Final Report

Deflecting the Wave: Using Coastal Vegetation to Mitigate Tsunami and Storm Surge

By

Dr. Andrew Kaufman, Dr. Timothy Gallaher, and Dr. Alberto H. Ricordi

Tropical Landscape and Human Interaction Lab
Department of Tropical Plant and Soil Sciences
College of Tropical Agriculture and Human Resources
University of Hawaiʻi at Mānoa

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Andy Kaufman[1]
Timothy Gallaher[2]
Alberto Henrique Ricordi[3]

[1]Tropical Landscape and Human Interaction Lab,
Department of Tropical Plant and Soil Sciences
University of Hawaii at Manoa, 3190 Maile Way, Honolulu, HI 96822
kaufmana@hawaii.edu

[2]Botany Department University of Hawaii at Manoa
gallahert@ctahr.hawaii.edu

[3]School of Architecture,
University of Hawaii at Manoa
albertoh@hawaii.edu

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CONTACT
For inquiries please send an email to: kaufmana@hawaii.edu

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Executive Summary

Tsunami and storm surge due to tropical cyclones regularly affect the coasts of Hawaii and other Pacific Islands, in many cases causing severe property damage, injuries, and deaths. Following the Indian Ocean tsunami of December 26, 2004, the anecdotal accounts of survivors and the observations of researchers pointed to a potential role of coastal vegetation in mitigating damage and in some cases reducing the death toll due to a tsunami. This deliberate use of vegetation as a buffer against ocean waves has been termed bio-shields, shelterbelts, and green/living sea walls.

The goals of the research described in this report was to focus on Hawaii and other Pacific islands to: (1) conduct research on the type of vegetation that has survived past tsunami and storm surge events, (2) gather information on vegetation that grows near the shore in Hawaii given different environmental factors; (3) examine whether past or existing vegetation has had an effect on mitigating beach erosion due to wave impact; and, (4) establishment of experimental coastal reforestation plots for evaluation of coastal re-vegetation planting strategies.

The investigation began with a search for historical documents that might shed light on the interactions between tsunami waves or storm surge and coastal vegetation in Hawaii and the Pacific however; little research on this topic has been published along with little more than anecdotal accounts.

On September 29, 2009 a tsunami inundated the southern coast of Upolu Samoa killing over 140 people and causing extensive property damage. In January 2010, a team for the Tropical Landscape and Human Interaction Lab at the University of Hawaii sent a team to make observations in Upolu to search for interactions between the tsunami and coastal vegetation. Also conducted, was vegetation surveys on the Islands of Oahu, Hawaii and Kauai to characterize existing coastal vegetation patterns.

The observations in Samoa lend support to the hypotheses that coastal vegetation mitigates the effects of a tsunami through several mechanisms: Coastal vegetation forms a physical barrier to an incoming wave which may result in reduced damage to structures and reduced erosion. Additionally, coastal vegetation builds elevation at the coast by trapping organic matter and sand, and coastal vegetation provides a vertical escape for people trapped in the wave. Finally, coastal vegetation acts as a filter which holds back coral, ships and debris, carried by the wave from being moved inland where it can be destructive to people and property and from being carried out to sea and onto sensitive reefs.

Conversely, the coastal forests in Hawaii are reduced in species diversity, complexity and stem density relative to their Samoan counterparts. This will seriously impact the ability of these forests to provide an effective barrier for tsunami or storm surge waves. In addition, many coastal areas in Hawaii have been completely deforested in favor of park-like landscapes and direct development at the coast. Hawaii‟s coastal forests are dominated by a few widespread invasive species including *Prosopis pallida* (Mesquite), *Rhizophora mangle* (American Red Mangrove) *Terminalia catappa* (Tropical Almond), *Casuarina equisetifolia* (Ironwood). *Prosopis pallida* was introduced to Hawaii in 1827 and has naturalized largely due to the action of cattle and feral animals. The mangrove, *R. mangle* is widely established on Oahu in coastal areas that are well protected from high energy waves. *Terminalia catappa* and *C. equisetifolia* were planted in the early part of the 20th century to reforest coastal areas. All three dominant coastal species form largely monotypic stands and disperse through floating propagules. Native species are not completely absent from Hawaii‟s coastal areas. Several of the transects encountered native coastal forest including forests of *Pandanus tectorius* (hala), often mixed with *Metrosideros polymorpha* („ohia lehua), and forests where *Thespesia populnea* (milo) is dominant. Little work has been done on identifying best practices of native coastal reforestation in Hawaii or the Pacific. The combined observations from Samoa and Hawaii form the basis for specific recommendations as to how such bio-shields could be most effectively designed and implemented in Hawaii and other Pacific Islands however additional research is urgently needed.

The third phase was to develop a method for restoration of native coastal vegetation using primarily native Hawaiian species and evaluate the method effectiveness, and its effects on wave power and erosion. The effects of vegetation on wave power has been observed by post-event surveys after the tsunami in Samoa and through visual documentation of storm water runoff at Bellows Air Force Station (BAFS) in Waimanalo, Hawaii. Beach erosion as much as two feet per year has been documented at BAFS, which is mostly attributed to hardened shorelines, but it is also associated with invasive species such as Casuarina equisitifolia which inhibits growth of native shrubs and ground covers. This research project tested a planting method for establishment of native plants after removal of C. equisitifolia, and verified the effectiveness of temporary windscreens for protection against wind and salt spray. Temporary windscreens proved beneficial to speed-up the establishment of the plants, especially in the foredune zone (ocean side). However, the windscreens were knocked down by a storm event three months after planting and there was no visual difference between the plots with or without windscreens one year after planting. Therefore, the use of windscreens may not be necessary and cost effective since it only has short term benefits and results in extra cost and potential debris in the beach if the wind screens and its supports are not completely removed, which also adds cost. A modular irrigation system was designed for easy removal and reassembly, so it can be re-used in additional restoration areas. The irrigation was gradually reduced and totally removed eight months after planting. Data revealed irrigation lines on the windward side of the plots were buried up to 6 ¼" (six and a quarter inches), and sand accretion was visually evident in the perimeter of the plots. Additionally, very clear plant zones corresponding to the beach berm, foredune, dune crest, and backdune zones were present. Sporobolus virginicus (ʻakiʻaki grass) and the beach morning glory vine Ipomea pes-caprae subsp. brasiliensis (pohuehue) were very successful to cover the ground throughout all zones, with I. pes-caprae growing up to fourteen feet beyond the irrigated areas. This report includes the detailed irrigation system used in this project, visual photographs with a timeline of the planting establishment, ground coverage and dry matter data collected one year after planting, and recommendations of native plants and their planting zones for coastal planting and landscaping in Hawaii.

Introduction –Tsunamis, Storm surge and Coastal Vegetation

Tsunami and storm surge due to tropical cyclones regularly affect the coasts of Hawaii and other Pacific Islands, in many cases causing severe property damage, injuries, and deaths. Following the Indian Ocean tsunami of December 26, 2004, the anecdotal accounts of survivors and the observations of researchers pointed to a potential role of coastal vegetation in mitigating damage and in some cases reducing the death toll due to a tsunami. This deliberate use of vegetation as a buffer against ocean waves has been termed coastal bio-shields, shelterbelts, and green/living sea walls.

Tsunami and storm surge due to tropical cyclones regularly affect the coasts of Hawaii and other Pacific Islands, in many cases causing severe property damage, injuries, and deaths. Hawaii has experienced destructive tsunami quite regularly with recent events in 1952, 1960, 1975, and 2011. Recent destructive tropical cyclones in Hawaii include Hurricanes Iniki (1992), Iwa (1982), Dot (1959), and Nina (1957) (Committee on Natural Disasters 1983, Chiu et al. 1995).

The goals of the research described in this report was to focus on Hawaii and other Pacific Islands to: (1) conduct research on the type of vegetation that has survived past tsunami and storm surge events, (2) gather information on vegetation that grows near the shore in Hawaii given different environmental factors and (3) examine whether past or existing vegetation has had an effect on mitigating beach erosion due to wave impact. The first phase of this investigation began with a search for historical documents that might shed light on the interactions between tsunami waves or storm surge and coastal vegetation in Hawaii and the Pacific however; little research on this topic has been published along with little more than anecdotal accounts.

On February 27, 2010 a tsunami in the Pacific Ocean was triggered by an 8.8 magnitude earthquake off the coast of Chile. This prompted officials of the Pacific Tsunami Warning Center to issue a Pacific-wide tsunami warning. In Hawaii, an orderly evacuation of coastal areas followed and much of the state waited and watched as the tsunami raced across the Pacific. Although the tsunami had a devastating impact on coastal areas in Chile, little effect was felt elsewhere in the Pacific. Had a destructive wave reached Hawaii's shores, the evacuation prompted by the early warning system would clearly have been responsible for saving lives.

Tsunamis are regular natural disasters in the Pacific. Pacific Islands have experienced destructive tsunami throughout history with recent events in 1952, 1957, 1960, 1975, and 2009 (NOAA 2011).The most significant natural disaster in terms of loss of human life in Hawaii continues to be the April, 1946 tsunami which cost 159 lives and $150 million (adjusted to 1982 dollars) in Hawaii and took additional lives across the Pacific. On September 29, 2009, a tsunami generated near Tonga inundated areas of Tonga, American Samoa and Independent Samoa. Due to the close proximity of the source event to these islands, there was little time for warning or evacuation and the tsunami claimed over 150 lives and caused extensive property damage.

While an early warning system along with an educated public is the centerpiece of an effective tsunami/storm surge mitigation strategy, early warning systems can fail and if a tsunami is generated locally, there may not be sufficient time for an effective alert or evacuation. In such cases, and particularly when early warning systems and education of the public are already well established, additional defensive measures can be taken that may protect people and property. Sea walls are one type of defensive measure that has been successfully employed. Sea walls however are expensive to construct and maintain, are not suitable for all coastal types, and they have in some cases been associated with accelerated sand loss from beaches (Pilkey and Wright III 1988, Kraus and McDougal 1996, Defeo et al. 2009, DLNR 2010, Fletcher et al. 2012). For these reasons, seawalls are often restricted to highly populated areas with suitable coastal geomorphology. Another type of defensive strategy employs coastal vegetation as a barrier to ocean waves. The use of vegetation as a buffer against ocean waves has been termed coastal bio-shields, shelterbelts, and green/living sea walls. Throughout this report the term "bio-shields" will be used due to the greater level of usage of this term in the scientific and popular literature.

Tsunami terminology and interaction with coastal vegetation

On December 26, 2004 a 9.3 magnitude earthquake occurred 100 km west of Sumatra. This earthquake generated a tsunami which was detectable in all ocean basins around the world (Titov et al. 2005).The immediate death toll from the tsunami was over 350,000. Over 5 million people were displaced and the cost of recovery efforts was estimated to be over eight billion US dollars (Athukorala and Resosudarmo 2005). In the aftermath of the tsunami, several anecdotal reports emerged that coastal vegetation, particularly mangroves, had mitigated loss of life and property (Padma 2004, Kremmer 2005).Although there had been some research on the interactions between coastal vegetation and tsunami waves prior to the 2004 Indian Ocean tsunami (see Hiraishi and Harada 2003; and for a summary of other early studies see Tanaka et al. 2009), the 2004 event produced renewed interest and provided a number of potential study sites to investigate these interactions.

In order to understand the existing research it is important to first be familiar with standard tsunami terms. The **inundation distance** is the distance from the shoreline to the inland limit of tsunami inundation. **Run-up elevation** is the elevation above sea level of a tsunami at the limit of penetration. **Tsunami height** is the height above ground level of a tsunami wave in a given point up to the limit of tsunami inundation (the tsunami height is 0 at the limit of tsunami inundation) and the Run-up elevation is the estimated elevation above sea level at the limit of tsunami inundation (USGS 2005). In this report, also defined is an **inundation point** as a geographic reference point (recorded with a GPS and/or displayed on a map) which is the best estimate of the limit of tsunami inundation based on, field reconnaissance or remotely sensed data and an **inundation line** as the straight-line interpolated connection of multiple assessed inundation points.

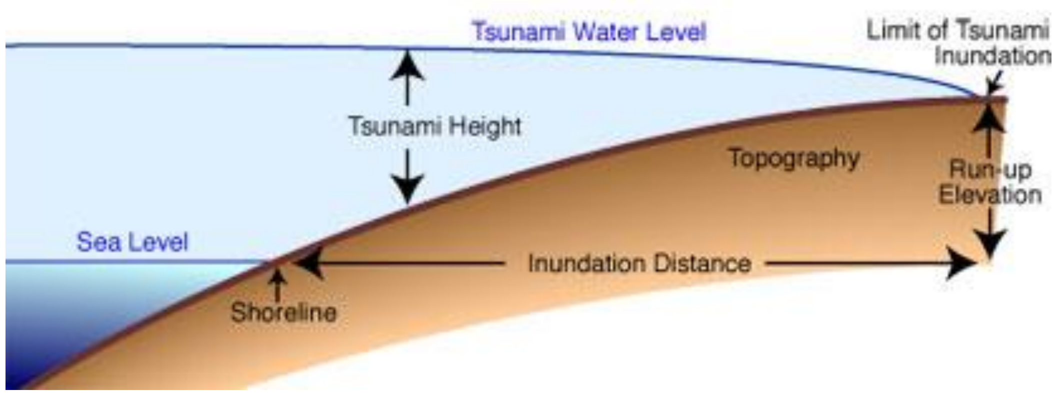


Figure 1. Terminology related to tsunami measurements. (USGS 2005)
(http://walrus.wr.usgs.gov/tsunami/srilanka05/images/run_up_height_inundation.jpg)

Many studies have attempted to correlate various measures of vegetation fronting developed areas with measures of the inundation such as run-up elevation, inundation distance, some measure of damage, or levels of human casualties. Each of these measures is open to reasonable criticism. For example, damage to structures should take into consideration variation in construction type (Dahdouh-Guebas and Koedam 2006) and orientation to the oncoming wave (Dall’osso and Dominey-Howes 2009). Death toll measures must take into account pre-event human population density, and site specific human activity patterns. Vegetation densities can be estimated or measured in a wide variety of ways that can influence the conclusions (Bhalla 2007, Kaplan et al. 2009). Finally, all studies should specifically take into account those factors that are known to be associated with inundation effects such as near shore bathymetry, elevation, and distance from shore. Studies have taken on a number of different methodologies including analysis based on, remotely sensed (satellite) data with GIS modeling, wave tank simulations, mathematical modeling and on the ground field studies of vegetation and direct observations of wave-induced damage.

In one of the earliest studies, Danielson et al. (2005) used pre-tsunami (May 4, 2003) satellite imagery of Cuddalore District, Tamil Nadu, India to classify coastal vegetation into three classes: dense tree vegetation, open tree vegetation, and no trees vegetation. They used post-tsunami (December 31, 2004) satellite imagery to assess damage into four categories, damaged, partially damaged, undamaged, and inundated but not damaged. Preliminary statistical tests indicated that, "dense tree vegetation was associated with undamaged areas and disassociated with damaged areas". Dahdouh-Guebas and Koedam (2006) pointed out that the preliminary analysis by Danielsen et al. does not take into consideration variation in construction type in determining damage classes for buildings, also they point out that results are presented without considering distance from the shore to villages. They suggest that future studies should compare villages that are at similar distance from shore and differ only in the level of protection conferred by coastal vegetation. Danielsen et al. (2006) responded that house construction was homogenous in the area.

In a follow up study of the same area investigated by Danielson et al. (2005), Olwig et al. (2007) inspected pre and post tsunami satellite imagery and made a map of areas with dense woody vegetation and open woody vegetation. In defining their site selection methodology, the authors identified a number of factors which should ideally be held constant to address in isolation the effect of coastal forest on tsunami inundation (run-up or damage). These include the presence of both vegetated and non-vegetated coastline, homogenous bathymetry and homogenous topography. A fourth criterion, substantial damage reports in the area, has been criticized since it may serve to bias the results against areas where coastal vegetation provided significant protective effects. The authors measured widths of (1) dense and (2) open vegetation along a GIS transect and areas with (3) no woody vegetation with widths of damage behind the vegetation. Damage was classified into four categories: severely damaged, (most of the physical structures destroyed; partially damaged (some damage but most physical structures intact), undamaged, and inundated (areas undamaged but inundated) following the criteria of Danielsen et al. (2005). One hundred transects separated by 200m were laid out over the area following the same direction as the incoming tsunami wave. The authors have not yet published the statistical analysis of the data although based on visual inspection of the map, however based on visual inspection of the map, they concluded that dense vegetation had much less damage behind it than open vegetation in most cases with outliers of this trend possibly occurring as the result of edge effects where neighboring gaps allowed the tsunami wave to run farther inland.

Another study from the same area specifically looked at human mortality, and a socioeconomic indicator "per-capita loss of wealth" to determine if vegetation may have had a protective effect. Kathiresan and Rajendran (2005) correlated human death toll and per-capita loss of wealth with distance from shore, elevation from mean sea level, and type of coastal vegetation in 18 coastal hamlets along the Parangipettai coast of Tamil Nadu State, India. They reported a negative correlation between death toll and distance of human inhabitation from sea ($r = -0.61$, $P < 0.01$), the elevation from mean sea level ($r = -0.63$, $P < 0.01$;), and the area of mangrove and other coastal vegetation ($r = -0.58$, $P < 0.01$). They also observed that many deaths were caused by the thorns of a single species, *Prosopis spicifera* (syn.= *Prosopis cineraria* (L.) Druce), indicating that some species may actually increase the risk from tsunami events. Although *Prosopis* was implicated as a major cause of mortality, presence or absence or abundance of this species was not analyzed as an independent variable to predict mortality.

Kerr et al. (2006) reanalyzed the data presented by Kathiresan and Rajendran (2005) using stepwise regression with tsunami mortality as the dependent variable and hamlet elevation, distance from sea and the area of coastal frontage given to vegetation as independent variables. Their reanalysis found that with the more appropriate statistical tests (stepwise regression vs. simple linear regression) differences in coastal vegetation area did not explain variation in human mortality which was mainly explained (87%) in their analysis by hamlet elevation, and distance from the sea. This prompted Kerr et al. to conclude that, "given hamlets of equal elevation and distance from the sea, differences in vegetation area did not mitigate human mortality caused by the tsunami." Vermaat and Thampanya also reanalyzed the data and after initially reporting a protective effect of vegetation (Vermaat and Thampanya 2006) retracted their findings when errors in their statistical analysis were revealed (Vermaat and Thampanyab 2007).

Another study, also from Tamil Nadu, India used a remote sensing technique to estimate the amount of vegetation between known inundation points and the coast along inundated areas (Bhalla 2007). Their methodology calculated the Normalized Difference Vegetation Index from satellite imagery (NDVI) [NDVI = (Near infrared – red)/(near infrared + red)] along a straight line transect between the known tsunami inundation points and the coast . This calculation, according to the authors, is an estimate of "the amount of chlorophyll present in a given pixel on a scale from 0 to 1, although this method does not indicate the type of vegetation present. Their analysis found no statistical significance (P=0.45) between tsunami inundation distance and NDVI.

Satellite imagery has provided the most often used data for investigations of coastal vegetation-tsunami interactions. In addition to the work in Tamil Nadu, India, researches have investigated effects in Phuket, Thailand and Banda Aceh, Sumatra with similar results. Chang et al. (2006) employed pre and post-tsunami 7-band satellite imagery, spanning the Thailand coast northward from Phuket Island. Tsunami damage in urban and forested areas was assessed and classified using post tsunami satellite imagery to detect scouring and debris. Damage maps were produced in urban areas based on the percent of collapsed buildings and field observations of damage were made on site eight months following the tsunami. A damage scale for buildings was assessed with five damage classes and three building types. Pre-tsunami land-use was classified using ENVI software. The following data sets were analyzed: Land use, change in land use, reports of damage to property and high loss of life, bathymetry, topography. Four sites were selected and within each site, “location pairs” defined as communities with similar bathymetric details and coastline exposure but which had “potentially different protection levels by mangroves”, were identified. Initial results indicate that lower levels of damage were observed in three villages situated behind mangroves, with an intermediate level of damage in one village that was "partially exposed" with the highest level of damage observed in four villages that were “completely exposed”.

Iverson and Prasad (2006) used satellite imagery of coastal Banda Aceh, Sumatra which they classified into forested and developed and compared with images of the same area which had been classified previously by "the US Government" into “damage” and “no damage” areas.

They calculated damage: undamaged ratios and in both areas found 2.0 and 2.5 more damage in developed as compared to forested lands. A model of damage was generated in Random Forests (RF) modeling software for use in R statistical software, using the following predictors: classified vegetation types, coastal exposure level, distance to shore, and elevation, was generated and compared with actual damage. In their model, elevation and distance to shore were the most important variables to predict tsunami damage followed closely by vegetation and then by exposure level. This model was able to correctly classify 93.9 percent of the study area. They also used the same data to produce predictive tsunami risk models for the larger area. The authors conclude that, "developed land was much more susceptible to tsunami damage than forested land" and that these results “provide further evidence of the protective power of coastal forests." Baird and Kerr (2008) have criticized Iverson and Prasad (2006) pointing out that their experimental design did not specifically test the protective role of coastal forest and that claims that this constitutes evidence for the protective role of coastal forests is unwarranted.

In addition to the work on coastal vegetation – tsunami interactions, various methods including satellite imagery has been used to assess interactions between coastal vegetation and the effects of storm surge. Das and Vincent (2009) analyzed death toll in villages in Kendrapada District, from a super cyclone that struck the state of Orissa India in 1999. They used pre-storm satellite imagery to assess the extent of mangroves and restricted the study to 409 villages that have historically had mangroves so that the absence of mangroves today is likely attributable to human removal of mangroves rather than some other factor which may have excluded them. This study found a significant negative correlation between mangrove width and deaths. The average mangrove width was 1.2km.

Although satellite imagery can be a powerful tool for assessing coastal vegetation-tsunami interactions, these studies are limited in that they are able only to show presence, and general shape of coastal vegetation. Studies based on satellite imagery alone are not able to assess qualities of coastal forest such as density, structure of the understory and branching and rooting patterns that might vary greatly between forest types and which will directly interact with an oncoming tsunami wave. The studies by Danielson et al. (2005) and Olwig et al. (2007) find a protective effect of dense vegetation however density of the vegetation is not directly measured and represents a categorical determination based on visual inspection of imagery. The study by

Bhalla (2007) which uses NDVI likewise does not directly address the physical structure of the vegetation sensed by satellites.

Another suite of tools used by researchers to assess coastal vegetation – tsunami/storm surge interactions includes wave tank simulations and mathematical modeling. In a wave tank simulation, Irtem et al. (2009) used a glass-walled wave channel 22.5m in length, 1.00m in width, and 0.50m in depth along with sand and artificial pine trees (4.6 cm in diameter and 9 cm in height) and wooden dowels (to simulate trees without leaves) to model a coastal forest in three and two configuration respectively. Wave run-up height behind the simulated vegetation was measured. They found that a dense configuration with leaves had the greatest reduction effect on run-up height. Thuy et al. (2009) also modeled vegetation using wooden cylinders with a diameter of 5mm mounted in a staggered arrangement and assessed the effect of gaps through the simulated vegetation. They found that as the gap width increases, the flow velocity at the gap exit increases at first, reaches the maximum value, and then decreases. For a forest with a width of 200m perpendicular to shore, the flow velocity at the end of a 15m wide gap located in the middle of the forest will reach a maximum value of 2.5 times the velocity without a gap and 1.7 times the velocity of an un-vegetated coast.

Mathematical modeling of the protective effect of coastal forests during a tsunami have been carried out by Harada and associates (Hiraishi and Harada 2003, Harada and Imamura 2005, Harada and Yoshiaki 2005) and also by (Nandasena et al. 2008). Harada and Imamura(2005) used forest parameters in a numerical modeling experiment. Their model was limited in that it could not model for the breaking of trees. Their model accounted for the effect of forest density(10, 30, 50 trees / m^2), trunk diameter (0.3, 0.15, 0.1m), forest width (50, 100, 200, 400), tree height (10m), branch height (2m), and the "projected area rate" of leaves (0.65). The model included the effect of coastal forest in the as the resistance force in the momentum equation. Resistance coefficients of coastal forests were taken from modeled hydraulic experiments (Harada and Imamura 2000).Tsunami heights of 1, 2, and 3m were tested with wave period of 10, 20, 30, 40, 50 and 60 minutes. The effect of vegetation was measured as: (maximum values with forest /max values without forest. = r).In their numerical simulation, the coastal forest reflected wave energy reducing run-up elevation behind the forest. When the tsunami reached the level of leaves and branches, a larger effect was observed. An increase in forest width from 50 to 400 m significantly reduced, maximum inundation depth, hydraulic force, and maximum current velocity. An increase in forest density from 10-50 trees / 100m^2 resulted in only small decreases in these variables.

Following up on work by Harada and Imamura (2003) (summarized in Harada and Imamura 2005), Harada and Yoshiaki (2005) calculated the tsunami resistance as a function of stand age using forest density, DBH, and branch height parameters for pine forests. They found that higher densities and lower branch heights contributed to a larger roughness coefficient and thus a greater effect of the coastal vegetation of the reduction of tsunami run-up elevation.

The simplified systems replicated in mathematical modeling and wave tank simulations in general tend to predict an attenuating effect of vegetation on tsunami and storm surge. Results from field studies are typically inconclusive and sometimes contradictory. This is likely due to the highly complex nature of modeling interactions in the natural and anthropogenically influenced environment.

As knowledge about coastal vegetation-tsunami/storm surge interactions has grown, models to explain these interactions and their subsequent effects on people and property have become more complex. Chatenoux and Peduzzi (2007) used a large data set covering 62 sites located in Indonesia, Thailand, continental India, Sri Lanka, and the Maldives. A set of parameters were investigated that might best explain the inundation distance (measured as the width of flooded land strip = D). For each site, maximal D was used as the dependent variable in the analysis. Each site represented a single data point. Maximal D was estimated from satellite images and from data available from other studies. Independent variables assessed included: bathymetry, location of epicenter coordinates, fault lines, elevation level, information on coastlines, land cover (in seven classes), distribution of coral, seagrass beds, and mangrove forests. Combinations of the following parameters were most predictive in the resulting regression model: the distance from the tectonic origin (distance from subduction fault line), the near-shore geomorphology, and also environmental features (percentage of coral and percentage of seagrass beds) (R^2 = 0.655). Their results indicate that (1) a steep slope blocks tsunami energy while a flatter slope builds a higher wave leading to a larger inundation distance (2) in inundated areas fronted by areas inhabited by seagrass, the distance of impact was less than other areas without seagrasses, (3) there was a positive correlation between the presence of corals and inundation distance. The authors found that most sites assessed did not have mangroves directly fronting exposed coast since mangroves are often present only in protected estuaries. This study therefore was not able to assess the role of mangroves however the authors concluded that, "In such case it is suspected that areas covered by mangroves forests were less impacted by tsunami just because mangroves forests communities tend to be located within sheltered coastal areas." The authors could not rule out if the interactions observed with seagrassess and corals were not due to unmeasured environmental variables stating, “A mechanism to explain the observations that the presence of coral reefs positively affected D remains unexplained” and “it is impossible to differentiate if the presence of seagrass beds has a mechanical influence that absorbs the energy of the waves or if the area that seagrass usually colonize is already protected from the wave.”

Kaplan (2009) found significant differences between three vegetation classes, which differed in overstory and understory, with regard to their effects on inundation depth (as determined by interview with home owners) and damage to surveyed houses in Sri Lanka. Their results indicate an effect of vegetation type on water height and damage levels. They report that the water level was significantly higher at houses behind the vegetation class consisting of dense undergrowth and coconut and *Pandanus* overstory) than vegetation classes consisting of (1) a belt of *Pandanus* backed by a loose coconut plantation with more or less no undergrowth and (2) vegetation consisting of only very few trees, but with a dense undergrowth of different shrubs. The researchers did not formally quantify the vegetation structure and completely unvegetated areas were not included in the analysis. From their analysis, it cannot be sure if the observed effect (if related at all to vegetation) was due to total vegetation, tree density, or the density of undergrowth.

Tanaka et al (2007) investigated several vegetation types in Sri Lanka following the Indian Ocean tsunami using both field surveys and subsequent modeling. They concluded that the ability of coastal forest to attenuate wave energy was related to both horizontal and vertical forest structure. They predict that greater stem density and greater above ground complexity in terms of branches, leaves, and prop roots, would produce greater drag forces on tsunami waves. They suggested that a forest with both small and large diameter trees may be particularly effective as the dense smaller trees and greater amount of above ground structures within the wave inundation height would reduce wave velocity while large diameter trees would be able to stop debris and would be less likely to break during the tsunami event. Using *Casuarina equisetifolia* as a single species example, they suggest that when the diameter was larger than 0.1

m, trunks were not broken by the tsunami and had sufficient stem density to be effective at wave attenuation, however with an average diameter greater than 0.5 m, stem density was low due to self thinning of the stand and they presumed that this density had little effect in reducing wave velocity. Likewise, they found that *C. nucifera* likely had little effect on the wave because it was growing in stands with very wide spacing and had a simple above ground structure within the inundation height. In contrast, their observations suggest that a two layer arrangement of vegetation in the vertical direction with *P. odoratissimus* in the understory and *C. equisetifolia* in the overstory seems to have provided the greatest level of protection from tsunami waves.

Feagin (2008) questioned whether coastal mangrove forests directly reduced the effect of large waves or if coastal forests indirectly affect waves by changing or engineer coastal topography through the formation of dunes. If this is the case, an engineered coastal forest should take into consideration those attributes of natural forests which allow it to build elevation.

It is well established that vegetation, through a combined effect of above ground and below ground dynamics, effects soil erosion. This occurs through physical intercepting raindrops, increasing infiltration through the soil, allowing for transpiration of soil water, increasing surface roughness, and by adding organic matter to soil. Through these mechanisms, there is a well established exponential decrease of soil erosion rates with increasing vegetation cover (Gyssels et al. 2005). The dynamic interactions between waves and coastal erosion is less well understood and few studies have specifically addressed the role of coastal forests in influencing patterns of erosion during a storm surge or tsunami event. Coastal vegetation provides erosion protection through the same mechanisms as other vegetation types. In addition, coastal vegetation: (1) increases the durability of the sediment root matrix; (2) forms dunes through the interception of sand, organic material and other particles while reducing wind erosion; (3) reduces wave heights leading to reduced offshore transport; and, (4) reduces wave velocity resulting in deposition from waves (Dean 1978, Lancaster and Baas 1998). While there has been some efforts to quantify these mechanisms, particularly for wetland species (Knutson et al. 1982, Fonseca and Cahalan 1992), and seagrasses (Fonseca 1996), there is still very poor understanding of how below and above ground parts of terrestrial coastal vegetation interacts with coastal erosional processes (Dean 1978).

The effects of erosion may have immediate impact on recovery efforts by undercutting roads and destroying utilities and may have longer impacts on coastal geomorphology.

Accelerated coastal erosion has been linked to development of coastal areas (with accompanying deforestation) (Dean 1978). For example, Mimura and Nunn (1998) attributed increased coastal erosion and beach loss in Fiji to increased clearing of coastal vegetation since the 1960's.Erosion resulting from the removal of vegetation in coastal areas may result in a longer and more gradual slope between the ocean and inland areas. This change in coastal geomorphology would present a reduced barrier to incoming tsunami or storm surge waves. In response, planting vegetation or encouraging natural vegetation at the coast has been employed for many years as a strategy to protect against coastal erosion (French 2002).

Some of the work related to tsunami or storm surge bioshields has focused on what species or vegetation types might best withstand the force of incoming waves as well as survive the inundation. Jayatissa and Hettiarachi (2006) assessed coastal vegetation in 15 sites to cover all the major climatic zones in Sri Lanka, 14, 44, and 134 days following the tsunami. Species were assessed for damage following the tsunami and classified into three groups: (1) Species unaffected, (2) species affected and recovered over time and (3) species affected and not recovered. Many of these species are common coastal species in the Pacific and Hawaii. A list of 47 species was compiled, 26 of these are also found in Hawaii (Table 1).

Table 1. Survivorship of species in inundated areas of Sri Lanka following the 2004 Indian Ocean tsunami. Only species also found in Hawaii are listed (Jayatissa and Hettiarachi 2006).

Species unaffected (12 species)
Barringtonia asiatica (P), *Calophyllum inophyllum* (N), *Clerodendrum inerme* (C), *Hibiscus tiliaceus* (I or N), *Ipomoea pes-caprae* (I), *Opuntia sp.* (N), *Pandanus tectorius* (I), *Prosopis juliflora* (N), *Terminalia catappa* (N), *Thespesia populnea* (I), *Casuarina equisetifolia* (N), *Cocos nucifera* (N,C), *Opuntia sp.*(N)
Species affected and recovered over time (12 species)
Artocarpus altilis (C), *Artocarpus heterophyllus* (C), *Citrus spp.* (C), *Ficus benghalensis* (N), *Hernandia ovigera*, (C), *Morinda citrifolia* (N, C), *Parkinsonia aculeata* (N), *Tamarindus indica* (P), *Mangifera indica* (N, C), *Tamarindus indica* (C), *Moringa oleifera* (C), *Anacardium occidentale* (C)
Species affected and not recovered (2 species)
Psidium guajava (N), *Macaranga sp.* (N)
Status in Hawaii (per Wagner et al. 1999) is given in parenthesis. (I = indigenous), (N = Naturalized), (P = present but not naturalized), (C = Cultivated).

Similar resilience of coastal assemblages has been reported by a number of post storm studies, however the ability of species and entire vegetation assemblages to survive these events are highly dependent upon the intensity and duration of the storm surge and. Post storm vegetation assessments were carried out on Jaluit atoll, Marshall Islands, after Typhoon Ophelia passed over the atoll in 1958 (Blumenstock 1961), in Tonga following Cyclone Isaac in 1982 (Woodroffe 1983), and following back-to-back cyclones Alix and Carol which struck Mauritius in January and February 1960 (Sauer 1962). These and other assessments indicate significant levels of damage due to wind, storm surge and salt spray. For example in Tonga, in the worst hit areas, coastal vegetation was destroyed up to 30 meters from the coast up to 6m above high tide due to storm surge (Woodroffe 1983). In this case the coasts were inundated for several hours with high waves. In Jaluit, researchers found that the greatest damage to vegetation occurred where there was a combination of strong winds and ocean inundation (Blumenstock 1961). The storm did not have as great of an effect on understory species except in inundated areas where they were almost completely wiped out (Blumenstock 1961). In both cases, strong winds were responsible for very high levels of mortality to trees, particularly *Pandanus* and coconut, that were emergent from the canopy. Sauer (1962) reported that following the second cyclone, in Mauritius, most of the common coastal species were recovering, however *Casuarina* , which survived the first cyclone well, showed significant levels of mortality. Sauer also noted that storm drift was stopped by mangroves (*Rhizophora mucronata*) which survived well and appeared to attenuate the effect of wave energy on the vegetation behind them. All of these accounts indicate that coastal vegetation was highly resistant to persistent effects of salt, spray and periods of inundation. Even when trees were blown over, and roots undercut by waves, most retained the capacity to re-sprout. For trees that suffered significant mortality, regeneration by propagule was rapid.

The specific assemblage of species able to grow at any particular coastal location on tropical Pacific islands is strongly influenced by climate and the type of coastal ecosystem most importantly whether the site is a sandy beach or rocky coastline or whether the site is exposed to wave action, wind, and salt spray or whether the site is protected such as in a bay or harbor (Richmond and Mueller-Dombois 1972, Mueller-Dombois and Fosberg 1998). Most studies have focused on particular species assessing species and population parameters (Tanaka et al. 2007). Few studies have specifically addressed the dynamics of a diverse native coastal vegetation community such as the interaction between species of various forms of both below and above ground structures.

While most research to date has focused on natural (although undoubtedly anthropogenically influenced) systems and simulated models of those systems, few studies have applied the theories generated by coastal green barrier research to specific design recommendations for denovo coastal bioshield construction (Tanaka et al. 2009). Further, other studies or coastal projects which have incorporated the findings of coastal bioshield research into the restoration of native coastal ecosystems were not found. The de-novo design of a bioshield should consider not only the performance of the green barrier during a tsunami or storm surge event but also how the event may change the structure of forest following the event (Hayasaka et al. 2009). Finally, many have pointed out that coastal bio-shield designs must take into account expected changes in sea-level rise which are likely to alter coastal vegetation assemblages (Greaver and Sternberg 2007).

The 2004 Indian Ocean tsunami also prompted research on coastal forest rehabilitation (restoration) and site-specific manuals for coastal re-forestation have been developed (Hanley et al. 2008).The majority of coastal revegetation efforts and related research has focused on the reestablishment of mangroves (Chan and Ong 2008).Most of the published reports on non-mangrove coastal forest rehabilitation or re-vegetation are general guidelines for the implementation of coastal reforestation projects rather than technical reports based on completed projects. One technical report following the successful implementation of a coastal reforestation project in Tonga in the mid 1990's although not implemented specifically with the idea of producing a tsunami or storm surge bio-shield, provides good technical information useful for the planning of similar projects on tropical Indo-Pacific Islands (Thaman et al. 1995). A summary of the findings from that report is given below. In addition, the report provides species specific propagation and performance information.

Case study: Coastal re-vegetation at Tonga

In response to the negative effects of coastal deforestation in Tonga, including salt spray damage to crop plants and structures and the loss of species of cultural importance, a coastal reforestation program was launched at Houma on the South west coast of Tongatapu (Thaman et al. 1995). The re-vegetation zone ranged from about 5 to 25 m (15 to 75 ft), and averaged 12 m in width and 2 km long (36ft in width and 1.3 miles long). The project began in 1993. Alien undesirable species were removed from the re-vegetation area from 1993-1994. Plantings, fencing and signs were used to demarcate the re-vegetation area. Coastal species were collected from natural populations and grown at a nursery until large enough for out-planting to the re-vegetation site. The project concluded in 1995. Total direct costs were USD 12,000. Estimated man-hours over the two year project was 11,858 with an average of 12.5 days worked per month. The project relied upon involvement and volunteer from nearby communities. Planting was done in three phases involving the initial planting of highly salt tolerant pioneer species, the subsequent planting of salt tolerant non-pioneer species and finally the enrichment planting of key species. Site maintenance included regular weeding, periodic watering during times of drought and the addition of soil amendments. Plantings were done in sections to ensure that: 1) there are enough trees and associated vegetation to establish a good windbreak and a substantial zone of salt-tolerant and fire-resistant vegetation; 2) to facilitate care and maintenance in the early stages of reforestation; and, 3) to monitor and learn from the performance of the trees in initial plantings. Pioneer species planted as part of the study included: *Pandanus tectorius, Hibiscus tiliaceus, Excoecaria agallocha, Calophyllum inophyllum, Scaevola taccada, Terminalia catappa, Terminalia litoralis, Casuarina equisetifolia, and Tournefortia argentea.* These species were planted to provide a protective buffer for the establishment of the non-pioneer species. Non-pioneer species were planted beginning six months after the planting of Pioneer species. These included: *Neisosperma oppositifolium, Hernandia nymphaeifolia, Barringtonia asiatica, Vitex trifolia, Cerbera manghas, Cocos nucifera, Pisonia grandis, Guettarda speciosa, Acacia simplex, and Cerbera odollam.* Following the establishment of non-pioneer species, enrichment plantings involving species that were harder to propagate or which required even greater levels of protection from exposure begun to "give the resultant forest greater species diversity and greater cultural utility; and to enrich the species composition of the original forest”.

Summary of Coastal Vegetation, Tsunami, and Storm Surge Studies.

Following the Indian Ocean tsunami of December 26, 2004, the anecdotal accounts of survivors and the observations of researchers pointed to a potential role of coastal vegetation in mitigating damage and in some cases reducing the death toll due to a tsunami. The hypothesis generated by these observations was that coastal vegetation could provide a protective barrier against tsunami inundation. By extension, research has also turned to the role of coastal vegetation to mitigate against risks related to storm surge, erosion and the effects of projected sea level rise which is expected to exacerbate the effects of all of the above named natural phenomenon (IPCC 2007).

It has been observed that coastal vegetation can stop rocks, debris, ships and other material carried by the tsunami wave from reaching land and causing destruction. It can act as a safety net and vertical escape for people who might be trapped in a wave and who would otherwise be washed out to sea. Coastal vegetation also traps sand forming sand dunes, reduces erosion, and traps organic matter which together act to build elevation, increasing the beach slope and therefore reducing the ability of some waves to inundate the land. Vegetation has been found to slow down an oncoming tsunami wave, reducing the force of the wave and its destructive potential. Vegetation may also prevent debris and soil from land from being washed into the ocean providing a protective effect for coral reef and other near shore ecosystems which are doubly affected by the direct effect of tsunami and storm surge and the subsequent input of harmful materials from land. In addition to protective effects, coastal vegetation provides other important services including providing habitat for seabirds, turtles and other animals and a potential resource base for people who may use the products of the coastal forest for food, recreation, materials, medicines, and many other uses (Thaman 1992).

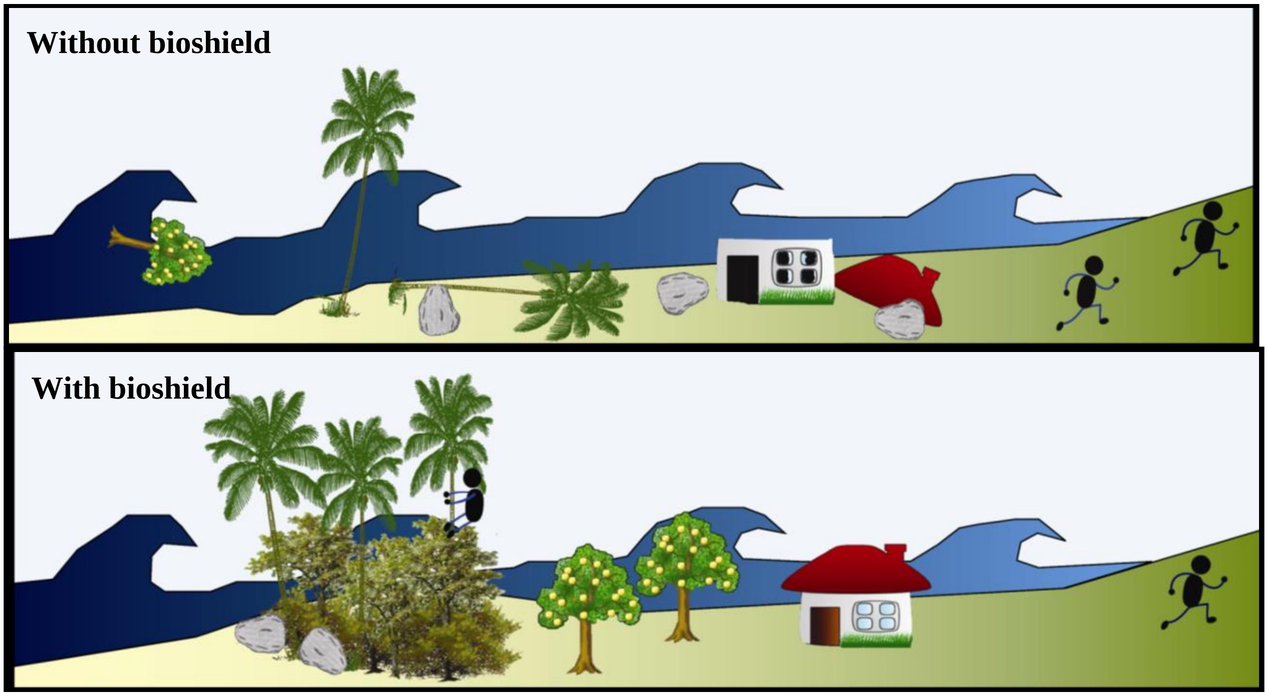


Figure 2. An illustration of the proposed interactions between dense coastal vegetation and tsunami or storm surge waves. A bio-shield may reduce the velocity of an incoming wave, build elevation by trapping sand and organic matter, reduce foreshore erosion, reduce damage to structures through a reduction in wave energy due to hydraulic resistance and reflection, hold back coral, debris, & ships carried by the wave which may cause damage inland or may cause damage offshore to sensitive reef ecosystems., and provide a vertical escape for people, Coastal vegetation may however be a source of floating woody debris which may cause damage inland. The configuration of coastal vegetation can alter the tsunami flow direction and flow speed

Evidence from wave-tank studies and mathematical modeling provides evidence to support the hypothesis that coastal vegetation should be able to attenuate the energy of tsunami or storm surge waves. Further, these studies suggest that greater vegetation density and greater surface areas (in terms of leaves, branches, roots and stems) within the inundation depth of a wave, should increase the resistance of the coastal vegetation on an incoming wave. In addition the specific configuration of coastal vegetation, like any other barrier, may change the flow of an incoming wave. In the case of a straight channel through the vegetation perpendicular to the front of the incoming wave, the configuration may channel water, increasing its velocity potentially resulting in increased damage inland of the gap. A major criticism of these highly controlled studies is that they may fail to adequately simulate complex natural-system parameters.

Evidence from post inundation studies, including field studies and studies based on remotely sensed data are equivocal and all studies performed to date have been subjected to valid criticisms. Critics and proponents alike conclude that variations in bathymetry, increased distance from shore, and increased elevation reduces risk from a tsunami (Cochard et al. 2008).

Once these factors are taken into consideration, many studies point to, but have not conclusively demonstrated, some protective role of coastal vegetation. Given the equivocal results of bio-shield research, Baird and Kerr (2008) concluded that, "There is, in fact, no empirical data published to date to suggest that forests provided any meaningful protection from the Indian Ocean tsunami and much to refute it."

The conflicting results and interpretations of the data from field studies is likely due to the highly uncontrolled, extremely complex, and temporally rare and ephemeral situations which characterize these natural events. It is important to note that many of the studies that have addressed these questions were undertaken in areas inundated by the 2004 Indian Ocean tsunami which was larger in magnitude than most tsunami events. In addition, most studies have taken place in a very limited number of localities. One reason for this limited sample is simply that field researchers must wait for a tsunami or major storm surge event in order to study its affects, in addition, since there are so many environmental factors that may affect patterns of inundation and wave-induced damage, it is important to compare sites that share many characteristics yet vary, along its coastal extent, in certain variables of interest such as vegetation structure or density, the presence/absence of sea grass, or abundance of coral reefs.

Observations from Upolu Samoa

Methods

In January 2010, The University of Hawaii team made observations in six areas on the south shore of Upolu Samoa which had been inundated by the September 29, 2009 tsunami. Maximum inundation points were recorded with a handheld Garmin Rino 530 GPS unit. All position points were averaged for 60-70 seconds to improve precision. Ground scour and ferns or herbaceous plants killed by salt-water inundation were consistent indicators of the maximum inundation extent. At randomly selected points in areas where coastal vegetation fronted the shore, the vegetation structure was assessed using the variable area transect method along 2-3 transects at each site (Sheil et al. 2003). The transects were set to run from the beginning of the woody coastal vegetation at the top of the beach perpendicular to the shore for 20, 30, or 40 meters inland. The outer boundaries of coastal forest were mapped with a GPS. All points were projected in ArcMap for analysis. The GPS boundaries of coastal forests were converted to forest polygons and conformed well to satellite imagery. For inundation and damage assessment points, the following were measured using measurement functions in ARCMap: distance to shore for each inundation point, proportion forested along a straight line transect from each point to shore, reef distance from the closest coastal point, for each point, to the closest point on the fringing reef. Elevation for all points was interpolated using a 2m contour layer supplies by the government of Samoa. Slope of the foreshore was recorded using a clinometer.

Structures within the inundation zone were assessed for damage on a 3 category scale (1) undamaged or damage to contents only, (2) moderate damage including significant damage to doors, windows or partial collapse of attached structures such as cook houses, (3) destroyed wood frame or cement house. Species survivorship of woody plants encountered along transects within inundated areas was assessed on a three point scale (1) unaffected, (2) recovering, (3) dead/not recovering). In a few areas with extensive erosion along the coast, the volume of sand remaining behind isolated trees was measured.

Results

Observations are presented separately for each of the five sites visited (figure 3).

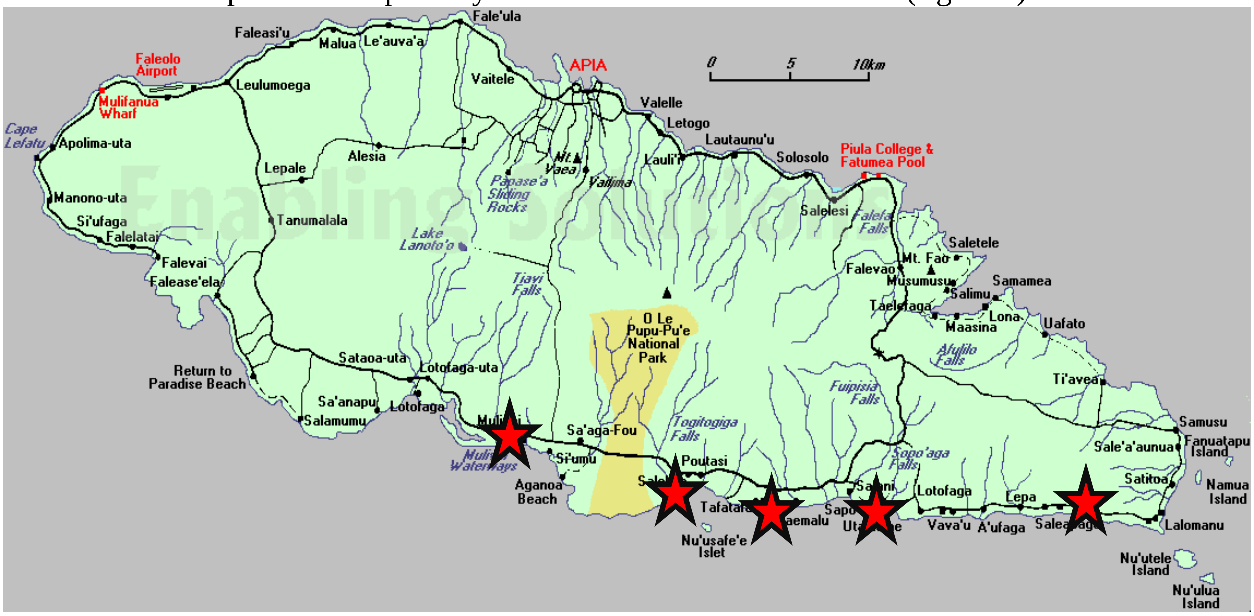


Figure 3. Observations were made at five sites along the coast of South Upolu. From west to east these are Coconuts beach Resort, Saleilua, Tafatafa, Utulaelae/Sapoe, and Saleapaga.

Site 1: Coconut Beach Resort

At the Coconuts resort site (figure 4), there was substantial damage to the resort itself and the numerous structures likely shielded a few houses just behind the resort. The tsunami travelled through a wetland of the sedge *Scirpodendron ghaeri* and the fern *Acrostichum aureum*, bordered by very dense *H. tiliaceus* to reach a maximum run-up elevation of approximately 4 meters (mean 3.243, standard error 0.178, standard deviation 0.472). The maximum inundation distance (max 372.5 mean 293.9, standard error 26.5, standard deviation 70.2) was clearly dependent upon elevation (see image). UNESCO reported a maximum run-up elevation of 5 meters with an inundation distance of 95 meters to the east of this location.

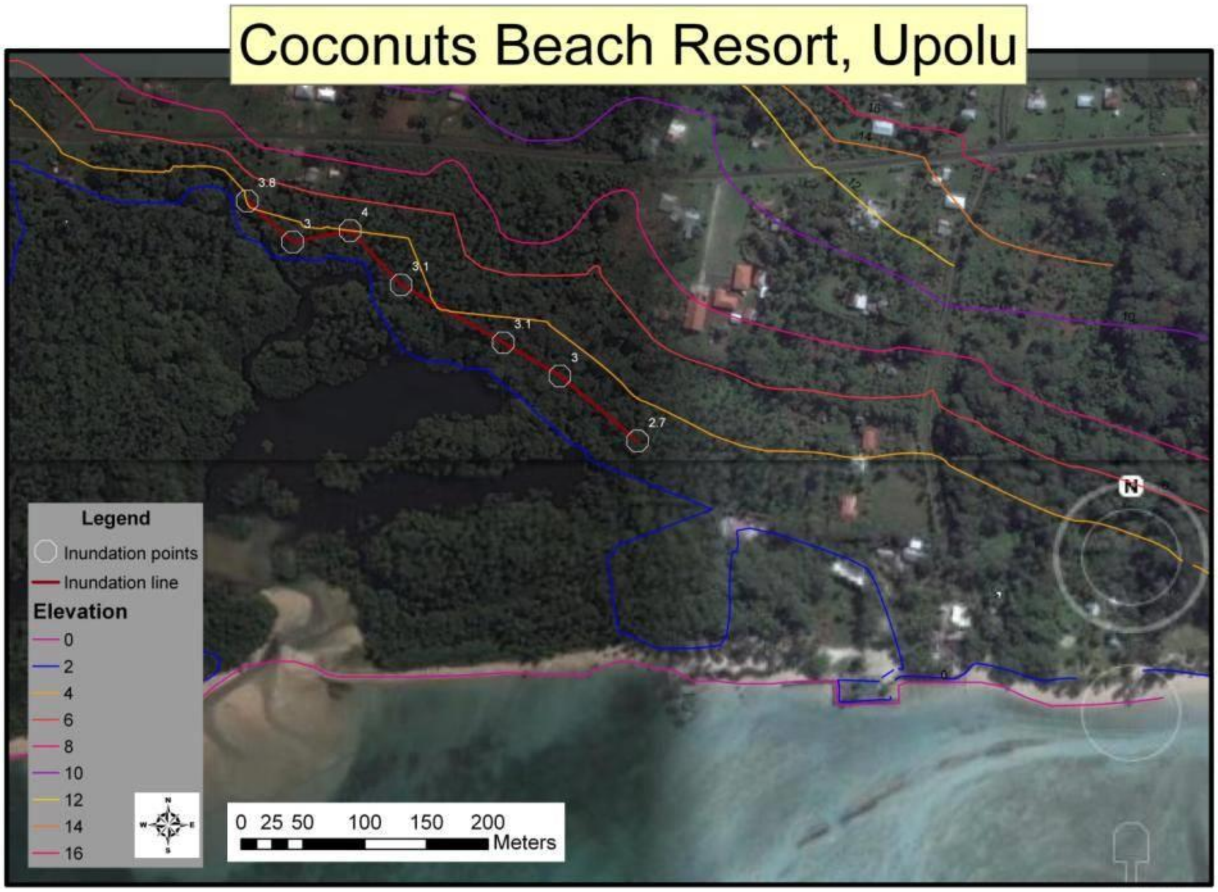


Figure 4. Inundated area near the Coconuts Beach Resort, Upolu, Samoa. The red line, and marked inundation points indicates the inundation limit of the tsunami wave. Elevation (in meters) courtesy of the Government of Samoa and James Atherton. Projection: WGS 1984.

The owner of the resort reported that most of the planted ornamental vegetation was destroyed. Other than uprooted trees within a few meters of the coast, there was little to no apparent damage due to inundation to trees and woody shrubs in the natural area west of the resort. Herbaceous plants and ferns were missing from the understory due to ground scour. No transects were carried out in this area due to presence of the dense (nearly impenetrable) coastal wetland dominated by *H. tiliaceus and Scirpodendron ghaeri*. Although it was reported that the vegetation near this resort may have had a protective effect, our team could find no evidence of that claim, as all undamaged structures within the inundated areas were near the edge of the inundation zone or were blocked by the physical structures of the resort including several large retaining walls. Species encountered at this site included *Cocos nucifera, Hibiscus tiliaceus, Terminalia cattappa. Hernandia nymphaeifolia*, *Ardesia eliptica* and, *Scirpodendron ghaeri*.

Site 2: Saleilua village

West of Saleilua village the team recorded observations in two locations. The first location was near a peninsula along the road leading to the Ili'ili Beach Resort (figure 5) which had been completely destroyed by the tsunami wave and has subsequently been abandoned. At this location a sea wall (see image) made up of large boulders had been destroyed and the boulders moved inland, in some cases over 100 meters (see point 216). A similar boulder field originating from a seawall was recorded in the village of Satitoa by the Unesco team (Dominey-Howes and Thaman 2009). The resort development was situated on land with an elevation of less than 2 meters above sea level. The coastal road leading to the resort passed through a coastal forest that extended to the shore surrounded on both sides along the coast by areas cleared of all but a few trees. The vegetated area was approximately 20 meters wide and 50m long with the long side running parallel to the coast. Although this area had been inundated, there was no visible damage to trees and shrubs within or behind this thin vegetated strand and there was little damage to the road that ran just behind the vegetated buffer. Considerable erosion and road damage and damage to trees in the relatively cleared areas on either side of this vegetated area was observed (Figure 5), however it cannot be determined if this damage was due to the proximity of the road to shore or due to a buffering effect of the vegetation.

At this site, the maximum inundation distance was approximately 83 meters. And the average run-up height was 1.6 Meters (Stdev = 0.56m). The team recorded inundation points along this coast to determine if there was any detectable affect of that vegetation on inundation distance or run-up. The analysis of these points is inconclusive since there was no evidence as to the direction of the tsunami flow, and it appears likely that the tsunami wave(s) past through the peninsula and struck the vegetated area from a direction nearly parallel to the coast. The slope of the shore in the cleared area to the south of the vegetated area was 7% (4 degrees) (see point 230 which was approximately 18 meters from approximate sea level with a measured elevation of approximately 1.3 meters). In the gap, (see point 228), 88 meters from shore, there was moderate damage to a house (now abandoned) and the team was informed by a local resident that the damage was due to the tsunami wave. The gap to the north of the vegetated area had a foreshore slope of 8% or 4.5 degrees and point 231 was 13.5 meters from approximate sea level, for an approximate elevation of 1.1 meter). The vegetated area had a somewhat higher elevation and greater foreshore slope of 14% for a distance of 6.2 meters to the high tide mark.

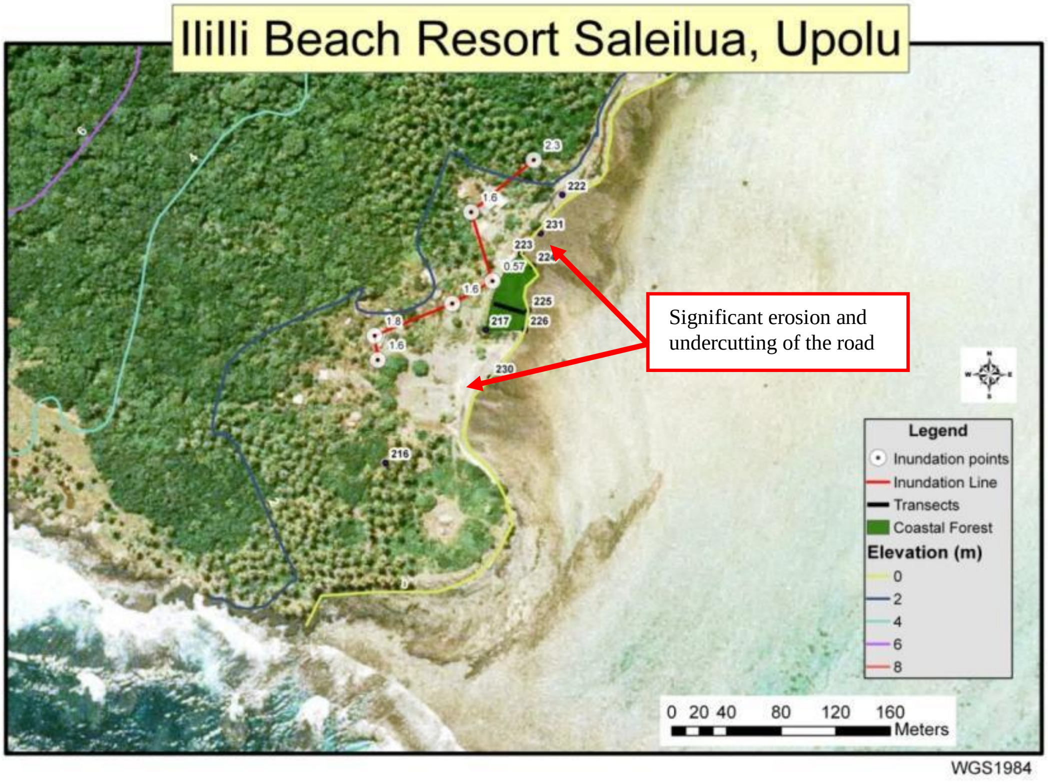


Figure 5. Inundated areas at the Iliili Beach resort area in Saleilua Samoa.

The vegetated area near Ili'ili resort was predominantly composed of dense *Hibiscus tiliaceus* and *Dendrolobium umbellatum*. With very high densities (3167 stems per hectare) of *D. umbellatum* in the first 10 meters from shore and 1146 stems per hectare of *H. tiliaceus* throughout the area (Table 2). *Morinda citrifolia* was also a co-dominant species (1129 stems/ha) along with *H. tiliaceus* in the inland 10 meters of the area. Other species encountered at low densities in this site included: *Asplenium nidus, Cocos nucifera, Premna serratifolia, Baringtonia asiatica, Terminalia samoensis, Glochideon ramiflorum,* and *Tacca leontepaloides.* All of these species appeared unaffected by both the force of the tsunami wave and by salt water inundation however two of two individuals of *Macaranga sp*. found within this area were dead likely due to salt water inundation. The trees in this area would only have experienced inundation of about 1 meter above ground at maximum. Average estimated height of the trees in this vegetated area was 5 meters (SE = 0.474) and the base of the canopy was at approximately 3 meters (SE = 0.382), mostly above the inundation depth.

Table 2. Stem density and mean basal area of dominant shrubs and trees in vegetated area on the road to Iliili Saleilua.

(Distance from Shore)	Avg. Plot Area	Relative density stems/ha				Mean basal area (cm^2/m^2 or m^2/ha)
		D. umbellatum	*H. tiliaceus*	*M. citrifolia*	Total	
(0-10m)	13.4	3166.6	0.0	0.0	3589.8	11.0
(10-20m)	10.4	0.0	2292.8	1128.7	4056.4	45.4
Average	11.9	3166.6	1146.4	1128.7	3823.1	28.2

On the peninsula at Saleilua the following species were observed: *Cocos nucifera, Pandanus tectorius, Terminalia cattappa, Baringtonia asiatica,* and *Crinum asiatica*. All appeared to have survived the tsunami well. The *Pandanus* in this case were tall and mature, growing in full sun with numerous above ground roots. A pre-tsunami image of the peninsula area was found on the internet and a comparison with a post tsunami image shows that most trees in this very sparsely planted area in fact survived the force of the wave while all of the buildings were destroyed or severely damaged (figure 10).

At the second location in Saleilua, witnesses reported that the wave came from nearly perpendicular to shore. The maximum inundation distance at this site was 175 meters and the maximum run-up elevation was 7m. This high elevation measurement was likely due to a low slope in this particular area. The average run-up elevation was 6.2 m SE 0.24 Stdev 0.59.) and the average inundation distance was 144.83m (SE 9.37 Stdev 22.94.) The measured foreshore slope in this was 8%. The tsunami wave pasted through approximately 20 meters of coastal vegetation and then through a wetland of *Erythrina fusca*. The only house in this area (which was not fronted by substantial vegetation) was completely destroyed and the owners were rebuilding approximately 200 meters inland.

The team completed one 30 meters long vegetation transect at the second Saleilua location. This vegetated area was composed of a mix of species without any clear dominant. This appears to be due to plantings and clearing by the owners of the land. The most commonly encountered species along this transect was the ornamental *Ixora findlaysoniana*. *Hibiscus tiliaceus* and *M. citrifolia* were also relatively abundant. Other species encountered at this site included *Leucaena leucocephala, Barringtonia asiatica, Inocarpus fagifer, Mangifera indica, Adenanthera pavonina, Metroxylon sp., Artocarpus altilis, Terminalia cattappa*, and *D. umbellatum.* There was little physical damage to vegetation in this area with some exceptions. A single individual each of *Cananga odorata*, *Dysoxylum samoense, and Psidium guajava* were dead, apparently killed by defoliation following inundation. The wetland stand of *Erythrina fusca* was completely defoliated by the salt water inundation. According to the land owner, this occurred several days after the tsunami and he did not know if the trees would survive. Although there was some indication of regrowth near the base of the stems on many individuals there was significant top kill and it is unclear if the stand will recover. The herbaceous weed *Physalis angulata* (wiwao) was a prominent feature of the understory, likely re-growing following the near complete removal of herbaceous vegetation by the tsunami.

A single house in this area which was not fronted by substantial vegetation was partially destroyed. Fronting this vegetation was a low to moderate level of erosion with indication that some of the initial trees were destroyed by the wave. The village proper of Saleilua, just east of this vegetated area was not inundated by the tsunami given its elevation mostly above 6 meters. The UNESCO report found a maximum run-up elevation of nearly 4 meters and an inundation distance of approximately 23 meters near this village.

Figure 6. Inundated area at Saleilua, Samoa. West of village.

Table 3. Stem density and mean basal area of dominant shrubs and trees in vegetated area west of Saleilua village, Upolu, Samoa.

(Distance from Shore)	Avg. Plot Area	Relative density stems/ha				Mean basal area (cm^2/m^2 or m^2/ha)
		I. findlaysoniana	M. citrifolia	H. tiliaceus	Total	
(0-10m)	27.4	479.8	533.3	0	1510.0	13.4
(10-20m)	36.0	327.6	223.7	223.7	1118.3	36.1
(20-30m)	114.4	0	0	169.4	771.9	32.1
Averages	59.2	403.7	378.5	196.5	1133.4	27.2

A Unosat Image of the area, taken immediately following the tsunami, shows damaged areas which are similar to the findings in the field. In the area west of the village (figure 6), no damage is visible from the Unosat image probably due to the high cover of trees. The *Erythrina fusca* began to defoliate following the recording of post tsunami aerial imagery and no detectable damage was visible in those images.

Figure 7: Extensive Damage to a resorts structures at the Peninsula West of Saleilua

Figure 8: Trees remain standing at the Iliili resort although buildings in this area were completely destroyed. This area was partially cleared and represents a low density cleared forest.

Figure 9: Large boulders from a coastal seawall, including the one shown here, were carried over 100 meters inland by the wave.

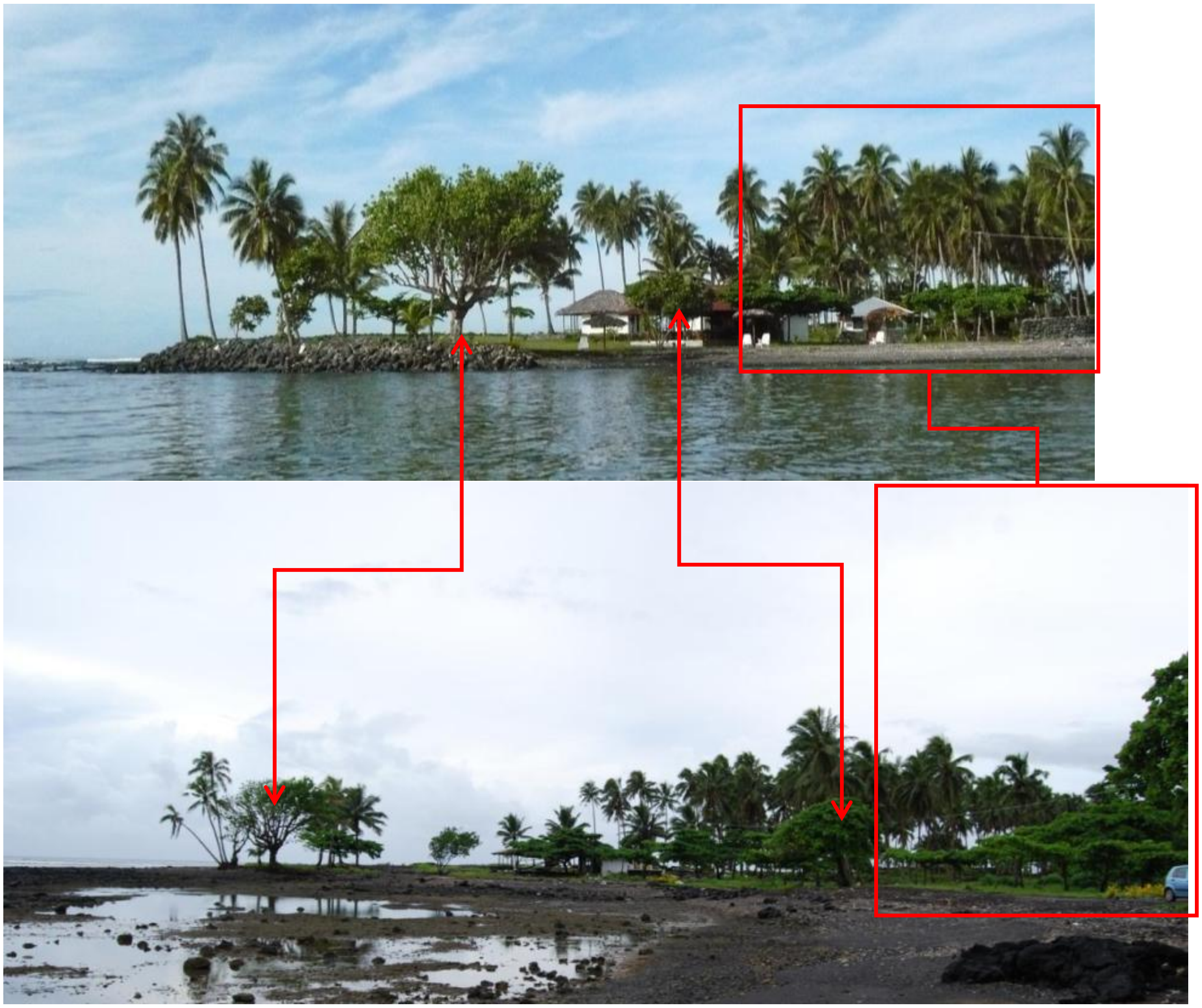


Figure 10. Before (top) and after (bottom) images at the Iliili resort in Saleilua. Nearly all the buildings at the resort were destroyed however most of the trees remained except several of the coconut trees closest to the coast. The rock wall facing the ocean was destroyed and rocks were carried inland up to 100 meters or more. Previous to the tsunami, this area had most of its coastal vegetation removed, the remaining trees did not provide a significant barrier to the tsunami wave.

Figure 11. Coconut tree roots planted near to a sea wall likely helped to prevent these rocks from being moved inland

Figure 12. This image shows the south edge of the densely forested buffer between the road to the Iliili beach resort and the coast. The vegetation is situated on (or may have contributed to the slight increase in elevation visible along the shore front.

Site 3: Tafatafa

At the Tafatafa Village site (figure 13), a coastal area 734 meters long was surveyed. Along this area there were areas with dense trees (a), areas with trees partially cleared (medium density) (b), and completely cleared portions (c). The elevation of inundation points were interpolated from the elevation contour GIS layer. In these areas there was very little erosion observed (even to un-vegetated areas) indicating that the effect from the tsunami was low. There appears to be very little difference in run-up elevation along this site. Four of the inundation points (176-179) are minimum estimates as the wave seems to have inundated the wetlands situated just behind these points, however there was no further sign of the inundation extent. In a simple regression using 1= forested and 0 = cleared on the inundation distance, there was no relationship between the variables ($F = 0.21$ $P = 0.664$) a regression of forested / cleared on the elevation at inundation points showed a statistically significant positive relationship between forested and the elevation. A positive affect between forest and inundation is an unlikely outcome and other variables are likely confounding the results in this case. The interpolation of elevation values are not able to detect fine scale differences in elevation which are not featured on the 2m interval GIS layer. It is a more plausible conclusion that the presence / absence or density of vegetation had no effect on inundation distance and run-up elevation at this site. One other possibility is that the team may have failed to detect the true inundation distance. This is possible if substantial regrowth of the understory had occurred. The elevation values ($n = 9$) were normally distributed (Anderson-Darling Normality Test A squared = 0.41 $P = 0.269$ while inundation distance was non-normally distributed (A squared = 0.79, $P = 0.025$) indicating that inundation distance was mostly dependent upon the run-up elevation.

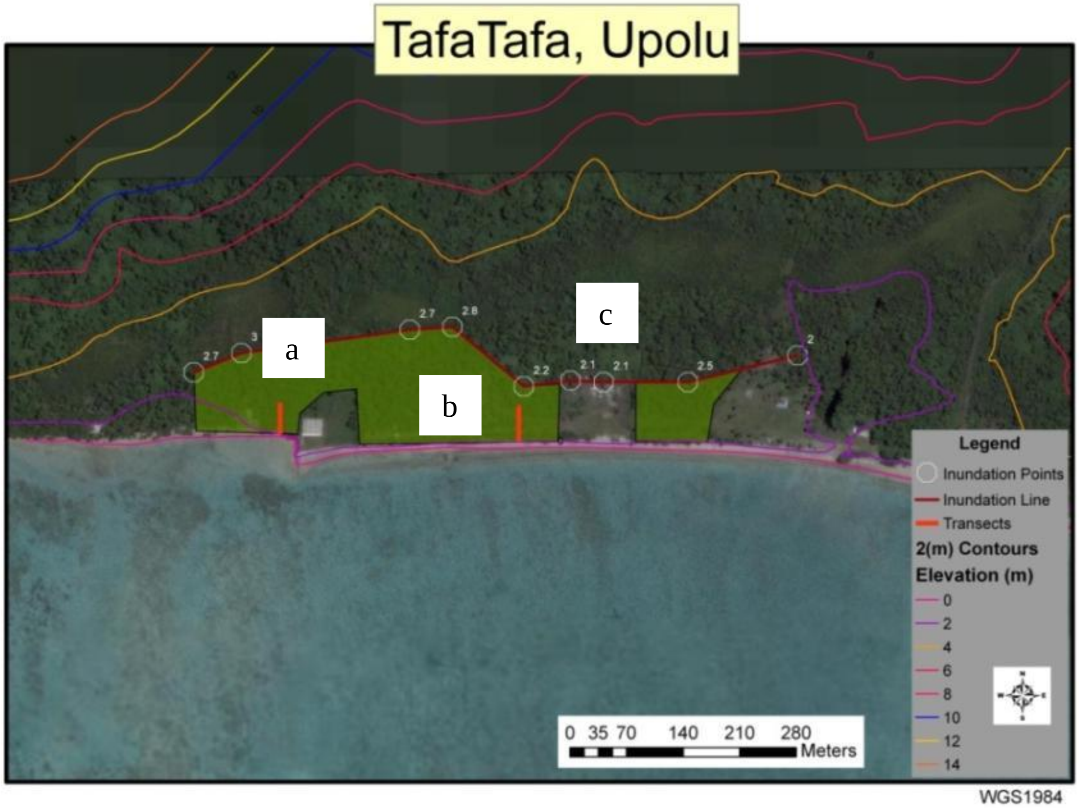


Figure 13. Inundated area at Tafatafa, Upoly, Samoa. This area consisted of dense forest (A), partially cleared areas of low density forest (B) and completely cleared areas (C). The presence, absence and density of forest did not appear to affect inundation distance or run-up height in this area.

The team completed two transects at the site. Tafatafa transect #1 was a partially cleared site likely part of a nearby beach fale establishment. Several beach fale showed moderate damage. At this site, most of the understory vegetation had been cleared resulting in a lower density of total stems (mean = 481 stems per hectare) compared with 2148 stems per hectare at transect #2.

Tafatafa transect #1 included what appeared to be predominantly planted vegetation. The most common species encountered in this transect was *Fluggea flexuosa* of which 4 out of 9 were dead likely due to inundation. *Morinda citrifolia* and *Flacourtia rukam* were the second most abundant species along the transect. Tafatafa transect #2 was a much more densely vegetated site. There was little to no observable damage to vegetation at both sites with the exception of the death due to salt water inundation of most individuals of *Fluggea flexuosa.*

Species encountered at this site include *D. umbellatum, Cerbera manghas, Barringtonia asiatica, Hernandia nymphaeifolia, Hibiscus tiliaceus, Callophyllum inophyllum, Morinda* *citrifolia, Leucaena leucocephala, Cocos nucifera, Ficus tinctoria, Fluggea flexuosa, Flacourtia Rukam, Glochideon ramiflorum, Premna serratifolia, Scirpodendron ghaeri, Sophora tomentosa*. Several *Fluggea flexuosa* in this area were dead.

Site 4: Utulaelae-Sapoe villages

The neighboring villages of Utulaelae and Sapoe (figure 14) represent an interesting case where vegetation may have provided significant protection from the full damaging effect of the tsunami wave. Utulaelae had previously cleared the vegetation fronting the village whereas the village of Sapoe maintained an approximately 30-50 meters wide strip of vegetation between the village and the shore.

To the west of Utulaelae the coastline shift toward the North and leads to a river approximately 0.5 kilometers away. Between the village and the river is a wetland known as Fusi pu which is primarily composed of the sedge and *Pandanus* look-a-like *Scirpodendron ghaeri.* The tsunami wave(s) moved through this wetland causing significant uprooting of this sedge however many were recovering. The leaves of this sedge presented a very useful indicator of the inundation distance of the tsunami. At the edge of the wetland these leaves were found up to 2.5 meters in the dense *H. tiliaceus* trees which bordered the wetland. (See points 82, 83, 84, 85, 87). The wave swept through the dense *H. tiliaceus* up to a run-up elevation of 4.5 meters, consistent with the run-up elevation in Utulaelae, Sapoe, and the forested area East of Sapoe.

Between the wetland and Utulaelae there were several low walls which seems to have held back the total inundation distance of the wave. Banana leaves from Utulaelae that were planted along the southwest corner of the village were swept into this area (see map Green Circles) and these met with leaves from the wetland sedge (see map Red Circles).

At the Utulaelae-Sapoe Site, 30 inundation points were recorded over a distance of 1.2 kilometers. The average inundation distance was 117.13 (stdev.=69.24) meters while the average run-up height was 4.2 +/- stdev. = 0.5981) meters above sea level. Eight of these points (72-79) were omitted from subsequent analysis since the wave in this area was obstructed by a number of low walls and the values recorded at these points do not represent the maximum inundation extent, another point (100) was omitted due to its close proximity to point 119. With the omitted points the mean inundation distance was 141.68 m stdev = 37.34 and for elevation 4.35 with a stdev of 0.6014. Both values were approximately normally distributed (Anderson-Darling Normality test Distance to shore p = 0.351, Elevation p = 0.083).

Utulaelae-Sapoe Villages (Upolu, Samoa)

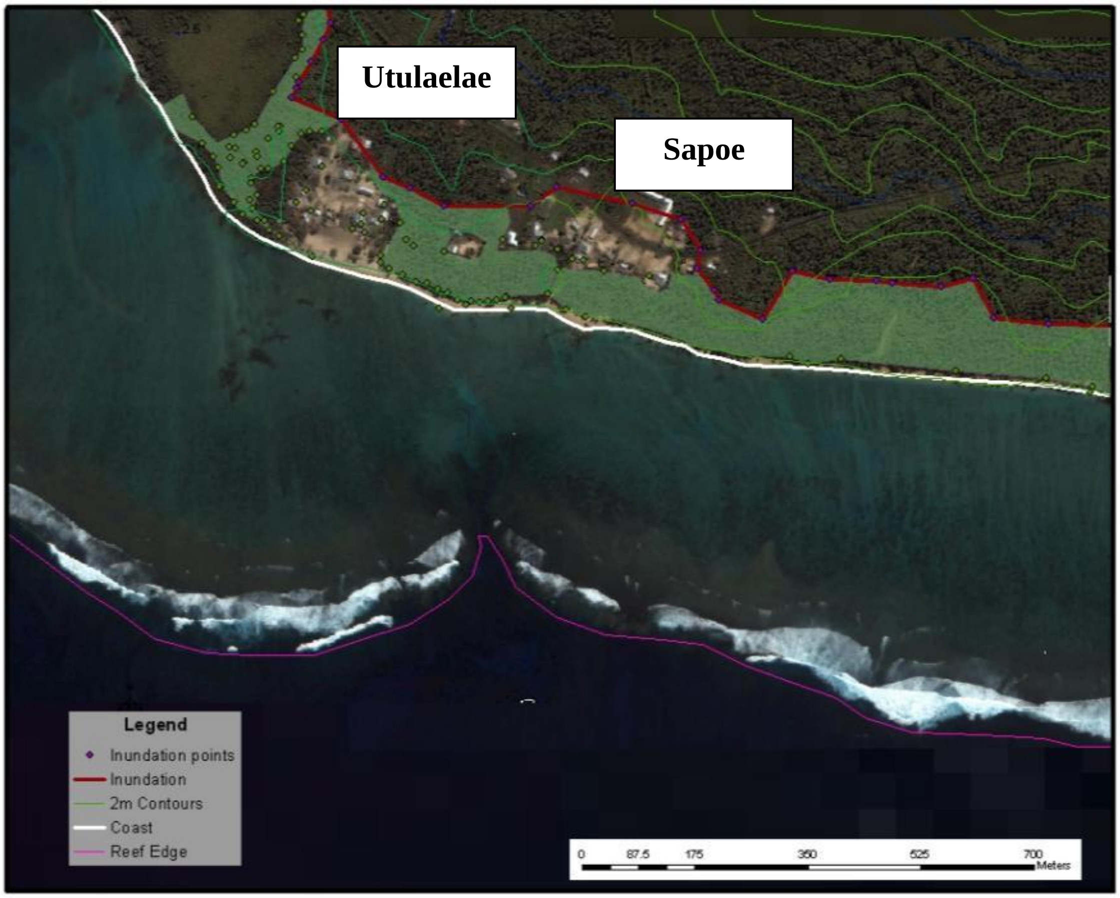


Figure 14. Inundated areas at Utulaelae and Sapoe villages. These villages primarily differed in the presence (Sapoe) and absence (Utulaelae) of a coastal forest between houses and the beach.

A correlation matrix was used to investigate the data, there were no apparent correlations between Elevation, Percent forested, distance to shore, and distance to reef. A regression of percent forested on the inundation run-up heights of the various points found no significant relationship (r^2 = 0% and p=0.922).

For the 29 houses assessed for damage in the area (figure 15), 19 were found to have little to no observable damage, (damage to contents was reported but not assessed as part of this study). Moderate to severe damage was observed to 10 structures (assessed damage value of 1). These included 4 post houses that were knocked over during the tsunami (assessed damage value of 2), 3 wooden frame houses that were destroyed (assessed damage value of 3), and 3 cement houses that sustained damage, two of which were completely destroyed (assessed damage value of 4), and one which sustained moderate damage to doors, and windows (assessed damage value of 2). Data was first explored using a correlation matrix. Significant p values were observed between the Damage value and Elevation (p = 0.011), Distance to shore (p=0.001) percent forested (p=0.005) and Reef length (p=0.016).

The elevation of structures in both villages were significantly different: T-Test of difference = 0 (vs. not = 0): T-Value = 3.75 P-Value = 0.003 DF = 12. The distance to shore between structures in the two villages were not significantly different T-Test of difference = 0 (vs. not =): T-Value = 0.73 P-Value = 0.479 DF = 16

		Elevation			Distance to shore		
	N	Mean	St Dev.	SE Mean	Mean	St Dev.	SE Mean
Sapoe	17	3.765	0.193	0.047	98.9	15.3	3.7
Utulaelae	12	3.125	0.567	0.16	92.7	26.8	7.7

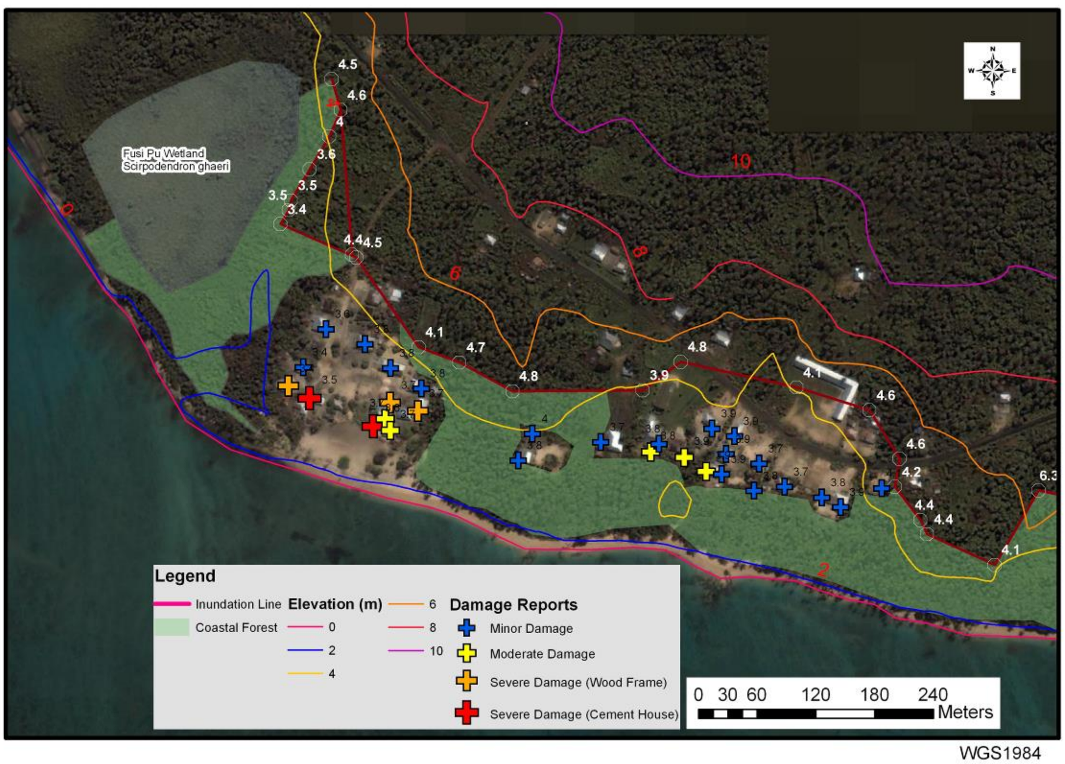


Figure 15. Damage assessments at Utulaelae and Sapoe villages, Upolu, Samoa. Damage was assessed on a three point scale, Minimal damage (Cosmetic Damage to structure or damage to contents only), Moderate damage (Structural damage requiring repairs), and Major damage (Damage to structure requiring rebuild).

Ordinal logistic regression analysis, using percentage forested, distance to shore, distance to reef and elevation on the response variable "Damage classification" was utilized. Only distance to shore and Percentage forested were significant variables and the ordinal regression was repeated with only these two predictive variables. Both variables was a significant predictor of damage Distance to shore ($p=0.008$ and Percentage forested ($p = .02$). Therefore, greater damage was associated with a closer distance to shore and with lower percentage forested.

Site 5: Saleapaga village

The tsunami was very powerful destructive in the area of Saleapaga (figure 16) as indicated by the highest wave heights and greatest levels of damage (Cite the UNESCO report). At this site, most of the coastal area had been cleared for villages and for the tourism industry. There were very few areas that had natural vegetation and nearly all houses in this area were destroyed. Satellite imagery shows vegetation behind the houses, most of this was destroyed by the tsunami wave and much of the debris had already been cleared in this area preventing us from making a clear assessment of the area (figure 16). A line of trees which were present at the coast remained standing allowing us to investigate the relationship between tree roots and erosion (See erosion section). This area had significant levels of erosion which removed a large amount of sand and altered the coast line.

The wave inundated the entire coastal plain and travelled several meters up the wall of the mountain. Inundation points were obtained however elevation contours were not obtained for this site and their analysis would not be appropriate given the very steep slope in this area and the restricted resolution of the teams GPS unit. The UNESCO study found a maximum run-up elevation of between 5 and 6.5 meters.

Figure 16. Inundated coastal plain showing debris field at Saleapaga.

Combined Vegetation Analysis

Nine variable area transects were carried out at 4 sites within the inundation zone, stem density and basal area were calculated based on the methodology of (Sheil et al. 2003). Using a General Linear Model with site and 4 plot distance categories, differences in stems per hectare among plots were found to be related to distance from shore and site. Differences between sites were highly significant ($F = 10.03$ $P < 0.001$) and with a general near-significant trend towards a greater number of stems closer to shore ($F = 2.94$ $P = 0.059$). Using a General linear model, there were no significant differences in mean basal area per plot either among sites or in distance to shore ($F = 0.80$ $P = 0.609$, $F = 0.51$ $P = 0.683$) (figure 17). These results include the partially cleared Tafatafa_1 site which had been cleared of most small trees and understory vegetation.

Table 4. Comparison of the number of stems per hectare by distance from the beach in 10 meter intervals. Statistical grouping uses the Tukey Method and 90.0% Confidence interval. Means that do not share a letter are significantly different.

Distance from Shore	Sample Size	Stems per hectare Mean (Stdev)	Grouping (Stems per hectare)	Basal area (cm^2/m^2 or m^2/ha) Mean (Stdev)
(0-10m)	9	1931 (1061)	A	51.4 (54.1)
(10-20m)	9	1550 (1098)	A B	37.86(18.56)
(20-30m)	7	1070 (455)	B	30.64(9.28)
(30-40m)	6	1211 (670)	A B	30.76(20.85)

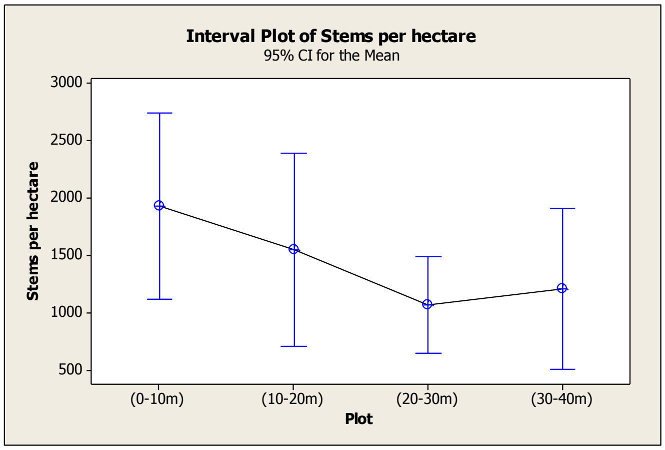


Figure 17. Statistical analysis of stems per hectare.

Survivorship of species encountered in inundated areas of all sites on the south coast of Upolu January 2010.

Overall there was little apparent damage to coastal species with the exception of the wetland mangrove *Bruguiera gymnorhizza.* Although this species was reported to survive well by the UNESCO report, the team observed many standing dead trees at several sites. Mortality was observed in eight additional species including *Cananga orodata*, *Dysoxylum sp.*, *Macaranga sp.*, *Musa sp*, *Psidium guajava.* Some individuals of *Artocarpus altilis*, *Fluggea flexuosa*, and *Pandanus tectorius* were found to have suffered some mortality however the team also found individuals of these species that had survived inundation. Identification was made of eleven species that were initially defoliated and which were slowly recovering. In some cases these species experienced top kill and were resprouting at the base. Twenty seven species appeared to be unaffected 110-130 days following the September 29, 2009 tsunami (Table 5).

Table 5. Species in inundated areas of Upolu Samoa 110-130 days following the September 29, 2009 tsunami

Species unaffected (27 species)
Adenanthera pavonina (n =3), Araucaria sp.(n = 2), Barringtonia asiatica (n = 7), Bischofia javanica (n = 1), Calophyllum inophyllum (numerous), Ceiba pentandra (n = 1), Cerbera manghas(n = 17), Cocos nucifera (numerous), Dendrolobium umbellatum (numerous), Erythrina variegata, Ficus elastica, Ficus tinctoria (n = 4), Geniostoma rupestre (n = 2), Glochidion ramiflorum (n = 3), Hernandia nymphaeifolia (n = 6), Hibiscus tiliaceus (numerous), Intsia bijuga, Ixora finlaysoniana (n = 7), Leucaena leucocephala (n = 7), Metroxylon warpurgii (n = 2), Morinda citrifolia (numerous), Pandanus tectorius(n = 8), Premna serratifolia (n = 5), Psychotria insularum (n = 2), Terminalia catappa (n = 10), Terminalia samoensis (n = 1), Thespesia populnea (n = 2).*
Species affected and recovered over time (11 species)
Artocarpus altilis (n = 2), Asplenium nidus (Numerous), Bruguiera gymnorhizza (Numerous), *Erythrina fusca, Flacourtia rukam (n = 7), Flueggea flexuosa* (n = 28 regrowing from base), *Inocarpus fagifer (n = 4), Mangifera indica (n = 3), Plumeria rubra (n =2), Scaevola taccada (n = 5), Scirpodendron ghaeri (numerous), Tournefortia argentea (n = 4)*
Species affected and not recovered (9 species)
*Artocarpus altilis (C)**, Bruguiera gymnorhizza* (numerous), *Cananga orodata (n = 1), Dysoxylum sp. (n=2), Macaranga sp. (n = 2), Musa sp.(numerous) (C), Pandanus tectorius(n = 2)*, (N), Psidium guajava* (n=2) *(N), Fluggea flexuosa* (n = 7) (approximately 20%),
Species encountered in inundated areas of Upolu Samoa 110-130 days following the tsunami. * *Pandanus* in open areas appeared to be unaffected by inundation whereas in areas with a dense over storey found instances of dead *Pandanus*. ** Observed was both dead and recovering Breadfruit trees. (The UNESCO report suggested that some varieties appear to have a higher level of tolerance of saltwater inundation.)

Erosion

At Saleapaga, tree roots held back soil and sand and the amount of soil and sand that was not removed due to the presence of the tree's roots was estimates by measuring the length / width and height of remaining sand behind the tree and calculated the volume of soil/sand held back by the roots. The team measured to the back of the adjacent groove, and it cannot rule out however that some of the groove area of the erosion front may have been exacerbated by an increase in flow velocity of the retreating water as it washed around the trees. Clear estimates measures from 13 coconut trees and 5 broad canopy coastal trees were made. The volume of soil/sand behind coconut trees was normally distributed (Anderson-Darling Normality Test: A squared = 0.22, P = 0.776.) with a mean of 5.248 m^3 (figure 18). This volume of sand is related to the width and depth of coconut roots, these are for the most part vertically oriented and extending 1-2 meters into the ground. It was not possible to get a significant sample size of the other species sampled. It appears from the limited data that other species would show a wide range of values depending upon the total size of the tree. Species and age may also be important factors that determine the volume of sand that these trees have the capacity to retain. Canopy extent may be a good indicator of total root extent which may estimate the potential volume of sand held back during a sudden coastal erosion event.

Table 6. Average volume of sand/soil remaining behind isolated trees at the coast in Saleapaga, Upolu, Samoa.

Species	Length (m)	Width (m)	Height (m)	Volume (m3)	StDev	Sample Size
C. nucifera	2.724545	2.127273	0.927272727	5.248	2.649	13
B. asiatica	3.245	2.35	1.1	9.79	11.93	2
H.nymph	2.18	5.25	0.53	6.0659	na	1
T.populnea	4.98	2.46	0.74	8.94	2.08	2

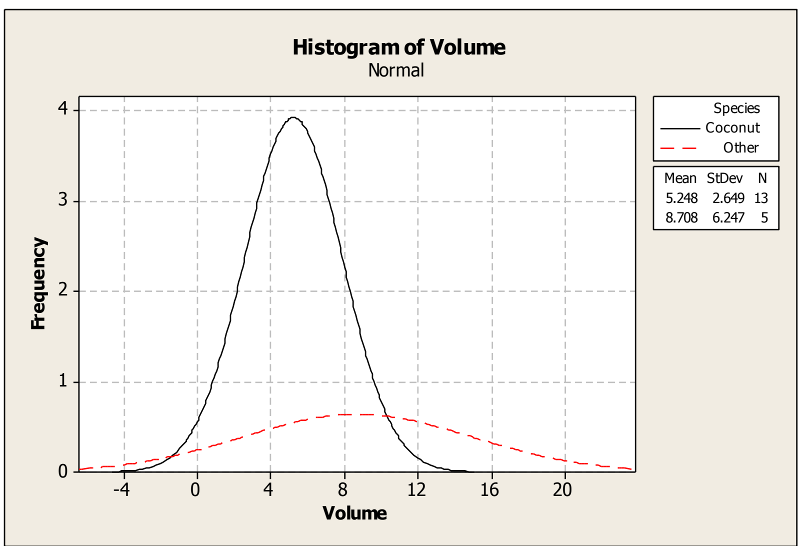


Figure 18. Histogram of the volume of sand/soil held back by isolated trees in Saleapaga village following the 2009 tsunami. Trees were classified into coconut tree and ‘other’ for this analysis.

The Coastal Flora of Hawaii

Introduction

The native coastal flora of Hawai`i has been significantly altered beginning with the arrival of the Polynesians (Kirch 1994). Coastal areas were among the first cleared for human use and extensive development at the coast for habitation, recreation, and tourism continues through the present day. Coastal ecosystems have also been impacted by clearing for agriculture and by the introduction of alien ungulates, rodents, and invasive plant species. As a result, the coastal ecosystems of the main Hawaiian Islands are highly altered from their pre-human state and in fact very little remains to provide evidence for what the coasts of Hawai`i looked like prior to humans arrived.

There have been several efforts to characterize the coastal vegetation communities in Hawai`i and to define the environmental factors that structure them. The most recent treatments include a detailed analysis of coastal ecosystem on Oahu (Richmond and Mueller-Dombois 1972) as well as descriptive summaries of coastal ecosystem from the entire Hawaiian archipelago (Gagne and Cuddihy 1990, Mueller-Dombois and Fosberg 1998). A more recent work provides an up to date assessment of the remaining native coastal vegetation communities (Warshauer et al. 2009).

Richmond and Mueller-Dumbois (1972) conducted transects and vegetation releves at 22 locations on Oahu. They documented 13 ecosystem types characterized by the following dominant species or species combinations, *Hibiscus tiliaceus, Scaevola taccada, Chlois barbata/Sida fallax, Chloris barbata/Prosopis pallida, Prosopis pallida, Batis maritima, Rhizophora mangle*, and *Scirpus californicus/Eichornia crassipes.* Of these, *Prosopis pallida* (mesquite, kiawe) and *Rhizophora mangle* (Red Mangrove) are the only true tree species, *Hibiscus tiliaceus* is a large “megashrub” and *Scaevola taccada* is a medium shrub. The remaining ecosystem types represent coastal grasslands or wetlands. The authors argue that coastal ecosystem on Oahu are primarily structures by wind exposure, rainfall, and substrate salinity. The later factor is somewhat dependent upon soil characteristics and hydrological properties of the area. Further the authors define the coastal floristic zone as the inland extent of: saltwater inundation, effects of salt-laden wind, and development of coastal geomorphic formations such as dunes.

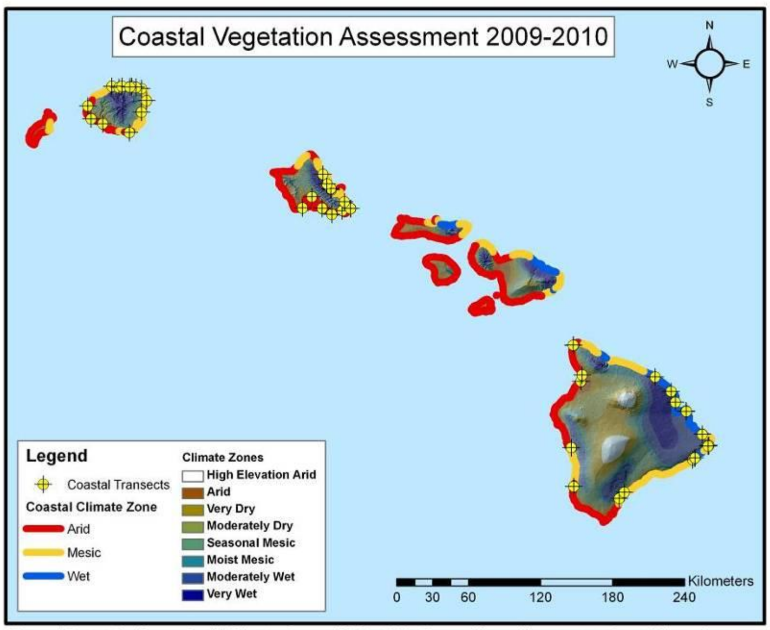
In their detailed description of vegetation communities throughout the island, Gagne and Cuddihy (Gagne and Cuddihy 1990) classified vegetation into three climate zones based on annual rainfall: Dry (<1,200 mm), Mesic (1,200-2,500 mm), and Wet(>2,500 mm) and into 5 physiognomic classes based on vegetation characteristics: Herblands, Grasslands, Mixed communities, Shrublands, and Forest (Table 7). In addition to rainfall, Gagne and Cuddihy list wind/wave exposure, substrate type, human disturbance, and the unique history of evolution and introduction of species as factors shaping the composition of coastal forests in Hawaii today. It is important to note that of the 25 vegetation types listed, 17 represent native species dominant ecosystems. However, only two of the coastal forest ecosystem, *Pandanus* and *Pritchardia* forests, are dominated by native species and both ecosystem types are very rare.

Table 7. Coastal vegetation communities by rainfall zone and physiognomic character as described by Gagne and Cuddihy (1990). Each community is listed by dominant species or dominant species combination.

Physiognomic class	**Dry (<1200 mm)**	**Mesic (1200-2500 mm)**	**Wet (>2500 mm)**
Herblands	*Nama* *Sesuvium*		*Batis*
Grasslands/ Sedgelands	*Sporobolus* *Eragrostis* *Lepturus*		*Schoenoplectus/Bolboschoenus/Cyperus*
Mixed Communities	*Sida* *Sida/Chloris*		
Shrublands	*Scaevola* *Sida* *Gossypium* *Heliotropium* *Santalum* Coastal cliff community *Chenopodium* *Myoporum* *Leucaena*		*Hibiscus* *Pluchea*
Forests	*Prosopis*	*Pandanus* *Pritchardia* *Casuarina*	*Bruguiera/Rhizophora* (Mangroves)

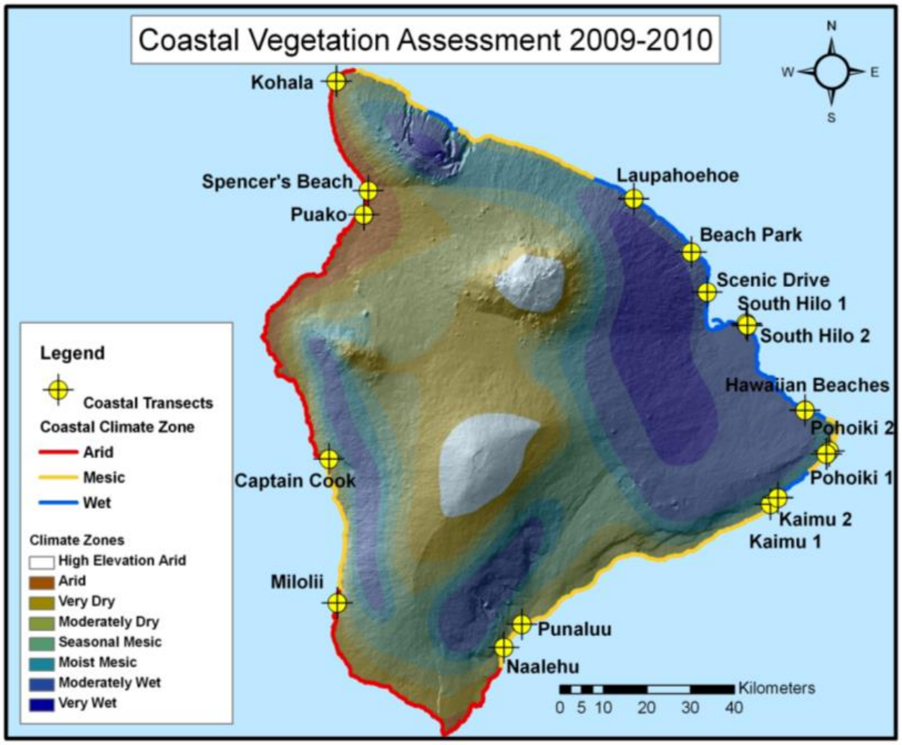
Methods

From November 2009 through August 2010 researchers from the Tropical Landscape and Human Interaction Lab “the team” conducted transects along 41 sites at coastal areas on Kauai, Oahu, and Hawaii (the Big Island) (Figure 19-22). Three separate methods were used to assess vegetation depending upon site conditions. At 41 sites the variable area transect method was used to a maximum of 50m from the start of woody vegetation. At three sites, the team recorded only a list of species present and at two sites used 10x5m or 10x10 m plots.



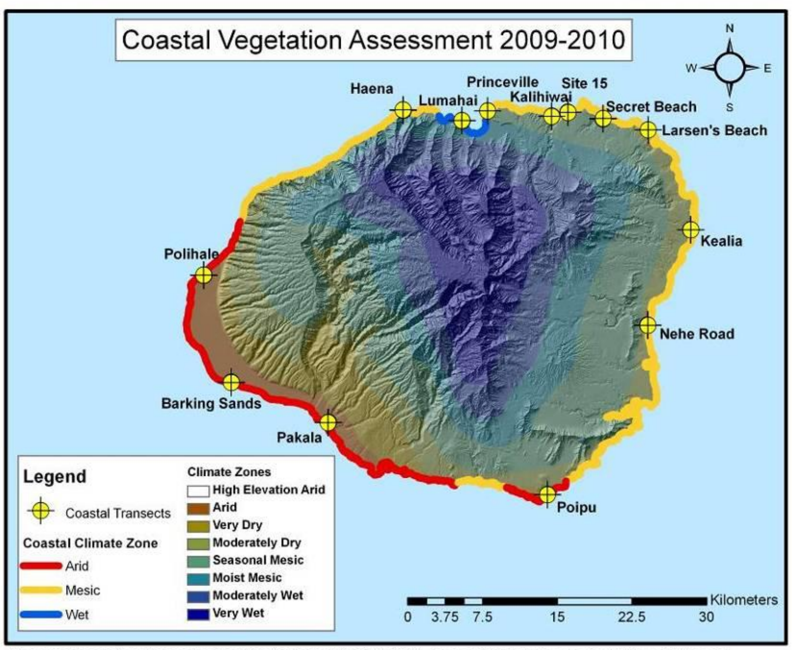
Tsunami Evacuation Zones: Pacific Disaster Center (PDC), 1998. Tsunami Hazard Assessment: Coastal Hazard Analysis Report 2009, Climate Zones: Price et al. 2008. Base Layer: Hawaii Digital Elevation Model USGS

Figure 19. Coastal vegetation assessments were carried out at 41 sites on three islands in Hawaii.



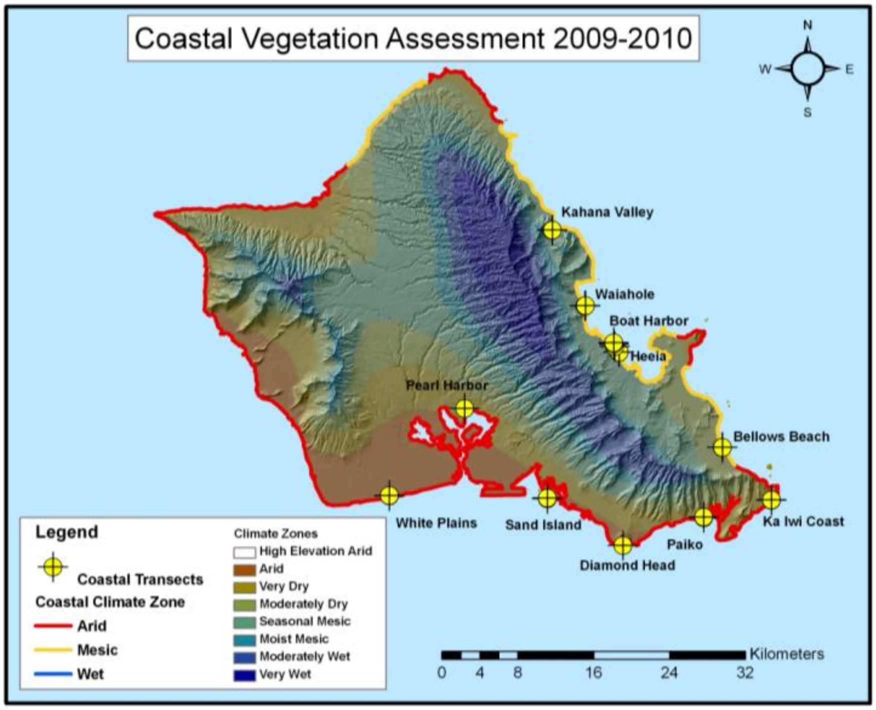
Tsunami Evacuation Zones: Pacific Disaster Center (PDC), 1998. Tsunami Hazard Assessment: Coastal Hazard Analysis Report 2009, Climate Zones: Price et al. 2008. Base Layer: Hawaii Digital Elevation Model USGS

Figure 20. The variable area transect method was used at all 17 sites on the Big Island Hawaii.



Tsunami Evacuation Zones: Pacific Disaster Center (PDC), 1998. Tsunami Hazard Assessment: Coastal Hazard Analysis Report 2009, Climate Zones: Price et al. 2008. Base Layer: Hawaii Digital Elevation Model USGS

Figure 21. The variable area transect method was used at 13 sites on Kauai while a list of species only was taken at Princeville



Tsunami Evacuation Zones: Pacific Disaster Center (PDC), 1998. Tsunami Hazard Assessment: Coastal Hazard Analysis Report 2009, Climate Zones: Price et al. 2008. Base Layer: Hawaii Digital Elevation Model USGS

Figure 22. The variable area transect was used at eight sites on Oahu. 10x5 and 10x10 m plots were used at the Boat Harbor site while species lists only were taken at Pearl Harbor and Diamond Head.

Sites were selected based on accessibility; as the team was restricted to sites that could be accessed by public roads or right of ways. In addition it was attempted to represent as many coastal vegetation types as possible. A third criterion of selection attempted to represent a great range of climate variability. Sampling was conducted from sites that represented each of the recognized moisture zones present on the three islands (Price et al. 2007) (Table 8). In this classification, zone 1 represents the most arid zone and zone 6 represents the wettest zone. The sites represent a range of average annual rainfall from 244 mm at Puako (Big Island) to 3465 mm of annual rainfall at Laupahoehoe (Daly and Halbleib 2006).

Table 8. Moisture zones for each assessment site by island. Moisture zones based on Price et al. (2007).

Island	**Moisture Zone 1**	**Moisture Zone 2**	**Moisture Zone 3**	**Moisture Zone 4**	**Moisture Zone 5**	**Moisture Zone 6**	**Total**
Big Island	2	2	3	4	1	5	17
Kauai	3	1	1	5	1	0	11
Oahu	3	3	3	4	0	0	13
Total	**8**	**6**	**7**	**13**	**2**	**5**	**41**

The sites also differed by several other variables including shoreline substrate, level of wind/wave exposure and elevation above mean sea level. Fifteen sites were dominated by a lava rock coast and shallow lava substrate. All of these sites were on the Big Island. Two Big Island sites had a mixed lava rock /coral sand substrate. In contrast, all of the Kauai sites had a coral sand coast and mixed sand/soil substrates. The Oahu sites had a variety of substrates including seven sites with mixed sand/soil substrates, two sites dominated by clay mudflats, and three sites with a shallow raised limestone substrate. Most sites were within 2 meters of sea level. However, also included are three sites on the big island which had substantial elevation above sea level. This includes Kaimu site 2 (16 m), "Scenic Drive" (20m) and Kohala (10m).

Finally, sites were selected where the vegetation was not obviously managed or maintained, however all coastal sites in Hawaii exhibit some degree of direct human impact including clearing, harvesting of some species, and the creation of paths and trails. A random approach was initially attempted to sites selection however, due to the high degree of human impact resulting in a large number of unsuitable sites, the team employed a non random approach to site selection where for a given accessible location they selected an area of vegetated coast that was relatively free of clearings, buildings and beachgoers.

A transect starting point was selected at each site that would place the transect (up to 50m long) within coastal vegetation and which would allow for access along the transect. Each transect was set perpendicular to shore and the starting point was placed at the first woody vegetation inland from the coast. For each 10 meters along the transect, a variable area plot was established on either side of the transect line for a maximum of 10 variable area plots. The dimensions of each plot (10 * x) was determined by the distance from the transect line to the centerline of the fifth tree with a DBH greater than 5cm up to a maximum plot dimension of 10x20 m if 5 trees of DBH > 5cm could not be located within a distance of 20m. The team recorded DBH (diameter at breast height), DDH (Diameter at decimeter height), and estimated total height and estimated height of the lower canopy for all trees within the plot with DBH greater than 5cm. All trees, smaller than 5cm DBH, along with shrubs and herbaceous species were tallied and growth form and heights recorded. In some cases transect were truncated in length or were altogether not possible due to clearings or obstructions. In these later cases, a species inventory was taken of species falling within approximately 50 meters from the top of the beach. At all sights a list of species that was encountered in the nearby vicinity (approximately within 0.5km of the transect origin point) but not recorded within transects was recorded. For all sites, an estimate of annual rainfall (Daly and Halbleib 2006), and the moisture zone (Price et al. 2007) was recorded. The team made an assessment of “exposure” based on storm exposure assessments from the Hawaii Coastal Group’s (Fletcher et al. 2002). Areas protected from significant wind/wave action by reefs or by coastal topology were given an exposure rating of “Low” and areas with direct exposure to prevailing winds and subject to strong wave actions were assessed a “high” exposure rating. These roughly correspond to the “High” and “Low” ratings for “High Waves” and “Storms” assessed by Fletcher et al. (2002).

Results

The 41 sites represented assemblages with 22 different dominant tree species or species combinations (Table 9). The Big Island had the greatest diversity of sites based on the total number of different dominant tree species with 14 assemblages. Kauai had the second most with 8 separate assemblages followed by Oahu with seven. The most commonly encountered dominant species was *Casuarina equisetifolia* which was the sole dominant species at 7 sites on all islands. *Prosopis pallida* or *P. juliflora* was the dominant species at 6 sites on all islands and *Terminalia cattappa* was the dominant species at five sites in Kauai and was a co-dominant species in sites on the Big Island and Oahu.

In total, 111 species were identified from 41 sites. The most often encountered species included *Cocos nucifera* (30/41 sites), followed by *Casuarina equisetifolia* and *Scaevola taccada* (28/41 sites), *Pandanus tectorius* (21/41 sites), *Leucaena leucocephala* and *Terminala catappa* (19/41 sites), *Sporobolus* virginicus (18 sites), *Thespesia populnea (milo)* (16 sites), *Tournefortia argentea* (14 sites), and *Pluchea spp.* (13 sites). Of these, only *S. taccada, P. tectorius*, *T. populnea*, and *S. virigincus* are native species, *C. nucifera* is a Polynesian introduction, and the remaining species are more recent human introductions. Fifty four species were found at only one or two sites.

Table 9. The dominant canopy species encountered at assessment sites by island.

	Dominant Species or species combinations	**Big Island**	**Kauai**	**Oahu**	**Total**
1	*Casuarina equisetifolia*	3	2	2	7
2	*Casuarina equisetifolia / Pandanus tectorius*	1	0	0	1
3	*Coccoloba uvifera*	1	0	0	1
4	*Cocos nucifera/Pandanus tectorius*	1	0	0	1
5	*Cordia subcordata/ Pithocellobium dulce*	1	0	0	1
6	*Leucaena leucocephala*	1	0	0	1
7	*Pandanus tectorius/ Metrosideros polymorpha*	1	0	0	1
8	*Pandanus tectorius/ Psidium spp.*	1	0	0	1
9	*Prosopis pallida or P. juliflora*	1	1	4	6
10	*Prosopis pallida/ Cocos nucifera*	1	0	0	1
11	*Prosopis pallida/ Pithecellobium dulce*	0	1	0	1
12	*Prosopis pallida/Scaevola taccada*	0	1	1	2
13	*Rhizophora Mangle / Terminalia cattappa*	0	0	1	1
14	*Scaevola taccada/ Metrosideros polymnorpha*	1	0	0	1
15	*Terminalia catappa*	0	5	0	5
16	*Terminalia catappa/Pandanus tectorius*	2	1	0	3
17	*Thespesia populnea*	1	0	0	1
18	*Thespesia populnea/ Bruguiera sexangula*	0	0	1	1
19	*Thespesia populnea/ Terminalia cattappa*	0	1	1	2
20	*Tournefortia argentea*	0	1	0	1
21	*Tournefortia argentea/ Schinus terebinthifolius*	1	0	0	1
22	*Various*	0	0	1	1
	Count of dominant canopy species assemblages	**14**	**8**	**7**	**22**

Stem density at sites (which includes only tree species with a DBH greater than 5.0 cm ranged from 25 or 30 stems per hectare to 1752 stems per hectare. There is a significant positive relationship between annual rainfall and stem density (per ha) (Pearson coefficient of 0.358, P= 0.030). This relationship is stronger when sites dominated by *Casuarina equisetifolia*, which forms stands with widely spaced large diameter trees, were removed (Pearson coefficient = 0.451, P = 0.014).

Similarity among sites was assessed for all locations using Bray Curtis similarity/dissimilarity as implemented in Primer version 6. In the first analysis, a matrix of presence/absence data for all species encountered was used along with 999 simulation permutations of the data to test for significance of the similarity measure. The resulting similarity dendrogram indicates four major groups (indicated by black lines leading to groups of red lines, red indicates that no further substructure is supported in the statistical analysis, Figure 23). A Spearman rank correlation of the following environmental variable: Island, substrate type, annual rainfall (mm), moisture zone, exposure, and dominant canopy species indicates that a combination of two environmental variables “Moisture zones” and “Exposure” best explained the similarity/dissimilarity between sites (Spearmen Coefficient = 0.427, significant at the .01 level). The Spearmen Coefficient can be interpreted as meaning that the combination of these two variables was sufficient to explain 42.7% of the variability among sites. The same results were also visualized using non-metric multi-dimensional scaling (MDS) which expresses the variation in the data along a 2 dimensional plane (Figure 24).

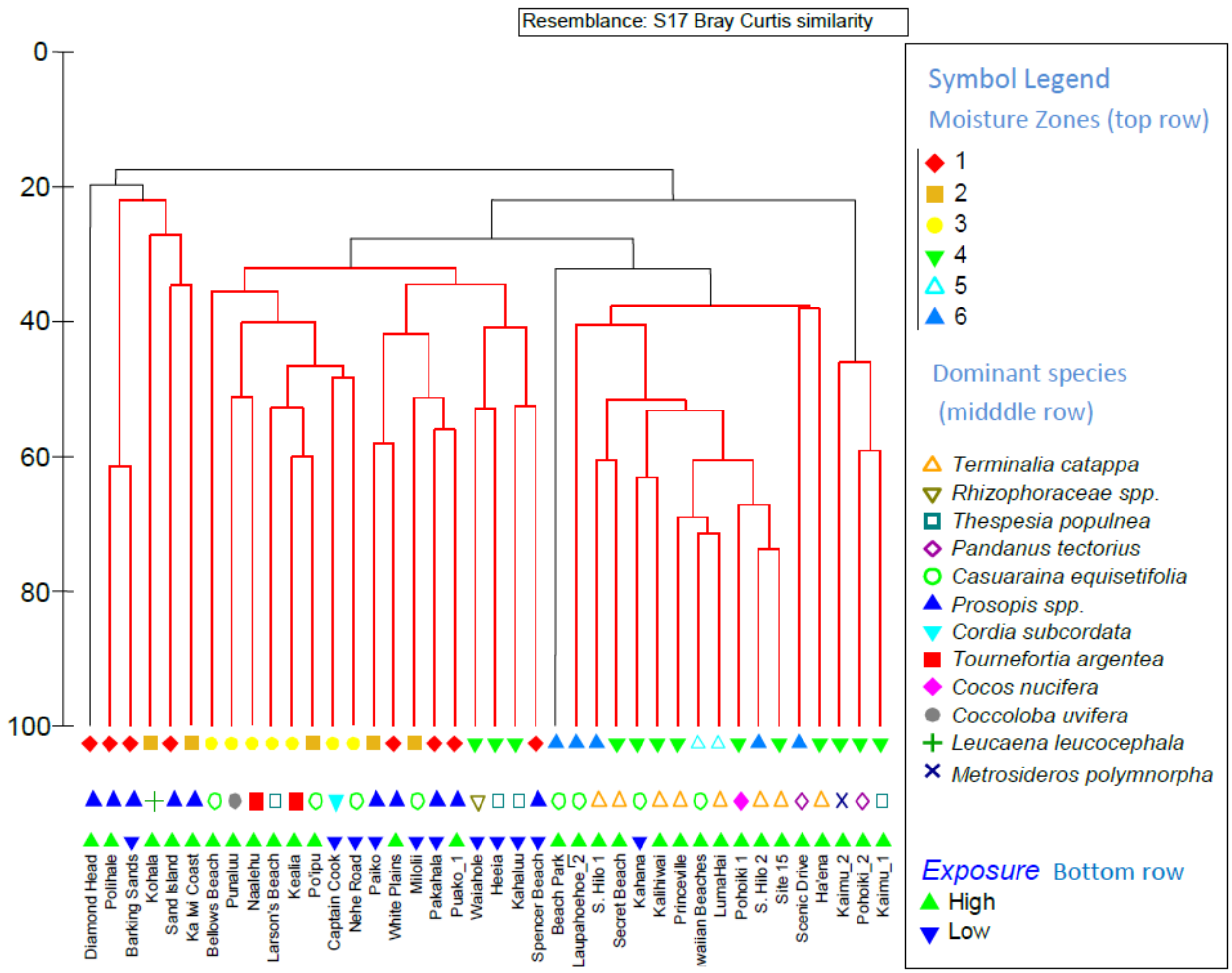


Figure 23. Dendrogram of Bray Curtis similarity among sites based on species presence/absence. 999 simulation permutations of the data were used to assess significance of similarity. Relationships indicated by black lines are statistically supported while no significant substructure was detected among samples represented by red lines.

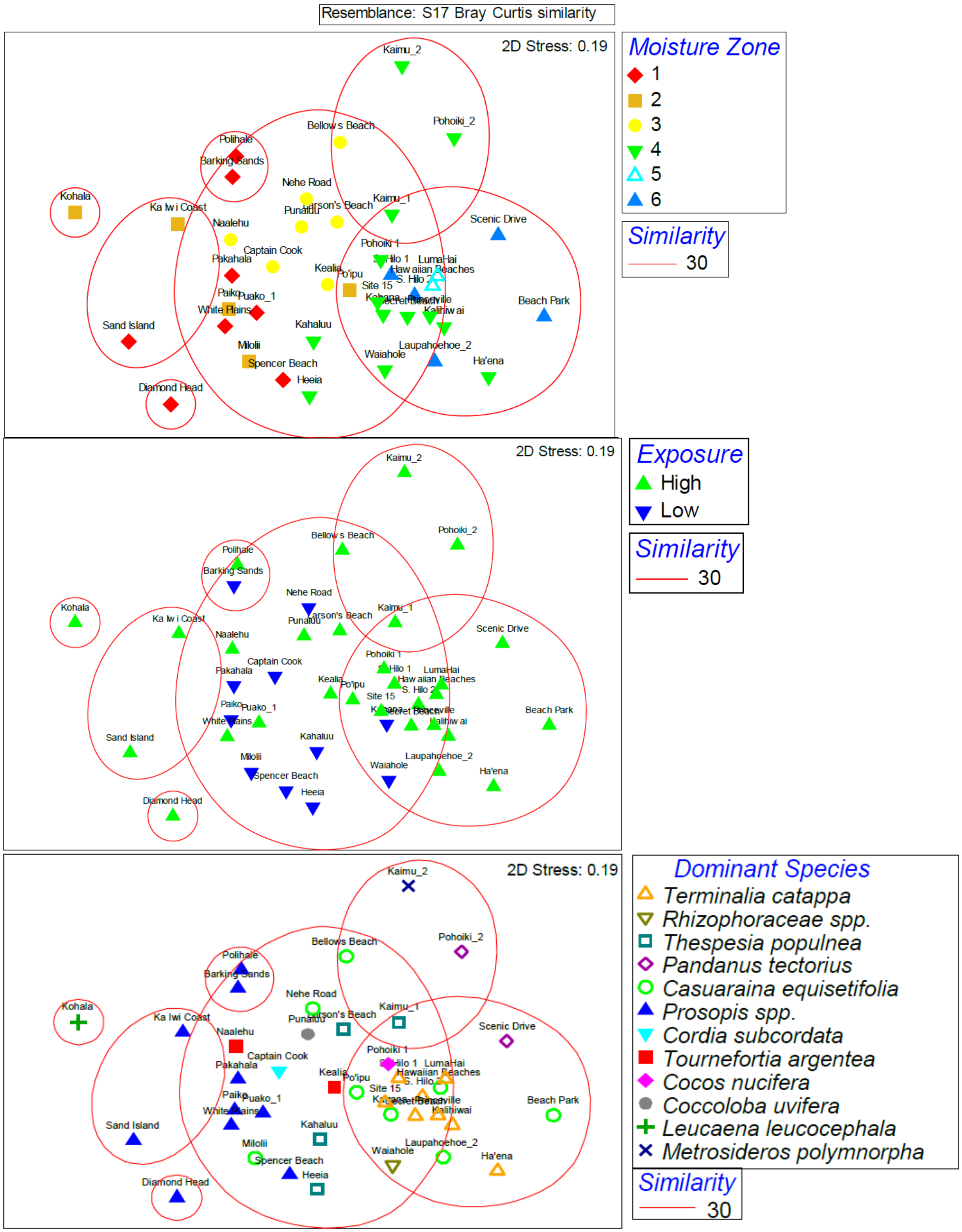


Figure 24. A non-metric multi-dimensional scaling ordination of species presence/absence data for 40 sites. Euclidean distance between points represents Bray-Curtis similarity. Red polygons representing similarity at the 30% level are drawn.

In a separate analysis, only sites for which transect and plot data was available were used to assess similarity/dissimilarity among tree species only. This analysis therefore excludes understory species. As in the previous analysis, Bray Curtis similarity/dissimilarity was used and visualized with both a dendrogram and with MDS (Figure 25-26). This analysis indicated 5 groups with significant similarity among samples along with several outliers. Once again climate as represented by the moisture zones together with exposure level were the most important environmental factor influencing variability among sites Spearman coefficient = 0.393).

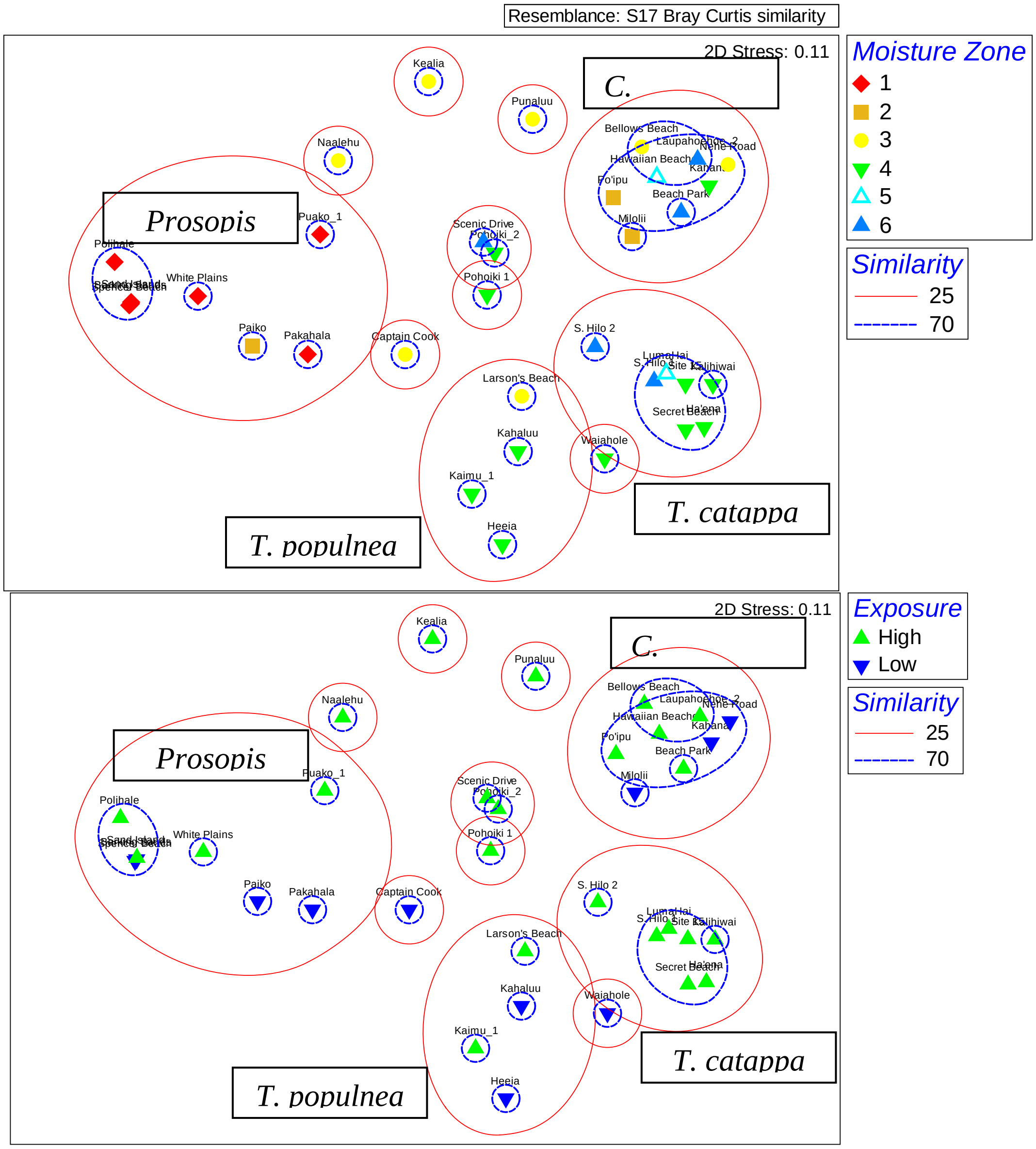


Figure 25. A non-metric multi-dimensional scaling ordination of dominant tree species abundance for 33 sites. Euclidean distance between points represents Bray-Curtis similarity. Red polygons representing similarity at the 30% and 70% levels are drawn.

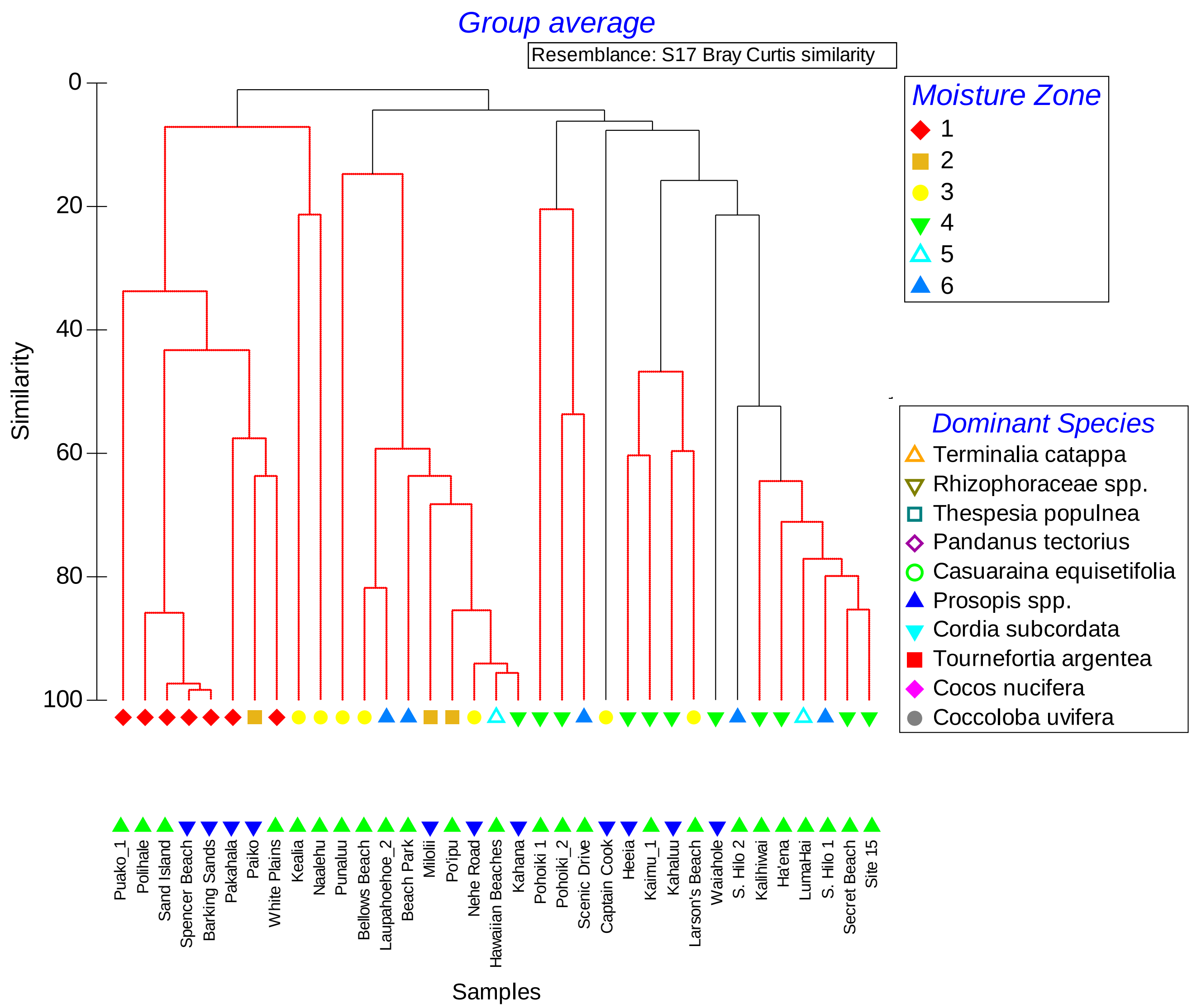


Figure 26. Dendrogram of Bray Curtis similarity among sites based on tree species abundance. 999 simulation permutations of the data were used to assess significance of similarity. Relationships indicated by black lines are statistically supported while no significant substructure was detected among samples represented by red lines.

Discussion

The coasts of Hawaii are dominated by a few communities dominated by alien plant species. Which community establishes at a given site is primarily dependent upon the amount of available moisture. Moisture in most cases is in the form of rainfall, however the availability of groundwater source likely has an important impact on the species assemblage at a given site. The presence of surface water, its salinity and depth are also important environmental factors structuring the vegetation community. A second main category of environmental variables structuring the coastal environment is the level of exposure to salt water inundation or persistent or seasonal salt spray. Periodic inundation or salt spray acts as a disturbance in the coastal ecosystem which will tend to remove species which are not tolerant to salt stress. Disturbance in this context will restrict the vegetation community from undergoing succession towards more diverse assemblages. The lack of salt spray or periodic inundation therefore tends to either allow succession from coastal strand pioneer species towards later successional diverse forest or allows lowland forests to invade the coast. Finally, there is a great deal of human impact on coastal vegetation, this often takes the form of clearing to make way for grassland parks, housing or tourism development. Many of these activities reduce the availability for coastal vegetation. Other human activities, such as the planting of *Casuarina* forest in coastal areas during the early 1900's, changes the community structure and successional trajectory of widespread areas of coastal vegetation.

This assessment identified three widespread dominant species assemblages and several less widespread or locally restricted assemblages. The most common coastal forest dominant tree species are *Casuarina equisetidolia*, *Prosopis pallida*, and *Terminalia catappa*. Several other rare or locally restricted assemblages were found including *Tournefortia argentea* forest and native *Pandanus* forest and *Pandanus/Metrosideros* coastal forest on the Big Island.

Casuarina equisetifolia was introduced to Hawaii prior to 1882 (Wagner et al. 1990) and was widely planted in coastal areas during the early 20th century as a windbreak (Figure 27-31). *Casuarina* typically forms monotypic stands although it is sometimes found in association with *Pandanus tectorius*. *Casuarina equisetifolia* has likely replaced native *Pandanus* forest and may have also replaced native *Thespesia populnea* forests in drier areas. This species is found in every moisture zone and substrate type along all coasts of all islands surveyed. It establishes in areas with both high and low wind/wave exposure and in flat sandy areas as well as on rocky areas and steep cliffs. *Casuarina* forms nearly monotypic stands with limited understory development. This is potentially due to allelopathy since the branch and leaf structure of a *Casuarina* canopy usually allows in a substantial amount of light. This species is also potentially self allelopathic. Seedlings of *C. equisetifolia* are rare under its own canopy but tend to be prolific on nearby areas such as on exposed otherwise unvegetated sandbars on Kauai. Trees however produce root suckers which in some cases may grow to form an independent tree. *Casuarina* can appear shrub-like and can form dunes particularly if left unmanaged and if its canopy is allowed to grow to the ground along the top of the beach.

Figure 27. Typical *Casuarina* Forest. Shown here from Bellows Beach Oahu.

Figure 28. *Casuarina* forests were planted in coastal areas in the 1900's as a windbreak. These forests form low density nearly monotypic stand where few other species are capable of establishment.

Figure 29. The understory of *Casuarina* forests is typically only sparsely vegetated. This may be due to a combination of shading as well as allelopathy. *Casuarina* seedlings are also rare indicating potential self allelopathy.

Figure 30. *Casuarina* will take on a windswept form and will contribute to dune formation in high exposure areas when left unmanaged. Images above from the Windward coast of Kauai show the outside (top) and interior view (bottom) of a windswept tangle of *Casuarina* under which a sand dune approximately 1.5 meters high has formed.

Figure 31. *Casuarina* established well on areas with a high slope including on sheer cliff faces.

Terminalia catappa was the second most common dominant tree species in coastal areas, particularly in mesic and wet coastal areas (moisture zones 4-6) with high levels of exposure (Figures 32-36). This alien species was introduced prior to 1871 (Wagner et al. 1990). *Terminalia catappa* fruit are buoyant and quickly spread coastally. Once established, this species out-competes other coastal trees by forming a thick canopy which excludes most sunlight and by developing a dense seedling and sapling bank which can take advantage of new openings in the overstory canopy. Very little development was observed in the understory of *T. catappa,* however unlike *Casuarina* which likely limits establishment through allelopathy, *Terminalia* forms a dense canopy which inhibits establishment of other species through light limitations. *Terminalia cattapa* appears limited to relatively flat coastal areas and does not establish on very rocky areas or on cliffs. *Terminalia cattapa* is often found in association with *Pandanus tectorius* and appears to be strongly competing with this native species. This species seems to be very actively colonizing and subsequently dominating new sites, particularly on Kauai.

Figure 32. Typical *Terminalia catappa* forest

Figure 33. Seeds and seedlings of *Terminalia catappa* often carpet the understory of *T. catappa* forest.

Figure 34. *Terminalia catappa* are often found growing in association with Pandanus tectorius. Pandanus appears to have an advantage in areas with steep slope.

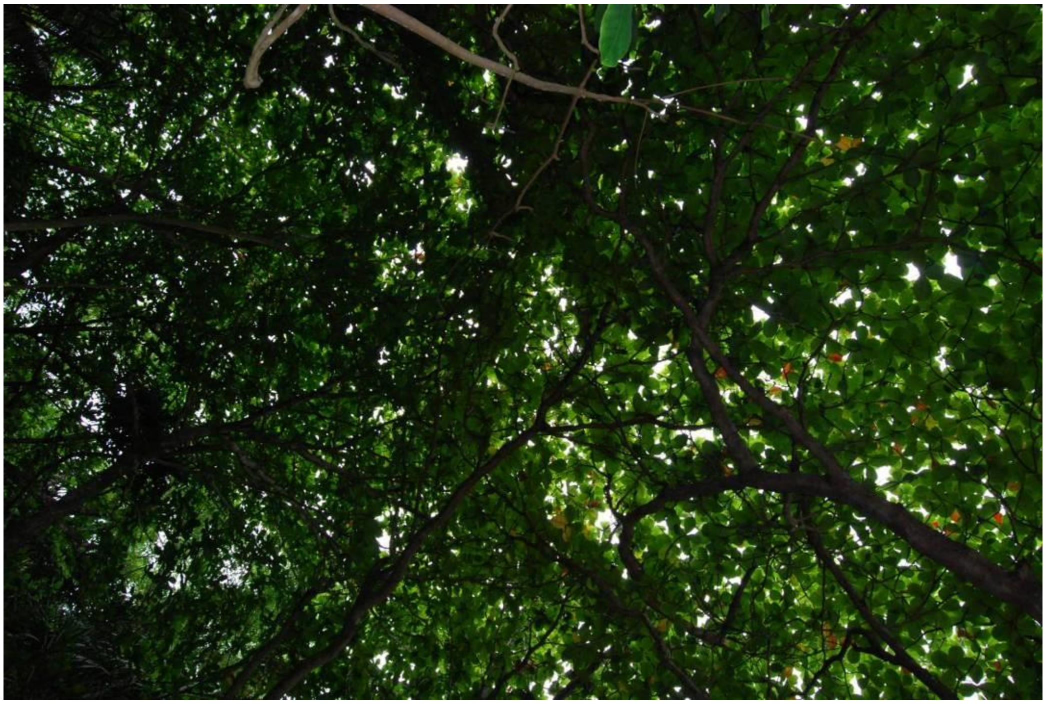


Figure 35. *Terminalia* canopy is often very thick allowing very little light to reach the understory below.

Figure 36. In many cases a dense seedling or sapling bank of T. catappa is found under *Terminalia* forest often to the exclusion of other species.

Prosopis pallida, and in some areas of ‘Oahu its congener *P. juliflora*, are the dominant tree species in the arid areas of Hawaii’s coasts (Figures 37-40). These species can assume either a tree-like or shrub-like growth form depending on local conditions. Both species form sharp thorns, however those of *P. juliflora* are much longer, up to 3 inches. The thorns of this species, was a significant source of casualties in Tamil Nadu State, India during the 2004 Indian Ocean tsunami (Kathiresan and Rajendran 2005). There are thornless varieties of *P. pallida* which are grown from cuttings and are sold commercially by local nurseries. *Prosopis pallida* was introduced in 1828 to Oahu and quickly spread to arid areas of all islands. This species had been called a "Blessing of the wastes" in the 1900's because due to deforestation, there were no other trees providing significant shade in many of the dry coastal areas of Hawaii. *Prosopis juliflora* was introduced to Oahu in the early 1970's. *P. pallida* is an important species for modern cultural practice in Hawaii due to its use as the favored fuel source for Hawaiian earth ovens (`imu). It replaces traditional native wood sources such as *Metrosideros polymorpha* or *Sophora chrysophylla* which are now rare or even absent from some islands. *Prosopis spp*. are restricted to moisture zones 1 and 2 and they can grow in most substrates from sand to relatively new lava. *Prosopis pallida* seed production is limited in areas with high exposure although this does not appear to be the case for *P. juliflora* (Gallaher and Merlin 2010). These species often form relatively pure stands with few other tree species. Recruitment of these species is somewhat limited by bruchid beetles and rodents which consume seeds, rodents also possibly consume seedlings. *P. pallida* can sometimes be found growing in association with *Thespesia populnea* or *Cordia subcordata*, both of which are native species and likely comprised the pre-human dominant tree vegetation in coastal areas with arid to dry climates (moisture zones 1-2).

Figure 37. Typical coastal woodland dominated by *Prosopis pallida.*

Figure 38. Prosopis pallida can grow to become a large often sprawling tree. Such individuals are occasionally pruned to provide wood for culturally important Hawaiian earth ovens (`imu).

Figure 39. Although both species may assume a shrublike or tree form, *Prosopis juliflora* (shown here) often takes on a more shrubby form and appears to be able to withstand a higher degree of salt exposure than *P. pallida*.

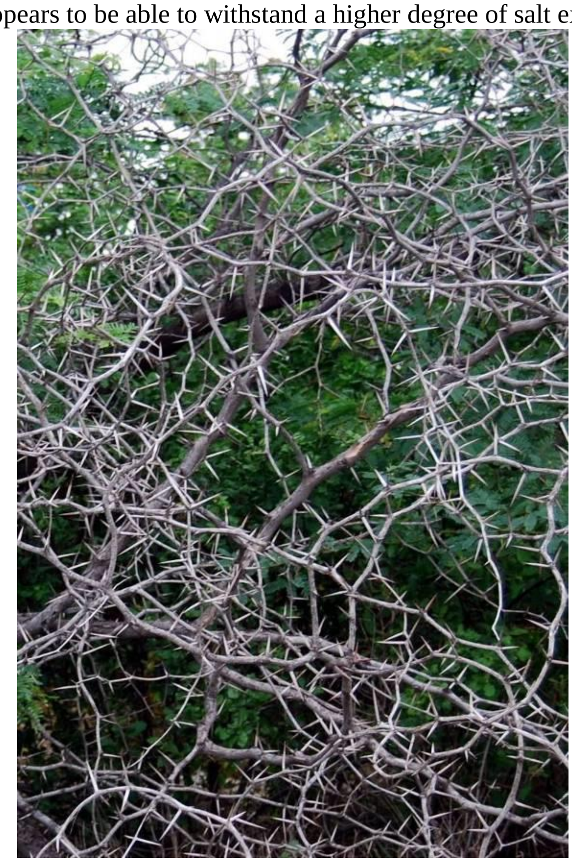


Figure 40. The long thorns of *Prosopis juliflora*.

The only native coastal forest ecosystems that were encountered in this assessment included *Pandanus tectorius* and *P. tectorius/Metrosideros polymorpha* forests (Figure 41-43). These forests were once likely widespread in mesic to wet areas of all islands however these are now very rare and are completely absent from Oahu and Kauai. In some cases *Pandanus tectorius* was found as a codominant with Terminalia cattapa however it is unclear if *Pandanus* seedlings will be able to successfully establish in the low light environment under the *Terminala* canopy. *Pandanus* outcompetes *Terminalia* in rocky and high slope coastal areas however *Casuarina* thrives in these areas and has likely replaced *Pandanus* in many places. *Metrosideros polymorpha*, which was once the most widespread forest species in Hawaii is not typically considered to be a coastal species however it was found in two coastal sites both of which had high levels of salt wind exposure. In both cases this species was restricted to areas 20-40 meters away from the coast indicating that it requires some buffering from the salt spray. As is found elsewhere in Hawaii, two species of guava (*Psidium cattleianum* and to a lesser extent *P. guajava*) has replaced *Metrosideros* in some coastal sites although guava tends to be even more sensitive to salt spray than *Metrosideros*.

Figure 41. Pandanus tectorius coastal forest with Scaevola taccada in the understory.

Figure 42. Pandanus tectorius coastal forest with Scaevola taccada in the understory.

Figure 43. *Metrosideros polymorpha* was found at two coastal sites on the Big Island in association with *Scaevola taccada and Pandanus tectorius.* Although not typically thought of as a coastal species *M. polymorpha can grow* at the coast if it has some protection from salt spray.

Altogether 111 plant species were identified from the 41 coastal assessments completed on three islands. This species does not represent a comprehensive list of species as most of our sites were areas of coastal forest, therefore coastal shrublands, grasslands and other coastal vegetation types and their associated species are not well represented. Table 10 combines the data on species occurrence from the 41 transects completed for this report with data taken from a recent assessment of native coastal ecosystems completed by Warshauer et al. (2009) and from descriptions of coastal species assemblages reported by Gagne and Cuddihy (1990). The resulting table lists 270 native and alien species grouped by growth form and categorized by the moisture zone that each species has been reported from, organized on a planting scheme (Figure 44). Arid zones (moisture zones 1-2) exhibit the highest number of species 160, followed by 155 species found in mesic zones (Moisture zones 3-4) and 92 species listed from wet zone s(moisture zone 4-5) table also lists salinity tolerance based on observations made during coastal assessments. This list can serve as a preliminary guide for species selection for coastal restoration projects.

Table 10. Species in the Coastal Zones of Hawaii their Form, Status, Climate distribution and Salt tolerance. (X = Observed during this study, X* from Wagner et al. (1990), X# from Warshauer et al. (2009).

		Salt Tolerant	Wetland Species	Arid-Dry (Moisture Zones 1-2)	Mesic (Moisture Zones 3-4)	Wet (Moisture Zones 5-6)
Native Tree Species						
1	***Antidesma pulvinatum***		No		X#	X#
2	***Diospyros sandwicensis**** [1]	No	No		X#	X
3	***Cordia subcordata***	Yes	No	X	X	
4	***Erythrina sandwicensis***		No	X	X#	
5	***Metrosideros polymorpha**** [2]		No		X	X*
6	***Munroidendron racemosum***		No		X*	
7	***Myoporum sandwicense* (shrub-tree form)**	Yes	No	X		
8	***Pandanus tectorius***	Yes	No		X	X
9	***Pipturus albidus***		No		X#	X#
10	***Pisonia umbellifera***		No			X#
12	***Pritchardia affinis***	Yes	No	X#		
13	***Pritchardia hillebrandii***		No		X#	
14	***Psydrax odorata***		No	X#	X	
15	***Rauvolfia sandwicensis***		No		X#	X#
16	***Reynoldsia sandwicensis***		No		X#	
17	***Thespesia populnea***	Yes	No	X	X	X#
Alien Tree Species						
1	*Aleurites moluccana*		No	X	X#	X#
2	*Ardisia elliptica*		No		X*	X
3	*Artocarpus altilis*		No		X#	
4	*Bruguiera sexangulata*	Yes	Yes		X	
5	*Calophyllum inophyllum*	Yes	No		X	X
6	*Casuarina equisetifolia*	Yes	No	X	X	X
7	*Citharexylum caudatum*		No		X	
8	*Clusia rosea*		No		X	
9	*Coccoloba uvifera*	Yes	No	X	X	
10	*Cocos nucifera*	Yes	No	X	X	X
11	*Conocarpus erectus*	Yes	Yes	X	X	
12	*Ficus microcarpa*		No	X	X	X
13	*Leucaena leucocephala*	Yes	No	X	X	
14	*Mangifera indica*		No			X
15	*Morinda citrifolia*	Yes	No	X#	X	X
16	*Persea americana*		No		X*	
17	*Phoenix dactylifera*	Yes	No	X		
18	*Pithecellobium dulce*	No	No	X	X	
19	*Prosopis juliflora*	Yes	No	X		
20	*Prosopis pallida*	Yes	No	X		
21	*Psidium cattellianum*	No	No		X	X
22	*Psidium guajava*	No	No		X	X

[1] Likely a codominant along with `Ohia prior to Polynesian colonization. These species likely extended from upland forests all the way to the coasts within wet climate zones.

		Salt Tolerant	Wetland Species	Arid-Dry (Moisture Zones 1-2)	Mesic (Moisture Zones 3-4)	Wet (Moisture Zones 5-6)
23	*Rhizophora mangle*[3]	Yes	Yes	X	X	X*
24	*Samanea saman*	No	No	X	X	X
25	*Schefflera actinophylla*		No		X	X
26	*Schinus terebinthifolius*		No	X	X	
27	*Syzygium cumini*		No	X	X	X
28	*Syzygium malaccense*		No		X*	
29	*Syzygium jambos*		No		X*	
30	*Tamarindus indica*		No		X	
31	*Terminalia catappa*	Yes	No		X	X
32	*Tournefortia argentea*	Yes	No	X	X	X
Native Shrub Species						
1	***Abutilon incanum***		No	X#		
2	***Achyranthes splendens***		No	X#		
3	***Adenostemma viscosum***		No	X#		
4	***Artemisia australis***		No		X#	X#
5	***Argemone glauca***		No	X#		
6	***Caesalpinia bonduc***		No	X#	X#	
7	***Chamaesyce celastroides***		No	X*	X#	X#
8	***Chameaesyce degeneri***		No	X*		
9	***Chamaesyce kuwaleana***		No	X#		
10	***Chamaesyce skottsbergii***		No	X#		
11	***Chenopodium oahuense***		No	X	X#	
12	***Colubrina asiatica***		No	X#	X	
13	***Dodonaea viscosa***		No	X		
14	***Gossypium tomentosum***		No	X		
15	***Kadua littoralis***		No	X*	X#	X#
16	***Kanaloa kahoolaweensis***		No	X#		
17	***Leptecophylla tameiameiae***		No		X	
18	***Lycium sandwicense***		No	X*	X#	X#
19	***Myoporum sandwicense* (prostrate form)**	Yes	No		X	
20	***Nototrichium sandwicense***		No		X#	
21	***Osteomeles anthyllidifolia***		No		X	X#
11	***Pittosporum halophilum***		No		X#	
22	***Plumbago zeylanica***		No	X#		
23	***Santalum ellipticum***	Yes	No	X*	X#	X#
24	***Scaevola coriacea***	Yes	No	X*		
25	***Scaevola taccada***	Yes	No	X	X	X
26	***Senna gaudichaudii***		No	X#	X#	
27	***Sesbania tomentosa***		No	X*		
28	***Sida fallax***	Yes	No	X	X#	X#
29	***Solanum americanum***		No	X#	X#	X#
30	***Solanum nelsonii***		No	X*		
32	***Tribulus cistoides***		No	X		

[3] The mangrove species *Rhizophora* mangle and *Bruguiera gymnorrhiza* will establish in all coasts with low levels of exposure. *Rhizophora mangle* clearly outcompetes *B. gymnorrhiza* by outcrowding the later species through production of a greater number of propagules, and higher stand densities.

		Salt Tolerant	Wetland Species	Arid-Dry (Moisture Zones 1-2)	Mesic (Moisture Zones 3-4)	Wet (Moisture Zones 5-6)
33	***Waltheria indica***	Yes	No	X	X	
34	***Wikstroemia oahuensis***		No		X#	X#
35	***Wikstroemia uva-ursi***		No	X#	X#	
36	***Wikstroemia sandwicensis***		No		X	
Alien Shrub Species						
1	***Abutilon grandifolium***		No	X		
2	***Acacia farnensiana***		No	X	X	
3	***Calotropis gigantea***		No	X		
4	***Chenopodium sp.***	Yes	No	X		
5	***Cordyline fruticosa***		No		X#	X
6	***Crinum asiaticum***	Yes	No		X	
7	***Crotalaria sp.***		No	X*	X	
8	***Hibiscus tiliaceus***[4]	Yes	Yes	X	X	X
9	***Indigofera suffruticosa***		No	X*		
10	***Lantana camara***		No	X*	X	
11	***Phyllostachys nigra***		No		X*	
12	***Pluchea carolinensis***	Yes	No	X	X	X
13	***Pluchea indica***	Yes	No	X	X	X
14	***Schizostachyum glaucifolium***		No		X*	
15	***Sophora tomentosa***	Yes	No		X	
16	***Stylosanthes sp.***		No		X	
Native vine						
1	***Alyxia oliviformis***	No	No		X#	
2	***Capparis sandwichiana***		No	X*	X#	
3	***Canavalia molokaiensis***		No		X#	
4	***Canavalia napaliensis***		No		X#	
5	***Canavalia pubescens***		No	X#	X#	
6	***Cassytha filiformis***	Yes	No	X	X	X#
7	***Cuscuta sandwichiana***		No	X*		
8	***Cocculus orbiculatus***		No	X*	X#	
9	***Ipomoea imperati***		No	X#		
10	***Ipomoea indica***	Yes	No	X*	X#	
11	***Ipomoea littoralis***	Yes	No	X#	X#	X#
12	***Ipomoea pes-caprae***	Yes	No	X	X	X*
13	***Ipomoea tuboides***		No	X#	X#	
14	***Jacquemontia ovalifolia***	Yes	No	X		
15	***Mucuna gigantea***		No		X	X
16	***Sicyos herbstii***		No	X#		
17	***Sicyos maximowiczii***		No	X*		
18	***Sicyos pachycarpus***		No	X*	X#	X#
19	***Sicyos waimanaloensis***		No	X#		
20	***Vigna marina***	Yes	No	X*	X#	X
21	***Vitex rotundifolia***	Yes	No	X	X	X
Alien Vine						
1	***Canavalia sericea***	Yes	No		X	

[4] *Hibiscus tiliaceus* can be found along all coasts there is adequate near surface ground water available.

		Salt Tolerant	Wetland Species	Arid-Dry (Moisture Zones 1-2)	Mesic (Moisture Zones 3-4)	Wet (Moisture Zones 5-6)
2	***Dioscorea bulbifera***		No			X#
3	***Dioscorea pentaphylla***		No		X#	X#
4	***Epiprennum sp.***	No	No		X	X
5	***Ipomoea batatas***	No	No		X#	X#
6	***Passiflora foetida***	No	No	X		
Native Herb						
1	***Anagallis arvensis***		No	X		
2	***Argemone glauca***		No	X		
3	***Bacopa monnieri***	Yes	Yes		X	X
4	***Bidens forbesii***		No		X#	
5	***Bidens hillebrandiana***		No		X#	X#
6	***Bidens mauiensis***		No	X#		
7	***Bidens molokaiensis***		No		X#	
8	***Bidens sandvicensis***		No	X#	X#	
9	***Boerhavia acutifolia***		No	X#		
10	***Boerhavia herbstii***		No	X#		
11	***Boerhavia repens***	Yes	No	X	X	
12	***Brighamia insignis***		No		X#	
13	***Brighamia rockii***		No		X#	
14	***Centaurium sebaeoides***		No	X#	X#	
15	***Cressa truxillensis***	Yes	No	X*		
16	***Dianella sandwicensis***		No	X#		
17	***Heliotropium anomalun***	Yes	No	X	X#	
18	***Heliotropium curassavicum***	Yes	No	X	X	
19	***Lepidium bidentatum***		No	X*		
20	***Lipochaeta heterophylla***		No	X#		
21	***Lipochaeta lobata***		No	X*		
22	***Lipochaeta rockii***		No	X*	X#	
23	***Lipochaeta succulenta***		No	X*	X*	X*
24	***Lysimachia mauritania***		No	X*	X#	X#
25	***Melanthera integrifolia***		No	X*		
26	***Melanthera lavarum***		No			
27	***Nama sandwicensis***	Yes	No	X		
28	***Peperomia blanda***		No		X#	
29	***Peperomia cookiana***		No			X#
30	***Peucedanum sandwicense***		No		X#	X#
31	***Pilea peploides***		No			X#
32	***Plectranthus parviflorus***		No		X#	
33	***Portulaca lutea***		No	X*	X#	
34	***Portulaca molokiniensis***		No	X#		
35	***Portulaca villosa***		No	X#		
36	***Potamogeton foliosus***		Yes	X#		
37	***Pseudognaphalium sandwicensium***		No	X*	X#	
38	***Rumex albescens***		No	X*		
39	***Ruppia maritima***		Yes	X#		
40	***Schiedea globosa***		No	X*	X#	
41	***Sesuvium portulacastrum***	Yes	Yes	X	X	X*
42	***Tetramolopium rockii***		No	X#		
43	***Tetramolopium sylvae***		No	X#	X#	

		Salt Tolerant	Wetland Species	Arid-Dry (Moisture Zones 1-2)	Mesic (Moisture Zones 3-4)	Wet (Moisture Zones 5-6)
Alien herb						
1	***Alocasia maccorhiza***	No	Yes		X#	X
2	***Aloe vera***		No	X		
3	***Atriplex semibaccata***	Yes	No	X		
4	***Aystasia gangetica***		No	X	X	
5	***Boerhavia coccinea***		No	X	X	
6	***Batis maritima***	Yes	Yes	X	X	X*
7	***Centella asiatica***		No			X
8	***Chamaecrista nictitans***		No	X*		
9	***Colocasia escuelenta***	No	Yes		X	X#
10	***Commelina diffusa***		No	X	X*	
11	*Desmodium triflorum*		No	X*		
12	***Kalanchoe pinnata***		No	X*		
13	***Musa x paradisiaca***	No	No			X#
14	***Oxalis corniculata***		No	X#	X#	X
15	***Plantago major***		No		X	
16	***Portulaca oleracea***		No	X*		
17	***Ricinus communis***		No	X		
18	***Rivina humilis***		No	X	X	
19	***Solanum lycopersicum***		No	X		
20	***Stapelia gigantea***		No	X		
21	***Tephrosia purpurea***		No	X#		
22	***Tetragonia tetragonioides***		No		X	
23	***Verbesina encelioides***		No	X		
24	***Wedelia biflora***		No		X	X
25	***Zingiber zerumbet***		No		X#	X#
Native grass/sedge						
1	***Agrostis avenacea***		No		X#	X#
2	***Arundina graminifolia***		No		X	
3	***Bolboschoenus maritimus***	Yes	Yes	X#	X#	
4	***Carex wahuensis***		No	X#	X#	X
5	***Chrysopogon aciculatus***		No	X#	X#	
6	***Cladium jamaicense***		Yes			X#
7	***Cyperus javanicus***		Yes	X#	X	X#
8	***Cyperus laevigatus***	Yes	Yes	X#		
9	***Cyperus pennatiformis***		No			X#
10	***Cyperus phleoides***		No		X#	
11	***Cyperus polystachyos***		No	X#	X#	X#
12	***Cyperus trachysanthos***		No	X#		
13	*Deschampsia nubigena*		No			X*
14	***Digitaria setigera***		No		X#	X#
15	*Eleocharis calva*		Yes	X#		
16	***Eragrostis paupera***		No	X#		
17	***Eragrostis variabilis***		No	X*	X#	X#
18	***Fimbristylis cymosa***	Yes	No	X	X	X#
19	***Fimbristylis dichotoma***		Yes	X#	X#	
20	***Fimbristylis hawaiiensis***		No	X#		
21	***Heteropogon contortus***	Yes	No	X*	X#	
22	***Ischaemum byrone***		No	X*	X#	X#

		Salt Tolerant	Wetland Species	Arid-Dry (Moisture Zones 1-2)	Mesic (Moisture Zones 3-4)	Wet (Moisture Zones 5-6)
23	***Lepturus repens***	Yes	No	X	X	
24	***Machaerina angustifolia***		No			X#
25	***Panicum fauriei***		No	X*	X#	
26	***Panicum niihauense***		No	X#		
27	***Panicum ramosius***		No	X#		
28	***Panicum torridum***		No	X*		
29	***Panicum xerophilum***		No	X#		
30	***Schoenoplectus juncoides***		Yes		X#	
31	***Schoenoplectus lacustris***		Yes	X#	X#	
32	***Scleria testacea***		No			X#
33	***Setaria verticillata***		No	X*		X#
34	***Sporobolus virginicus***	Yes	No	X	X	X
Alien Grass/Sedge						
1	***Cenchrus echinata***		No	X		
2	***Chloris spp.***		No	X	X	
3	***Cynodon dactylon***		No	X*		
4	***Eleocharis geniculata***		No	X*		
5	***Oplismenus hirtellus***		No		X*	
6	***Panicum maximum***		No	X	X	X
7	***Paspalum vaginatum***	Yes	No			X*
Native Ferns						
1	***Adiantum capillus-veneris***		No		X#	X#
2	***Asplenium nidus***		No		X	X#
3	***Sadleria sp.***		No		X	X#
4	***Cyclosorus interruptus***		No			X#
5	***Doryopteris decipiens***		No	X#		
6	***Marsilea villosa***		Yes	X#		
7	***Nephrolepis exaltata***		No	X#	X	X
8	***Ophioglossum polyphyllum***		No	X#		
9	***Psilotum nudum***		No		X	X#
10	***Selaginella arbuscula***	No	No			X#
11	***Sphenomeris chinensis***	No	No			X#
Alien Ferns						
1	***Cyrtomium falcatum***		No			X
2	***Polypodium scolopendrium***		No		X	X

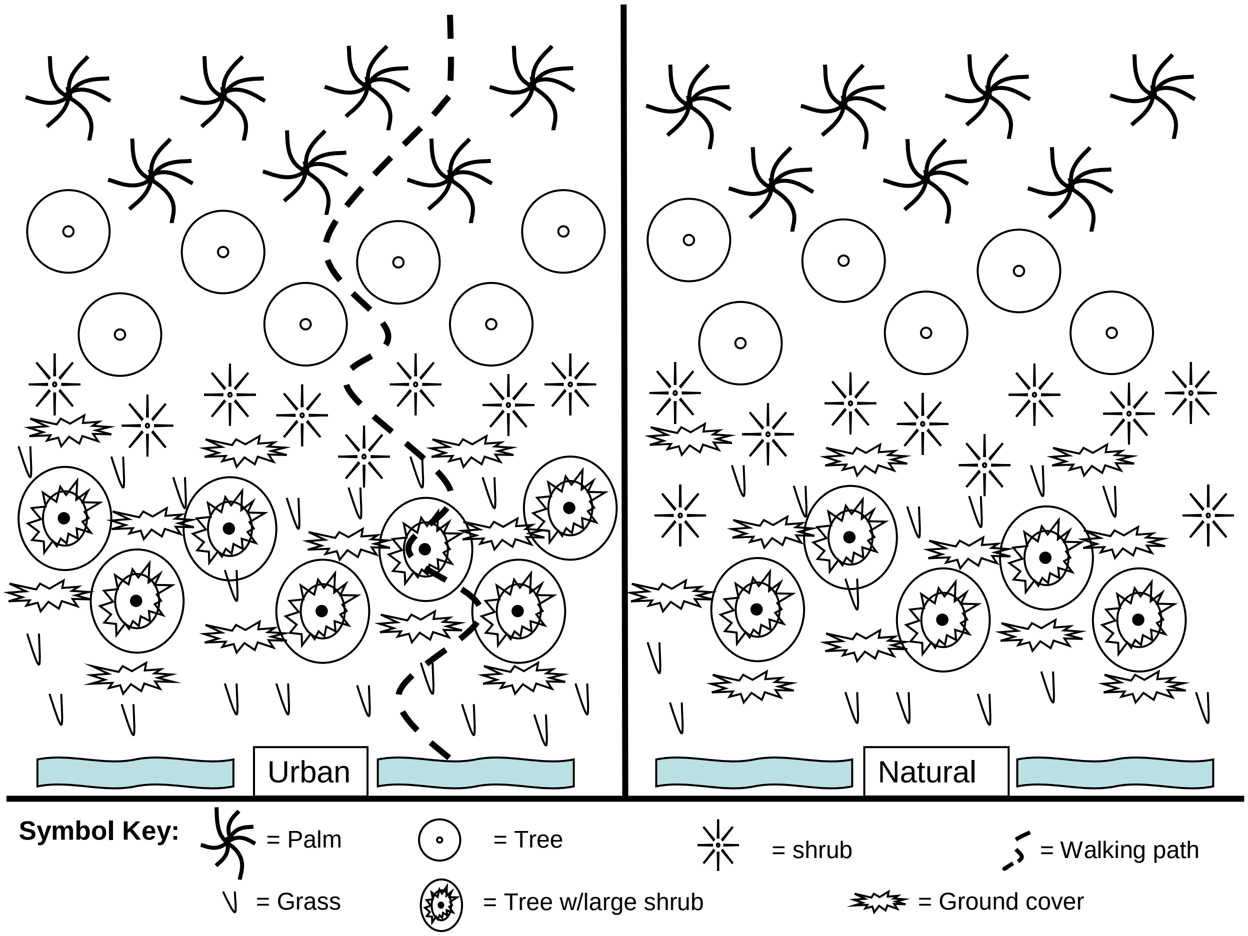


Figure 44. Based on data collected, this is a schematic design suggestion to help elevate coastal impact.

Conclusions

The relationship between tsunami waves and coastal forest is a complex one. It is nearly impossible to account for every environmental variable that may impact how a tsunami wave may interact with features at the coast. Interactions between coastal forest and tsunami are also dependent upon the magnitude of the tsunami and characteristics of the vegetation itself such as composition, height, and stem density. Observations indicate that there are some clear direct benefits, in terms of tsunami or storm surge risk mitigation, to maintaining some degree of coastal forest. A coastal forest acts as a porous barrier allowing the water to pass through while holding back debris including downed trees, coral, rocks, ships and urban debris and waste. This acts to prevent the mass of this material from contributing to the force of the tsunami wave, prevents this material from acting as a damaging projectile, and when the water recedes, prevents inland generated debris from washing out to sea contributing to further environmental and marine hazard. In some cases, underground structures hold back rocks, sand and soil preventing these materials from contributing to the mass of the flowing tsunami wave while preventing erosion which may undermine utilities and roads which are essential for prompt disaster relief efforts. In addition, nearly every tsunami event results in human accounts of people escaping injury or death by climbing onto trees or by holding on to vegetation as the wave passes through. Due to the porous nature of the coastal forest, there does not seem to be an effect on the total inundation distance of the tsunami in areas that was investigated in Samoa.

At the neighboring villages of Utulaelae and Sapoe in Uppolu Samoa there was more damage in Utulalelae which had cleared its forests, than in Sapoe which had allowed a 30-50m width of forest to remain. There are at least four possible explanations for this observed effect. First, the coastal forest may have acted to reduce the tsunami wave energy by reflecting wave energy laterally and back out to sea. Second, due to limitations in the sampling method, the team may not have detected small elevation differences of structures in Sapoe relative to Utulaelae which could have contributed to protecting homes from the effect of the wave. Third, the clearing fronting Utulaelae may have acted as a gap channeling water and therefore channeling energy away from Sapoe. Finally, difference in coastal bathymetry may have focused wave energy disproportionately towards Utulaelae relative to Sapoe. The only way to eliminate these potential explanations would be to have a greater sample size and consistent results however no additional suitable sample areas were available.

The ability of a coastal forest to contribute positive to tsunami or storm surge mitigation relies upon the ability of that forest to physically survive the wave impact. During a large tsunami event such as that which impacted the Indian Ocean in 2004 or Japan in 2011, even extensive areas of coastal forest did not withstand the physical force of the incoming wave. In such cases, debris from the destroyed coastal forest will contribute to floating woody debris and along with soil, rocks, and manmade debris to the mass and force of the inundating tsunami wave. For events such as the tsunami which impacted Samoa in 2009 or tsunami of the magnitude which have impacted Hawaii over the last century, available evidence indicates that most woody coastal vegetation actually withstands the physical inundation. The observations in Samoa suggest that dense coastal forest had much less physical damage to woody plants (in some cases undetectable levels of physical damage) than areas of sparse trees or occasional planted vegetation. This would suggest that coastal forests have community level physical resistance to a tsunami wave through both above ground stem supporting interactions as well as below ground root interlocking interactions.

In Samoa, forests with a wide range of stem densities survived inundation. The average coastal stem density was 1440 Stems per hectare. Based on the observations, 27 species survived inundation without evidence of effect, 11 species suffered defoliation and appeared to be recovering while 9 species had individuals which had been killed, by saltwater inundation. Those that survived or were recovering were for the most part, species highly adapted to conditions at the coast.

Hawaii's coastal forests are dominated by alien invasive species which tend to form low diversity forests with limited development of the understorey. The most common coastal assemblages includes a *Prosopis* dominated assemblage along arid coasts, a *Terminalia cattapa* dominated forest along mesic to wet coasts and a *Casuarina equisetifolia* dominated forest in all coastal areas where it was deliberately planted as a wind break in the early 1900's. Both *Terminalia* and *Casuarina* appear to be expanding in terms of their distribution while *Prosopis* dominated ecosystem has most probably reached its maximal extent in the main Hawaiian Islands. The limited diversity of Hawaii's coastal forests relative to Samoan coastal forests results in a much lower average stem density average of all transects (725 stems per hectare).

The team encountered very few examples of native coastal forest along 41 coastal areas assessed. There were however a few exceptions. In Puna on the Big Island (Hawaii) the team encountered native *Pandanus tectorius* forest sometimes in association with native *Metrosideros polymorpha.* Native *Scaevola taccada* shrublands also represent a relatively common coastal vegetation type along arid to mesic coasts of all islands.

A recent report on native coastal plant ecosystems of the main Hawaiian Islands (Warshauer et al. 2009) found 142 native plant species in the coastal zone of three islands , Maui, Molokai and Oahu. Many of these native coastal species are primarily found in refugia habitats which have not yet been developed, cleared for agriculture, or invaded by significant levels of invasive species. This is evident by their finding that sites on highly developed Oahu had fewer native species than on the other two islands. Warshauer and Price (2009) found that the moisture zone (Price et al. 2007) of a particular site was the most important factor in determining species composition. This relationship was not found for `Oahu, Likely due to the dominance of alien species and widespread disturbance that characterizes this island. This report highlights the fact that native coastal ecosystems in Hawaii are becoming rare and conservation and management plans should be considered, the data from this report while identifying key areas requiring conservation can also be used to suggest which species may be used for native restoration of other sites now dominated by alien invasive species. Finally, the report calls for the establishment of demonstration coastal vegetation restoration projects to generate stakeholder interest and develop. Existing successful coastal restoration projects Hawaii identified by the report in include the Moʻomomi Preserve, Molokaʻi, Department of Hawaiian Homes Lands Near Moʻomomi, Molokaʻi, Kalaupapa National Historical Park, Northeast Coast of Molokaʻi, and Kanahā Beach County Park, Maui

Very little work has been done on methods of coastal forest restoration. The best example completed in Tonga was documented by Thaman et al. (1995). Through implementation of a trial coastal forest restoration, they identified technologies which appear to mimic natural coastal strand flora development. This includes the early establishment of highly salt tolerant buffer species and species which can colonize exposed bare substrate. Once these species are established, less salt tolerant species that typically establish within existing stand of vegetation are added behind the vegetated buffer. Finally, the diversity of the vegetated coastal areas is enhanced with planting s of key desirable species. In some cases this could represent economically important species, in other cases, particularly in Hawaii, this could include rare native coastal or lowland species planted as a part of conservation efforts. Given the great variation in environmental factors in coastal areas of Hawaii, particularly the great climate variability from very arid to very wet coasts, additional research in conjunction with restoration trials in a variety of climate zones and exposure levels will be needed to establish best practices for coastal restoration in Hawaii. If tsunami bioshields are to be implemented in Hawaii, additional work is needed to develop designs for coastal areas with different uses such as areas frequented by community beach goers, and areas fronting tourism-related establishments.

Much of Hawaii's coasts have been de-vegetated. In some cases homes and businesses extend to the top of the beach. These areas are directly threatened by storm surge and tsunami. One potential risk mitigating option for these areas is to preserve and expand upon coral reefs which have been shown to provide a physical barrier to incoming storm and tsunami waves (Cochard et al. 2008). Given the benefits of coastal forest in terms of providing a barrier against the destructive forces of waves, salt spray, erosion and the projected effects of sea level rise, existing undeveloped areas of Hawaii's coasts should be protected and managed and the coastal forest properties as a bioshield should coincide with restoration, conservation and management plans. Such plans should consider the establishment and management of the appropriate species for a given coast planted in an arrangement and density to maximize the ability of that vegetation to resist incoming destructive waves. A simple goal may be to maximize the total stem density within in area. A more nuanced goal may be to arrange vegetation to allow for a maximal canopy stem density while providing for the successful establishment of a dense understory. Both strategies will be more likely accomplished by maximizing the total diversity of species within a given area.

The combined evidence supports the conclusion that implementing a tsunami/storm surge bioshield can be an effective strategy to mitigate some of the risks of storm surge. Such a strategy will not be effective against a very large tsunami or prolonged storm surge events however they may be effective against the magnitude of these events that most frequently impact Hawaii and other Pacific islands. The benefits of a coastal bioshield includes several indirect effects particularly limiting erosion, building elevation, acting as a porous two-way barrier for debris and acting as a potential escape or holdfast for people potentially caught in a tsunami wave. Evidence for a direct effect of the coastal forest on attenuating the energy of an incoming tsunami or storm surge wave resulting in reduced destruction while not rejected based on the evidence contained in this support is by no means strongly supported due to sample size limitations. Logic would suggest that an effective bioshield will remain porous but would have great complexity. This is achieved by greater stem density and by a combination of vegetation at multiple vertical layers. These physical characteristics can be achieved by designing a bioshield with a maximum of species diversity. Further work is needed to learn best practices for coastal forest restoration so that specific design recommendations can be made for a given locality.

On September 29, 2009 a tsunami inundated the southern coast of Upolu Samoa killing over 140 people and causing extensive property damage. In January 2010, a team for the Tropical Landscape and Human Interaction Lab at the University of Hawaii was sent to make observations in Upolu to search for interactions between the tsunami and coastal vegetation. Also conducted, was vegetation surveys on the Islands of Oahu, Hawaii and Kauai to characterize existing coastal vegetation patterns.

The observations in Samoa lend support to the hypotheses that coastal vegetation mitigates the effects of a tsunami through several mechanisms: (1) Coastal vegetation forms a physical barrier to an incoming wave which may result in reduced damage to structures and reduced erosion; (2) coastal vegetation builds elevation at the coast by trapping organic matter and sand, and coastal vegetation provides a vertical escape for people trapped in the wave; (3) coastal vegetation acts as a filter which holds back coral, ships and debris, carried by the wave from being moved inland where it can be destructive to people and property and from being carried out to sea and onto sensitive reefs.

Conversely, the coastal forests in Hawaii are reduced in species diversity, complexity and stem density relative to their Samoan counterparts. This will seriously impact the ability of these forests to provide an effective barrier for tsunami or storm surge waves. In addition, many coastal areas in Hawaii have been completely deforested in favor of park-like landscapes and direct development at the coast. Hawaii's coastal forests are dominated by a few widespread invasive species including *Prosopis pallida* (Mesquite), *Rhizophora mangle* (American Red Mangrove), *Terminalia catappa* (Tropical Almond), and *Casuarina equisetifolia* (Ironwood). *Prosopis pallida* was introduced to Hawaii in 1827 and has naturalized largely due to the action of cattle and feral animals. The mangrove, *R. mangle* is widely established on Oahu in coastal areas that are well protected from high energy waves. *Terminalia catappa* and *C. equisetifolia* were planted in the early part of the 20th century to reforest coastal areas. All these dominant coastal species form largely monotypic stands and disperse through floating propagules, seeds or root suckers. Native species are not completely absent from Hawaii's coastal areas. Several of transects encountered native coastal forest including forests of *Pandanus tectorius* (hala), often mixed with *Metrosideros polymorpha* (ohia lehua), and forests where *Thespesia populnea* (milo) is dominant. The combined observations from Samoa and Hawaii form the basis for specific recommendations as to how such bio-shields could be most effectively designed and implemented in Hawaii and other Pacific Islands however additional research is urgently needed.

The third phase of this project, presented in this report, consisted of an experiment to re-introduce the native vegetation of a coastal strand that is dominated by invasive trees (*Casuarina equisitofila*) that, besides its documented function to reduce wave height and speed, has high canopy and low density of stems, which is not efficient to reduce tsunami waves. Also, the location of the experiment is presenting beach erosion with sand loss, partly because of the current vegetation, but also because of hardened seashores (beach wall).

Coastal Vegetation Restoration in Waimanalo, Hawaii

The third phase of this research was to develop a method for restoration of native coastal vegetation using primarily native Hawaiian species and evaluate the method effectiveness, and its effects on wave power and erosion. The effects of vegetation on wave power has been observed by post-event surveys after the tsunami in Samoa and through visual documentation of storm water runoff at Bellows Air Force Station (BAFS) in Waimanalo, Island of Oahu, Hawaii (figure 45). Beach erosion as much as two feet per year has been documented at BAFS, which is mostly attributed to hardened shorelines, but it is also associated with invasive species such as *Casuarina equisitifolia* which inhibits growth of native shrubs and ground covers. This research project tested a planting method for establishment of native plants after removal of C. equisitifolia, and verified the effectiveness of temporary windscreens for protection against wind and salt spray. Temporary windscreens proved beneficial to speed-up the establishment of the plants, especially in the foredune zone (ocean side). However, the windscreens were knocked down by a storm event three months after planting and there was no visual difference between the plots with or without windscreens one year after planting. Therefore, the use of windscreens may not be necessary and cost effective since it only has short term benefits and results in extra cost and potential debris in the beach if the wind screens and its supports are not completely removed, which also adds cost. A modular irrigation system was designed for easy removal and reassembly, so it can be re-used in additional restoration areas. The irrigation was gradually reduced and totally removed eight months after planting. Data revealed irrigation lines on the windward side of the plots were buried up to 6 ¼” (six and a quarter inches), and sand accretion was visually evident in the perimeter of the plots. Additionally, very clear plant zones corresponding to the beach berm, foredune, dune crest, and backdune zones were present. *Sporobolus virginicus* (‘aki‘aki grass) and the beach morning glory vine *Ipomea pes-caprae* subsp. *brasiliensis* (pohuehue) were very successful to cover the ground throughout all zones, with I. pes-caprae growing up to fourteen feet beyond the irrigated areas. This report includes the detailed irrigation system used in this experiment, visual photographs with a timeline of the planting establishment, ground coverage and dry matter data collected one year after planting, and recommendations of native plants and their planting zones for coastal planting and landscaping in Hawaii.

Figure 45. Location of Bellows Air Force Station in the Island of Oahu, Hawaii. Source: Google Earth.

Beach erosion in Hawaii

Through the effects of the processes of geological formation, continued weathering and human interaction, Hawai‘i’s shorelines are under continuous change. Due to multiple environmental stressors, a majority (60%) of shorelines and beaches on Oahu are eroding (Fletcher, C.H., 2012). The northern end of the beach at Bellows Air Force Station (BASF) in Waimanalo, Oahu, Hawaii, is eroding as well. Due to several environmental factors, the fine white sandy beaches of Bellows and Oahu are receding and in danger of disappearing. Northern sections of the beach have already been lost and a U.S. Geological Survey study reports losses of up to a foot per year for other parts of the installation’s shoreline.

The shorelines and beach ecosystems in Hawai‘i exhibit some of the most interesting, attractive and rare habitats around the world. Because of these unique properties the shoreline areas have become one of Hawai‘i’s most valuable commodities, capturing the attention of scientists, outdoor adventurers and vacationers alike. Over 500,000 military personnel and guests visit BAFS annually and the high quality sandy beach at Bellows is a substantial reason for the visitors. Bellows Air Force Station (BAFS) and the surrounding community has instituted this plan to stabilize and restore the dunes and ultimately the shoreline of Bellows Beach from erosion through the removal of invasive species, and restoration of native plant species and ultimately if possible, ecological processes.

Bellows Beach is located on the windward side of the island of Oʻahu. To the North and Northwest Bellows is bordered by the Keolu Hills, Waimānalo bay to the East, and the town of Waimānalo to the South and Southwest. The BASF shoreline lies between Wailea Point to the north and Waimanalo Stream to the south. The Marines are responsible for the Shoreline from Waimanalo Stream to Inaole Stream. BAFS is responsible for the shoreline from Inaole Stream to Waimanalo State Recreational Area.

On the base there are three distinct types of geological formations; lithified Pleistocene dunes, volcanic hills, and unconsolidated Holocene sands. Much of the sand found on the low plains of BAFS were deposited when sea level fell from mid-Holocene conditions to present day levels.

These plains are made up of unconsolidated calcareous sand that have formed beach ridges and swales. Further inland there is a sequence of lithified (compacted and hardened) Pleistocene dunes that are elevated above the coastal plains (Dye, 2007).

History of Bellows Beach

Since the time of the early Polynesian arrivals, the land that is now Bellows Air Force Base Station has gone through many anthropogenic changes. Numerous archeological findings demonstrate that Waimānalo beach and surrounding areas were used extensively by ancient Hawaiians.

Through archeological digs and surveys, stratified prehistoric sites located in the sand dunes were found to contain remnants of living areas, house remains, fire pits, burial sites, agriculture, and aquaculture production (Pearson, 1971). At the time of the Great Māhele in 1848 the lands of Waimānalo were placed into Crown Lands held at that time by Kamehameha III (Dye, 2012). Two years later in 1850 this land was leased into ranch lands and eventually put into production of sugar cane and pineapple (Bellows Air Force Station, 2012).

In 1917 the land was designated the Waimānalo Military Reservation but saw little military activity until 1933 when it became Waimānalo Military Reservation, Bellows Field and an airstrip was constructed (Dye, 2012). Base activity peaked during World War II. Today, the base is the home of the Detachment 2, 18th Force Support Squadron. The base has numerous cabins and camping grounds for vacationing military personal (Bellows Air Force Station, 2012).

Beach Processes

Hawaiian coastlines are subject to seasonal changes. These changes can be severe and are caused by the shift in intensity and direction of wave patterns and wind. Across the islands winter seasons are influenced by large North Pacific storms, while summer months are dominantly found to have Southern Hemisphere swells and trade wind swells. Waimānalo bay has dominant onshore trade winds blowing in from the northeast. These trade winds create waves that break against

Bellows Beach all year long with variations in wave strength due to seasonality (University of Hawai'i Sea Grant Extension Service and State of Hawai'i Department of Land and Natural Resources Office of Conservation and Coastal Lands, 2004). In Hawai'i, Beach sediments, or sands, are generally finest on the windward or northeastern facing coasts such as Bellows Beach (Hawai'i County Department of Planning, 2005). Trade wind frequency has decreased overtime from approximately 90% to 60% but still serves to generate relatively consistent wave patterns that rapidly sort sediments into the fine, highly desirable "sugar sand" that draws so many people to windward Oahu Beaches such as Bellows (Fletcher, 2012).

Sand dunes provide an important aspect to beach systems. Dunes are able to store excess sand reserves, create buffers to erosion, and storms, catch windblown sand and store it, and create a berm of plant life with roots that protects inland areas from wave events. Dunes are able to provide a supply of sand that protects beaches and inland areas from massive erosion events. With the predominant trades winds on Bellows, sand that is driven up on the beach, especially at low tide, on stronger wind days, is then further shifted landward or mauka, to form dunes. Historical photos of Bellows show an extensive system of dunes reaching back hundreds of yards. Human activities and development have removed or covered much of this system, but excavations often reveal deposits of sand multiple feet deep. Nonetheless, a highly altered but dynamic dune system remains extant along much of Bellows Beach and can better serve as a sand reserve, erosion mitigation system and storm surge buffer if properly managed. There are several native plant species that have adapted to live in these types of conditions and are crucial for the formation and stability of sand dunes (University of Hawai'i Sea Grant Extension Service and State of Hawai’i Department of Land and Natural Resources Office of Conservation and Coastal Lands, 2004).

Beach Erosion

Annually, more than 500,000 Airmen and guests are drawn to the beautiful beaches of Bellows Air Force Station, Hawaii. Unfortunately, the fine white sandy beaches are receding and in some sections in danger of disappearing. Northern sections of the beach have already been lost and a U.S. Geological Survey study reports losses of up to a foot per year for other parts of the installation’s shoreline.

The University of Hawaii Coastal Geology Group produced shoreline change maps for southeast Oahu as part of the SEO/RSM report (Figure 46). The maps include average annual shoreline change rates at 20-meter intervals based on historical shorelines dated from 1911 to 2005. The shoreline change rates were used in conjunction with wave and circulation model results to produce longshore and onshore-offshore transport rates for the region. The Bellows map, has been updated since the RSM report and shows annual erosion rates of up to 8.5 feet per year in the location of the revetments.

Based upon the high rates of erosion at Bellows, The Honolulu District of the U.S. Army Corps of Engineers (USCOE) developed an analysis of options to address the erosion, and to replenish the shoreline. The report presented three concepts for beach restoration:

1. Artificially nourish the beach to provide a minimum 30-foot wide beach crest extending from Wailea Point to Waimanalo Stream. The initial nourishment would require 247,400 cubic yards of sand and cost $42,964,000. With periodic re-nourishment necessary, the projected total 50-year cost is $94,800,000.
2. Produce a 30-foot wide beach crest measured from the vegetation line, extending from Wailea Point to 200 feet past the southern end of the revetments. Initial nourishment would require 105,600 cubic yards of sand and cost $18,504,000. The estimated total 50-year cost with re-nourishment is $55,200,000.
3. Remove the revetments and allow the shoreline to achieve a natural position. The USCOE determined that revetments have caused an estimated sand deficit of 46,000 cubic yards. The cost of removing the revetments and disposing of the material is estimated at $460,000. Removing the revetments could result in shoreline retreat of

up to 52 feet as well as the destruction of several buildings and the threat of destroying others.

To date, none of these recommended actions have been adopted. Based upon historical trends and predictions of sea rise and increased storm energy from climate change, in lieu of the exceptional costs of options 2 & 3 above, BAFS should prohibit any new construction west of the existing revetment, and at minimum, should allow the revetment to slowly degrade so the beach can return to a naturally function system. BAFS should also consider the potential value of removing the revetments in order to protect the remaining beach sand that is still available to the beach at Bellows. Essentially, the USCOE has calculated that 30 feet of sandy beach at BAFS has a replacement cost of between $.1B and $.05B. Visitors to BAFS might place that value even higher.

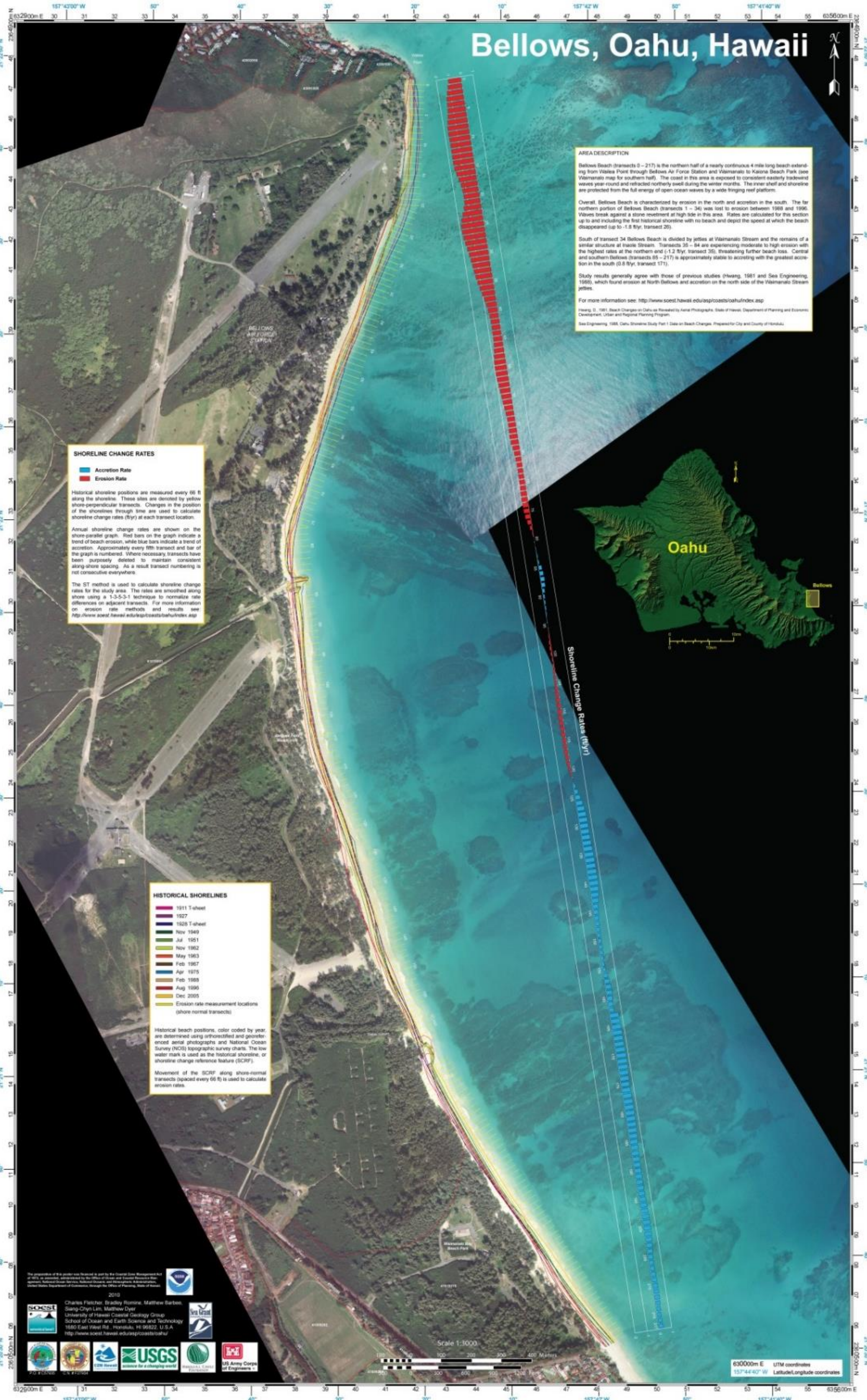


Figure 46. Map of beach accretion and erosion over time. The red bars indicate erosion, and the blue bars indicate accretion perpendicular to the graph axis. (Source: Fletcher et al, 2010).

Beach hardening

A series of seawalls and revetments were constructed along the northern portion of the Bellows shoreline after WWII. The revetments extend about 2,300 feet south from Wailea Point. The structures were apparently constructed in a series of phases. USCOE aerial photographic analysis indicates that they were built between 1948 and 1961. The analysis shows a wide beach in the present location of the revetments in 1948, while the revetments are shown in the 1961 photograph, the next in the series of historical aerial photographs.

Due to the complexity of coastal erosion processes, it is difficult to prove exact cause and effect, but based upon rates of erosion and experience at other installations of seawalls in Hawai'i, it is reasonable to conclude that the seawall at BAFS is increasing rates of erosion at the beach. Ironically, it may be a major risk factor in the ultimate loss of the swimming beach and near shore cabins. Until the seawall is removed or allowed to slowly become undermined, the northern, or upper reaches of the beach adjacent to the seawall will continue to accelerate erosion rates at BAFS.

As noted in the previous section, USCOE estimated the seawall has caused a sand deficit of 46,000 cubic yards. Removing the revetments and disposing of the material is estimated at $460,000. A key issue is that removing the revetments could result in shoreline retreat of up to 52 feet as well as the destruction of several buildings and the threat of destroying others. One key planning recommendation is to prohibit any further development of infrastructure within at minimum 52 feet landward of the revetment. Unless a decision and funding are executed to remove the seawall, sand dune restoration and management is one of the few available erosion mitigation options.

Invasive Plant Species

Nonnative plant species are dominant at BAFS, all with varying degrees of influence on native ecosystem processes. For the sand dune ecosystem at Bellows, the species with the greatest apparent negative impact on is the Australian Pine or Casuarina Tree (*Casuarina equisetifolia)*. Casuarina is commonly known as ironwood in Hawai'i, is a tree native to Australia, Southeast Asia and many South Pacific Islands (Kozusko, 2007). Like many other invasive species in Hawai'i, ironwood has no known native pests that can control them.

Ironwood Management

Since Casuarina has been established in Hawaii for so long, and provides an excellent wind break, and good shade, removing the tree has been controversial. For many Casuarina is an elemental part of their experiences at Bellows and removing them has raised valid concerns and questions. This relatively extensive review of Casuarina is intended to provide a greater understanding of the tree species, its impact on the dune system at Bellows and how it can be better managed.

After its introduction to Hawaiʻi, ironwood was often used for windbreaks and for erosion control. Ironwood is extremely salt resistant and will grow in windy, saline conditions. The fruit is an oval honeycombed structure 10–24 mm (0.39–0.94 in) long and 9–13 mm (0.35–0.51 in) in diameter, similar to a conifer cone, made up of numerous carpels each containing a single seed with a small wing 6–8 mm (0.24–0.31 in) long. It is an actinorhizal plant, able to fix atmospheric nitrogen. In contrast to commonly known nitrogen fixing species of the Fabaceae (pea) family of plants (e.g., beans, alfalfa, Acacia), *Casuarina* harbors a symbiosis with a *Frankia actinomycete*. It grows rapidly and is highly propagative, reaching heights of 40 meters. Once established, it can lay down a thick carpet of needles which can completely cover the surrounding ground. During the decomposition phase the needles release phenols, which greatly inhibit the growth of other plants. If allowed to spread, ironwoods will displace other plants to the point of complete removal. Once planted for erosion control, ironwoods are found to actually increase erosion rates through their lack of deeply penetrating root systems and the exclusion of other plant species (Hawai'i County Department of Planning, Community Development Plans, 2005). Simmilarly, Mimura and Nunn (1998) attributed increased coastal erosion and beach loss in Fiji to increased clearing of coastal vegetation since the 1960's.

It was demonstrated in the lab and field by Hata et al, that leaf litter from Casuarina equisetifolia, inhibits seed germination and initial growth of a native tree (Schima mertensiana) on the Ogasawara or Bonin Islands (Hata et al. 2010). Severity of impact was associated with increasing depth of the fallen leaves – as the litter accumulation increased so did growth suppression.

Studies in India demonstrated that *Casuarina equisetifolia* exhibited allopathic (chemical suppression) in regulating understory vegetation growth including germination and seed growth of bidens, a genus native to Hawaii (Batfish and Singh, 1998). Leaves, litter and soils were found to contain high concentrations of phytotoxic phenolics. The 14 year old plantations of Casuarina equisetifolia showed how they reduced understory vegetation in comparison to the adjoining open areas. The number of plants, species type and biomass were greatly reduced under the plantations. The leachates from fresh leaves and litter and the understory soil were found to be rich in phenolics and exhibited phytotoxic effects against *Bidens pinnata* and *Parthenium hysterophorus* which were no longer present at the plantations but were in the adjoining area. Germination and seedling growth of these two plants was significantly reduced in response to the different leachates. Thus, allelopathy was observed to play a significant role in regulating the understory vegetation dynamics in *C. equisetifolia* stands.

Casuarina initially sprouts as a vertical seedling which can be removed relatively easy from the sandy dunes at BAFS by pulling on the trunk. Once the shrub exceeds approximately 3 to 5 feet, the root ball has to be dug out before it can be removed. Once overhead, they are very difficult to remove mechanically and must be cut and treated with an effective systemic herbicide to ensure they do not regrow. Once they mature and harden in, they take on a weathered, stunted morphology and removal is very difficult. At windward beaches, Casuarina may persist in this stunted form for a number of years until it is sufficiently established. Then it will grow vertically into a tall tree eventually often exceeding 100 feet, with diameters in excess of 30 inches. As the canopy rises it deposits a layer of organic litter that prevents ground cover plants from establishing. At BAFS aki 'aki grass (Virginica, sporobolis) one of the most hardy native coastal plants in Hawai'i, is also one of the few ground covers that can be marginally successful in areas with *Casuarina* trees and litter.

Many of the Casuarina at BAFS are now over 50 years old and are in senescence, with branches and even entire trees falling during high wind events, causing damage to cars and structures. PACAF Safety personnel have identified the Casuarina tree fall hazard as a level X? Risk Assessment Code (RAC Code). Thus Casuarina presents a high risk to life and property at BAFS and has been an expensive management challenge at BAFS.

With no natural pests in Hawaii, ability to fix nitrogen and grow in windy saline environments, Casuarina trees are very invasive. They have accelerated dune erosion which contributes to beach loss. Due to phenolic compounds in Casuarina leaves, they suppress native plants that can help rebuild dunes. Old Casuarina trees have become a safety hazard that requires very expensive trimming or removal. Removal of Casuarina along the shoreline is critical to establishing a stable mosaic of native ground covers that will capture sand and reestablish a functioning dune system. To restore and retain natural sand dunes at BAFS and the surrounding region, eradication of ironwood trees must come first. Due to the phytotoxic nature of the leaves and seeds, when possible all leaves should be removed from restoration sites before native plants are installed. Once removed, Casuarina cleared areas must be maintained to ensure the dune, the plants that retain the dunes, and beach system remain functional.

Jayatissa and Hettiarachi (2006) assessed inundated areas of Sri Lanka following the 2004 Indian Ocean tsunami and registered *Casuarina equisitofolia* as one of the species unaffected by the tsunami. Tanaka et al (2007) also found that trunks *of Casuaraina equisetifolia*, as a single species with trunk diameter larger than 0.1 m, were not broken by the Indian Ocean tsunami and had sufficient stem density to be effective at wave attenuation. However with an average diameter greater than 0.5 m, stem density was low due to self-thinning of the stand and they presumed that this density had little effect in reducing wave velocity. In contrast, their observations suggest that a two layer arrangement of vegetation in the vertical direction with *P. odoratissimus* in the understory and *C. equisetifolia* in the overstory seems to have provided the greatest level of protection from tsunami waves. The *Casuarina* forests along the beach at Bellows are large, mostly over 0.5 m in diameter, and the stand is very sparse, especially along the beach since it is thinned for recreation. Based on the observations of Tanaka (2007) and Kaufman and Gallaher (2011), *Casuarina* alone with the current configuration at Bellows is not effective in proving protection against tsunami waves and is probably not effective at reducing beach erosion as well. An enrichment of species in the lower canopy would be necessary, since mangroves, are not recommended to be planted in Hawaii because of its invasive status.

Man Made Alterations of Bellows Beach

Depending on the season, the area of available beach at Bellows changes with the different types of wave and storm patterns. At some points of the year the beach will recede by several feet due to the erosion of sand, however the effects of this will fade later on in the season when the sand is accreted back to the beach. In an effort to mitigate these effects, the beach at the northern end of Bellows Field was armed with stone revetments, and two jetties were erected at the mouths of both Waimānalo Stream and Inaole Stream (Romine et al, 2008). Because armoring a beach fixes the location of the shoreline when put under constant erosion pressure the beach will eventually reach a state of complete erosion.1 In most cases it is better to leave a beach unarmed and to incorporate seasonal shifts in the shoreline into future building and management plans.[5]

Sea-Level Rise

Sea-level rise is a great concern for all coastal communities and ecosystems and is estimated at 3 mm/yr. Since the year 1980, sea-levels have risen worldwide over 19.5 cm. The rate at which the sea-level is rising also increasing. Estimated by the Intergovernmental Panel on Climate Change (IPCC), the most likely outcome will be an increase in sea-level of 0.9 to 1.3 m by the decade 2090 to 2099. Sea level rise is the result of the thermal expansion of water and increased volume of land ice melt to the ocean. As atmospheric and ocean temperatures rise, molecules of seawater expand taking up more volume than they would at lower temperatures. This coupled with the increasing amount of land ice-melt that is deposited into the ocean each year, is causing sea-level to rise at an alarming rate (State of Hawai'i, Department of Land and Natural Resources and University of Hawai'i, Sea Grant College Program, 2010).

Effects of Sea-Level Rise in Hawaiʻi

In Hawai'i, due to local oceanographic patterns, and volcanic uplift, sea level rise is estimated to be approximately 1.5 mm/yr. – approximately half of the global average. 8 Cumulatively, this constant rise will place increasing erosion and storm pressure on Bellows.

With higher sea-levels many of Hawai'i's ecosystems, natural resources, infrastructure, and residential communities will be negatively impacted. Ground water systems, where the majority of people in Hawai‘i obtain their water, will be intruded by salt water, coastal wetland areas will expand and become more saline, higher tides will create greater drainage problems, and ocean front properties will be at risk of submersion and water damage (State of Hawai'i, Department of Land and Natural Resources and University of Hawai'i, Sea Grant College Program, 2010).

Experimental Site at Belows Air Force Base

Objective

The main objective of this experiment was to address the following questions:

1. Does the restoration of the coastal vegetation in degraded sites play a significant role in sand dune forming?
2. What is the rate of dune forming due to coastal vegetation?
3. Is the use of fences and screens necessary for the restoration of coastal vegetation in degraded coastal sites?

It was possible to document sand accretion in isolated points of the experiment, however, the timeframe of this experiment (one year) is too short to answer question 2. It was possible to answer questions 1 and 3. This project allowed to register changes in dune profile, especially in the foredune, resulting from the presence of vegetation, which trapped and held sand blowing with the wind. The use of fences accelerated the development of plants, however, they were damaged by the first storm. They could be designed to withstand storms, which would probably result in more materials, labor and cost, which also reflects the sustainability of the practice. However, it seems like it is not reasonable to invest in wind screens, since the plots with no screens "catch-up" with the plot with screens, and actually were more able to withstand after irrigation was removed, probably because the plants developed in an environment that required them to develop deeper root system and facilitated the accumulation of sand (which helps to preserve moisture).

Site location

The experiment consists of two treatments with two replications which, resulting in a total of four plots. Each plot measures 30 ft wide and 50 ft deep from the shoreline (Figure 47-50).

"The shoreline is defined as the "upper reaches of the wash of the waves, other than storm and seismic waves, at high tide during the season of the year in which the highest wash of the waves occurs, usually evidenced by the edge of vegetation growth, or the upper limit of debris left by the wash of the waves" (Chapter 205A-1, HRS). In 1990, the Hawaii State Legislature amended the definition of state marine waters to "the water column and water surface, extending from the upper reaches of the wash of the waves onshore, seaward to the limit of the state's police power and management authority, including the United States territorial sea, notwithstanding any law to the contrary." (Chapter 190D-3, HRS). In a 1988 proclamation, President Reagan extended the territorial sea of the U.S. from three to twelve miles (Id)."

(DLNR Hawaii Coastal Erosion Management Plan, 2000)

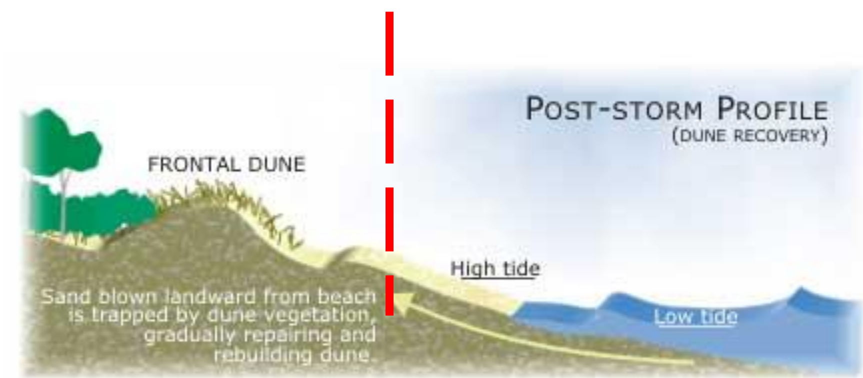


Figure 47**.** The dashed line marks the shoreline, defined as the "upper reaches of the wash of the waves, other than storm and seismic waves, at high tide during the season of the year in which the highest wash of the waves occurs, usually evidenced by the edge of vegetation growth, or the upper limit of debris left by the wash of the waves". (DLNR Hawaii Coastal Erosion Management Plan, 2000).

Two site locations:

Figure 48. Project sites at Bellows Air Force Station, Waimanalo, HI.

Figure 49. **Site 1 In front of Cabins / by Gas statin** 21°22'22.1"N , 157°42'27.6"W

Figure 50**. Site 2 Next to Pavilion** 21°22'05.2"N, 157°42'33.5"W

Plant Selection and planting design

Based on Kaufman and Gallaher (2011) observations in six areas on the south shore of Upolu Samoa which had been inundated by the September 29, 2009 tsunami, the density of the natural vegetation in the observed area was 1500 stems per hectare and it mitigated the damage from the tsunami. Therefore, our first attempt was to use the density of 1500 stems per hectare as a baseline for this restoration project.

The density of 1500 stems per hectare equals .0139 plants per square foot, or 71.75 square feet per plant, resulting in a spacing of 8.5 feet between plants. For each plot of 20mx10m, would be necessary 30 plants. However, this spacing seems to be too large based on the average size of plants growing naturally in Makapu'u and Kaiwi coast. Large shrubs seem to occupy a diameter of 6 ft, while smaller herbs seem to cover a diameter of 3 to 6 ft.

Another factor that should be considered regarding the use of Samoa's density is the maturity of the system. Samoa's forests were more "mature", with plants with larger canopy and larger spacing.

If this project aims at covering the soil in a short period of time, even if it requires "overpopulation" when planting to ensure that the soil will be fully covered, it might be necessary to adopt a higher density than the observed in Samoa. Table 11 shows two scenarios with two different populations, and figures 51 and 52 show different plant schemes.

Table 11. Different density scenarios.

Plants / hectare	Spacing (ft)	Plants for each plot	Plants for 4 plots
1500	8.5	30	120
3000	6	60	240

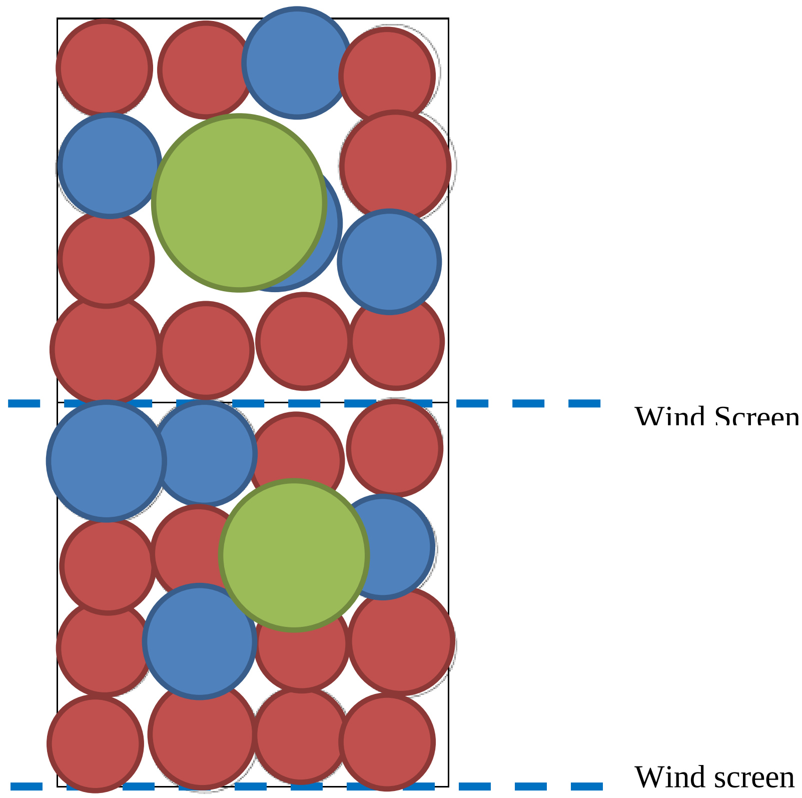


Figure 51. Density of 1,500 plants per hectare, resulting in 8 lines with 4 plants per line. Red: groundcovers (aki’aki, pohuehue, akulikuli, pa’uohi’iaka, aweoweo, ohelokai, ihi, hinahina kahakai, ilima papa); Blue: shrubs (aweoweo, pohinahina, mau’u akiaki, naupaka, nanea, maiapilo, ulei, ohai, hinahina ku kahakai); Green: trees (ma’o, hala, naio, iliahilo’e, aulu, kou, loulu, wiliwili).

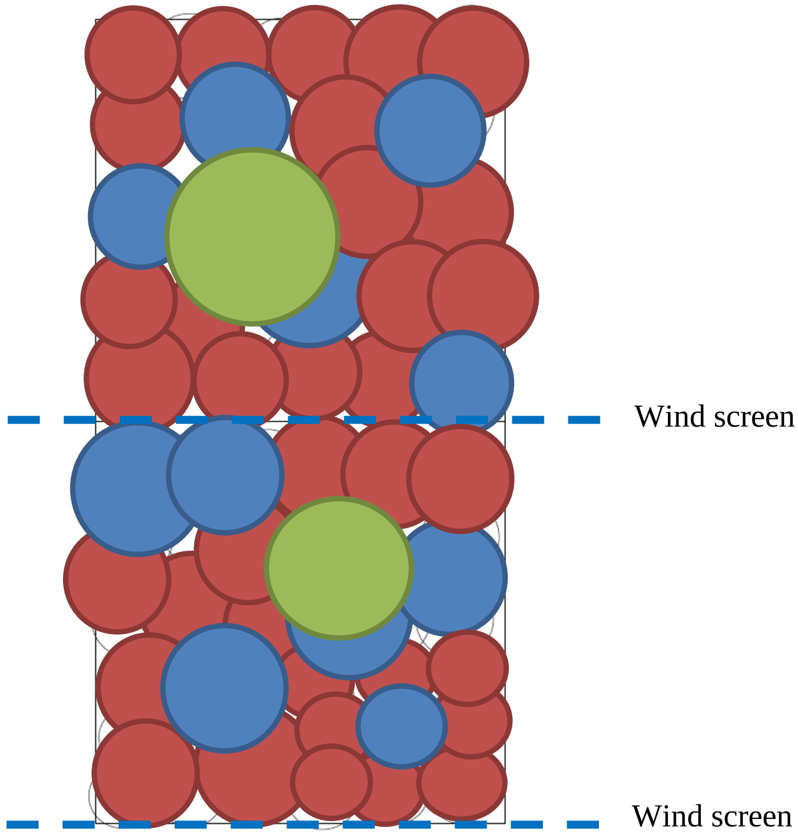


Figure 52**.** Density of 3,000 plants per hectare, resulting in 10 lines with 6 plants each line. Red: groundcovers (aki'aki, pohuehue, akulikuli, pa'uohi'iaka, aweoweo, ohelokai, ihi, hinahina kahakai, ilima papa); Blue: shrubs (aweoweo, pohinahina, mau'u akiaki, naupaka, nanea, maiapilo, ulei, ohai, hinahina ku kahakai); Green: trees (ma'o, hala, naio, iliahilo'e, aulu, kou, loulu, wiliwili).

Bellows Air Force Station had done some out-planting projects in the same area and noticed that plants need to be planted at higher densities for satisfactory ground coverage. Also, nurseries specialized in native plants recommended spacing varying between 12" for grasses and sedges, 6" to 36" for shrubs, and 4' to 6' for trees. A plant list was generated based on field observations of native plant occurrence and availability in nurseries (table 12), and a planting map was used to guide planting at the field (figure 53). The plant selection also considered the fact that the beaches in the location of the experiment is frequently used for recreation, therefore species with thorns were avoid,, since they may cause injury during normal conditions and caused deaths in previous tsunamis, as reported by Kathiresan and Rajendran (2005).

Table 12. List of plants used for this project.

	Hawaiian Name	Genus species	Common Name	Description	Plants per PLOT	SPACING
	HERBACEOUS					
1	Kōkoʻolau or Koʻokoʻolau	*Bidens sp*	Beggarticks	Perennial or annual herbs	2	24"
	GRASSES & SEDGES					
2	ʻAhuʻawa	*Cyperus javanicus*	Java sedge	Perennial grass	60	12"
3	Kawelu, Kalamalo	*Eragrostis variabilis*	Lovegrass	Clumping grass	15	18"
4	Mauʻuʻakiʻaki	*Fimbristylis sp.*	Button sedge	Perennial sedge	2	12"
	SHRUBS					
5	Hinahina kū kahakai	*Heliotropium anomalum*	Seaside heliotrope	Low shrub, miniture sword plant (MCBH Pyramid rock)	4	6"
6	ʻIlieʻe	*Plumbago zeylanica*	White leadwort	Sprawling Shrub	70	8"
7	Ilima	*Sida fallax*		Shrub	30	36"
8	Naio shrub	*Myoporum sandwicense*	Bastard sandalwood	Shrub	5	4'
	Naio papa	*Myoporum sandwicense*	Naio papa	Ground cover	-	12”
9	Naupaka kai	*Scaevola taccada*	Beach naupaka	Low-growing perennial shrub	10	24"
10	Pōhinahina	*Vitex rotundifolia*	Beach vitex	Low, trailing shrub	20	8-12"
11	ʻŪlei	*Osteomeles anthyllidifolia*	Hawaiian hawthorn or rose	Sprawling Shrub	4	12"
	TREES					
12	Kou	*Cordia subcordata*		Tree	3	
13	ʻIliahi aloʻe	*Santalum ellipticum*	Coastal sandalwood	Tree	4	4'
14	Loulu	*Prichardia hillebrandii Molokai*	Hillebrand's Loulu, Blue dwarf palm	Palm tree	6	6'
	VINES					
15	Pāʻūohiʻiaka	*Jacquemontia ovalifolia sandwicensis*	Oval-leaf clustervine	Sprawling vine, purple flower	15	6-8"
16	Pōhuehue	*Ipomoea pes-caprae*	Beach morning glory	Perennial vine	20	6"
	TOTAL				270.00	

Mauka

6 6	6 6	10	7	10	6 6	6	6		7	7	7
6 6	6 6	6 6	10		14	6 6	6 6	13	7 7	7	7 7
6 6	7	14	11	6	15	6 6	7	14	7	7 7	7
16	7	8	8	15	15	15	8	16	10	10	
3 3	10	6 6	6	14	3 3	3 3	11		10	6	4
3 3	13		12	3	3 3	3 3	9	12	15	14	4
3 3	7	10	8	10	2 2	2 2	14	10	6	15	6 6
16	5	7	2 2	11	2 2	2 2	2 2	2	15	9	
5	7	7		2	1	13	12		1	5	16
5	2 2	7	6	6 6	6 6	6 6	6 6	6	7	7 7	6 6
6	6 6	9	9	7	11	6 6	6 6	6	7	7	16
16	7	6	9	2 2	16	2	6	10		7	
2	6	16	7	16	16	2	2	15	9	15	
2	7	15	8	10	13 2	10	8	10	15	9	2
2 2	6 6	15	9	15	16	16	10	16	9	2 2	2 2
2	2 2	15	15	9	10	16	7	16	2	2 2	2
2 2	2 2	7	10	6	7	11	15	7	15	7	6 6
2	2 2	2	6	16	16	8	10	15	10	6 6	6 6
2	2 2	2	2 2	10	16	10			10	6 6	6
2	2 2	2 2	2 2	6 6	6 6	6 6	16 2	16	10	16	6 6

Makai

Screen

Screen

Figure 53. Map used for planting. Each number correspond to the respective plant in figure 8.

Irrigation Design 1

Irrigation plays a key role in plant survival because of the high temperatures, high salinity and wind. Localized irrigation is the most suitable because of the sandy soil and frequent winds. The use of a combination of DIG Corp ½ in. Poly Drip Tubing with DIG Corp 360 Degree Adjustable Drippers would address this need (Figure 54). They are found at $5.46 a 10-pack at Home Depot (quote made on 06/10/13). Figure 55 shows a diagram of the irrigation, and Table 13 the estimated cost.

Figure 54**.** DIG Corp 360 Degree Adjustable Drippers. (Source: Home Depot Web Page)

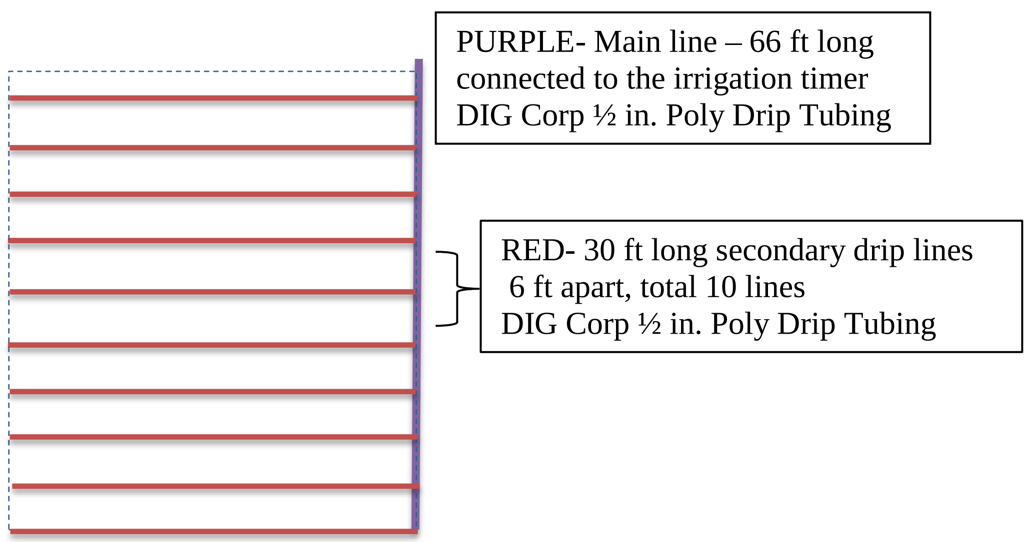


Figure 55**.** Irrigation diagram.

This system was used in a previous project by the UH Tropical Landscape and Human Resources Lab and we notices that this system could have problems when used in large scale projects: varying irrigation along the plot; the drippers or its caps "pop-out", affecting the whole irrigation system; it needs constant supervision; because the drippers are not flush to the line, it is hard to slide the lines under the plants when it needs to be moved; irrigation lines are not as recyclable as the other systems can be. The drip line system, although more expensive, doesn't have these issues, is more reliable, and was chosen instead.

Irrigation Design 2 – Drip line

Since the use of shrublers and sprinkers was not the best option, as described before, the second option to explore is dripline. Dripline offers the benefit of uniform flow rate, and modular design, which in turn allowed to easily remove the irrigation system after the plants where established (Figure 56). In this experiment, the drip lines were removed ten months after planting and re-used in new plots, avoiding debris on site, and reducing the cost for new restoration sites. The system (Figure 57) was designed using the TECHLINE desing manual, and a cost estimated is presented on table 15.

Figure 56**.** Drip-lines removed from an established plot, ready for a new planting.

Based on TECHLINE TM DESIGN MANUAL provided by NETAFIM USA

TECHLINE™ DESIGN MANUAL

http://www.midwestturf.net/documents/rescom%20literature/Netafim/Techline%20Design%20Manual.pdf

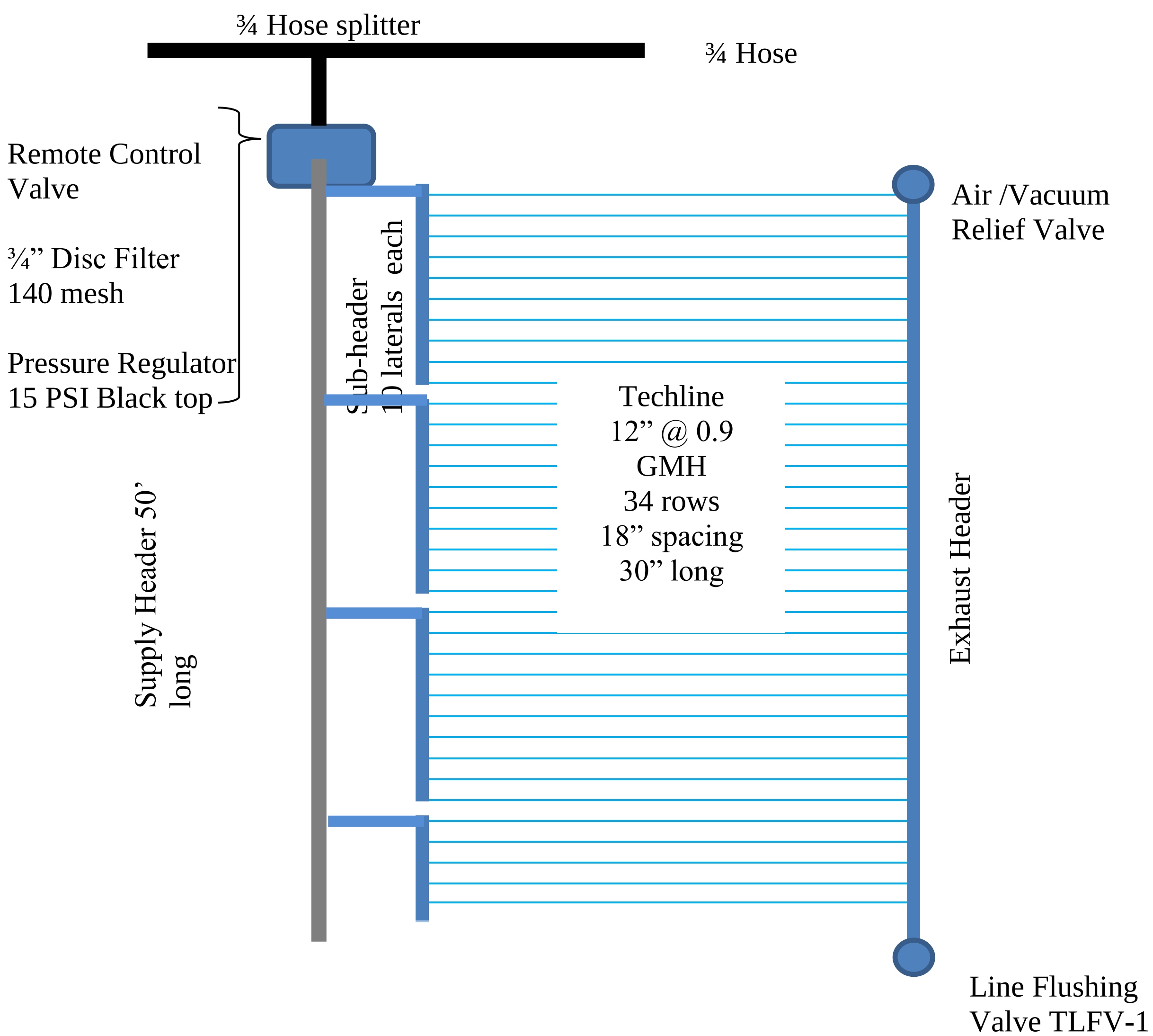


Figure 57. Irrigation diagram based on Netafim USA Techline™ Manual.

Table 13. Estimated irrigation cost for 6,000 sf ft of planted area.

Quantity	Unit	Item Number	Description	Price	Unit	Extension
4	EACH	NODE 100	HUNTER NODE ONE STATION BATTERY TIMER & DC SOL.	85.250	EA	341.00
4	EACH	HY-100	HUNTER DRIP FILTER 1"WY W/150 MESH SS SCREEN	12.953	EA	51.81
4	EACH	PGV-101G	HUNTER VALVE PGV 1" PLS IN-LINE GLOBE W/FLOW CONT	15.813	EA	63.25
4	EACH	PMR25MF4F4FV	SENNINGER PRESS.REG.25P medium flow, 1" fpt	13.700	EA	54.80
4	EACH	TLCV9-1210	NETAFIM TECHLINE 1/2"W- .9 GPH,12"SPACNG,1000'ROL	369.113	EA	1,476.45
1	EACH	TLCV9-1201	NETAFIM TECHLINE 1/2"W- .9 GPH,12"SPACNG,100'/ROL	36.923	EA	36.92
300	EACH	TLTEE	NETAFIM TEE BARB X BARB X BARB INSERT	.459	EA	137.70
16	EA	402-131	RED TEE 1 x 1 x 3/4 SST 1.520 SCH40	EA	24.32	
16	EACH	TLELL	NETAFIM TECHLINE ELBOW INSERT FITTNG	.425	EA	6.80
4	EA	447-010	CAP 1" SCH40 SLIP .530 WHITE	EA	2.12	
4	EACH	TLAVRV	NETAFIM AIR/VACUUM BREA 1/2" MPT.	8.430	EA	33.72
4	EACH	TLFV-1	NETAFIM FLUSH VALVE ROU 1GPH W/TECHLINE CONN.RING	14.017	EA	56.07
2,200	EACH	TLS6	NETAFIM 6" STAPLE WIRE	.145	EA	319.00
800	FT	PVC 40 X 1	PVC PIPE SCH.40, 1.0 SCHEDULE 40, WHITE 1	.405	FT	324.00
4	EA	401-010	TEE 1" SXSXS SCH40 WHITE	.860	EA	3.44
4	EACH	458200	HUNTER SOLENOID D.C LATCHING FOR PLASTIC VALV	20.350	EA	81.40
4	EACH	BATTERY 9VOLT	BATTERY 9 VOLT SOLD INDIVIDUALLY	2.990	EA	12.00

*** Q U O T E *** Sale Amt $ 3,018.78

Str: 2 Reg:204 Drw:204 Usr:JJ 16:16

Sales Tax $ 142.24

Total **$ 3,161.02**

*Estimate from Diamond Head Sprinklers on Sept 3rd, 2013.

Planting

The planting methods varied slightly from the two plots in the Pavilion to the other two plots by the bathroom. The techniques evolved as the team learned more about the practicalities involved in this type of work, particularly the installation of the irrigation system and windscreens. The entire process is described below.

Site 1

The vegetation at Site 1 consisted of ironwood, ‘aki‘aki grass and beach heliotrope (Figure 58). The ironwood trees were cleared out entirely by the project team (Figure 59). Each tree was cut using best technique practices, and the logs were cut down to smaller sizes to be used as plot limits.

Figure 58. Location of Plot 1 before cutting down the ironwood trees and planting.

Figure 59. All trees from plot 1 location had to be cut down by the project team.

Once cleared, the plot limits (32 feet long by 52 feet deep) were delineated with tree logs cut on site). After the plots were cleared, the logs from the cut ironwood trees were used to draw the boundary of the plots, measuring 30 feet long and 50 feet deep (figures 60 and 61). All branches and accumulated ironwood leaves were raked out of the plots. Weeds were removed as well.

Figure 60. Plot 1 after cutting down the ironwood tree, partially ready for irrigation and planting.

Figure 61. Plots ready for planting.

The irrigation was pre-assembled prior to the day of planting. The sub main lines with all the tees and connections already assembled were laid down on both sides of the plots, stapled with wire staples and logs, and the lateral lines were measured and cut one by one, as they were being connected. The staple wires did not fix to the ground very well because the sand was loose, so it was necessary to work in two or more people to install the irrigation: some holding the sub main and others running and cutting the lines. The lines were cut as they were connected. This reduced a lot the number of cuts and made the process cleaner, with less litter in the beach, compared to Site 2 where the lateral lines were pre-cut in estimated 30 feet long pieces.

The planting was made with volunteers from the Youth Challenge Academy (YCA). The YCA cadets, circa 80 of them, helped with planting and installing the irrigation.

The crew was divided in groups and some people started allocating and planting the plants as the irrigation lines were placed. One of the project leaders, designated "plant caller", was in charge of reading the planting map to facilitate the allocation of plants. In addition to the planting grid map with the location for each individual plant, a second map was generated with the number of each species in each subplot. Therefore, the plant caller first called the number of plants in each subplot, and then the plants were placed in the specific location. This facilitated the process and reduced the risk of errors compared to the Site 2 where the plant caller did not have a second map, because the plant caller of Site 1 didn't have to count the number of plants in each sub-plot.

The irrigation was completed and turned on after everything was planted. The plants were hand watered as well to ensure moisture in the soil.

The wind screen as installed right after planting. They were not installed before because it would interfere with the installation of the irrigation, mulching and planting, however, maybe it could be installed before to ensure wind protection from the moment of planting, since environmental conditions prevented the installation of the wind screens in the second site. First, the lodge-poles were pounded in the sand using a pole pounder. The poles were 8ft long, and were bared 2.5' in the ground, so the final height of the poles was 5.5'. Three poles were placed in the middle of the plot (25 feet from the ocean border), and tree in the ocean side boundary of the plot, 15ft apart each (Figures 62-63). The poles were drilled with ¼" drill bits and the cables were passed through the poles and locked in placed using cable clamps. The distance between the poles were measured and each segment of screen was measured to ensure that the screen length was matching the distance between poles, and five grommets were then placed on each side of the screens (Figure 64-65). The screens were tied to the pole using zip-ties (Figure 66).

The system used in site 1 was more effective than the system used in Site 2. The plant allocation was easier, the irrigation was faster, and the screen was tighter and had a better look, which is important since it is a recreational area.

Figure 62. Poles installation (photo from site 2).


Figure 63. Steel cables used for sind screen support.


Figure 64. Plots planted and with wind screen installed.


Figure 65. Plots planted and with wind screen installed.


Figure 66. Windscreen attachment detail.

The plots at Site 1 were heavily damaged by a storm that occurred about one month after planting. The plot without screen was washed off by storm water that run thought the experiment, and the drip lines were buried more than 2 feet deep when the sand returned naturally through tide and wave action (Figures 67-70). The irrigation lines were dug out of the sand, re-organized, and the vegetation (mostly *Ipomea pes-caprae* and *Sporobolus sp.)* completely covered the plot, which was partially uncovered, with exposed sand before the experiment (Figures 71-73).

The plot with screen suffered damage as well. The wind screen on the beach side of the plot did not resist the wind and the center pole broke. The screens were removed to avoid damage on the plants, and the screen in the middle of the plot was removed with a second storm warning (Figures 74-82). As the plot with no screen, the vegetation completely covered the ground, growing beyond the planting limits.

Figure 67. Plot after storm, 07/21/2014

Figure 68. Plot after storm, 07/21/2014

Figure 69. Sand recovered to plot with wave action and buried irrigation, 08/27/2014

Figure 70. Sand recovered to plot with wave action and buried irrigation, 08/27/2014

Figure 71. Sand fully recovered to plot, irrigation unburied, 09/03/2014.

Figure 72. Sand fully recovered to plot, irrigation unburied, 09/03/2014.

Figure 73. Vegetation recovery after storm (*Ipomoea pes-caprae* subsp. *brasiliensis*), 04/09/2015

Figure 74. Plot with screen, 07/08/2015**.**

Figure 75. Wind screen damaged by storm. 07/21/2014.

5

Figure 76. Wind screen was removed after second storm. 08/20/2014

Figure 77. Plot initially with windscreen, 05/01/2014.


Figure 78. Plot seem from north side, foredune, 08/27/2014.


Figure 79. Plot seem from north side, foredune, 05/01/2015.


Figure 80. Plot seem from north side, dune crest, 05/01/2015.

Figure 81. Plot seem from north side, back dune, 09/03/2014.

Figure 82. Plot seem from north side, back dune, 05/01/2015.

Site 2

The Site 2 was located near the Pavilion B, next to the life guard tower (figure 83).
21°22'05.2"N, 157°42'33.5"W

Figure 83. Site 2 location.

Most of the ironwood trees at plot 2 were cut by the Marine reserves. The trees were marked with paint spray and the Marines cleared an area of 100 ft long and 60 ft deep. Only a few trees were left, which were cut by the project team. The planting was made with help of the YCA and other volunteers (Figure 84).

The plots were then measured and marked with colored tape (Figure 85-86), marking the four corners of each plot, using the existing shoreline vegetation as a reference to define the limits for the ocean side of the plots. From that line, the plots were marked 52 ft deep and 32 feet wide, to give 1ft clearance for irrigation lines and tolerance. Iron wood logs were laid down along the boundaries of the plots to define the plot area and prevent beach users from walking inside the plots (stepping on plants, Figure 87).

After laying down logs, the mulch was spread to cover the ground about 1” thick, so that sand could not be seen though. After mulching, the irrigation lines were laid down and cut in place, and arranged parallel to each other, based on the irrigation design (Figure 88). A grid was marked to form the sub-plots in the plot, following the planting diagram (3 columns, 5 rows), using orange tape mark the lines diving the sub-plots (Figure 89).

The plants were placed in each plot based on the planting map. One person experienced with identifying the plants was responsible for calling the plants and positioning it on the plot, and the volunteers were responsible from moving the plants around (Figure 89). This was an important learning opportunity, since the young cadets learned about the native plants and how to organize the planting. When all plants were set in place, the volunteers actually planted the plants in the sand using small shovels, scoops and the hands (Figures 90-91).

Figure 84. YCA cadets in formation before starting the work day.


Figure 85. Plot marked with sticks.


Figure 86. Project site ready for planting.

Figure 87. YCA cadets at the project site, used logs to demarcate the plot boundaries.

Figure 88. Graduate assistant Kalani Matsumura, volunteer, and Air Force Environmental Programs Director Mark Ingoglia, with mulch and irrigation were ready for planting.

Figure 89. A project leader orienting a cadet on how to read the plant table and planting map. Note the orange tape diving the plot in subplots for plant allocation.

Figure 90. Volunteers planting the plot..

Figure 91. Plot right after planting.

Once everything was planted, the plots were hand-watered with a water hose and the irrigation was completed. Small segments of 17” were cut to connect the lateral lines using TEEs. This process was very inconvenient and lengthy, because the lines were not all the same size and had to be recut. Also, it was hard to make all the connections in the field. This process was improved for planting of site 1, as described above, with pre-assembled pieces to reduce the irrigation work on the day of planting. Once the irrigation was completed, the water line was connected to the irrigation system and setup for 2 cycles of 6 hours per day each, for a total of 12 hours/day. The irrigation time was gradually reduced, about 10% per month, until completely shut and removed to be used in another restoration site.

The windscreen was installed about three weeks after planting (figure 92-97), similarly to Site 1. First, the lodge-poles were pounded in the sand using a pole pounder. The poles were 8ft long, and were bared 2.5’ in the ground, so the final height of the poles was 5.5’. Three poles were placed in the middle of the plot (25 ft from the ocean border), and tree in the ocean side boundary of the plot, 15ft apart each. After the poles were in place, the windscreen was prepared with three grommets in each side, and tied to the poles using wiring cables. After tying the windscreens to the poles, cables were added to provide a back support and reduce the “sailing effect”, to prevent the screen from ripping off.

There were some learning experiences installing the screen in these first plots. First, the screens were not actually 15 ft long as described by the manufacturer, so some where shorter or longer than others, and there were excesses or gaps when tying them to the poles. We went around it by rolling the screens in case of excess, and using long wires to tie them if they felt short. It would be better if we had placed the poles closer, to avoid gaps. Also, three grommets seemed not enough, and the screen would look better with more grommets. The screens were more stable at Site 1, with five grommets.

One of the concerns was the aesthetics of the screens, since Bellows is a recreational/touristic destination for the military. The screen color was chose to blend with the environment. After installed, the wind screens were easily noticeable, however they did not block the view and actually helped to increase awareness of visitors about the experiment, since many of them would ask about it during installation and routine maintenance and data collection, generally with positive feedback.

Figure 92. Screens installed

Figure 93. Plot with screen on the left (south side); plot without screen on the right.

Figure 94. Plots, north east view.

Figure 95. View from north.

Figure 96. View from the pavilion.

The plot with screen had a clearly advantage in the first months after installation, covering the soil faster than the plot with no screen (Figures 97 to 112). However, the plot without screen eventually catch up and started to look similar about 6 to 10 months after planting (Figures 113-116). Finally, the plot without screen looked better than the plot with screen one year after planting (Figures 117-118). These observations will be discussed in the results, conclusions and recommendations sections.

Figure 97. Plot with screen, foredune, view from north 05/08/2015.


Figure 98. Plot with screen, back dune, view from west 05/08/2015.


Figure 99. Plot without screen, backdune, view from west 05/08/2015.

Figure 100. Plot with screen, foredune, view from north 2.5 months after planting (07/03/2014).

Figure 101. Plot without screen, foredune, view from north 2.5 months after planting (07/03/2014). Note how the vegetation in the plot with screen cover the plot a lot better.


Figure 102. Plot with screen, foredune, view from west 4 months after planting, 08/20/2014.


Figure 103. Plot without screen, foredune, view from north 4 months after planting, 08/20/2014.

Figure 104. Plot with screen, backdune, view from west 4 months after planting, 08/20/2014.

Figure 105. Plot without screen, backdune, view from west 4 months after planting, 08/20/2014.


Figure 106. Plot with screen, foredune, view from east, 4 months after planting, 08/27/2014.


Figure 107. Plot without screen, foredune, view from east, 4 months after planting, 08/27/2014.

Figure 108. Plot with screen, foredune, view from north, 5 months after planting, 9/17/2014.

Figure 109. Plot without screen, foredune, view from north, 5 months after planting, 9/17/2014.

Figure 110. Plot with screen, foredune, view from east, 5 months after planting, 9/17/2014.

Figure 111. Plot with screen, foredune, view from east, 5 months after planting, 9/17/2014.

Figure 112. Plots with and without screen, foredune, panoramic view from east, 5 months after planting (9/17/2014).

Figure 113. Plot with screen, foredune, view from north, 6 months after planting, 10/27/2014.

Figure 114. Plot without screen, foredune, view from north, 6 months after planting, 10/27/2014.

Figure 115. Plot with screen, foredune, view from east, 6 months after planting, 10/27/2014.

Figure 116. Plot without screen, foredune, view from east, 6 months after planting, 10/27/2014.


Figure 117. Plot with screen, foredune, view from north, 13 months after planting, 05/18/2015.


Figure 118. Plot without screen, foredune, view from north, 13 months after planting, 05/18/2015.

Plant Survival

Plant survival varied greatly among species. This experiment tried 14 species, and each of them will be reported individually. Plant population and size was accessed three months after planting. Plant population was recorded monthly initially, however, considering that the ground was covered mostly by vines with prostrate growth, it became unpractical to determine plant count and size after the plants were established. The plots were documented monthly with pictures and field notes, quantitative data was obtained twelve months after planting (ground coverage, plant height and dry-weight of ground covers, described below).

Plant population was determined by dividing the plot in 15 subplots, forming a grid (figures 119 and 120). Field notes were taken using the table shown in figure 121.

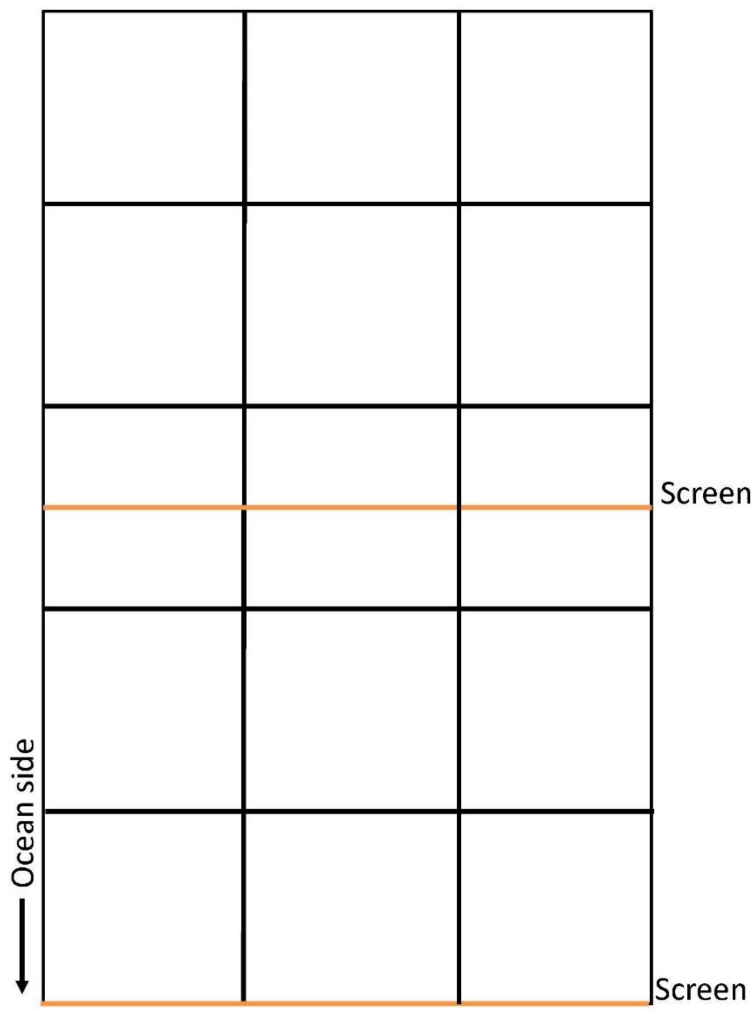


Figure 119. Grid used to evaluate plant survival three months after planting.


Figure 120. Plot market with orange tree-tapes, used to guide planting and evaluations.

Deflecting the Wave: Using Coastal Vegetation to Mitigate Tsunami and Storm Surge

Evaluation by:________________ **Pavilion Plots NO SCREEN** Date: ___/___/___

Block 1	**Count**	**Width**	**Height**	**Observations**
ʻIlieʻe				
Ilima				
Naio shrub				
Pōhinahina				
ʻŪlei				
Loulu				
Block 2	**Count**	**Width**	**Height**	**Observations**
ʻIlieʻe				
Ilima				
Naio shrub				
Pōhinahina				
Loulu				
Pāʻūohiʻiaka				
Block 3	**Count**	**Width**	**Height**	**Observations**
Ilima				
Pōhinahina				
ʻIliahi aloʻe				
Loulu				
Pōhuehue				
Block 4	**Count**	**Width**	**Height**	**Observations**
ʻAhuʻawa				
Kawelu				
Hinahina kū kahakai				
ʻIlieʻe				
Ilima				
Naio shrub				
Pōhinahina				
Kou				
ʻIliahi aloʻe				
Pōhuehue				
Block 5	**Count**	**Width**	**Height**	**Observations**
ʻAhuʻawa				
Kawelu				
Naupaka kai				
Pōhinahina				
ʻŪlei				
Loulu				

Page 1 of 3

Figure 121**.** Table used for field evaluation.

Ground Coverage

The percentage of ground coverage was obtained with digital analysis using image editing software. The photos were taken using a digital camera and a square wooden frame measuring 3ft by 3ft internally, for a coverage of 9sq ft per sample. The pictures were taken by hand, approximately 5.5 feet above ground level, perpendicular to the frame. Each dune zone (foredure, crest, and backdune) had four samples, both plots (with screen and without screen). A label was placed next to the frame to identify the samples (figure 122).

Figure 122. Wood frame measuring 3ft by 3ft, used to take pictures for coverage analysis and to collect samples for dry weight.

The digital pictures were downloaded into a PC and analyzed with the software Adobe Photoshop CS5, using a method similar to the described by Stewart et al. (2007). One picture for each sample was opened in Photoshop and the area within the wood frame was cropped adjusted to cover the entire canvas size. All shades of green and yellow representing green material (live plants) were selected using the "Color selection" tool. The selections were moved to a new layer, until all plant material was moved to new layers, which were merged into a single layer isolated form the ground (sand, debris, etc). A new layer was created under the layer with plants and filled with red, since there was no red pixels in any of the plant materials. Since some samples had sand over the leaves, especially in the foredune zone, the layer red was overposed by the green materials layer and selected red areas were erased to make sure that leaves covered by sand counted as leaf coverage (Figure 123). Finally, the layer with plants and red layer were merged into a single layer, and the pixels filled with red were selected using the color selection tool, which would be ground not covered by plants. The selection was inverted, so that all plant material was selected. The number of pixels in the selection was obtained thought he Histogram menu, and divided by the total number of pixels in the image, resulting in the ground coverage ratio.

Figure 123. Image cropped and manipulated to calculate the ground coverage by green plants.

Ground Cover Height

The height of three ground covers was compared: *Ipomoea pes-caprae*, *Vitex rotundifolia*, and *Jacquemontia sandwicensis*, the three predominant ground covers in the studied plots.

Ground cover height was determined in the same sample used to determine the ground coverage. The wood frame was visually divided in four parts (Figure 124) and the highest point of each species was recorded in each quadrant, for a total of 4 height measurements per sample. The measurements were then averaged, and the averages were used to calculate total average of each species per dune zone, screen treatment, and standard deviations.

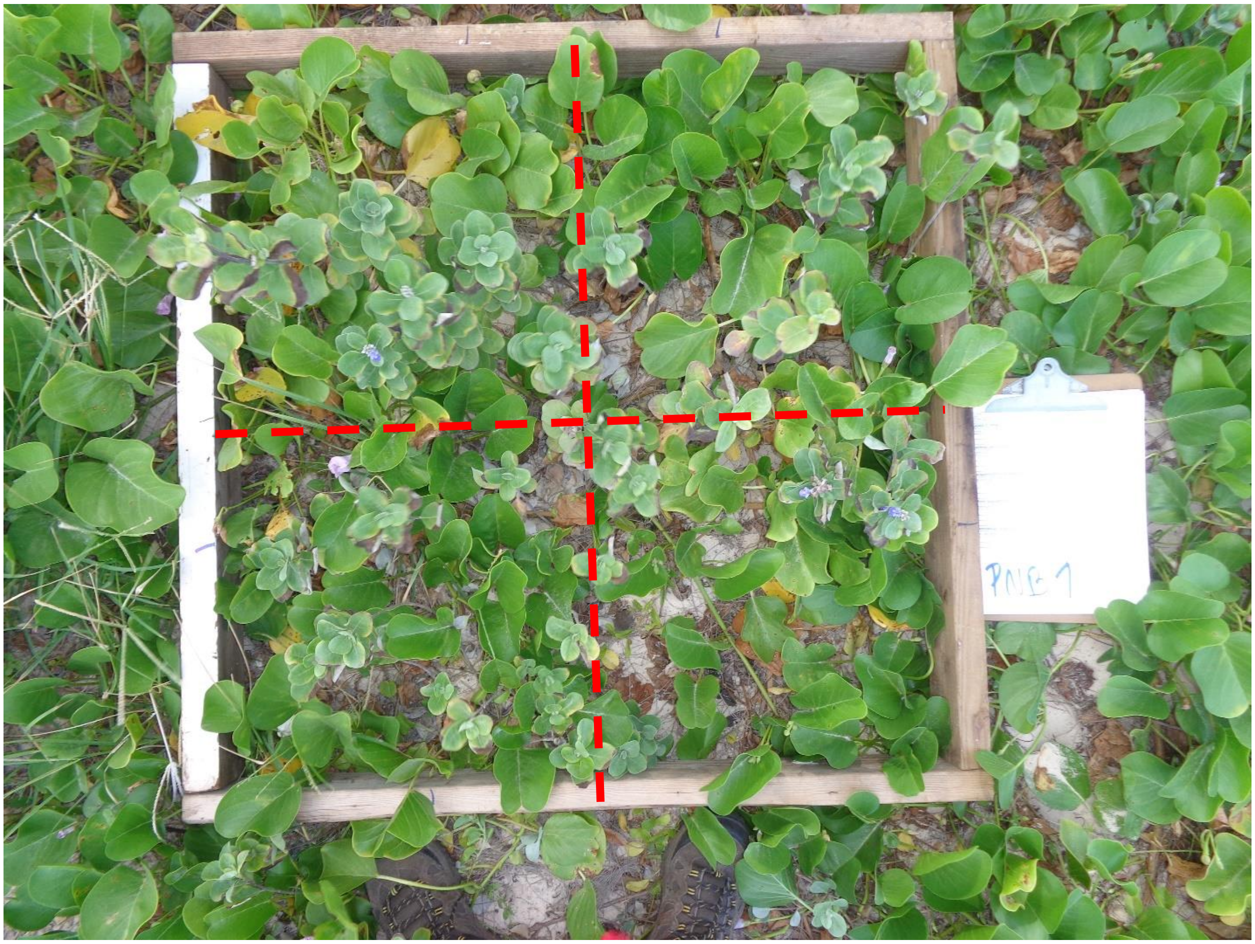


Figure 124. Wood frame divided in four quadrants through visual lines for height measurements.

Dry Weight

The dry weights of the three predominant ground covers were compared (*Ipomoea pes-caprae*, *Vitex rotundifolia*, and *Jacquemontia sandwicensis*).

The samples were taken in the foredune zone of the two plots on Site 2 (four samples per plot). After taking the pictures for ground coverage determination and measuring plant heights, all live plant material above ground and within the wood frame was collected for dry weight determination, without moving the frame. All plant material (leaves and stems) was collected and stored in paper bags, identified by the sample code and species (for example, FS1-VR meant Foredune Screen 1 – *Vitex rotundifolia*). After all samples were collected, the paper bags were placed to dry in a dry oven for 7 days, until all plant materials were dry. The samples were then weighted in a precision scale (two decimals of gram) and compared among species and screen effect.

Results an Discussion

Plant Survival

All plant species were evaluated in terms of survival rate, average size, and appropriate dune zone for planting. After one year of observations, the entire plot was covered with vegetation, with ground covers growing beyond the planted area (Figure 125). Each plant will be reported individually.

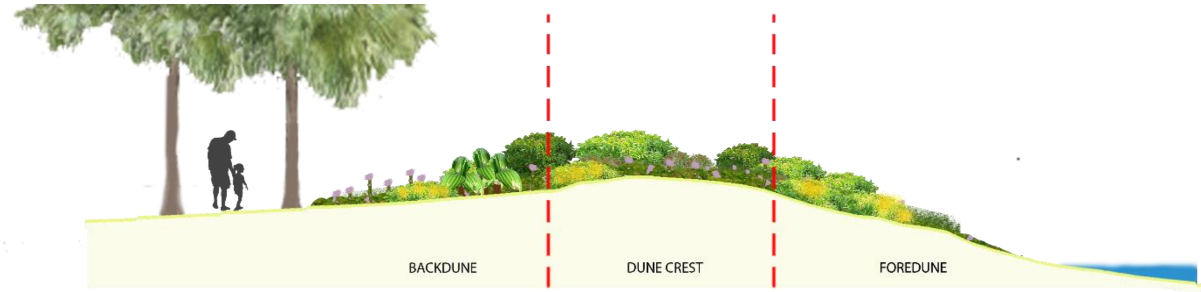


Figure 125. Vegetation distribution in the dune profile.

Koʻokoʻolau – *Bidens* sp.

Koʻokoʻolau is not recommended to be planted in bare beaches, without protection of other plants or structures. All plants (two per plot, total 8 plants) dried out within two weeks after planting (Figures 126 to 128). It seemed to don't tolerate salt spray, therefore, it could be planted in the back dune after other plants have established, protected from wind and salt spray, instead of planting at the beginning of the dune restoration. Therefore, future restoration projects should consider staged planting.

Figure 126. Bidens the day of planting.

Figure 127. Bidens 4 days after planting (04/23/2014).


Figure 128. Bidens 15 days after planting (05/05/2014)

ʻIlieʻe - *Plumbago zeylanica*

The Hawaiian plumbago survived only in the back-dune zone, however, it was struggling after the irrigation was removed, with yellow leaves and dry appearance (129 to 132), and were eventually dominated by *Ipomoea* and *Vitex*. It might not be a plant suitable for dune restoration, with low salt tolerance, but should be considered for areas not exposed to salt spray.

Figure 129. ʻIlieʻe the day of planting.

Figure 130. ‘Ilie‘e in the foredune, 2 weeks after plangin, very sensitive to salt spray.

Figure 131. ‘Ilie‘e five months after planting.


Figure 132. ‘Ilie‘e 10 months after planting, starting to turn yellow.

Ilima – *Sida falax*

Ilima is a native ground cover widely used for landscaping and is also found naturally occurring in Waimanalo in natural landscapes such as Makapuʻu Beach Park and Kaʻiwi. It has been previously used in similar projects at Bellows Air Force Base, growing across all dune zones (Figure 133).

However, the plant supplier provided a different cultivar, with round leaves (Figure 134 and 135), instead of the typical narrow leaf ilima found at Bellows. The plants did not show signs of stress from wind and salt, however, were infested with mealy bugs (Figures 136 to 139), which were controlled with organic pesticides only after most of the plants were killed. The plants that survived were up to 36" wide by 16 inches high at 3 months after planting, and 3 ft wide by 2 ft high 13 months after planted (Figure 140).

Insecticidal soup was not efficient on the control of the mealy bugs, even after three application (Figure 141). The "EcoSMART Organic Insecticide", however, controlled the mealybugs after liquid and granular application (Figures 142). The insecticide also burned some plants where the insecticide was applied.

Narrow leaf ilima was propagated and successfully transplanted into the plots after the mealy bug population as controlled (Figures 143 and 144).

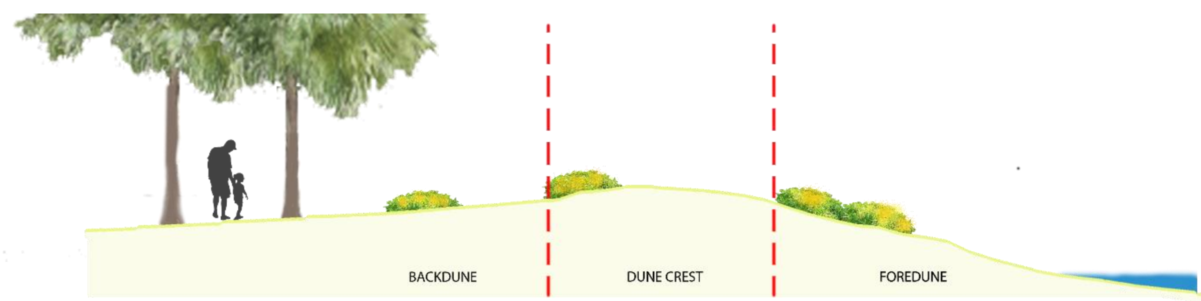


Figure 133. Ilima distribution in the dune profile.


Figure 134. Broad leaf ilima at the day of planting.


Figure 135. Ilima two weeks after planting.

Figure 136. Ilima 2.5 months after planting, attacked by mealy bugs.

Figure 137. Ilima 2.5 months after planting, attacked by mealy bugs.


Figure 138. Ilima 2.5 months after planting, attacked by mealy bugs.


Figure 139. Ilima 2.5 months after planting, attacked by mealy bugs.

Figure 140. Broad leaf Ilima that survived from initial planting, thirteen months after planted.

Figure 141. Insecticidal soap, which didn’t work for mealy bug control.

Figure 142. EcoSMART Organic Insectcide, which helped to control mealybug.


Figure 143. Ilima propagated in the nursery from planting growing at Bellows and transplanted to the experimental plots (10/28/2014)

Figure 144. Ilima propagated at Bellows, 6 months after transplant (05/01/2015).

Mauʻakiʻaki - *Fimbristylis sp.*

Mauʻakiʻaki is a small sedge that performed well in this experiment (figures 145 to 147). Unfortunately, only 2 plants were planted in each plot, because of availability and no previous experience. It is a promising plant for dune restoration, and have been used in other projects at Bellows after this trial.

Figure 145. Mauʻakiʻaki at the day of planting.

Figure 146. Mau‘aki‘aki 3 months after planting.

Figure 147. Mau‘aki‘aki 6 months after planting.

Pōhuehue - *Ipomoea pes-caprae*

Pōhuehue, or beach morning glory, was the most effective ground cover in this trial. It was also documented by Jayatissa and Hettiarachi 2006 as one of the species not unaffected in inundated areas of Sri Lanka following the 2004 Indian Ocean tsunami. Pōhuehue successfully covered the entire plot and grew up to 14 inches beyond the planted area (Figure 149 to 161). The leaves were larger and taller in the back due than in the fore dune (Table 14), however, the plant was uniformly distributed along the dune profile (Figure 148). *Ipomoea pes-caprae* is an excellent ground cover to trap sand, as shown in Figure 149. It allowed other groundcovers such as pohinahina and naio papa to grow in the same area. Pōhuehue grew well with ʻakiʻaki grass as well. It was very effective to trap sand, as sand mounds could be seen after wind days, held by Pōhuehue vines and roots.

Table 14. Height of Pōhuehue at the different dune zones (average from 16 samples, in centimeter, 12 months after planting; standard deviation in parenthesis).

	FOREDUNE		CREST		BACKDUNE	
Screen	6.63	b	8.38	a	9.00	a
	1.76		1.26		1.51	
No Screen	6.94	b	9.50	a	10.88	a
	1.72		1.86		1.59	

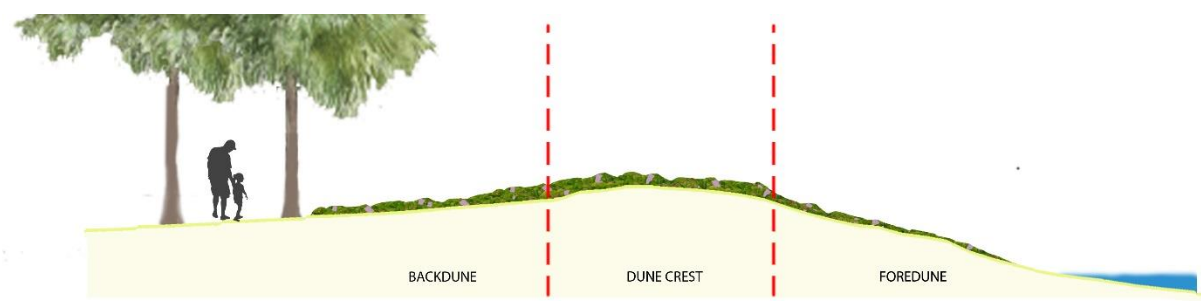


Figure 148. Pohuehue distribution in the dune profile.

Figure 149. Sand trapped by *Ipomoea pes-caprae* subsp. *brasiliensis* and *Jacquemontia sandwicensis* ground on the beach side of the plot.

Figure 106. Picture taken 13 months after planting (05/18/2015), showing the advancement of *Ipomoea pes-caprae* subsp. *brasiliensis* beyond the planting area, and clearly helping to trap and hold sand. The dashed line represents a

profile of the sand dune level 13 months after planting, and the dotted lines represents a profile of the beach before planting.

Figure 98. Plots two weeks after planting. Note that there is nothing planted between the two plots.

Figure 150. Detail of gap between the two planted plots, identified by the two dashed lines, five months after planting (9/17/2014). Not vine *Ipomoea pes-caprae* subsp. *brasiliensis* starting to grow beyond the plots, from both sides.

Figure 151. Detail of area covered by *Ipomoea pes-caprae* subsp. *brasiliensis*, 9 months after planting (01/27/2015). The area between the two dashed lines was not planted nor received irrigation.

Figure 152. Detail of area covered by *Ipomoea pes-caprae* subsp. *brasiliensis*, 9 months after planting (01/27/2015). The area between the two dashed lines was not planted nor received irrigation.

Figure 153. Detail of area covered by *Ipomoea pes-caprae* subsp. *brasiliensis*, 9 months after planting (02/27/2015). The area between the two dashed lines was not planted nor received irrigation.

Figure 154. Detail of area covered by *Ipomoea pes-caprae* subsp. *brasiliensis*, 12.5 months after planting (05/01/2015). The area between the two dashed lines was not planted nor received irrigation.

Figure 155. Plot 1 three months after planting (07/09/2014), with a wide space between plots, around 10ft.

Figure 156. Plot 1, thirteen months after planting (5/01/2014), *I. pes-caprae* almost closed the walkway between the two plots.

Figure 157. Picture taken 13 months after planting (05/18/2015), showing how the ground cover *Ipomoea pes-caprae* subsp. *brasiliensis* is associated to the trapping of sand, adjacent to a plot planted in November 2014. The dashed line represents a profile of the sand dune level 13 months after planting.

Figure 158. Picture taken 13 months after planting (05/18/2015), showing how the ground cover *Ipomoea pes-caprae* subsp. *brasiliensis* is associated to the trapping of sand, adjacent to a plot planted in November 2014. The dashed line represents a profile of the sand dune level 13 months after planting.

Figure 159. Picture taken Detail 13 months after planting (05/18/2015). Ground cover vines such as *Ipomoea pes-caprae* subsp. *brasiliensis*, *Vitex rotundifolia* and *Jacquemontia sandwicensis* grew beyond the plot planted area, indicated by the dashed lines.

Figure 160. Picture taken 10 months after planting (02/27/2015), showing the advancement of plants on the lateral and beach side of the plot. Ground cover vines such as *Ipomoea pes-caprae* subsp. *brasiliensis*, *Vitex rotundifolia* and *Jacquemontia sandwicensis* grew beyond the plot planted area, indicated by the dashed lines.

Figure 161. Picture taken 13 months after planting (05/18/2015), showing the advancement of plants on the lateral and beach side of the plot. Ground cover vines such as *Ipomoea pes-caprae* subsp. *brasiliensis*, *Vitex rotundifolia* and *Jacquemontia sandwicensis* grew beyond the plot planted area, indicated by the dashed lines. Note the influence of the vegetation to hold sand.

Pa‘uohi‘iaka – Jacquemontia sandwicensis

Pa‘uohi‘iaka is another excellent ground cover along with *Ipomoea pes-caprae* subsp. *brasiliensis* for a fast cover of sand dunes, growing throughout the entire dune profile (Table 15 and figures 162 to 166). Pa‘uohi‘iaka can be seen growing on the edges and empty patches of the plots. However, this attractive ground cover has a short life, and does not grow in competition with other plants such as *Ipomoea pes-caprae* subsp. *brasiliensis.*

Table 15. Height of Pa‘uohi‘iaka at the different dune zones (average from 16 samples, in centimeter, 12 months after planting; standard deviation in parenthesis).

	FOREDUNE	CREST	BACKDUNE
Screen	2.89	0.00	0.00
	(1.02)	(0.00)	(0.00)
No Screen	2.35	3.75	3.31
	(1.14)	(1.61)	(1.01)

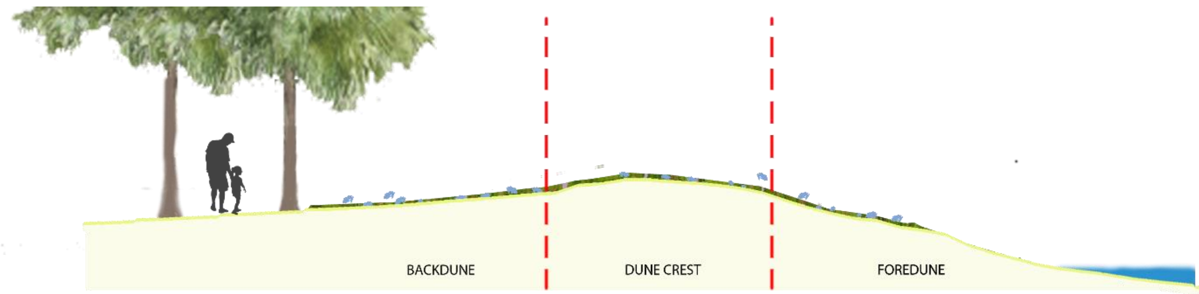


Figure 162. *Jacquemontia sandwicensis* distribution in the dune profile.

Figure 163. Jacquemontia sandwicensis at the day of planting.

Figure 164. *Jacquemontia sandwicensis* one month after planting.

Figure 165. *J. sandwicensis* three months after planting, growing with other groundcovers but not competing with each other.

Figure 166. *J. sandwicensis* nine months after planting (01/27/2015).

Pohinahina – *Vitex rotundifolia*

Vitex rotundifolia is another excellent groundcover along with *Ipomoea pes-caprae*. *Vitex rotundifolia* is very drought and salt tolerant, growing throughout the dune profile and beyond the planted and irrigated areas (Table 18, figures 167 to 171). *V. rotundifolia* grew beyond the planted area towards the mountain, however, it did not grow towards the beach.

Table 18. Height of Pa‘uohi‘iaka at the different dune zones (average from 16 samples, in centimeter, 12 months after planting; standard deviation in parenthesis).

	FOREDUNE	CREST	BACKDUNE
Screen	8.25	0.00	16.69
	(2.24)	(0.00)	(3.57)
No Screen	7.59	11.06	15.00
	(1.34)	(2.49)	(2.42)

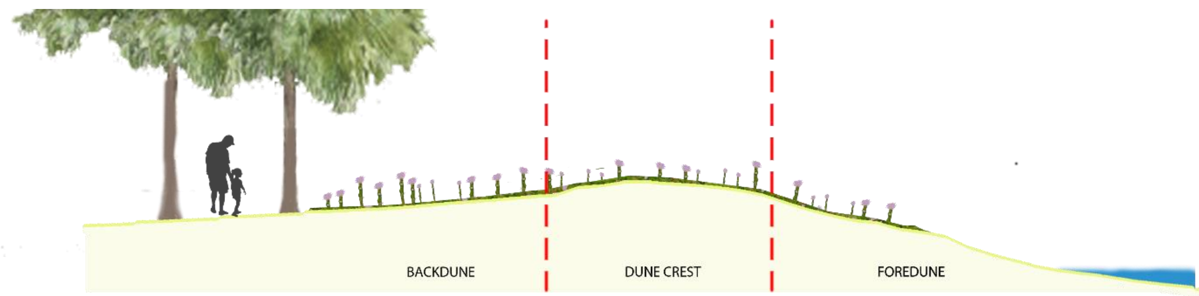


Figure 167. Pohuehue distribution in the dune profile.

Figure 168. *V. rotundifolia* at the day of planting.

Figure 169. Vitex rotundifolia two weeks after planting. Most of the plants lost their leaves and looked like dead, however, they recovered shortly after.

Figure 170. Vitex rotundifolia presenting very vigorous growth in the back dune zone, 6 months after planting (10/27/2014).

Figure 171. *Vitex rotundifolia* growing towards the mountain side of the plot, 13 months after planted (05/01/2015).

‘Aki‘aki grass – *Sporobulus virginicus*

‘Aki‘aki grass is a very drought and salt tolerant native grass, growing naturally up to the shoreline in Waimanalo. ‘Aki‘aki grass spreads very easily when irrigated, and can be easily planted with plugs. Existing patches of ‘aki‘aki grass were maintained when existing, and new populations were planted, with a high success. It was notable the capacity to trap sand and to stabilize the sand mounds, growing through the accumulated sand, forming thick carpets that hold the sand in place (Figures 172 to 175).

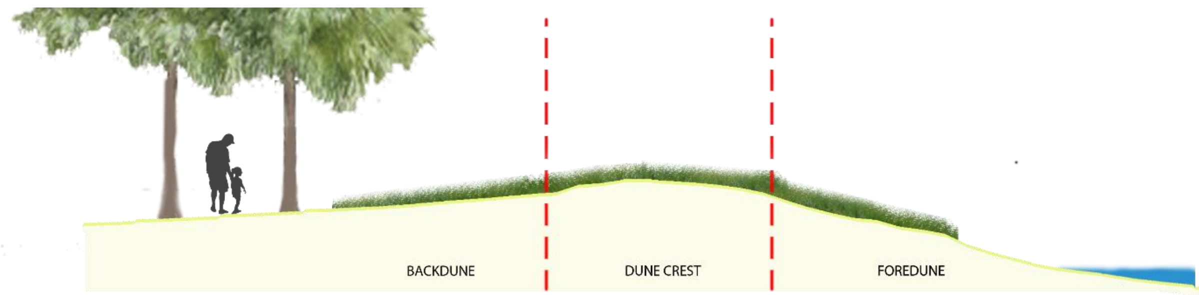


Figure 172. ‘Aki‘aki grass distribution in the dune profile.

Figure 173. ‘Aki‘aki grass holding the sand dune after storm.

Figure 174. Six months old ‘aki‘aki grass plantings holding sand dune blown with the tradewinds, grass planted from plugs.

Figure 175. ‘Aki‘aki grass growing through *I. pes-caprae*.

‘Ahu‘awa - *Cyperus javanicus*

‘Ahu‘awa is a native sedge that grows naturally in the wetland along the Waimanalo stream. ‘Ahu‘awa did well in all dune zones (Table 16), with higher heights when protected by the wind. However, plant survival was higher with no windscreen, even though plants were more vigorous when protected from the wind (figures 176 to 183). Plants from the plot with screen seemed to dry faster than those that grew without any protection, probably as a result of stress. Considering that ‘ahu‘awa is a wetland plant, it this difference could be associated to water stress. Plants growing with screes were protected from the wind and the sand was moister than the plot with no screen, which probably resulted in plants with shallower root system compared to the plants growing without screen that had to seek deeper for water. Simultaneously, the plot with no screen experienced more deposit of sand, because the screen did not pose a barrier and the plot with no screen was more exposed to the wind, which comes from the NE direction. Therefore, sand accumulated more in the plot with no screen, which covered the irrigation system, making it deeper, resulting in less loss of water through evaporation. Therefore, when the screen was removed, the plants form the plot with no screen were adapted to the wind and salt spray, and with deeper root system and deeper irrigation dripline, and more able to overcome stresses form the elements. This conditions apply to many other plants.

Table 16. Survival rate (%), width (in) and inches (in) of ‘ahu‘awa (*Cyperus javanicus*) 3 months after planting.

	FOREDUNE		
	Survival rate	**Width**	**Height**
With screen	39%	18.33	24.33
No screen	76%	6.77	11.33
	CREST		
	Survival rate	**Width**	**Height**
With screen	67%	9.00	16.00
No screen	100%	22.00	26.50
	BACKDUNE		
	Survival rate	**Width**	**Height**
With screen	100%	17.00	23.00
No screen	85%	6.00	11.00

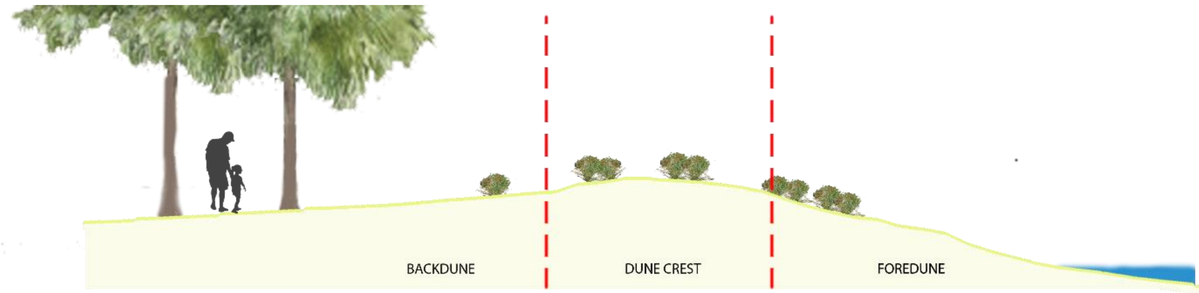


Figure 176. ʻAhuʻawa distribution in the dune profile.


Figure 177. ʻAhuʻawa the day of planting (04/19/2014).

Figure 178. ‘Ahu‘awa growing in plot without windscreen, 3 months after planting (07/11/2014)

Figure 179. ‘Ahu‘awa sheltered by windscreen, 3 months after planting (07/11/2014).

Figure 180. ‘Ahu‘awa flowing in August, 3.5 months after planting (08/06/2014). Plants growing with windscreen.

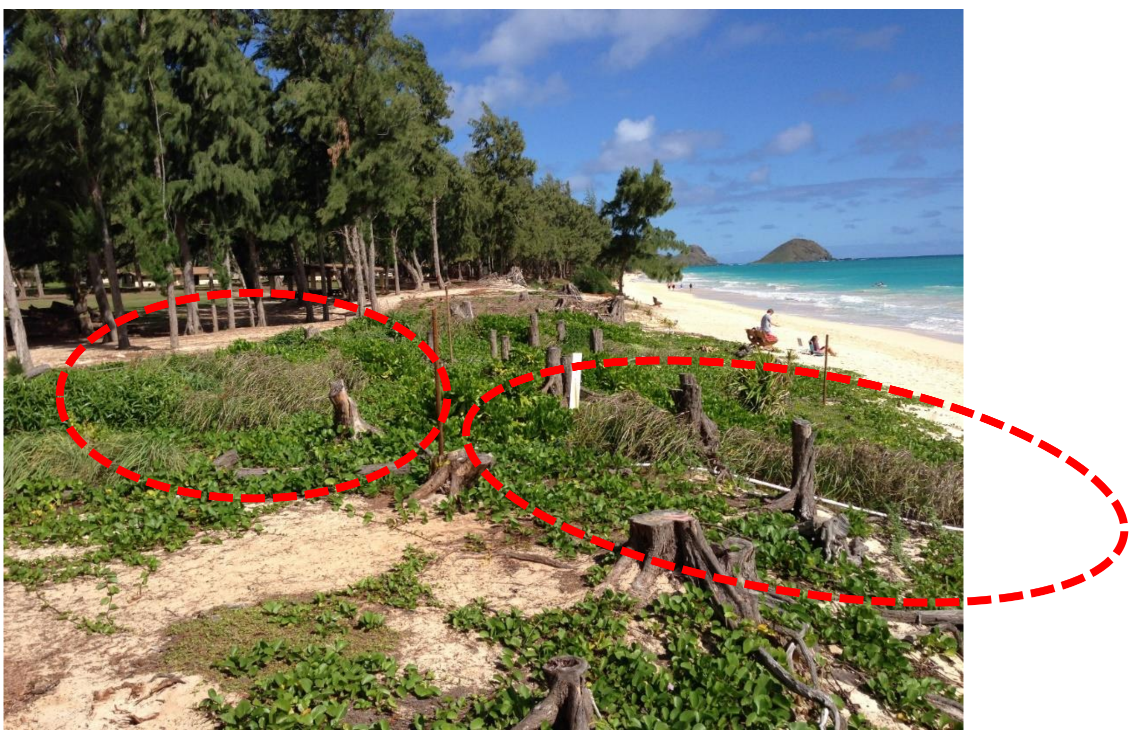


Figure 181. Nine months after planting (01/27/2015), ‘Ahu‘awa was still thriving. Plants from the plot that had windscreen for two months were clearly larger than those plants that did not have any protection.

Figure 182. ‘Ahu‘awa growing in the plot without windscreen (picture taken on 05/18/2015, 13 months after planted).

Figure 183. ‘Ahu‘awa growing in the plot with windscreen during the first 2 months (picture taken on 05/18/2015, 13 months after planted).

Naupaka – *Scaevola toccata*

Naupaka is a popular shrub in the landscape industry and is easily found growing all around the coast of the Hawaiian Islands. It is very common in Waimanalo and provides wind and salt protections for other native plants such as *Sida fallax*, *I. pes-caprae* and *J. sandwicensis.* The plants in this trial did very well (Table 17) and, as in the natural environment, provided protections to other plants that grew behind them, following their growth rate, such as *Cordia subcordata* (184 to 190). This phenomenon was previously described in the work of Thaman et al. (1995) in Tonga. Naupaka can grow in all dune zones, however, it is more appropriate to the dune crest and back dude, since it tends to spread and form large volumes.

Table 17. Survival rate (%), width (in) and inches (in) of naupaka (*Scaevola taccata*) 3 months after planting.

	FOREDUNE		
	Survival rate	**Width**	**Height**
With screen	100%	34.00	22.50
No screen	100%	28.67	22.67
	CREST		
	Survival rate	**Width**	**Height**
With screen	100%	32.00	21.00
No screen	100%	32.00	21.00
	BACKDUNE		
	Survival rate	**Width**	**Height**
With screen	100%	36.00	25.50
No screen	100%	32.50	22.00

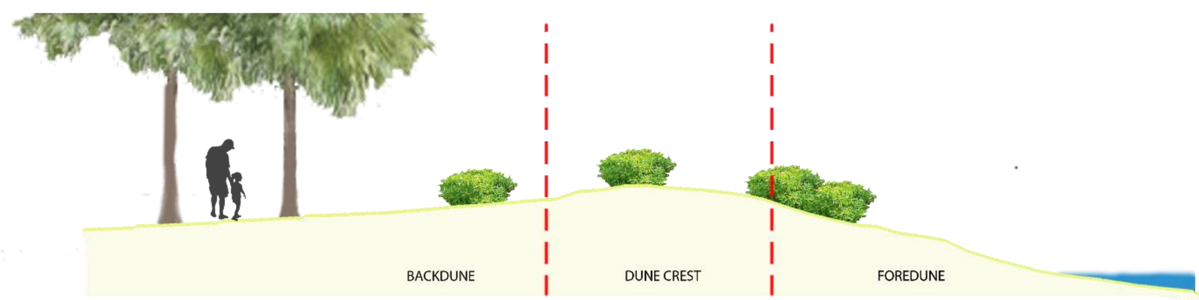


Figure 184. *Scaevola taccata* distribution in the dune profile.

Figure 185. *Scaevola taccata* at the day of planting.

Figure 186. *Scaevola taccata* two weeks after planting.

Figure 187. *Scaevola taccata* three months after planting (07/03/2014).

Figure 188. *Scaevola taccata* 6 monhs after planting (10/27/2014)

Figure 189. *Scaevola taccata* 10 months after planting (02/27/2015)

Figure 190. *Scaevola taccata* 13 months after planting (05/18/2015).

Naio – *Myoporum sandwicense*

Naio (*Myoporum sandwicense*) is a native plant cultivated in two forms: shrub and prostrate. Both forms did very well in these trials (Table 18). The shrub form suffered from mealy bug attack, which was controlled with organic insecticide (191 to 195). Naio has a dense canopy, which provides protection to young and less salt-tolerant plants, similar to naupaka.

Table 18. Survival rate (%), width (in) and inches (in) of ‘ahu‘awa (*Myoporum sandwicense*) 3 months after planting.

	FOREDUNE		
	Survival rate	**Width**	**Height**
With screen	67%	24.00	23.00
No screen	67%	23.50	11.50
	CREST		
	Survival rate	**Width**	**Height**
With screen	-	-	-
No screen	-	-	-
	BACKDUNE		
	Survival rate	**Width**	**Height**
With screen	100%	26.00	15.00
No screen	75%	24.00	10.00

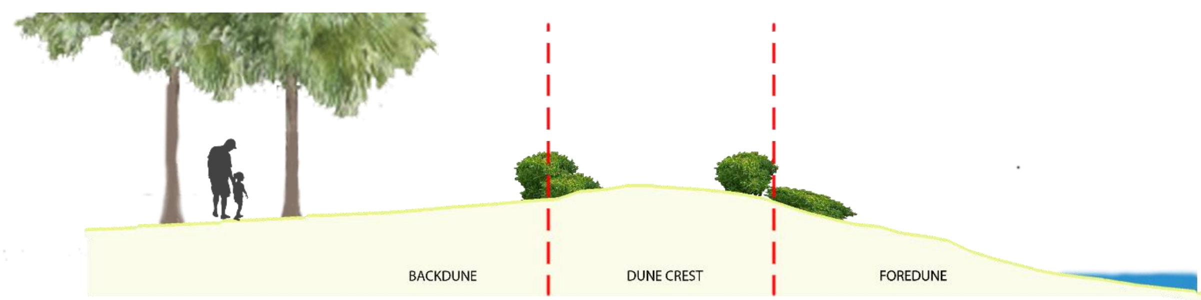


Figure 191. Naio distribution in the dune profile.

Figure 192. Naio at the planting day.

Figure 193. Naio four months after planted (08/27/2014)

Figure 194. Naio infested with mealy bugs, five months after planting (09/17/2014). The mealy bugs disappeared after application of EcoSMART Organic Insecticide.

Figure 195. A health naio shrub, 12.5 months after planting (05/01/2015).

Loulu – *Pritchardia sp.*

Loulu did well in both plots, with or without screen. It was planted in the backdune of the plots (figures 196 to 199). Because of its slow growth rate, there not much to say about it in one year, besides the fact that it is a promising palm for dune restoration.

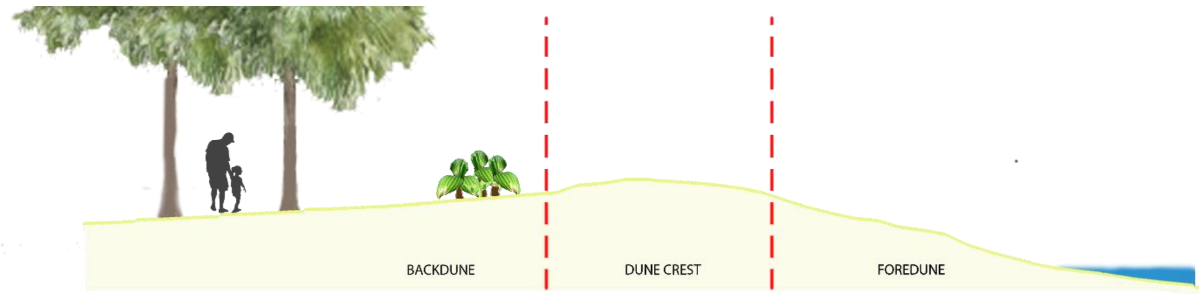


Figure 196. Loulu distribution in the dune profile.

Figure 197. Loulu at the day of planting


Figure 198. Loulu 3 months after planting.


Figure 199. Loulu 6 months after planting.

Kou – *Cordia subcordata*

Kou is a popular native tree, widely used for landscaping, especially as a street tree. However, this trial demonstrated that kou is salt sensitive to a degree that the planted trees would not grow taller than the shrubs (naupaka, naio and beach heliotrope) growing in front of them (figures 200 to 202). There were signs of salt damage, such as burnt leaves and apical meristems, and lateral branching. However, most of the specimens survived. Maybe this species will require more time to grow above the surrounding vegetation, and is more suitable as a back dune tree.

Figure 200. Kou, three days after planting.


Figure 201. Kou, three months after planting.


Figure 202. Kou twelve months after planting, following naio's growth rate.

Ground Coverage

Initially, the plot with screen was clearly more covered by ground covers than the plot with no screen (Figures 102-103). However, thirteen months after planting, the plot with no screen had higher ground coverage when compared to the plot that had wind screen in the first three months after planting (Table 19, Figures 117 and 118). This result corroborates with the height of ground covers.

Table 19. Ground coverage of different dunes zones for the two plot treatments – with wind screen and without wind screen. Readings one year after planted, in Waimanalo, HI, in a beach previously dominated by *Casuarina equisitifolia*, an invasive species associated to beach erosion.

	SCREEN			**NO SCREEN**		
	FOREDUNE	**CREST**	**BACKDUNE**	**FOREDUNE**	**CREST**	**BACKDUNE**
1	62.38%	61.96%	78.61%	61.09%	75.13%	77.62%
2	37.85%	70.66%	57.43%	60.09%	72.52%	91.99%
3	65.18%	68.55%	65.54%	92.39%	71.09%	81.65%
4	59.79%	68.30%	68.39%	78.69%	76.94%	87.43%
AVERAGE	**56.30%**	**67.37%**	**67.49%**	**73.06%**	**73.92%**	**84.67%**
Std.Dev.	12.50%	3.76%	8.75%	15.46%	2.62%	6.32%

Plants growing with screes were protected from the wind and the sand was moister than the plot with no screen, which probably resulted in plants with shallower root system compared to the plants growing without screen that had to seek deeper for water. Simultaneously, the plot with no screen experienced more deposit of sand, because the screen did not pose a barrier and the plot with no screen was more exposed to the wind, which comes from the NE direction. Therefore, sand accumulated more in the plot with no screen, which covered the irrigation system, making it deeper, resulting in less loss of water through evaporation. When the screen was removed, the plants from the plot with no screen were likely to be more adapted to the wind and salt spray, and with deeper root system and deeper irrigation dripline, and more able to overcome stresses form the elements. This could explain the better results of plants growing in the plot without screen, thirteen months after planting.

Ground Cover Height Comparisons

Vitex rotundifolia had higher values of plant height (Table 20), however, *Ipomoea pes-caprae* was more consistent along the dune profiles and treatments, demonstrating a more aggressive growth rate. *Jacquemontia sandwicensis* did better in the foredune and planting edges, generally growing along with *Ipomoea pes-caprae w*here the vegetation was sparser and with less competition.

Table 20. Height of ground covers in the different dune zones, in inches (standard deviation in parenthesis).

	FOREDUNE					
	IP		VR		JS	
Screen	6.63	a	8.25	a	2.89	b
	(1.75)		(2.23)		(1.02)	
No Screen	6.94	a	7.59	a	2.35	b
	(1.72)		(1.34)		(1.14)	

	CREST					
	IP		VR		JS	
Screen	8.38	a	0.00	b	0.00	b
	(1.25)		(0.00)		(0,00)	
No Screen	9.50	a	11.06	a	3.75	b
	(1.86)		(2.48)		(1.61)	

	BACKDUNE					
	IP		VR		JS	
Screen	9.00	b	16.69	a	0.00	c
	(1.50)		(3.57)		(0.00)	
No Screen	10.88	b	15.00	a	3.31	c
	(1.58)		(2.42)		(1.01)	

Dry weight

Ipomoea pes-caprae presented highest dry weight (Fgiure 203), while *Vitex rotundifolia* and *Jacquemontia sandwicensis* presented high variability (Table 21). *Ipomoeae sp.* form denser vegetation, and is noticeable how it has a higher performance on trapping and holding sand. *Ipomoea* sp. is generally the first of these three vines to grow beyond planted areas, followed by *Jacquemontia* sp., growing on the edges, and *Vitex* sp., following, *Ipomoea sp*. *Ipomoea* sp. growing on the edges of the plots contributed to the formation of "sand bumps" (figure 204), and it was documented up to 6.75 inches of sand deposited over the dripline on the windward side of the plots, ten months after planting (figures 205 and 206). This phenomenon and sand building was previously described by Dean (1978) and Lancaster and Baas (1998).

Table 21. Dry weight of three ground covers (*Ipomoea pes-caprae*, *Vitex rotundifolia*, and *Jacquemontia sandwicensis*) one year after planted in Waimanalo, HI, in a beach previously dominated by *Casuarina equisitifolia*, an invasive species associated to beach erosion.

	Dry Weight (g)		
Sample	Ipomea pes-caprae	Vitex rotundifolia	Jaquemontia
1	408.65	77.19	47.76
2	194.22	141.26	0
3	415.71	66.78	137.99
4	441.25	53.27	86.71
Average	364.96	84.63	68.12
STDDEV	114.68	39.01	58.54

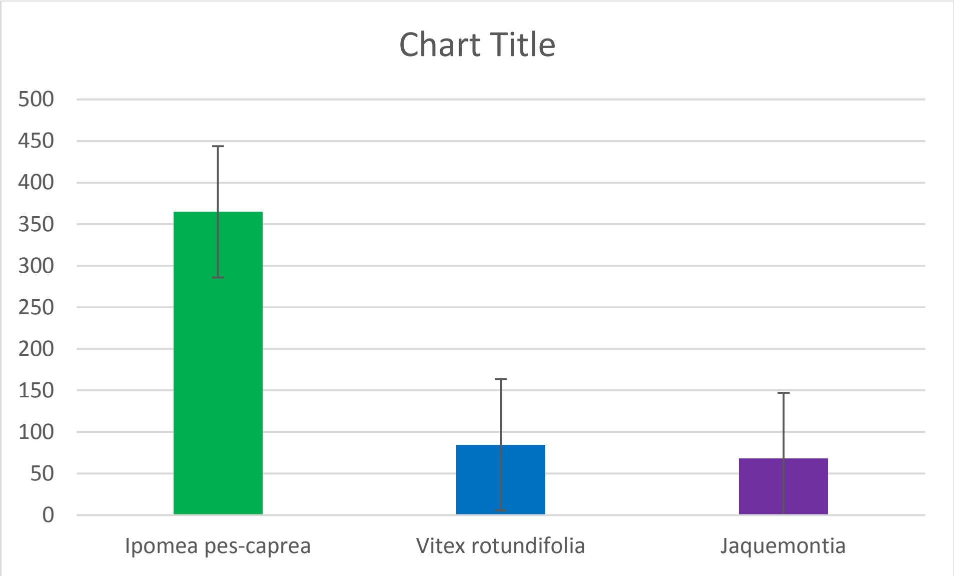


Figure 203. Average of dry weight of three ground covers (*Ipomoea pes-caprae*, *Vitex rotundifolia*, and *Jacquemontia sandwicensis*) one year after planted in Waimanalo, HI, in a beach previously dominated by *Casuarina equisitifolia*, an invasive species associated to beach erosion. The bars are the standard deviation of the entire population. Values in grams (g).

Figure 204. *Ipomoea pes-caprae* subsp. *brasiliencis* growing in the foredune. The dashed lines represent the buildup sand (accretion) after planting. The dotted line represent the original sand profile, before planting.

Figure 205. Dripline on the mountain side of the plot, facing north east (windward), 12 months after planting, buried 5”. The sand accreted naturally, probably as a result of wind action.

Figure 206. Dripline on the ocean side of the plot, facing north east (windward), 12 months after planting, buried 6 3/4”. The sand accreted naturally, probably as a result of wind action.

Conclusions and Recommendations

This project allowed the development and evaluation of a method for planting native plants in a dune eco-system occurring in Waimanalo, Windward side of the Island of Oahu, Hawaii. This method could be replicated in areas with similar conditions. It could also be used as a reference for other locations with different scenarios, providing its necessary adaptations, since the geography between islands can vary dramatically among and within themselves.

This planting method was proven efficient for replacement of *Casuarina equisitifolia* vegetation, and indicated signs of dune building through sand accretion, blown with the wind and trapped by plants, especially ground covers. Long term data collection of sand dune profiles could determine sand accretion and/or erosion rate, and comparisons with other methods of dune stabilization.

This project also allowed to test different native species for their use in dune stabilization projects in Hawaii. The most efficient ground cover was *Ipomoea pes-caprae* subsp. *brasiliensis*, followed by *Vitex rotundifolia* and *Jacquemontia sandewicensis. Sida falax* was also a successful brush, preference the narrow leaf form, since the broad leaf seems to have low resistance to mealy bugs. *Scaevola toccata* and *Myoporum sandwicensis* are good shrubs to protect less salt-resistant plants in their initial growth stages. *Pandanus tectorius* was not planned in this project, but it seems to be a promising shade tree, to meet beach users demand for shade. Other trees should be tested in future research.

The irrigation system used in this project is very practical and is very efficient from the perspective that it can be easily removed after plant establishment by simply cutting the sub main line and sliding the laterals underneath the plants, to be re-used in other dune restoration sites, without leaving any debris on site. This process was successfully implemented in this project.

Temporary windscreens proved beneficial to speed-up the establishment of the plants, especially in the foredune zone (ocean side). However, the windscreens were damaged by storm events and there was no visual difference between the plots with or without windscreens one year after planting. There was little visual difference six months after planting (three months after removal of the screens). Twelve months after planting, the plot without screen overcame the plot that had protection with screen, presenting higher plant coverage, probably because plants growing with screen were not as adapted to the harsh beach environment as the plants growing without protection. Therefore, plants initially growing with protection of wind screen suffered from salt and wind stress once the screens were removed. Also, plots with no screen had higher deposits of sand. The sand accumulated more inland, inside the plot, because there was no screen blocking the sand. The plots with no screen were also more exposed to the trade winds, which could favor the accumulation of sand on the plots without screen. This extra layer of sand in the plot without screen could have buried the roots and irrigation lines deeper, holding more moisture in the root zone. Therefore, the use of windscreens may not be necessary and cost effective since it only has short term benefits, and results in extra cost and potential debris in the beach, unless if short term results are necessary.

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