Investigating the relationship between plant biomass and defense against coastal erosion on O’ahu

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Abstract

Oahu's shoreline has been extensively developed and heavily impacted due to high population density, tourism, and military installations, leaving only a few natural dune environments intact. As coastal dunes provide a key natural defense to coastal erosion, developed coastal lands where construction has encroached into the dune environment often lack the ability to naturally adapt to changing conditions. The eroding beaches along the North Shore of Oahu dramatically illustrate this phenomenon. Global concern about the problem of coastal erosion is fueled by growing awareness of rising sea level and the expectation of an increased intensity of damaging storms. Previous studies demonstrate that vegetation can enhance dune stabilization in some cases, and there is anecdotal evidence that root mass has a role in how much influence vegetation has in dune stabilization. However, there is a paucity of data on root mass and structures of native Hawaiian plants. This report presents a literature review of methods to characterize root mass and the role this material can play in mitigating erosion. Charbonneau et al. (2016) conducted a study on Island Beach Park, New Jersey, investigating biomass, root to shoot ratio and root density of two dominant dune plant species: Native American beach grass, *Ammophila breviligulata*, and invasive Asiatic sand sedge, *Carex kobomugi*. Results obtained in this study, using approaches similar to those of Charbonneau et al. (2016), provide measurements of below ground root mass associated with two coastal native Hawaiian plants – Beach Naupaka, *Scaevola taccada* and ʻAkiʻaki grass, *Sporobolus virginicus*. Plant and root sampling took place along the coast of Marconi Point in Kahuku, Oahu, where a variety of coring and excavation methods were utilized. Results were normalized to mass per unit area down to depth for each sampling technique to allow direct comparison to results from the Island Beach Park study. We found that ʻAkiʻaki grass generally exhibits underground root mass similar to the Native American beach grass from the New Jersey coast. Naupaka, on the other hand, behaves plastically in the sense that there is no fixed root to shoot ratio as the conditions it grows in have major implications of geometry and amount of below ground root mass. While we did not develop a clear connection between below ground root mass and its effect on erosion, we offer insight to how variable this relationship could potentially be and propose improvements to sampling methods for future research.

Table of Contents

List of Figures

List of Tables

Introduction

This project has two main objectives. The first is to review the scholarly literature on methods to characterize below ground root mass and the role this material may play in mitigating erosion. The second is to contribute primary data on below ground root mass associated with native Hawaiian plants. By combining these two types of information I hope to contribute to emerging efforts to understand the role below ground root mass may play in mitigating shoreline erosion. As discussed more fully below, this project is based upon a study conducted on the coast of New Jersey. Charbonneau et al. (2016) compared density and depth of root systems associated with two dune plant species that are common to the area, native American Beach grass (*Ammophila breviligulata*) and an invasive Asiatic sand sedge (*Carex kobomugi*). There are many different types of native plants that inhabit the coasts of Hawaii, ranging from grasses and vines to shrubs and even trees. Such plants include Naupaka (*Scaevola taccada*), seashore rushgrass, ʻAkiʻaki (*Sporobolus virginicus*), Pôhuehue, or the beach morning glory (*Ipomoea pes-caprae subsp. brasiliensis*), and Naio (*Myoporum sandwiches*) (Ellicott, 2009).

Oahu's shoreline has been extensively developed and heavily impacted due to high population density, tourism, and military installations, leaving only a few natural dune environments in tact. Consequently, only a few natural dune environments remain (SOEST, 2013). Dunes not only serve as a defensive barrier, but they also serve as a sand resource, distributing sand to replenish adjacent beaches

Figure 1. Beach erosion on Papa'iola beach, Haleiwa April 2018. Naupaka is seen on either side of the eroding scarp.

after natural erosion events, such as seasonal shifts in wave regime and severe storms. When a large demand for sand is met with little supply, beach erosion can lead to beach loss (Fletcher, 2010). Future sea level rise will likely exacerbate this issue. The IPCC projects that global sea level could increase 0.3-0.6 feet by 2030 and 0.5-1.2 feet by 2050 (Losada, 2014).

This study was initiated through discussions with previous MGeo student/shoreline science engineer Robert Walker, and motivated by his interest in the role dune stabilization might play on the coastlines of the North Shore, Oahu, where aggressive coastal erosion is occurring. Beachfront property owners in this area are already fighting a losing battle against beach erosion. Although there is no sand "savings account" to replenish the failing scarp face, short-term solutions are sought to stabilize and preserve the artificial sand dune that owners have had bulldozed from the shore break to the back beach zone.

Figure 2. Dune planting along bike path at Sunset Beach, Haleiwa, September 2018.

This study was initiated through discussions with previous MGeo student and coastal scientist/engineer Robert Walker, and motivated by his interest in the role native coastal vegetation might play in dune stabilization efforts in Hawaii. There was a tentative plan to develop a pilot study to plant various types of native dune vegetation along a recently restored dune face on the North Shore of Oahu, and evaluate the effectiveness of each plant species in mitigating coastal erosion. However, it was impractical to integrate my MGeo project with such an effort because of the long time line and uncertainties associated with regulatory permitting, as planting vegetation on dunes is currently prohibited by State of Hawaii policy. Fortunately, we had the opportunity to assist with a project that was later initiated by the North Shore Community Land Trust. On September 8, 2018, nearly 100 volunteers outplanted over 4,000 native coastal plants along the Paumalū (Sunset Beach) bike path. Naupaka and Naio were the main types of vegetation planted. A fence was also built out of repurposed, invasive ironwood trees from Kahuku Point to designate public access points and decrease foot traffic, which also contributes to erosion in the area. The newly planted area is being maintained and progress is being monitored via ground and drone photos. This project provides a tangible example of how native vegetation is already being planted on the shoreline in the hope of mitigating coastal erosion.

Some benefits resulting from dune vegetation are widely accepted based upon past experiences. For example, vegetation on dunes acts to localize foot traffic on designated pathways effectively deterring damaging foot traffic across most of the dune surface. In addition, the vegetation above the ground surface provides a mechanism to catch aeolian transport, which aids in beach accretion. This subareal biomass also dissipates hydrodynamic forces of waves. Other benefits, such as erosion mitigation during storms by enhanced dune stabilization, have been proposed but are difficult to demonstrate. However, limited field studies have been conducted to qualitatively record how vegetation dampens over wash effects in natural dune environments (Charbonneau et al. 2017). A study by Feagin et al. (2015) investigates how ecological and engineering systems are most effective in joint action. That way, coastal protection is achieved in a sustainable and credible way. They report on wave flume laboratory experiments that replicate dune environments but replace vegetation with wooden dowels. Results imply that dune erosion is in fact reduced by the water's collision with the dowels. Above ground Naupaka branches and exposed roots appear to act similarly, causing waves to break sooner than they otherwise would.

A traditional way to respond to beach erosion is to construct a seawall against the edge of land that is being eroded by wave energy. While hard infrastructure stops additional land loss, it often has negative regional impacts, compromising the long-term accretion of beaches and dunes (Salgado and Martinez, 2017). Ecosystem-based coastal protection such as mangroves, saltmarshes, and coastal dunes, is an alternative to disruptive shoreline hardening. Salgado and Martinez 2017 comprised evidence from anecdotal observations, experimental tests, field observations, mathematical analyses, models and projections, and economic evaluations to conclude that vegetating coastal areas can be a viable protection option. However, the large space required and long periods of time, and specific species required for nourishment are all limiting factors.

There is a paucity of data on below ground root mass and structures of native Hawaiian plants in general, including Beach Naupaka. Many physical or direct means of extracting/viewing roots not only damages large root samples but also leaves behind fine root mass. According to Addo-Danso et al. (2016), this critical fine root mass may provide more to the plant biologically, as well further stabilize the surrounding soil than larger coarse roots. Physical sampling methods involve trenching, coring, and excavating. Indirect root sampling methods include empirical modeling, as well as ground penetrating radar. However, all means of studying roots have significant limitations. For example, coarse-root biomass excavation yields accurate results but a correction for lost and broken roots is required, field application is difficult and not feasible in certain sites, it can be costly, labor intensive, inefficient, and destructive to the environment. However, many scientists opt for root excavation and soil pit methods to study roots despite the high cost and labor required (Addo-Danso et al., 2016). There is currently no standard for estimating or measuring roots characteristics, thus further complicating root system surveying. The use of ground penetrating radar (GPR) may yield promising results for studying in situ

Naupaka roots in Hawaii. GPR has been utilized for detecting the architecture, size, and biomass of coarse roots (>2 mm diameter) since 1999 (Guo, 2012). This method has shown to be useful in well-drained sand that is low in organic content, much like Hawaii's carbonate sand (Addo-Danso et al., 2016).

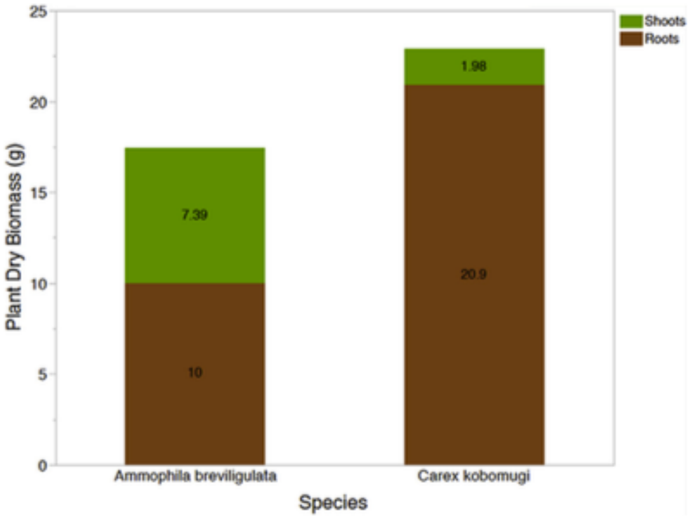

Figure 3. Invasive *Carex kobomugi* exhibits more root than shoot mass compared to native *Ammophila breviligulata (from Charbonneau et al. 2016)*

Coastal erosion is a topic of great interest and in addition to sea level rise, climate change will cause hurricanes and other weather systems to increase in intensity (Losada, 2014). One example of this was Superstorm Sandy, a Category 3 hurricane that battered the east coast of the United States in 2012. Characteristically, areas protected by dunes experienced less damage than those more exposed to the destructive wind and waves. Charbonneau et al. 2016 conducted a study on Island Beach Park, New Jersey, investigating biomass, root to shoot ratio and root density of two dominant dune plant species. Native American beach grass, *Ammophila breviligulata*, and invasive Asiatic sand sedge, *Carex kobomugi* were the two species under study. Fifteen cores of each species were randomly collected throughout the dune to measure the depth and density (key stabilizing factors) of living root biomass. Charbonneau's findings show that the invasive *C. kobomugi* exhibits a denser root mass thus offering a higher degree of stabilization. This poses the question whether it is more beneficial to have monoculture areas that increase resilience of dune structure at the cost of biodiversity. Figure 3 depicts the notion that significant above ground plant mass (green) isn't always indicative of a large below ground root mass (brown) (Charbonneau et al. 2016).

Evidence that below ground root mass can stabilize coastal dunes is mainly anecdotal (Ghestem et al. 2014) but in hill slope environments the area of study is more mature. For example a study by Ghestem et al. (2014) demonstrates how to choose plant species based on root traits to efficiently and effectively stabilize slopes in western Yunnan, China, where 50 years of deforestation, urban development, and road construction have caused an increase in landslides. They compare species efficiency for stabilizing slopes by associating three different plant properties with desirable traits. Properties include root abundance in soil, root mechanical resistance, and root metabolic activity. The most ideal plants have deep and extensive root networks that are fast growing, strong, and slow to decompose. Results showed that not one species exhibits all desirable traits and that using a variety of species with different root architectures on a vulnerable slope would offer the most stability. Additionally, they state that deep-rooted species should be planted in the middle of a slope to act as an anchor in the soil. Roots that grow upslope from the stem of the plant would be beneficial near the top of the slope, as they would be able to cross the potential shear plane. Finally, species with a down-slope root system should be near the bottom of the degraded slope (Ghestem et al., 2014).

The main objective for my project is to learn enough about the below ground root mass of Naupaka and ‘Aki‘aki grass so that we can provide similar data to those produced by Charbonneau et al. (2016). Ellicott (2009) provides an overview of the characteristics of Naupaka, which are summarized as follows. Naupaka is heat, drought, wind, and salt spray tolerant, it binds the sand, retains moisture in the ground, helps produce soil, and offers shelter for other native species. The native indigenous shrub can grow anywhere from 2 to 10 feet high and up to 15 feet wide with a long lifespan, which is considered to be greater than 5 years. Naupaka is found on all of the main Hawaiian Islands and is native to the tropical Pacific and Indian Ocean coasts. It is able to grow in sand, clay, cinder, organic, and coral dominated soils. As common and useful as Naupaka seems, it is puzzling how little is known about the root structures. ‘Aki‘aki grass can also tolerate drought, brackish water, wind and salt spray. Size can vary due to the spreading of rhizomes. It can occupy a small area or grow into great mats of ground cover. ‘Aki‘aki can also live for longer than 5 years and is also used in accent landscaping and for erosion control (Ellicott, 2009).

Methods

Overview

Sampling was performed in a total of five different ways, each with the goal of quantifying the dry weight of plant biomass, above and below ground. This variety of sampling methods reflects our aim to (1) make a preliminary assessment of complete individual Naupaka plants, and (2) measure above and below ground plant mass per unit area of both Naupaka and Aki’aki. The latter approach was chosen in order to generate data comparable to that reported by Charbonneau et al. 2016. While reporting data on a “per unit area” basis for Aki‘aki was a natural choice because Charbonneau et al 2016 also report data on dune grasses, it was unclear that this approach is well suited to Naupaka sampling. The main reason for concern is that the large size of Naupaka compared to dune grasses increased the difficulty of obtaining a representative sample with a coring tool, which samples a small cross-sectional area of 130 cm^3. For this reason, pit samples of modest size were collected in addition to ager cores and individual Naupaka plants (both wild and cultivated) were harvested in their entirety.

For in situ root mass sampling, it was imperative that we found a site in which sub-surface sampling would not cause ecological nor cultural damage to the environment. With permission from Makai Ranch LLC president, Jeremy Henderson, we collected samples along the coast of Marconi Point in Kahuku. We coordinated our sampling days with Site Manager, Ben Lessary and informed the North Shore Community Land Trust and US Fish and Wildlife of said plans. In addition to harvesting cultivated Naupaka plants, four different field-sampling methods were employed along a portion of this coastline. Two of these methods focused on Naupaka, and two concentrated on ʻAkiʻaki grass. Plants were collected two different times, one week apart (April 9 and 26, 2019). A location map can be found in Appendix A. Below I describe the various procedures that were used to sample Naupaka and ʻAkiʻaki grass with the intent to emulate the methods developed by Charbonneau et al. 2016.

Naupaka

Potted Plants

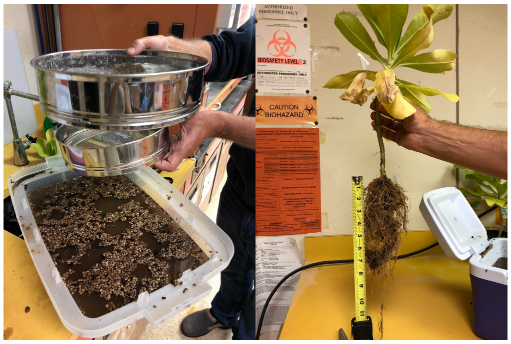

Figure 4. Processing the trial Naupaka in Greg Ravizza's lab. The second photo shows the full plant biomass after flushing dirt and vermiculite out of the roots.

We began by examining four juvenile potted Naupaka plants that were donated by botany professor Mike Ross of Kapiolani Community College. One plant was processed immediately as a trial methods forming exercise. The other three plants were repotted and irrigated for five months at Greg Ravizza's house before being processed. Root extraction for Potted Naupaka Plant 1 was performed over a lab sink. Rubber tubing was attached to the faucet to control water flow while separating dirt and vermiculite from the root mass. A series of coarse and fine sieves were used to catch broken roots. The entire procedure was done while the roots were wet. We quickly learned just how tedious and time consuming it was going to be to process all of the plants associated with this study. All processed and cleaned plant biomass for this project was transferred to a drying oven set to 60°C until a constant dry weight was achieved. Above and below ground dry weights were recorded separately.

Harvesting of the first potted Naupaka revealed that these individuals were root-bound. This observation motivated us to transfer the remaining three plants to large pots to determine if root mass would expand to fill the available space in the pots. Plant 2 was repotted in a 2400 cm^3 pot that contained only calcium carbonate sand. Plant 3 was repotted in a 9050 cm^3 pot that was a mix of carbonate sand and dirt while Plant 4 remained in its original pot that was then placed on top a larger pot, dominated by dirt and cinder. Estimated volume of Plant 4's growing environment is 3519 cm.^{3} The roots of this individual grew through its primary pot and into the dirt/cinder mix of the larger pot. Note that the root ball of each plant still contained dirt and vermiculite from their primary pots. Also, there was no specific methodology or reason for the plants to be repotted in these varying growing

Figure 5. Three of the juvenile potted Naupaka plants before they were repotted and irrigated.

Figure 6. The three repotted Naupaka after five months of being irrigated. This photo was taken just before being processed.

environments; it was simply what was available. Figures 5 and 6 show the before and after repotting conditions for these plants.

Figures 7 and 8. Sieves and a yard hose were used to rinse dirt from the roots.

Processing was done by replicating the trial procedure but on a larger scale. The plants were unpotted and a series of sieves were used under a yard hose to separate the dirt, sand, and vermiculite from the roots while trying to capture as much fine root mass as possible (Figures 7 and 8). Loose roots were collected and bagged with the rest of the root mass. The above ground portion (stalk and leaves) was severed from the below ground root system and each were transferred to a drying oven set to 60°C until a constant dry weight was achieved. I later found that it was easier to remove dirt and sand from the roots after they had air dried for a few days. However, initial wet sieving still proved necessary to quickly remove the bulk of the dirt.

It was found that sieving was not straight forward as fine roots could pass through the mesh in certain orientations. To correct for lost and broken roots from processing, subsamples of the total sieved volume (potting mixture from one plant/pot) were collected. The total volumes were added and multiplied by the weight of roots found in each subsample:

6 gallons total of sieved material from one plant’s pot

1 gallon of sieved material from total volume (subsample)

.8734 g of subsample roots

root loss = 5.2 g per 6 gallons of potting material

*root loss amounts to 6.3% of below ground root mass recovered from Plant 4 (82 g)

Naupaka Pit

Figure 9. Greg Ravizza stands in a mound of Naupaka where “Naupaka Pit” sampling took place.

Naupaka pit sampling took place at three different sites on Marconi Point. For each location, a five-gallon bucket with a 30.5 cm diameter (1 ft) was placed upside down on a mound of Naupaka (Figure 9) so that the above ground portion of the plant was inside of the bucket. Next, garden shears were used to clip the stalks around the circumference of the bucket. This step is important because it delineates where your sampling area begins and ends. After this, the bucket was lifted and any of the clipped plant material lying inside of the “circle” was collected and the remaining above ground plant matter was also cut at the ground surface level. Old, fallen Naupaka leaves and other dead plant material were also collected from the inside of the circle and bagged separately. At this point, all of the above ground plant biomass has been harvested and bagged. A shovel was then used to dig to a variable depth. The material, composed of sand, roots, dead plant

Figure 10. Field photo and schematic of Naupaka Pit sampling geometry.

matter, shells, coral and rocks, was recovered for later processing to isolate root mass, and the depth of the excavated pit was recorded. This material was later taken to the lab to be dumped out and air-dried for a few days before root material was sorted by hand and plastic tweezers. Next, a hand auger with a 6.35 cm diameter and 20.32 cm long barrel was used to core the bottom of the pit to extend the sampling depth deeper into the dune. Figure 10 shows a schematic of what this "pit" consists of. A minimum of two auger cores was recovered at each site in order to examine root mass in sequentially deeper intervals. Auger coring began at the bottom of the excavated volume (Cite figure here). This below ground material, bagged separately, was also taken to the lab to be processed at a later time. We found the amount of root-mass in the cored portions to be nominal, especially in the deeper cored interval within the same hole. Final dimensions of each pit can be found in Table 3.

Excavated Naupaka

Although it would be ideal to excavate an entire bush of Naupaka to achieve a more realistic root to shoot ratio and overall anatomy of the root system, it is not feasible without the use of damaging, heavy equipment. Instead, we applied this excavation idea on a smaller scale. Two excavations were performed. For the first one, I chose one stalk along the edge of some clustered Naupaka and followed its roots into the sand. I was able to dig out and collect the single root that this individual was attached to and assume minimal loss of root mass due to the simplicity of the sample's morphology (Figure 11).

Figure 11. Naupaka Excavation Plant Number 1, harvested on the first day of sampling.

The second excavation was of a small cluster of the Naupaka plant. As seen in Figure 12, the above ground portion covered a 72.12 x 50.80 cm area. The plant was carefully excavated by hand making an effort to trace larger roots as far from the center of the plant as possible. While digging, we were able to follow the roots as they branched out. However, you could periodically feel the root that you were following break in your hands. Most of the broken portions that were still below ground were not recoverable as they could not be located again. We noted that our furthest root from the center of the plant extended 40.64 cm laterally at a depth of 30.48 cm. We assume that the roots continued on as there was a branch point but we were unable to retrieve it after root breakage. The collected plant parts (Figure 13) were then snipped at the above/below ground interface before being bagged separately.

Figure 12 and 13 Naupaka Excavation, Plant Number 2. Harvested on the second day of sampling. A portion of the root system is not pictured in this photo as it was still being uncovered.

‘Aki‘aki Grass

‘Aki‘aki Pit

‘Aki‘aki grass was sampled two different ways in the field. The first method involved digging a pit and coring into the bottom to see how root concentration varies at depth (Figure 14). Sampling took place on the beach berm with 10 meter spacing in between each. The grass coverage was consistently

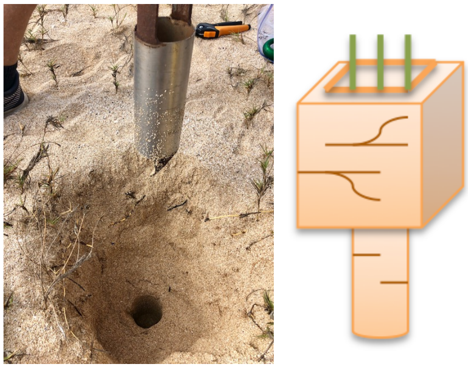

Figure 14. Field photo and schematic of ‘Aki‘aki Pit sampling geometry.

sparse throughout the berm area. To begin, a 20 x 20 cm square footprint (length of shovel blade) was made in the sand with the shovel blade (Figure 15). We opted for sampling a larger area pit rather than using only an auger core for two reasons. First the sand was poorly consolidated and was not consistently retained in the core barrel of the auger. Second, the sparse coverage of the Aki’aki on the shore face suggested that a larger area should be sampled to obtain a representative sample. Within this area, the above ground portion of the grass was then snipped at the sand surface (Figure 16). The rest of the steps are similar to what was done for the Naupaka Pits but for ‘Aki‘aki, a right rectangular prism was dug out rather than a cylinder (shovel lengths vs round bucket). After digging a certain depth with the shovel, the auger was used to remove two cores of sand. Final dimensions of each ‘Aki‘aki Pit can be found in Table 2. The beach and root material that was dug and cored out was processed immediately on location.

Figure 15. 20 x 20 cm sampling area footprint.

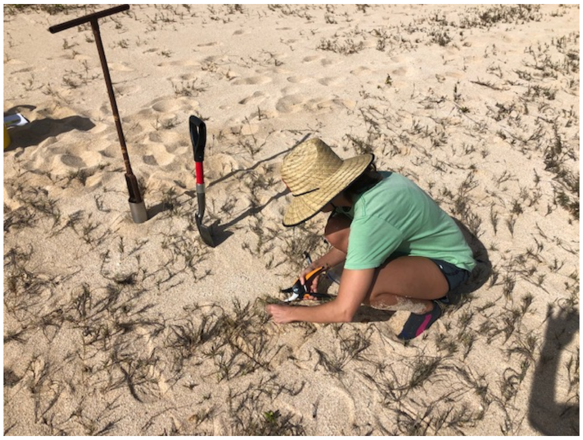

Figure 16 Snipping grass shoots within the 20 x 20 footprint.

Cored ʻAkiʻaki

The hand auger was also used to take samples of ʻAkiʻaki grass at three different locations along the back dune face (Figure 17). In this area, the grass grows much thicker and taller than it does on the beach berm. The grass shoots were first cut (Figure 18) and bagged before cores of below ground material were extracted. At the first location, two consecutive cores were sampled. At the second, a total of five cores were taken, and at the third, three cores were taken. The number of cores removed from each spot was directly related to the point of refusal. The substrate of the back dune environment was mostly fine dirt with some sand mixed in. It can be noted that all holes and pits were filled in with sand after sampling was concluded.

Figure 17. ʻAkiʻaki core samples were taken from the back dune environment where the grass grows thicker than it does on the beach.

Figure 18. Cutting ʻAkiʻaki shoots before using the hand auger to core into the ground.

Results

Results were normalized by scaling all dry biomass to mass per unit area, or g/m^2. These values are reasonable compared to each other and to results from Charbonneau et al. 2016; some results vary by a factor of two but there are no major outliers. Both Naupaka and ʻAkiʻaki grass exhibit root to shoot ratios similar to that of Charbonneau's *A. breviligulata* (AB), which was reported as 1.62:1. The root to shoot ratio for the Naupaka Pits ranged from 0.5 – 1.6 and the ratio range for Cored ‘Aki‘aki was 0.8 – 1.7. Our sampling methods show that both Naupaka and ‘Aki‘aki can be very variable depending on their growing conditions. In the field, coarse Naupaka roots generally found within 30 cm depth while course ‘Aki‘aki roots found within 10 cm below the sand surface. Excavated Naupaka Plant 1 had one single root that extended 177.8 cm laterally toward the ocean. For all field sampling methods, a minimal amount of roots (<1 g) or zero roots were found at the depth interval spanned by the second auger core, which extended down to 60 cm below the dune surface at the deepest sample hole.

Potted Naupaka results varied based on pot size and potting matrix (Figure 21). Root to shoot ratios range from 0.4 – 1.3 (n=4). These are not far from the field sampled Naupaka Pits, which had root to shoot ratios from 0.5 – 1.6 (n=3). Despite the similarity, Naupaka should not be identified with fixed ratios from these results due to the fact that it behaves so variably in different environments. Additional scaled dry biomass data for the potted Naupaka individuals can be found in Table 2.

Tables with raw data and scaled results for each sampling method can be found in the Appendix B: Tables. Raw above vs below ground biomass charts for all 5 sampling methods can be found in Appendix C. Supplemental Figures 8-10 show dried versions of shoots and roots of one sample for each field sampling method.

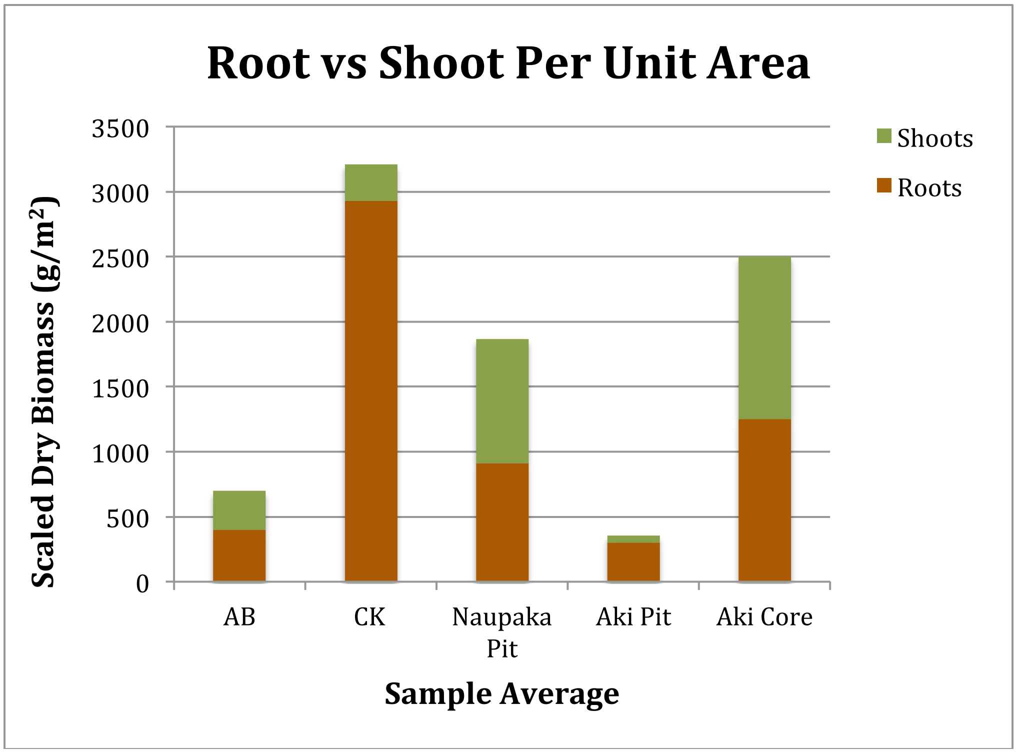

Figure 19. Results from our three field sampling methods compared to results from Charbonneau et al. 2016 results. Note Naupaka Pits, ʻAkiʻaki Pits, and ʻAkiʻaki cores data represent aggregate of three individual samples each

Discussion

Field vs. Potted Naupaka

There were distinct differences between Naupaka collected in the field and the potted Naupaka. First, root to shoot ratio shows a much greater range in variation among the potted Naupaka (range: 1.3 – 1.4; n=4) relative to the 3 pit samples collected in the field (range: 1.6 – 0.5; n=3). Second, the root morphologies of wild and potted were distinct. Naupaka harvested from the field had fewer fine roots than the potted individuals. This can be easily recognized in supplemental figures by comparing SF 6 to the middle image of SF 8. Furthermore, among the field samples which aimed to harvest entire wild plants, coarse roots extended laterally rather than penetrating directly below the stem of the plant, and, like the Naupaka pit samples, fine roots were rare compared to the Naupaka harvested from pots; potted

Naupaka had a semi even mix of fine and coarse roots. In contrast to large areal extent of course roots in of the wild Naupaka, potted Naupaka grew roots into its entire accessible space, likely due to constant availability of freshwater (SF 1 of Potted Plant 3 is a good example of this root growth), the presence of nutrients in the potting soil, and the available volume for growth defined by the pot. Thus, it is likely the observed differences in root morphology are a consequence of environmental factors. Therefore, we classified Naupaka as behaving plastically in the sense that there is no fixed root to shoot ratio as the conditions it grown in have a major implications of geometry and amount of below ground root mass. These results suggest that the root structure of Naupaka that are planted and maintained by property owners will have significantly different root structure than Naupaka growing in a dune environment. Specifically, wild dune Naupaka are expected to display a shallow root network with a large areal extent in order to access scarce freshwater and nutrients, while irrigated/cultivated Naupaka are expected to display a much denser and deeper root network analogous to the potted Naupaka studied here.

‘Aki‘aki Pits vs. ‘Aki‘aki Cores

‘Aki‘aki that was sampled from the lower shore face exhibited a root to shoot ratio range of 5 – 8 (n=3) while the ratio for the back dune cored ‘Aki‘aki was 0.8 – 1.7 (n=3). Supplemental Figures 9 and 10 show the visual differences between the roots and shoots for each of these sampling methods. Roots within ‘Aki‘aki Pits contained much more fine root matter than the ‘Aki‘aki cores did.

Potential Artifacts and Refinements of Methods

It seems improbable that coarse and fine root mass offer the same degree of resistance to erosion. Future work might consider analyzing these root sizes separately. A characterization could be made, for example, stating that all roots with a 2 mm diameter or less are deemed as “fine,” making anything larger than that “coarse.”

While sampling at Marconi Point, there were times where it was questionable whether or not the biomass we were collecting was actually from the species of interest. Some of the Naupaka mounds where we deployed the Naupaka Pit sampling technique had ‘Aki‘aki growing within the Naupaka shoots. Overall, it was easy to distinguish between the two species’ living roots but some of the dead plant matter was difficult to differentiate. This could be due to the dune environment being dynamic in nature. Sand can bury plants and other loose debris when moved by wind and waves. The substrate can then become mixed, challenging the effectiveness of the methods we used when aiming to distinguish new and actively growing plants. An attempt should be made to establish background values for dead or dissimilar plant material within the above and below ground realms.

Temporal evolution of plant communities could contribute to variable root:shoot ratio. For example, the back dune ‘Aki‘aki grass and the beach face grass had very different root to shoot ratios. However, it is unclear why this is. One hypothesis could be that shoots experience more stress than roots on the shore face and a higher root to shoot is characteristic of this environment. Or, it could be that when this grass colonizes a new area, roots grow outward at first and then later grow into a dense mat with concentrated and thriving shoots. Charbonneau et al. implicitly assumed that all core sites were equivalent. The small uncertainty she gives for above and below ground biomass indicated that the grass setting in which she sampled in were all very similar. This could give a false impression that a given plant species always exhibits a fixed root to shoot ratio.

Lastly, the approach may need to be modified to fit specific species, similar to how we utilized the Naupaka excavation and Naupaka Pit techniques since Naupaka is a shrub and cannot be cored into as easily as grasses can. Future work can also pursue further understanding between above and below ground plant matter and how it can offer defense against erosion by measuring the tensile strength of sand grains, roots, and shoots. This data could then be applied to power of wind and wave energy.

Conclusion

We conclude that under ground root mass is a qualitative metric when comparing one grass to another, within the same species, for example, but should not be used as a general metric across multiple plants types (‘Aki‘aki vs Naupaka). Although in an attempt to mitigate erosion, planting mixed assemblages of plant species may provide the best stabilization and protection (Ghestem et al. 2014). It was found that neither of our two plant species has extensive under ground root mass like CK (*Carex kobomugi*), the invasive Asiatic sand sedge from New Jersey coastal dunes. Also, sampling a fixed area seems prone to bias even after normalizing the results. While we did not develop a clear connection between below ground root mass and its effects on erosion, we offer insight to how variable this relationship could potentially be and propose improvements to sampling methods for future research.

While dense vegetation can aid in mitigating or even preventing erosion, it does so at the expense of losing beach area, which defeats the purpose of beach preservation. Additionally, it must be noted that vegetation alone cannot protect coastal areas from the impacts of sea-level rise. The great underlying problem is of social origin. Given that approximately 10% of the global population resides in coastal areas that are less than 10 meters above sea level, initiatives must be taken to adapt to changing coastlines (Zhu, 2017). Although vegetation may provide temporary dampening to the rate of coastal erosion in certain areas, what society chooses to do with the time gained is yet to be seen. Realistically, coastal homes and other structures will be forced to respond to the encroaching sea by moving further inland or building more resiliently.

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References

Addo-Danso, Shalom D., et al. "Methods for estimating root biomass and production in forest and woodland ecosystem carbon studies: A review." *Forest Ecology and Management*, vol. 359, 9 Sept. 2015, pp. 332-51. Accessed 13 Oct. 2018.

Charbonneau, B.R., 2015. A Review of Dunes in Today's Society. *Coastal Management*, *43*(5), pp.465-470.

Charbonneau, B.R., Wnek, J.P., Langley, J.A., Lee, G. and Balsamo, R.A., 2016. Above vs. belowground plant biomass along a barrier island: Implications for dune stabilization. *Journal of environmental management*, *182*, pp.126-133.

Ellicott, Daniela D. *Native Plants Hawaii*, edited by Shari Y. Tamashiro and David Eickhoff, University of Hawaii, 2009, nativeplants.hawaii.edu/general/.

Feagin, R.A., Figlus, J., Zinnert, J.C., Sigren, J., Martínez, M.L., Silva, R., Smith, W.K., Cox, D., Young, D.R. and Carter, G., 2015. Going with the flow or against the grain? The promise of vegetation for protecting beaches, dunes, and barrier islands from erosion. *Frontiers in Ecology and the Environment*, *13*(4), pp.203-210.

Fletcher, C.H. et al. 2010. Hawaii Coastal Erosion Website: Oahu Shoreline Study Erosion Maps. http://www.soest.hawaii.edu/coasts/erosion/oahu/

Ghestem, Murielle., et al. "The Influence of Plant Root Systems on Subsurface Flow: Implications for Slope Stability." *BioScience*, vol. 61, no. 11, Nov. 2011, pp. 869-79, doi:10.1525/bio.2011.61.11.6. Accessed 25 Oct. 2018.

Ghestem M, Cao K, Ma W, Rowe N, Leclerc R, et al. (2014) A Framework for Identifying Plant Species to Be Used as ‘Ecological Engineers’ for Fixing Soil on Unstable Slopes. PLoS ONE 9(8): e95876. doi:10.1371/journal.pone.0095876

Guo, Li., et al. "Application of ground penetrating radar for coarse root detection and quantification: a review." *Plant Soil*, vol. 362, 5 Oct. 2012, pp. 1-23, doi:10.1007/s11104-012-1455-5. Accessed 24 Oct. 2018.

Losada, I.J., et al. 2014: Coastal systems and low-lying areas. In: Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 361-409.

Office of Conservation and Coastal Lands, Department of Land and Natural Resources, 2019, dlnr.hawaii.gov/occl/.

Salgado, Karla, and M. Luisa Martinez. "Is ecosystem-based coastal defense a realistic alternative? Exploring the evidence." *Journal of Coastal Conservation*, vol. 21, 16 Aug. 2017, pp. 837-48, doi:10.1007/s11852-017-0545-1.

SOEST Coastal Geology Group, University of Hawaii at Manoa, 19 Mar. 2013, www.soest.hawaii.edu/coasts/publications/hawaiiCoastline/oahu.html.

Zhu, Juwang. *The Ocean Conference*, United Nations, 2017, oceanconference.un.org/.

Appendices

Appendix A: Field Site Map

Figure 20. Location/field map of sampling area at Marconi Point in Kahuku, Oahu. All sampling points are within 80 m along the coast.
Purple Circles: Naupaka Pits 1-3
Green Diamonds: Excavated Naupaka 1-2
Red Circles: ʻAkiʻaki Pits 1-3
White Squares: ʻAkiʻaki Cores 1-3

Appendix B: Tables

Table 1. Raw and Scaled data from 4 Potted Naupaka samples

Potted Naupaka	Sample	Area (cm^2)	Dry Plant Biomass (g)	Volume (cm^3)	g/m^2	g/m^3	Root:Shoot
Above	1	38	15	N/A	3947	N/A	0.5
	2	88	11		1250		1.3
	3	145	145		10000		0.6
	4	48	119		24792		0.4
Below	1	38	7	3016	1842	2321	
	2	88	14	2400	1591	5833	
	3	145	82	9050	5655	9061	
	4	48	42	3519	8750	11935	

Table 2. Scaled and averaged data from Potted Naupaka Individuals

Potted Naupaka	Dry Biomass Range (g)	Scaled Dry Biomass (g/m^2)
Total Plant	22-227	14457
Shoot	11-145	9997
Root	7-82	4460

*data represent aggregate of 4 samples

Table 3. Raw and scaled data from 3 Naupaka Pit samples

Naupaka Pits	Sample	Area (cm^2)	Dry Plant Biomass (g)	Depth (cm)	Volume (cm^3)	g/m^2	g/m^3	Root:Shoot Ratio
Above Ground	1	730	95	Above Ground	N/A	1301	N/A	0.7
	2	730	51			699		0.5
	3	730	63			863		1.6
Pit	1	730	58	0-20	14600	795	3973	
	2	730	18	0-24	17520	247	1027	
	3	730	102	0-19	13870	1397	7354	
Core	1	40	0.6821	20-60	1600	171	426	
	2	40	0.5152	24-60	1440	129	358	
	3	40	0	19-65	1840	0	0	

Table 4. Raw and scaled data from 3 ‘Aki‘aki Pit samples

‘Aki'aki Pits	Sample	Area (cm^2)	Dry Plant Biomass (g)	Depth (cm)	Volume (cm^3)	g/m^2	g/m^3	Root:Shoot Ratio
Above Ground	1	730	2	Above Ground	N/A	27	N/A	8
	2	730	5			68		5
	3	730	5			68		5
Pit	1	730	5	0-23	16790	68	298	
	2	730	11	0-29	21170	151	520	
	3	730	8	0-25	18250	110	438	
Core	1	40	0.6034	23-66	1720	151	351	
	2	40	0.8706	29-65	1440	218	605	
	3	40	0.8010	25-63	1520	200	527	

Table 5. Raw and scaled data from 3 ‘Aki‘aki Core samples

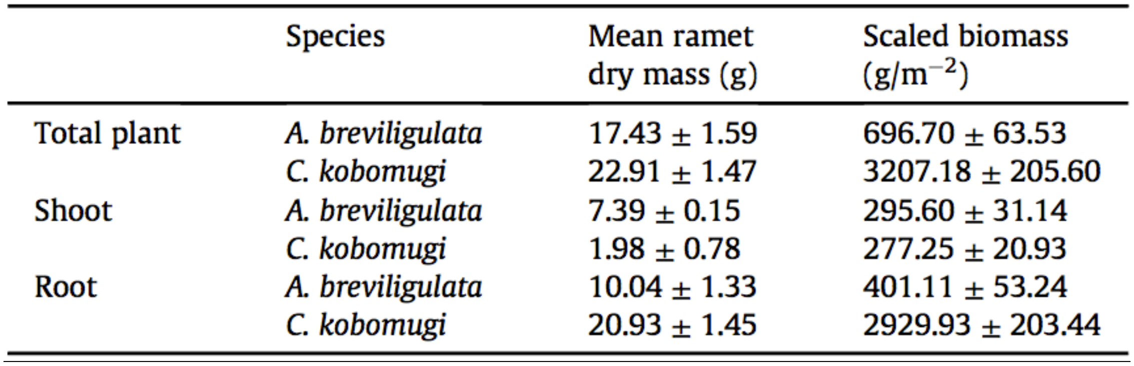
‘Aki'aki Cores	Sample	Area (cm^2)	Dry Plant Biomass (g)	Depth (cm)	Volume (cm^3)	g/m^2	g/m^3	Root:Shoot Ratio
Above Ground	1	40	4	Above Ground	N/A	1000	N/A	1.0
	2	40	8			2000		0.8
	3	40	3			750		1.7
Core	1	40	4	0-30	1200	1000	3333	
	2	40	6	0-38	1520	1500	3947	
	3	40	5	0-38	1520	1250	3289	

Table 6. Scaled and averaged data from each field sampling method

	Sample	Dry Biomass Range (g)	Scaled Dry Biomass (g/m^2)
Total Plant	Naupaka Pits	2266-1074	1867
	Aki'aki Pits	437-247	354
	Aki'aki Cores	3500-2000	2500
Shoot	Naupaka Pits	1301-699	954
	Aki'aki Pits	68-27	55
	Aki'aki Cores	2000-750	1250
Root	Naupaka Pits	1397-375	913
	Aki'aki Pits	368-219	299
	Aki'aki Cores	1500-1000	1250

*Naupaka Pits, ‘Aki‘aki Pits, ‘Aki‘aki cores data represent aggregate of three individual samples each

Table 7. Scaled and averaged data from Charbonneau et al. 2016 study



	Species	Mean ramet dry mass (g)	Scaled biomass (g/m^{-2})
Total plant	*A. breviligulata*	17.43 ± 1.59	696.70 ± 63.53
	C. kobomugi	22.91 ± 1.47	3207.18 ± 205.60
Shoot	*A. breviligulata*	7.39 ± 0.15	295.60 ± 31.14
	C. kobomugi	1.98 ± 0.78	277.25 ± 20.93
Root	*A. breviligulata*	10.04 ± 1.33	401.11 ± 53.24
	C. kobomugi	20.93 ± 1.45	2929.93 ± 203.44

Appendix C: Root and Shoot Data for Each Sampling Method

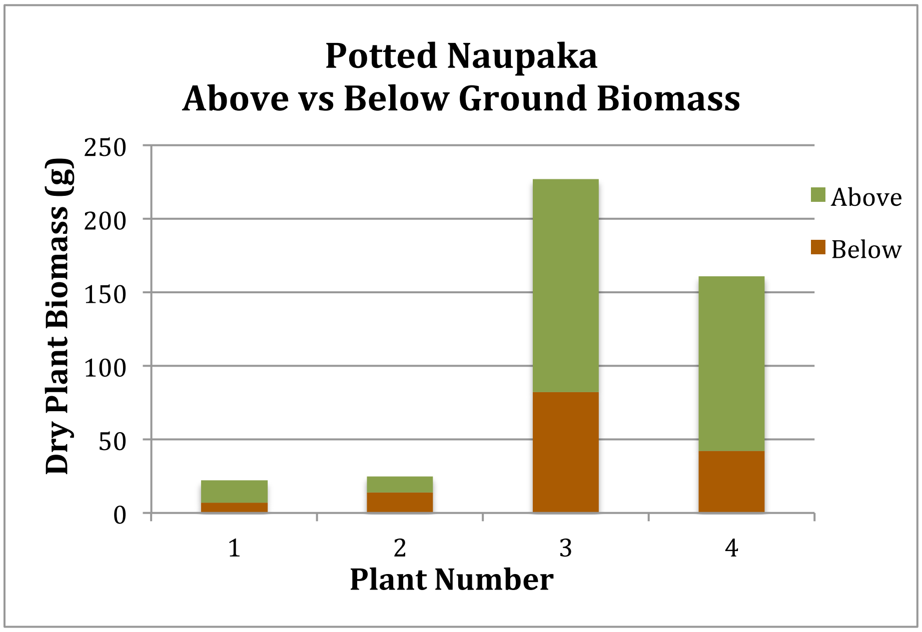


Figure 21. Potted Naupaka Above vs Below Ground Biomass

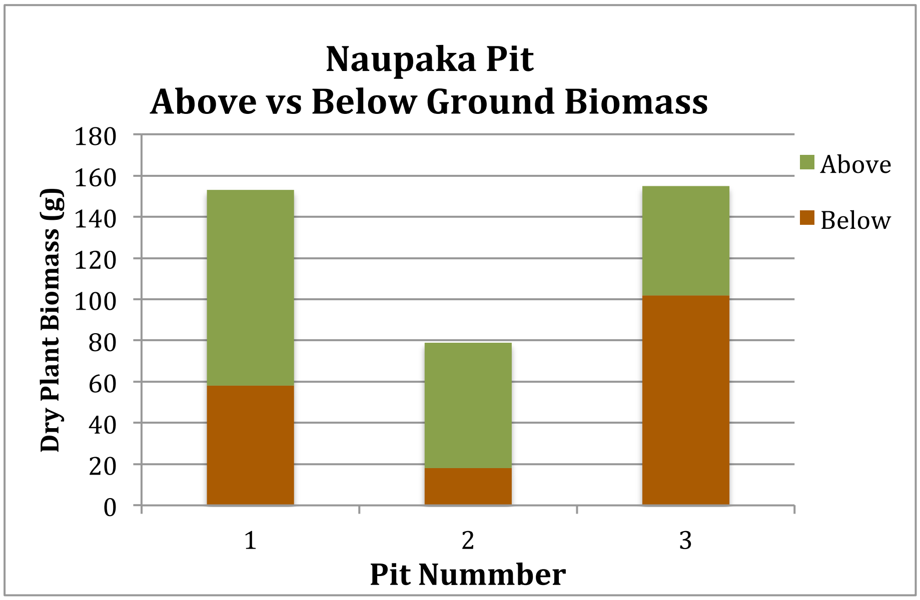


Figure 22. Naupaka Pit Above vs Below Ground Biomass

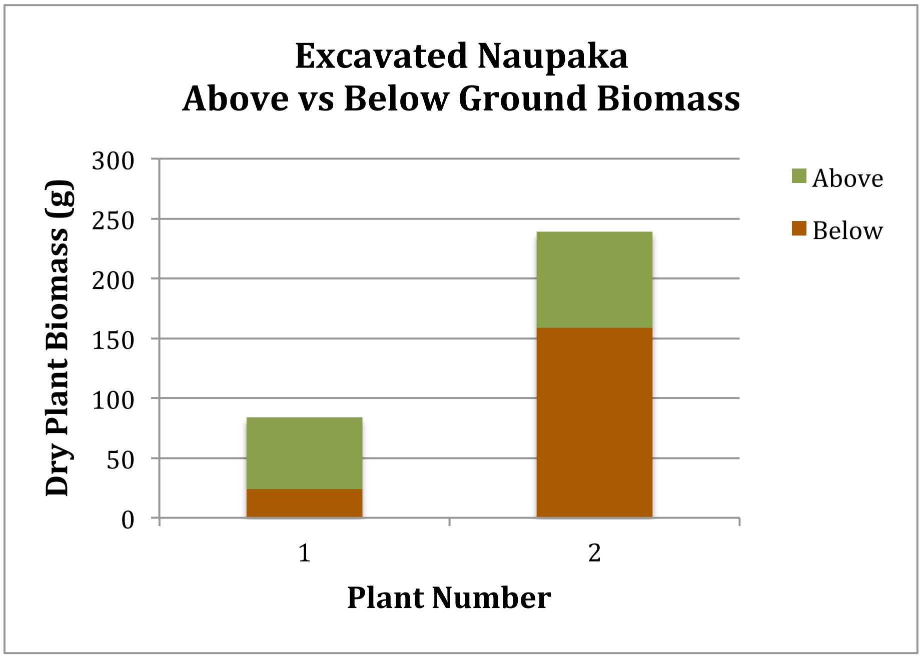


Figure 23. Excavated Naupaka Above vs Below Ground Biomass

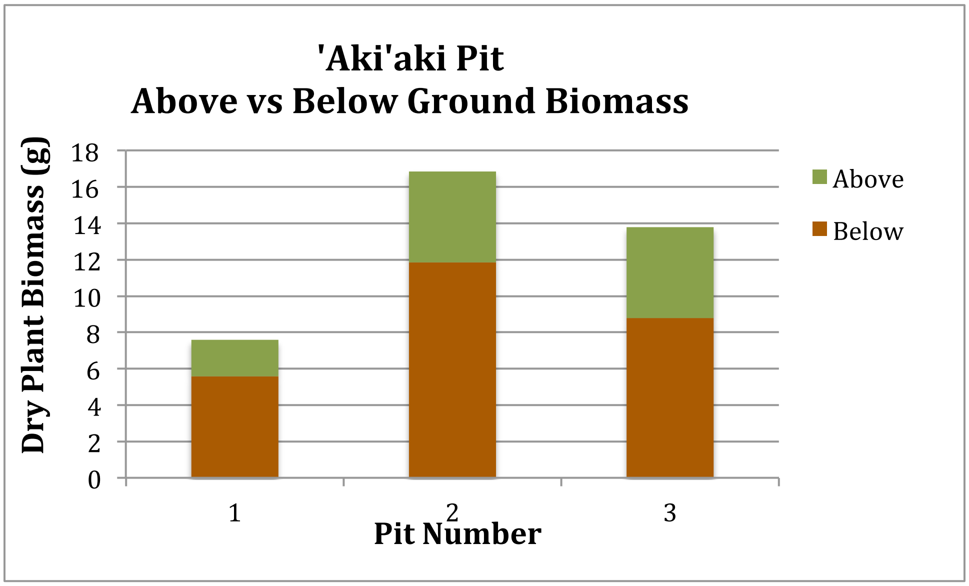


Figure 24. ‘Aki‘aki Pit Above vs Below Ground Biomass

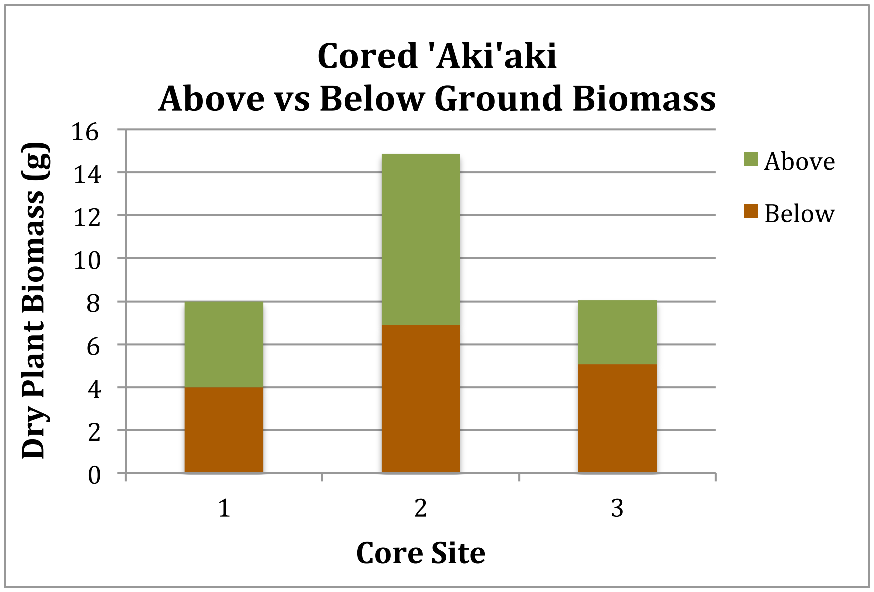
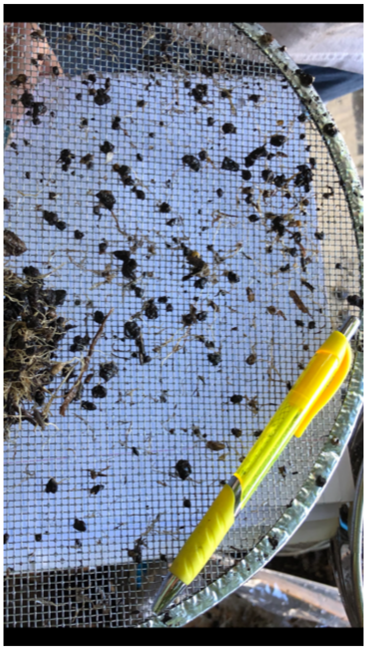


Figure 25. Cored ‘Aki‘aki Above vs Below Ground Biomass

Appendix D: Supplemental Figures (SF)

SF 1 and 2. Extensive roots of Potted Naupaka 3. Also shows shoot growth after 5 months of irrigation compared to Figure 5.

SF 3 and 4. Roots surpassing primart pot of Potted Naupaka 4. Also shows shoot growth after 5 months of irrigation compared to Figure 5.



SF 5. Fine Naupaka roots able to pass through sieve at correct orientation.

SF 6. Roots of Potted Naupaka 2, 3, and 4, respectively. Note dense and extensive roots of Naupaka 3.

SF 7. Very fine, hair-like roots seen while processing roots in ʻAkiʻaki Pit. It is possible that some of these were missed in the damp, coarse sand.

SF 8. Dried versions of shoots and roots of one Naupaka Pit sample. Very few roots were found in the cored section.

SF 9. Dried version of shoots and roots of one ‘Aki‘aki Pits ample. The grass shoots are much shorter and more sparse compared with Cored ‘Aki‘aki shoots.

SF 10. Dried version of shoots and roots of one Cored ‘Aki‘aki sample. Shoots grow more dense in the back dune environment.