculture as well as its many beaches and protected territories. Joined to the UC system in 1944, UCSB has had a long history of altering the landscape around it as its campus expanded. More recently, the school has developed a history of environmental advocacy, which has resulted in the protection of habitats around the university, including an important nesting and breeding site for the Snowy Plover. UCSB's Campus Lagoon is a brackish

coastal lagoon that serves as an aesthetic centerpiece for the school while providing a range of ecosystem services (Figure 1). The lagoon's relatively natural state means it acts as an important habitat for plants, fish, and both local and migratory bird species. However, the Campus Lagoon also serves as a runoff catchment for the university, draining and receiving flows from the surrounding campus. Due to its size, the flow of runoff waters into the lagoon minimally impacts the lagoon's environmental quality, but has contributed to minor algal overabundances and low levels of dissolved oxygen, both of which endanger the lagoon's environmental health, while also occasionally making it less aesthetically appealing, as an emanating sulfurous smell often accompanies the algal blooms.

The lagoon's status as an important ecological centerpiece, its role as a catchment, and its location on UCSB's research forward campus make it a good candidate for the experimental implementation of phytoremediative treatment through the introduction of artificial floating wetlands. The introduction of FWIs on the UCSB Lagoon has the potential to expand our current understanding of the role plants play in the health of brackish ecosystems and whether they can be implemented as a tool to treat ecological damage. Implementing FWIs on the UCSB Lagoon could help answer the questions: Is phytoremediation an effective tool in the brackish waters of UCSB's Campus Lagoon? And if so, what would it look like? Could its implementation be expanded to treat other coastal systems?

An experimental setup was designed to be built and installed on the UCSB Campus Lagoon to understand the potential of phytoremediation in brackish waters. Located centrally on the UCSB campus, the Campus Lagoon is intrinsically intertwined with the university's history and fundamentally shapes the campus's coastal aesthetic.

The backdrop for events ranging from research summits to graduation, the lagoon is a powerful entity whose presence symbolizes students' passage through UCSB and ties the campus to the ocean. Initially a salt marsh flat, whose water levels fluctuated with the seasons, the UCSB Lagoon moved towards its current form in the 1960s, when the university built up its boundaries and began pumping water into it, transforming it into a deeper, more stable, lake-like environment. This forced transformation resulted in a 31-acre lake with a volumetric capacity of around 4,630,000 ft³. Around 650 gallons of seawater flow into it from the Pacific Ocean every minute, making up a brackish system with high aquatic exchange rates. As the campus grew around it, the lagoon eventually became an area for runoff to flow into, with 80% of the Lagoon's flow represented by "nuisance flows of irrigation waters" (Campus Lagoon Water Quality Assessment 2016 Update). Eventually, the lagoon's management, and that of the land around it, were handed to UCSB's Cheadle Center for Biodiversity and Ecological Restoration, whose goal is to transform the lagoon and its island into a healthy, native landscape, thus ensuring it continues to be the campus's centerpiece. Frequent monitoring and data collection in the lagoon itself and the areas surrounding it make for a study site that is already well understood.

To assess the feasibility of phytoremediation on brackish bodies of water, research was conducted to determine what plants and structural design would be best suited for implementation in the UCSB Lagoon. In early 2024, two floating wetland islands were placed on the UCSB Campus Lagoon, following an extensive period of research based on the following literature review (Figure 2).

Chapter 3

LITERATURE REVIEW

Before implementing FWIs on the UCSB Lagoon, a literature review was conducted to determine implementation feasibility. This review helped determine 1) the materials most commonly used in FWI construction, 2) the efficacy of FWI implementation in the removal of pollutants and excess nutrients, and 3) the most common analytical methods used to quantify nutrient removal from bodies of water. Sources were found using the UCSB Library's EBSCO Environmental Science Index database, Google Scholar, Multidisciplinary Publishing Institute (MDPI), Science Direct, and the Nature Magazine database. Due to the relatively recent implementation of phytoremediation and FWIs as treatments for aquatic environmental damage, searches were limited within the years of 1990 to 2024. Phytoremediation was first coined as a term in 1983 by R.L Chaney, who studied the potential for *Vigna unguiculata* to remove zinc from contaminated soil (Chaney, 1983), and references to artificial wetlands began in the early 2000s, most of which were used by ornithologists to evaluate their use as habitat for birds. However, following the early 2000s, the use of artificial wetlands began to be investigated as a method of aquatic phytoremediation.

The following case studies were included in this literary review: *Floating Wetland Treatment, an Ecological Approach for the Treatment of Water and Wastewater – A Review*, *Nutrient Sequestration by Two Aquatic Macrophytes on Artificial Floating Islands in a Constructed Wetland*, *Floating Wetland Islands as a Method of Nitrogen Mass Removal: Results of a 1 year Test*, *Performance Evaluation of a Floating Treatment Wetland in an Urban Catchment*, and *Components of Floating Emergent*

Macrophyte Treatment Wetlands Influencing Removal of Stormwater Pollutants.

Additional sources were also analyzed.

Throughout the papers and case studies analyzed, FWIs were effective in removing pollutants and excess nutrients from bodies of water in all cases. Differences in the efficacy of artificial wetlands stemmed from the type of plants used, the body of water being treated, and the length of time plants spent on the water. Most of the literature analyzed focused on freshwater bodies or research in experimental, controlled mesocosms. All papers recommended the use of artificial floating wetlands as a treatment measure to remediate high levels of pollution, excess nutrients, and other imbalances in shallow aquatic systems. The recommendation to use FWIs as a treatment tool in damaged aquatic ecosystems stemmed from their efficacy, relatively low cost, and ease of installation and maintenance. While information and recommendations regarding freshwater systems were abundant, there was a noticeable lack of research surrounding systems of higher salinities, such as coastal lagoons. Additional research involving brackish waterbodies could provide useful information regarding what the management and conservation of coastal lagoons should or could look like.

ANALYSIS

Removal of Pollutants and Contaminants

In total, twenty-two papers and case studies were read. Of the case studies, seven discussed the use of artificial wetland treatments for eutrophic waters, three discussed waste and sewage waters, two discussed stormwater runoff, and one discussed recreational and industrial waters. All of the papers and case studies demonstrated improved environmental conditions following treatment with FWIs.

The majority of the papers read pertained to the implementation of FWIs in eutrophic freshwater systems. In these case studies, the contaminants removed from eutrophic bodies of water were Nitrogen (N), Phosphorus (P), Phosphate (PO_4^{3-}), Ammonium (NH_4^+), Nitrite ($\text{NO}_x\text{-N}$), and Nitrate ($\text{NO}_x\text{-N}$). Heavy metals as well as organic and inorganic pollutants were also listed, and included polycyclic aromatic hydrocarbons (PAHs) and sulfates (SO_4^{2-}). Every study regarding eutrophic waters clearly showed a decrease in the presence of harmful substances following the implementation of phytoremediation through FWIs. Differences in removal rates for each of these studies varied based on the study area and the plants used as uptakers.

Analysis conducted in the paper *Nutrient Sequestration by Two Aquatic Macrophytes on Artificial Floating Islands on a Constructed Wetland* showed that the implementation of phytoremediation can significantly lower the presence of excess nitrogen in bodies of water. In this paper, Chen and Costa observed that plant uptake contributed 58.5% to nitrogen removal (Chen and Costa, 2023) while Karstens et al. determined that nitrogen content in plants' biomass increased by an average of 1.61% after being implemented to remediate environmental damage in eutrophic freshwater. Similarly, phosphorus levels also decreased when FWIs were implemented. Chen and

Costa also observed a significant increase in plant phosphorus levels after the plants had spent time on a body of water, strongly suggesting that removal was occurring.

Similarly, Karstens et al. reported an increase in phosphorus presence in plants' biomass after having been implemented for phytoremediation in eutrophic coastal lagoons in the Baltic Sea.

The case studies analyzing FWI treatment in waste and sewage waters evaluated the removal of Nitrogen (N) (organic and oxidized), Phosphorus (P), TSS (total suspended solids), heavy metals, and pesticides. Of the case studies analyzed, all indicated a decrease in nitrogen and phosphorus, as well as heavy metals and pesticides. In *Floating Wetland Treatment, an Ecological Approach for the Treatment of Water and Wastewater – A Review*, Nitrogen had a removal range of 24.57% – 100% with an average removal rate of 72.8%, while the removal efficiency of Phosphate was 29.5%. In *Floating Wetland Islands as a Method of Nitrogen Mass Removal: Results of a 1 year Test*, a 30% reduction in nitrogen was observed in the treated body of water. While phosphate removal was not reported in this study, the authors indicated that the removal rate of phosphorus improved between 2% to 55% following the installation of artificial floating wetlands (Dodkins and Medzil, 2014).

Case studies on the treatment of stormwater runoff by artificial floating wetlands also indicated a strong decrease in contaminants and pollutants following the installation of FWIs. As described in *Performance Evaluation of a Floating Treatment Wetland in an Urban Catchment*, TSS removal was calculated to be around 80%, while total phosphorus removal was calculated to be 53%, and total Nitrogen removal was calculated to be 17%. The paper *Components of Floating Emergent Macrophyte Treatment Wetlands Influencing Removal of Stormwater Pollutants* discussed the

removal of heavy metals from storm runoff waters. Unlike the relatively high removal rates for organic materials, the removal of heavy metals was smaller but still significant. DO levels remained above 75%, and 34-42% of the associated turbidity was removed, indicating a significant impact of FWI treatment.

Building Materials

Of the case studies analyzed, the most commonly used materials were polyvinyl chloride (PVC) pipes (5), foam or substrate mats (5), natural materials (such as bamboo) (2), cork agglomerates (1), and fiberglass (1). Different materials resulted in structurally different FWIs and had an impact on the cost of construction and implementation. The most cost-effective method of construction used PVC, as PVC is easily accessible, has a relatively low cost, and can easily be structurally manipulated and altered. Foam and substrate mats (such as BioHaven mats) were the second most common material used to implement FWIs. However, the cost of these projects was higher, as prefabricated floating islands themselves were more costly and also included costs related to acquiring them. The cost of natural materials, cork agglomerates, and fiberglass was difficult to analyze as it was not listed in the case studies.

FWI construction also took a range of forms, with some of these materials used in conjunction with one another. The most common combination of materials was between PVC pipes and foam/substrate mats. PVC pipes were also commonly used in conjunction with meshes, plastic containers (pots, buckets), and natural materials. The case studies demonstrated that the relationship between nutrients and contaminants removed from water was not dependent on the materials used to keep plants afloat. While the article and case studies all demonstrated the ability of different materials to

be effective in FWI construction, the possibility for bodies of water to be affected by materials used to make FWIs was suggested. However, the impact on water was either not well studied or minimal compared to the benefits of using FWIs to treat eutrophication and contamination in bodies of water.

Biomass Analytical Methods

The most common analytical methods used to determine what amount of excess nutrients or pollutants were removed from the studied body of water were periodic harvesting of plant clippings, observation of plant viability and size (including root and shoot length, weight, and presence of biofilm), and laboratory analysis of dried plant biomass samples. The collection of aquatic data was also used to determine the efficacy of FWIs. However, this method was not used to quantify the removal that the plants had done, and instead aimed to understand whether water quality was affected when artificial floating wetlands were installed. All case studies that analyzed plant biomass, dried plant samples in an oven at temperatures over 80 °C, and then chemically analyzed the plant samples to quantify which nutrients were taken up by the plants from the body of water they were placed on.

In all cases, the implementation of FWIs improved water quality by removing excess nutrients, pollutants and contaminants, and decreasing turbidity. The materials most commonly used in the construction of artificial floating wetlands were PVC and floating substrate mats. However, the materials used in construction had no correlation to the plant's ability to remove nutrients and pollutants. While there is a need for more research on the implementation of FWIs on different types of waterbodies, the papers and case studies analyzed demonstrate that FWI implementation does have a positive

effect on bodies of water and is a viable, cost-effective, and environmentally friendly management strategy.

METHODS AND RESEARCH DESIGN

Plants and FWI Construction

The implementation of FWIs on the UCSB Lagoon can be divided into five progressive steps. 1) Project analysis through literature review, 2) identification of plants suitable for phytoremediation, 3) construction of floating structures that could support them, 4) implementation and observation of FWIs, and 5) removal and data analysis.

The above literature review provided sufficient background to select plants suitable for phytoremediation and to design a floating structure. For this study, four different native halophytic plants were chosen to be placed on the lagoon on artificial floating wetlands. Species were selected based on the following criteria: 1) presence around the UCSB Lagoon, and 2) adaptation to brackish conditions. The selected plants for this study were *Bolboschoenus maritimus*, *Salicornia pacifica*, *Jaumea carnosa*, and *Juncus auctus*. Respectively commonly known as Alkali Bullrush, Pickleweed, Marsh Jaumea, and Spiny Rush, these four plants represent a range of life histories and growth forms, allowing for analysis over a range of families and traits. Once it was determined which species would be used as test subjects, 20-40 individuals of each species were grown at UCSB's Cheadle Center for Biodiversity and Ecological Restoration (CCBER) nursery. These individuals were grown until they reached an adequate size and mature life stage to increase their odds of survival once transplanted. Twelve individuals of each species were chosen for experimental and control use, resulting in a total of forty-eight plants. Eight individuals of each species were then chosen to be placed on the FWIs on the Campus Lagoon, while four individuals of each

species would be kept and placed in a controlled hydroponic environment to act as a control group.

While the plants were grown at the CCBER nursery over the course of six months, the study's structural design was researched, determined, and built. Design and construction criteria called for a highly stable floating structure that could house hydroponic plants while allowing their roots to penetrate the water without overly submerging them in order to avoid asphyxiation. To ensure flotation and stability, the islands' frames were constructed out of PVC pipes and elbows 15.2 cm in diameter to form a 71 cm by 71 cm outside frame which would keep the entire structure afloat. These PVC pieces were joined together using PVC glue and sealant. In addition to the construction of the frame, 2.5 cm PVC was used to make a 2 x 2 grid, which was then placed onto the structural frame, resulting in space for four 5-gallon pots. The pots were perforated at the bottom and fastened to the 2 x 2 grid with zip ties and filled with a thin layer of hydrated soil and compost into which the plants were planted. Each pot contained four individuals of each plant species to ensure accurate biomass and nutrient analysis. To give the islands a more natural feel and to make them safe for wildlife use, their sides were covered with burlap bags, reducing the likelihood of wildlife getting snagged on the islands and instead adding texture for birds to perch on. Two identical FWIs were constructed, with each island containing 16 individuals. Once launched into the lagoon, the islands were anchored using cinder blocks to limit their movement.

Monitoring

The FWIs remained on the Campus Lagoon for five months, during which they were regularly monitored to ensure their structural integrity and to observe plant health and survival. Plant health was quantified through a plant viability index (PVI) that periodically assigned each individual a score between zero and five, with zero representing plant death and five indicating optimal health. These scores were then averaged, resulting in an Average Plant Viability Index (APVI) for each species. This value was found by summing the individual PVIs and dividing them by the total number of observations per plant species.

Once removed from the Campus Lagoon, measurements were taken of the surviving plant individuals. These measurements included shoot and root length and weight, as well as a final viability index determination. Plant biomass and nutrient content were chemically analyzed to determine whether the plant individuals removed excess nutrients from the UCSB Lagoon.

Additionally, observations were also made regarding bird use of the islands.

Chapter 4

DATA AND RESULTS

Data and plant material were analyzed following removal from the UCSB Lagoon. Plant data and results were collected from one FWI, due to the sinking of the second island following strong rains.

Chemical analysis was conducted to determine the carbon, nitrogen, and hydrogen content of plant matter for each species and individual. Plant matter was divided into shoots and roots. The carbon-to-nitrogen ratio of each sample was also determined to understand the capacity at which FWI plants were absorbing nutrients from the water they were placed in.

Wildlife Use

While on the Campus Lagoon, wildlife use was observed and recorded. FWIs were primarily used by sea and shorebirds, many species of which are already present on the UCSB Lagoon. To quantify wildlife use, use was defined as the perching or presence of birds on the floating islands. Birds on the water around the islands were not recorded as wildlife use. Observed bird species included the American Coot, the Western Gull, the Brown Pelican, and the Red-Breasted Merganser. American Coots were the most common of the four observed species with over 25 recorded observations. Western Gulls were present in smaller numbers, with around 10 recordings of this species. Brown Pelicans and Red-Breasted Mergansers were rare, with two and one recording of each species, respectively. American Coots were almost always present on and around the FWIs, irrespective of hour, and were often seen feeding in and around the islands, indicating the potential presence of aquatic life under the FWIs.

Plant Health, Plant Viability Index (PVI), and Average Plant Viability Index (APVI)

Each plant individual was monitored using a plant viability index (PVI) to assess plant health while on the Campus Lagoon. Individuals periodically received a score between zero and five, with zero representing plant death and five indicating optimal health. These scores were then averaged amongst species, resulting in an Average Plant Viability Index (APVI). *Bolboschoenus maritimus* received an APVI score of 1.62, *Juncus acutus* received a 4, *Jaumea carnosa* received a 3.31, and *Salicornia pacifica* scored a 1.62 (Figure 5). Based on their APVI ratings, *Juncus acutus* and *Jaumea carnosa* were determined to be best adapted to surviving in hydroponic environments, while both *Bolboschoenus maritimus* and *Salicornia pacifica* were unable to survive. Both *Bolboschoenus maritimus* and *Salicornia pacifica* finished with PVIs of 0, indicating plant death.

Salicornia pacifica, a perennial succulent, had the most significant decline in plant health while on the lagoon (Figure 5). Over its first month on the lagoon, its APVI remained at a score of four, but then it sharply declined until it was rated at a zero a month and a half after being initially placed on the water. Similarly, *Bolboschoenus maritimus* began with a score of 3 due to slight signs of stress, before being briefly rated at a 4 about a month into the experiment (Figure 5). Following this rating, the individuals on the FWI all slowly declined until being rated a zero at the four-month mark.

Upon its introduction on the lagoon, *Jaumea carnosa* was given an APVI value of 5. Over half a month, it declined to a score of three, before steadying at a final score of four. *Juncus acutus* was initially given a score of three, reflecting some signs of stress,

and then fluctuated between three and four, before settling on a final score of five (Figure 5).

The PVI and APVI allowed for easy characterization of plant health while on the Campus Lagoon. *Jaumea carnosa* and *Juncus acutus* were ultimately determined to be the best survivors of the four chosen species, while *Bolboschoenus maritimus* and *Salicornia pacifica* were uniquely unadapted to a hydroponic environment.

Shoot and Root Measurements

Shoot measurements were taken for each individual before being placed on the UCSB Lagoon. Following the experimental run, shoot and root measurements were taken for each surviving individual. Shoots were separated from the substrate by hand. Results will focus on *Jaumea carnosa* and *Juncus acutus* as the surviving plant species. These measurements were averaged among species.

Before being placed on the lagoon, *J. carnosa*'s control group had an average shoot length of 8.3 cm, while the experimental group had an average shoot length of 10.20 cm (Figure 10, 12). After being removed from the lagoon, the *J. carnosa* control group had an average shoot length of 18.4 cm, while the experimental group had a value of 16.1 cm (Figure 11, 13). Root measurements were also taken following removal from the UCSB Lagoon, resulting in an average length of 49.1 cm for the experimental group, larger than the 46.3 cm for the control group (Figure 11, 13). Root measurements were not taken for control or experimental groups previous to placement on the lagoon.

Prior to placement on the UCSB Lagoon, the *J. acutus* control group had an average shoot length of 46.7 cm, while the experimental group's average was 46.1 cm (Figure 6, 8). Following the plants' removal from the lagoon, the control group had an

average shoot length of 48.8 cm and an average root length of 78.2 cm (Figure 7). The experimental group's average shoot length was 50.4 cm, while its average root length was 63.5 cm (Figure 9). Root measurements were not taken previous to placement on the lagoon.

Laboratory Analysis

Following their removal from the Campus Lagoon, UCSB's Marine Science Institute (MSI) conducted laboratory analysis on individual samples of surviving *J. carnosa* and *J. acutus* plants. There were four control individuals for both species, six experimental individuals for *J. acutus*, and three for *J. carnosa*. The low number of *J. carnosa* individuals returns to the sinking of one FWI.

In preparation for analysis, the shoots and roots of the individuals of both these species were separated and put into paper bags. These samples were then oven dried over several weeks at a temperature of 45 °C. Once dry, samples were sent to MSI, where smaller samples were taken, ground, and loaded into tin capsules. These were then analyzed for carbon, nitrogen, and hydrogen content through an Automated Organic Elemental Organizer using the Dumas combustion method. The detection limit (µg) for these three elements was 0.3 (C), 2.0 (N), and 1.1 (H), respectively. A precision of +/- 0.3% was reported for the analytical instrument. Carbon to Nitrogen ratios were reported for each plant sample.

Individual sample analysis was summed and averaged, resulting in values for Average Sample Weight (µg), Average C content, Average N content, Average H content, and an Average C/N Ratio for each sample group (Figures 3, 4). Samples were grouped

according to their classification as a control or experimental group, and on their plant part (either shoots or roots). Analysis was conducted in RStudio.

Data Analysis

Analysis of *J. carnosa* indicated significant differences in carbon and nitrogen content, as well as in C:N ratios between control and experimental groups. A significant difference was found between the carbon content of *J. carnosa*'s control and experimental shoots, with less carbon present in *J. carnosa*'s experimental shoot group than in its control shoots (Figure 14). The plant's nitrogen content also showed a significant difference, with experimental shoots and roots both having larger N contents than those of the control plants, suggesting that plants were taking up nutrients from the water around them, investing in root growth, and minimizing carbon uptake and shoot growth (Figure 18). This likely indicates nutrients were freely available around *J. carnosa*'s roots, allowing it to focus its energy on growing roots and taking up nitrogen. The significantly smaller C:N ratio found for the experimental *J. carnosa* group indicates a smaller gap between carbon and nitrogen contents in these plants, again suggesting nutrient uptake from the lagoon's waters (Figure 20).

Analysis of *J. acutus* was divided into two groups, Experimental Group 1 and Experimental Group 2, due to the large number of surviving plants, some of which came from FWI2. Experimental Group 1 (EG1) showed significant differences in carbon content in plant roots (Figure 15), but showed no significant differences in hydrogen and nitrogen contents between the two groups (Figures 17, 19). There was a significant difference in the C:N ratio between the control and EG1, with a significantly higher carbon content in both the experimental roots and shoots, suggesting that plants in this

group likely had trouble taking nutrients up from the lagoon and instead focused on taking up carbon through shoots (Figure 21).

Experimental Group 2 (EG2) was marked by significant differences across all analytical markers. Significantly higher carbon levels were present in *J. carnosa*'s experimental roots compared to the control plants (Figure 15). Experimental roots also held higher hydrogen and nitrogen concentrations than their counterparts in the control plants (Figures 17, 19). The C:N of the experimental plants was significantly lower than that of the control group, indicating they were likely taking up nutrients from the UCSB Lagoon and incorporating those into their tissues (Figure 21).

Despite variability among groups, data indicate that experimental *J.carnosa* and *J.acutus* likely absorbed nutrients from the water they were placed on. This is reflected in the incidence of lower C:N ratios in these plants, which indicate that nutrients were likely easily accessible for these plants. Higher C:N ratios for the control plants, and larger shoot sizes suggest difficulty in nutrient uptake through roots and compensatory shoot growth.

Chapter 6

CONCLUSION

The results of the study conducted on the implementation of floating wetland islands on the UCSB Campus Lagoon, using the species *B.maritimus*, *J. carnosa*, *J.acutus*, and *S.pacifica*, suggests that the implementation of phytoremediative techniques is possible on the UCSB Lagoon and may be expanded as a tool for environmental remediation in other brackish bodies of water. These are only partially supported, given the small sample size analyzed.

Observation and analysis of the plants while on the FWIs clearly showed that, of the four species, *J. carnosa* and *J. acutus* were best adapted to growth in aquatic environments, while *B. maritimus* and *S. pacifica* were unable to survive on the lagoon. This outcome is likely related to the life histories and physiologies of these four plants. Unlike *B. maritimus* and *S. pacifica*, which have relatively shallow, non-expansive root systems, *J. carnosa* and *J. acutus* have longer growing roots that can penetrate deeper into substrate or water columns. In aquatic environments, deeper, extensive root systems likely aid in plant survival by allowing plants to get established and absorb nutrients from their environment.

Analysis of data collected on *J. carnosa* and *J. acutus* suggests both plants absorbed nutrients from the lagoon's waters, indicating that, if used in larger numbers, these plants likely could have a phytoremediative impact on the UCSB Lagoon. While data seems to answer the guiding questions of this study positively, additional research is needed on this topic to further clarify what impacts FWI implementation might have on brackish bodies of water. Future research on this topic should aim to conduct a similar study while utilizing and analyzing data from a larger sample size. While the

results of this study indicate that some of the species used on the UCSB Campus Lagoon FWIs did absorb nutrients from the lagoon, the small sample size makes it impossible to assertively conclude this.

In addition to answering the question regarding which of the four analyzed species would function best for this purpose, this experiment also answered questions regarding FWI design and construction. While PVC pipes are generally accessible and manipulable, issues were encountered in the construction and implementation of this study due to the chosen FWI design. While PVC pipes ensured flotation and stability, the pot and grid system they supported made the FWIs difficult to manage. Removal from the UCSB Lagoon was complicated by the weight of water that had settled in the PVC pipes, as well as in the pots attached to them, making it difficult to hoist the FWIs out of the water. Employing a mat or other lightweight support system for the plants would likely have eased management issues encountered during this experiment.

Understanding of the UCSB Lagoon and the potential for phytoremediation in its brackish waters would be advanced by further research regarding the use of *J.carnosa* and *J.acutus* as uptakers. Future studies should aim to analyze data from larger sample sizes to more conclusively understand the impact, if any, of FWIs on the lagoon. Analysis of the lagoon's waters would provide additional insight into the lagoon's water makeup and quality, and, again, could help more concretely quantify nutrient uptake by *J. carnosa* and *J. acutus* on the lagoon.

While difficult to say what the impact of a large-scale installation of FWIs would be on the lagoon, or another coastal lagoon, this study suggests that plants can be used as phytoremediative tools in brackish waters. Further analysis to confirm this interpretation is required, but the addition of phytoremediation through FWIs as a tool

for environmental remediation in brackish coastal systems could significantly aid in protecting and conserving these fragile but essential ecosystems. Implementing FWIs offers an additional avenue through which to remediate anthropogenic damage done to brackish ecosystems. Coupled with other strategies, such as the designation of protected zones and the diversion of runoff, these ecosystems might have a fighting chance at survival, thus giving the organisms who rely on these systems a second lease of life. The importance of our coastal systems and their impact on the rest of our planet's environmental regimes cannot be overstated, and in turn neither can their protection.

Appendix (Figures)



Figure 1. UCSB Campus and Campus Lagoon



Figure 2. Placement of FWIs on UCSB Campus Lagoon

Table 1: Results of Chemical Analysis for Control Group

Sample ID	Average Weight (ug)	Avg C (%)	Avg N (%)	Avg H (%)	Avg C/N Ratio (%)
JC Shoots	2,653	41.44%	5.94%	0.75%	56.81
JC Roots	2,067	36.43%	4.96%	0.70%	51.71
JA Shoots	2,311	33.07%	4.05%	1.03%	32.25
JA Roots	2,519	33.56%	4.07%	0.87%	40.89

Average sample weight, C, N, H content, and CN ratio for shoots and roots of both *Jaumea carnosa* and *Juncus acutus*

Figure 3. Results of Chemical Analysis for Control Group

Table 2: Results of Chemical Analysis for Experimental Group

Sample ID	Average Weight (ug)	Avg C (%)	Avg N (%)	Avg H (%)	Avg C/N Ratio (%)
JA1 Shoots	2,550	41.12%	5.28%	1.32%	41.99
JA1 Roots	2,156	38.56%	4.54%	0.79%	49.24
JC1 Shoots	2,509	34.84%	5.27%	1.41%	24.68
JC1 Roots	2,792	32.61%	4.59%	1.13%	28.97
JA2 Shoots	2,183	39.99%	5.38%	1.49%	26.97
JA2 Roots	2,299	36.07%	4.66%	0.98%	36.75

Average sample weight, C, N, H content, and CN ratio for shoots and roots of both *Jaumea carnosa* and *Juncus acutus*

Figure 4. Results of Chemical Analysis for Experimental Group

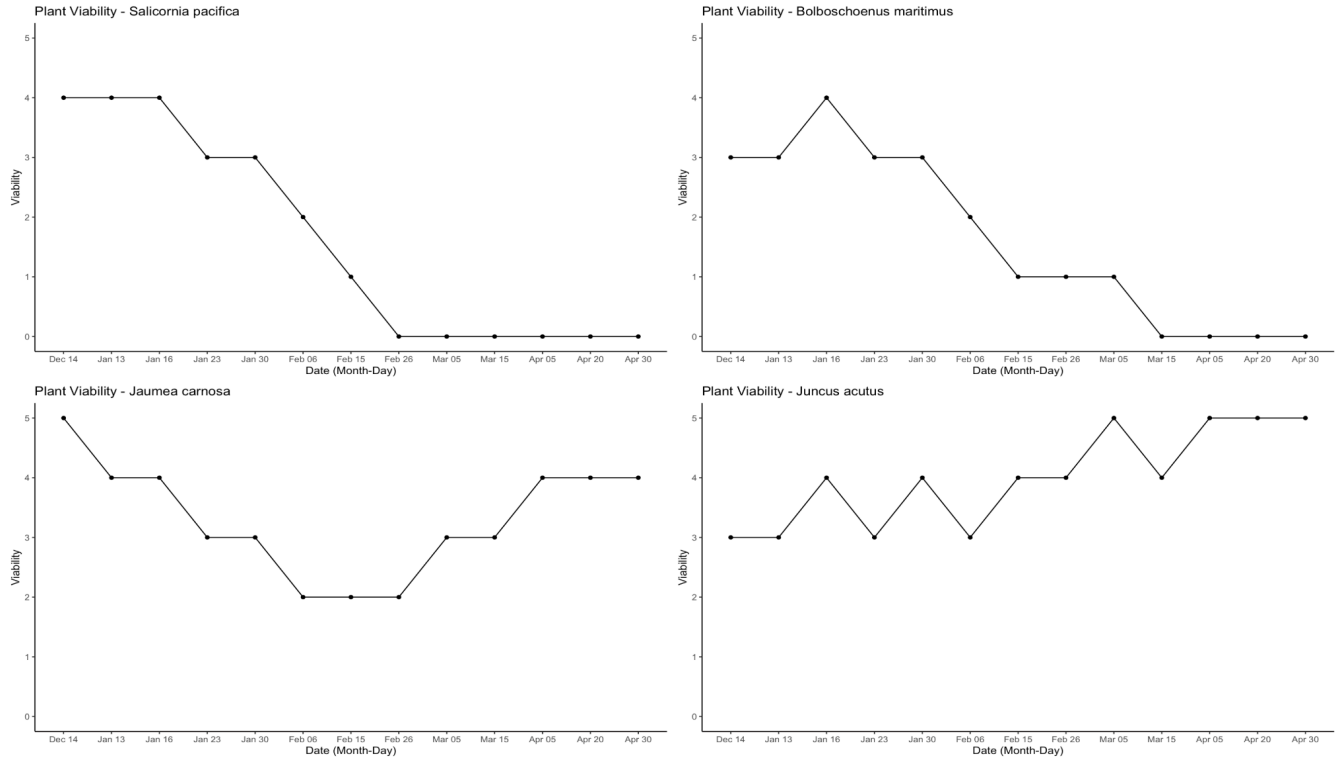


Figure 5. APVI for four study species (*Salicornia pacifica*, *Bolboschoenus maritimus*, *Jaumea carnosa*, and *Juncus acutus*)

Table 3: Control *Juncus acutus* shoot length (cm) prior to FWI

Plant_Sample	Shoots(cm)
JA1	46.8
JA2	50.1
JA3	44.3
JA4	45.6
Average	46.7

Measurements of control
Juncus acutus shoot lengths
prior to control treatment

Figure 6: Control *J.acutus* shoot lengths and average (cm) prior to control treatment

Table 4: Control *Juncus acutus* shoot and root length (cm) post FWI

Plant_Sample	Shoots(cm)	Roots(cm)
JA1	50.8	119.0
JA2	48.3	76.2
JA3	45.7	43.8
JA4	50.8	73.7
Average	48.8	78.2

Measurements of control *Juncus acutus* shoot and root lengths following control treatment

Figure 7. Control *J.acutus* shoot and root lengths and average (cm) following control treatment

Table 5: Experimental *Juncus acutus* shoot length (cm) prior to FWI

Plant_Sample	Shoots(cm)
JA1	40.6
JA2	45.7
JA3	50.8
JA4	45.7
JA5	48.3
JA6	45.7
Average	46.1

Measurements of experimental *Juncus acutus* shoot lengths prior to being introduced to the Campus Lagoon on FWIs

Figure 8. Experimental *J.acutus* shoot length and average (cm) before being introduced to the Campus Lagoon on FWIs

Table 6: Experimental *Juncus acutus* shoot and root lengths (cm) post FWI

Plant_Sample	Shoots(cm)	Roots(cm)
JA1	45.7	106.7
JA2	53.3	50.8
JA3	50.8	35.6
JA4	48.3	38.1
JA5	55.9	68.6
JA6	48.3	81.3
Average	50.4	63.5

Measurements of experimental *Juncus acutus* shoot and root lengths after being introduced to the Campus Lagoon on the FWIs

Figure 9. Experimental *J.acutus* shoot, root, and average lengths (cm) after being introduced to the Campus Lagoon on FWIs

Table 7: Control *Jaumea carnosa* shoot lengths (cm) prior to FWI

Plant_Sample	Shoots(cm)
JC1	10.16
JC2	10.16
JC3	7.62
JC4	5.08
Average	8.30

Measurements of control *Jaumea carnosa* shoot lengths before control treatment

Figure 10: Control *J.carnosa* shoot, root, and average lengths (cm) prior to control treatment

Table 8: Control *Jaumea carnosa* shoot and root lengths (cm) post FWI

Plant_Sample	Shoots(cm)	Roots(cm)
JC1	20.30	50.1
JC2	17.80	49.8
JC3	25.40	45.0
JC4	10.16	40.2
Average	18.40	46.3

Measurements of experimental *Jaumea carnosa* shoot and root lengths following control treatment

Figure 11: Control *J.carnosa* shoot, root, and average lengths (cm) following control treatment

Table 9: Experimental *Jaumea carnosa* shoot lengths (cm) prior to FWI

Plant_Sample	Shoots(cm)
JC1	10.16
JC2	10.18
JC3	10.12
Average	10.20

Measurements of experimental *Jaumea carnosa* shoot lengths before being introduced to the Campus Lagoon on FWIs

Figure 12: Experimental *J.carnosa* shoot lengths and average (cm) before being introduced to the Campus Lagoon on FWIs

Table 10: Experimental *Jaumea carnosa* shoot and root lengths (cm) post FWI

Plant_Sample	Shoots(cm)	Roots(cm)
JC1	15.24	50.8
JC2	10.16	55.9
JC3	22.90	40.6
Average	16.10	49.1

Measurements of experimental *Jaumea carnosa* shoot and root lengths after being introduced to the Campus Lagoon on FWIs

Figure 13: Experimental *J.carnosa* shoot, root, and average length (cm) after being experimental treatment

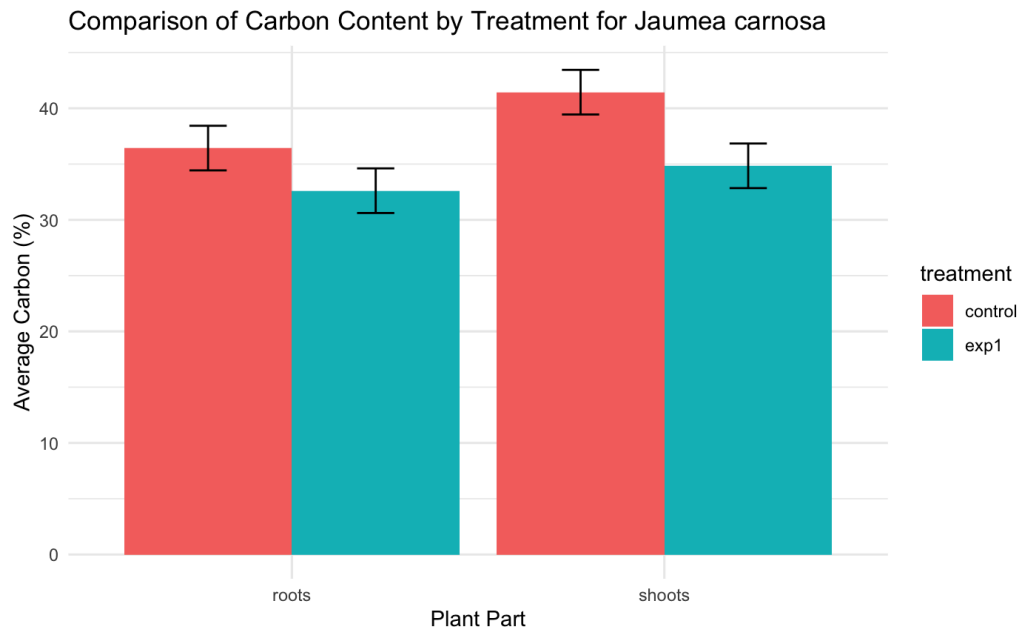


Figure 14. Comparison of carbon content by treatment (experimental vs control) for *Jaumea carnosa*

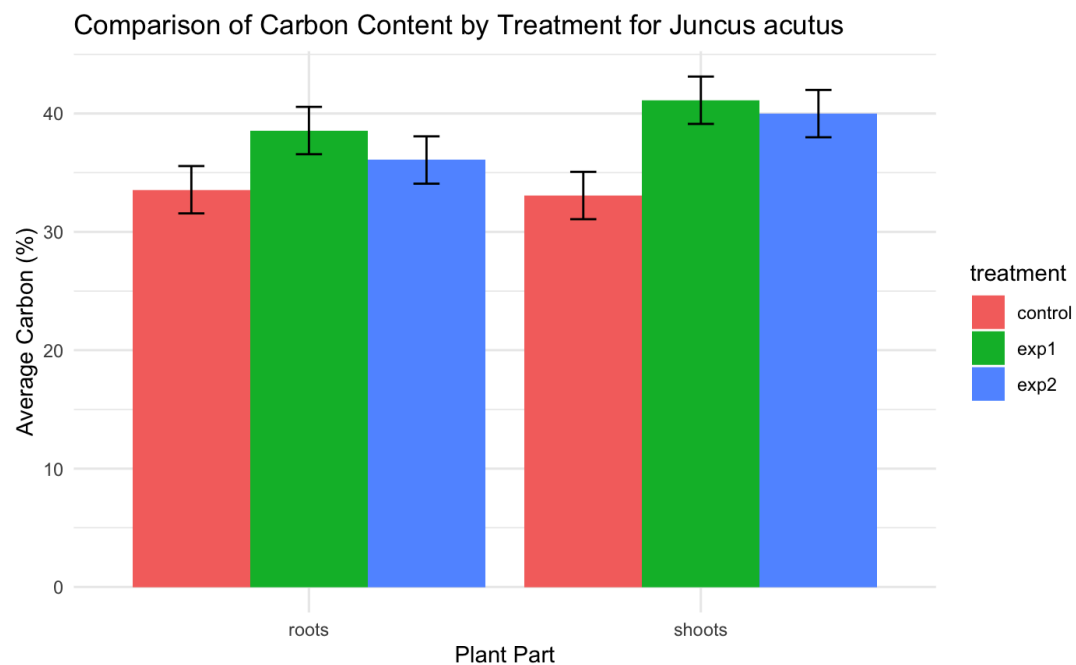


Figure 15. Comparison of carbon content by treatment (experimental vs control) for *Juncus acutus*

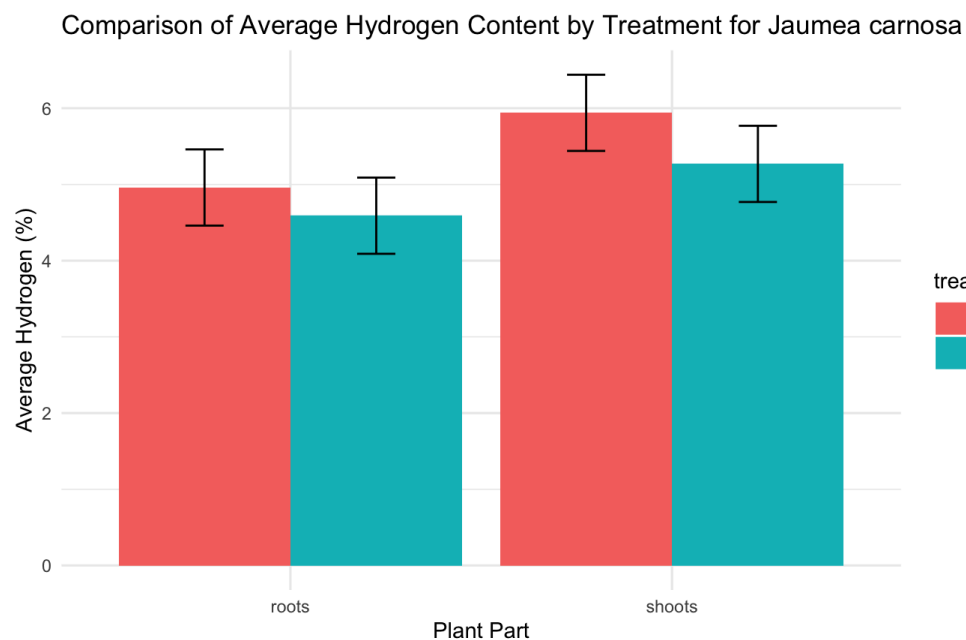


Figure 16. Comparison of average hydrogen content by treatment (experimental vs control) for *Jaumea carnosa*

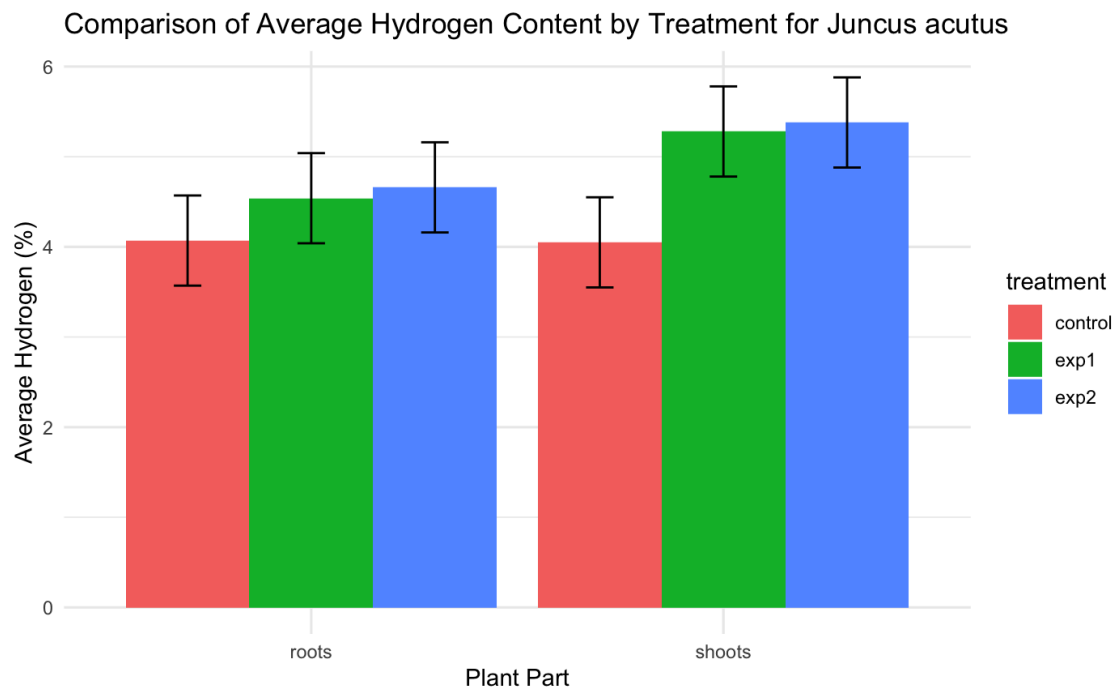


Figure 17. Comparison of average hydrogen content by treatment (experimental vs control) for *Juncus acutus*

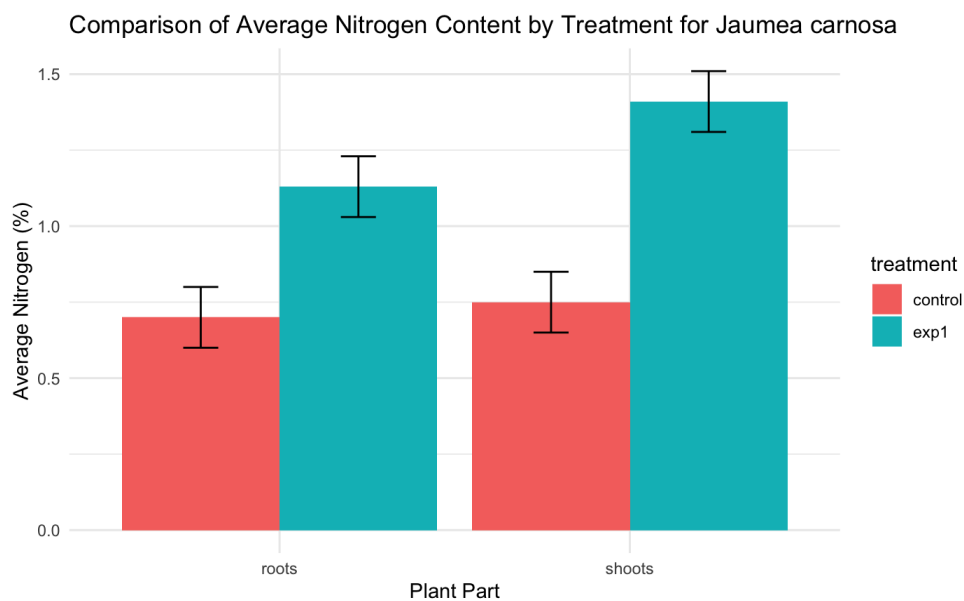


Figure 18. Comparison of average nitrogen content by treatment (experimental vs control) for *Jaumea carnosa*

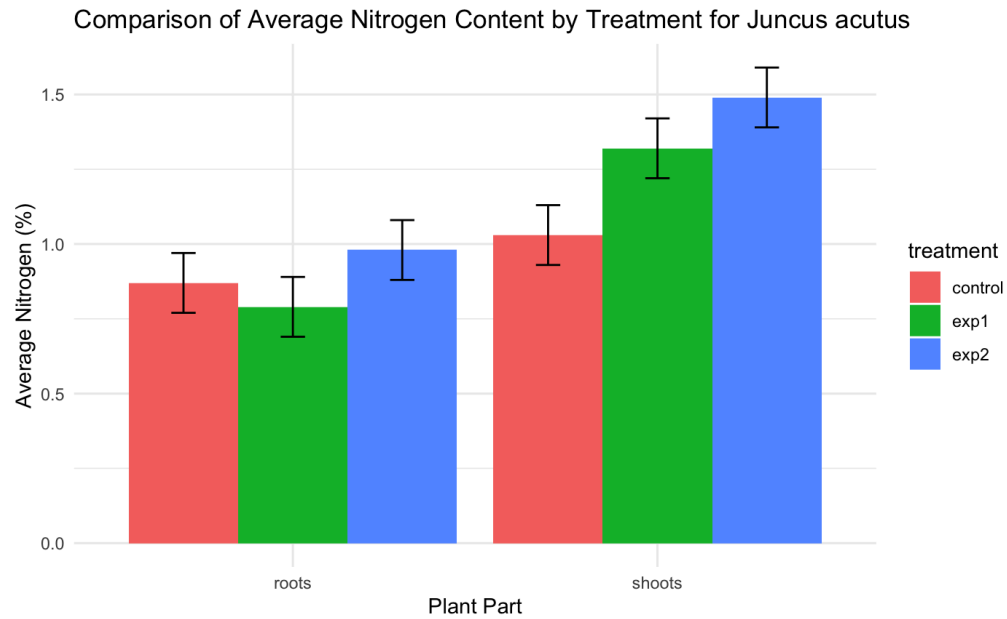


Figure 19. Comparison of average nitrogen content by treatment (experimental vs control) for *Juncus acutus*

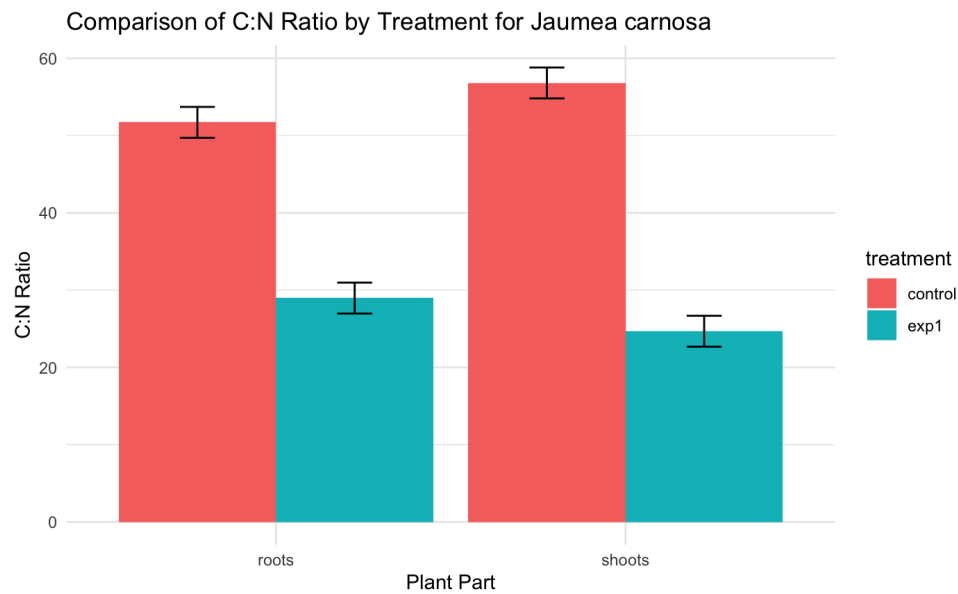


Figure 20. Comparison of C:N ratio by treatment (experimental vs control) for *Jaumea carnosa*

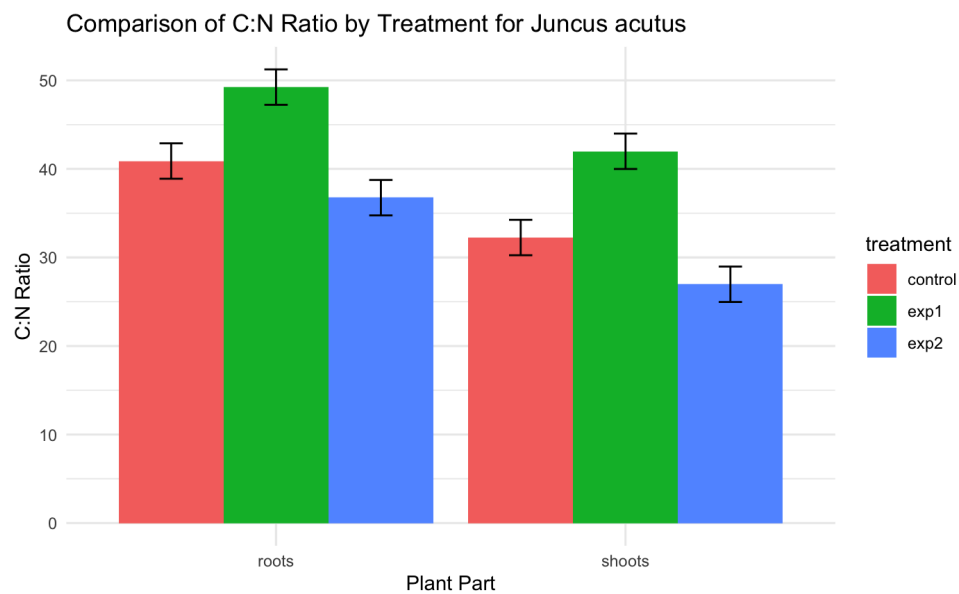


Figure 21. Comparison of C:N ratio by treatment (experimental vs control) for *Juncus acutus*

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