AN ANALYSIS OF ARMORED SHORELINES AS BARRIERS FOR COASTAL VEGETATION

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Abstract. To combat coastal erosion from disrupting human development, coastlines are physically armored for coastal stabilization, but ecological impacts of installing these anthropogenic structures are typically ignored. This study aims to measure the biotic response of coastal vegetation to armored coastline in comparison to natural, undisturbed coastline. 4 quadrats per coastal type were randomly sampled at 8 paired sites of adjacent natural and artificial coast were surveyed to record abundance of mature woody and herbaceous plants, seedlings, seeds, soil texture, and crab hole abundance. Species richness and abundance of seeds and seedlings of woody, ocean-dispersed plants were higher along natural coastlines, but species richness and abundance of herbaceous plant species were higher along armored shorelines. Both natural and rock wall coastlines share similarities in composition, but each coastal type houses different types of plants. Higher seed and seedling abundance of native, coastal, and woody ocean-dispersed-plants along natural coastline suggest armored shorelines pose challenges for new recruits to successfully deposit and establish.

Key words: geomorphology; artificial coastline; coastal strand; Moorea, French Polynesia; ocean-dispersed seeds; soil texture; woody plants; herbaceous plants; seedlings; seeds; land crab predation

INTRODUCTION

The land-ocean interface is a valuable place for crucial exchanges of natural matter and energy (Heip et al. 2011). High biological and physical activity occurs along coastal margins due to the abrupt transition between marine and terrestrial communities, high biological productivity, and physical processes of erosion and storms. Consequently, coastal ecosystems are defined by more diverse range of habitats than other ecosystems like forests or grasslands (Burke et al. 2001). Due to its high productivity and accessibility, human development has also been concentrated along coastal margins (Creel 2003). Indeed, 44% live within 150 km of the ocean (Nganyi et al. 2010).

However, development along the coast has negative effects on coastal zone ecosystems in both the short and long-term. Shifts in ecology and physical processes are expected as human communities replace and remove natural habitats. For example, urbanization is associated with habitat degradation that risks complete loss of beach, wetland, and intertidal habitats (Kay and Alder 1999, O’Connell 2010). One common form of shoreline disruption in developed regions is shoreline hardening or armoring, which is a common approach for stabilizing coastal erosion for development protection. When shorelines are hardened by means of rock walls, sandy coastal vegetation and water-dispersed seeds cannot penetrate inland and establish cover (Araujo and Pereira 2008). Coastal vegetation is further influenced by physical changes along the coast that include disruption of sediment transport and deposition, which are associated with loss of beaches or coastal dune landscapes. Source sediment impoundment occurs as the sediment budget is lowered, carrying smaller volumes of sand from the fronting and adjacent beaches (Ruggiero 2009). As an example, O’Connell (2010) found that in Massachusetts and Kauai, housing and hotels are concentrated along coasts with more than 70% long-term erosion trends, prompting coastal stabilization as a management intervention. Shoreline armoring reduced sand movement along the coast of both states and sufficiently decreased the main source of sediment to its beaches, dunes and barrier beaches. A similar study by Fletcher et al. (1997) surveyed armored shorelines on Oahu and estimated a 92% long-term (defined by 12 years) retreat of narrowed beaches. With a high loss of beach shores, lack of sediment accumulation pose less suitable conditions for vegetation to establish. The above studies
account for abiotic attributes of armored shorelines.

Documenting the abiotic and biotic responses to anthropogenic changes in the physical environment will help facilitate more informed predictions of global coastal change for beach ecosystems (Defeo et al. 2009). Islands are valuable systems for studying these responses because the ratio of shoreline to land mass is higher on islands than continents. Flora and fauna found on coastal platforms of islands are highly affected by sediment transport, high temperatures, flooding, salinity, and low nutrient availability (Martinez and Vazquez 1994). Moreover, in comparison to continental ecosystems, islands have simpler plant communities because their isolation and distance from the mainland challenges successful establishment (Quiroz et al. 2008).

The diversity of plants found on islands is conditioned by island age, elevation, soil and geology, but also by mechanisms of plant dispersal (Fall and Drezner 2013). Each plant species' own adaptation for dispersal is demonstrated by its movement of seeds or other diaspores from the source plant to a suitable environment for successful reproduction (Fall and Drezner 2013). Seed mobility remains crucial for vegetation establishment and reproduction on islands. In addition, external factors, such as predation, influence plant dispersal and establishment. One study investigates the control of seedling recruitment by land crabs on Christmas Island, Indian Ocean with results that suggested rain forest species were readily eaten by land crabs and affected plant establishment (Green et al. 1997).

The island of Moorea, French Polynesia is a rich setting for investigating the floral response of armored shorelines and determine the effects of artificial shorelines on coastal strand vegetation. Moorea is a volcanic high island with a low-profile coastal platform. Its topography ranges from flat to rugged and mountainous, shaped by weathering and erosion (Dieter and Fosberg 1998). Moorea’s low coastal platform provides habitat for coastal and predominantly native strand plant communities. Past studies have analyzed seed dispersal of specific coastal strands on Moorea, determining a common mechanism is floatability for marine dispersed seeds (Zerbib 2005, Sanchez 2007). The available literature on armored shorelines is heavily focused with surveys of physical and abiotic consequences, but current literature also has little discussion and field data of coastal vegetation responses explicitly to armored shorelines, especially on islands. There is an imbalance of literature regarding biotic effects of armored shorelines.

The overall goal of this study is to compare the vegetation along armored natural shorelines on the island of Moorea as a measure of biotic response to human manipulation of the coastline. I will explore the vegetation at paired sites that include natural coastline and armored coastline. Because coastlines are influenced by various external factors, I will use multiple approaches to detect biotic response. Through a field survey, I will compare vegetation, soil substrate, and land crab hole abundance at paired natural sites and armored sites. Soil texture samples taken from each site will be used to detect any patterns of seedling abundance and soil texture type. Moreover, learning the history of when and why these armored shorelines were installed enhances the informational efficacy of this survey and ultimately help predict long-term impacts on coastal ecology. Therefore, through interviews, I aim to learn the history of shoreline armoring on Moorea. I hypothesized that armored shorelines are barriers for ocean-dispersed plants to reestablish naturally, strongly hindering habitat biodiversity by limiting new growth to trees and herbaceous species already existing on site. I also hypothesized that substrate is a dominant factor that controls which species establishes along these coastlines. I further hypothesize that there is a correlation between land crabs and seedling abundance. Through a combination of field surveys and historical analysis, the aim of the study is to determine vegetation response of artificial shorelines on the island of Moorea.

**Methods**

**Study sites**

Coastal surveys were completed in both Cook’s and Opunohu Bay Moorea, French Polynesia (Fig. 1). Armored and open coastlines have varying patterns in both bays. Cook’s Bay is more developed with restaurants, hotels, and recently built residential areas along its coast. Therefore, armored shorelines dominate the coastal type versus natural coast. On the other hand, more than half of Opunohu Bay’s coastline is unarmored and while artificial shoreline occurs along residential sections as well as the
mouth of Opunohu River, its natural coastline still remains extensive. Five sites were surveyed in Cook’s Bay and three sites were surveyed in Opunohu Bay. All sites were chosen only under the condition of adjacent, 30-meter sections of rock wall and natural coastline. Due to difficulty viewing coastal types from the main road on Moorea, a boat tour of both bays was made for observation and historic background. 8 paired sites were surveyed (Appendix A).

![Diagram of study sites](Image)

**Fig. 1.** Sites sampled in this study.

**Survey design**

Each coastal type was analyzed as a 25-meter segment with a 5-meter buffer extending both directions from the divide to avoid influence from either coastal type on the other. Transect tape was placed at the mean high-water mark indicated by a zone of abundant vegetative and gravel debris. Four 2-m² quadrats were randomly selected between meters 2 through 25 for both coastal types at each paired site. Quadrat supply was limited to two 1 meter quadrats, so each 1 meter quadrant was flipped left along the transect tape to fulfill a 2-m² square sampling area. Data taken within each quadrat included the abundance of mature woody and herbaceous plants, seedlings, and seeds by species. Only unbroken, potentially viable seeds were counted. Percent cover was noted for trees, herbaceous plants, and seedlings. Crab hole abundance was additionally recorded per quadrat.

**Species identification**

A reference document was made of expected coastal strand trees that included photos of tree leaf morphology and seed references. Encountered vegetation that was not on the reference chart was identified through online aids of the Moorea Digital Flora Project (http://ucjeps.berkeley.edu/moorea/) and the Moorea Biocode (mooreabiocode.org/). Professor Brent Mishler from University of California, Berkeley and Orlo Steele from University of Hawaii also helped identify plant species.

**Soil texture sampling**

Soil texture was measured to determine the proportion of sand, silt, and clay in the soil. Information of the soil’s texture provides an estimate of water-holding capacity, water mobility through soil, soil strength, and the natural soil fertility. Each 2 m² quadrat was split into 16 squares. Quadrats 1-8 for each paired site were given a random number between 1-16. A trowel was used to remove roughly 3 oz. of soil at 10 cm depth, consistent with seed start containers. Soil texture was determined by a flow diagram by feel analysis (Thien 1979). Only 25-50 grams of soil is needed for the above analysis’ procedure.

**Coastal history**

A coastal survey has previously been done on the Society Islands and includes some information on armored and natural coastlines of Moorea (Aubanel et al. 1999), but an account of its recent changes has not been recorded. Hinano Murphy (pers. comm.) provided historic information about coastal morphology before shorelines were hardened.

**Statistical analyses**

All statistical analyses were performed using the software RStudio (R Development Core Team). Wilcoxon rank sum tests were performed for species richness and abundance of woody and herbaceous plants, seedlings, and seeds between rock wall and natural coastline. Wilcoxon rank sum tests were additionally used for a species-specific analysis between paired coastal variables. Only species with counts of 4 or more were analyzed. PERMANOVA (Anderson 2001) was performed using the vegan package (Oksanen 2013) in R to test for differences in community structure between coastal types. PERMANOVA was also performed for abundance of woody and herbaceous plants,
seeds, and seedlings between rock wall and natural coast. Another PERMANOVA test was used to compare community composition across soil texture categories. A Kruskal Wallis test was performed to detect differences in seedling abundance and soil texture between natural and rock wall coast. Another Kruskal Wallis test was run to detect differences in the two most abundant species, *Hibiscus tiliaceus* and *Theespesia populnea*. A linear regression test (Ambrose III *et al.* 2007) was performed using abundance of crab holes as the independent variable and seedlings as the dependent variable.

**RESULTS**

_Surveyed biotic response_

A total of 28 species were identified collectively from taxa of woody and herbaceous plants, seedlings, and seeds surveyed in 8 paired sites. The number of seedlings was 1.5 times more abundant along natural coast than rock wall coast. Seeds were over 4 times more abundant along natural than rock wall coast. Herbaceous species were 9 times more abundant along rock wall coasts than natural coastlines. 42% more woody plants were found along natural coast than rock wall. The abundance across plant group for natural coastline compared to rock wall coastline is displayed in Fig. 2. No significant difference (p > 0.05) was found in species abundance of woody plants, herbaceous plants, and seedlings between both coastal types, but seed abundance was significant (p < 0.05) along natural coastline using the Wilcoxon rank sum test.

Species richness varied by different taxa between coastal types (Fig. 3). Herbaceous species richness along rock wall coast was more than 2 times that along natural coastline. Seedling species richness was 68% more along natural coastline. More than double the species of seeds were found along natural coastlines versus rock wall coasts. No significant difference (p > 0.05) was found in species richness of woody plants, herbaceous plants, and seedlings between both coastal types, but seed richness was also significant (p < 0.05) along natural coastline (Fig. 3).

![Fig. 2. Species abundance by plant group comparing between natural and rock wall coastline. *Seed p-value < 0.05.](image)

![Fig. 3. Species richness by plant group comparing between natural and rock wall coastline. *Seed p-value < 0.05.](image)

Strong differences between coastal types (p < 0.05) were observed using PERMANOVA, where more woody plants are housed along natural coastline as compared to artificial coastline. Natural coastline houses more seeds and seedlings of woody species (Fig. 4). NMDS analysis (stress=0.02) of woody and herbaceous composition between natural and rock wall coasts show there were some shared elements of the community composition for both coastal types (Fig. 5).

Only 13 of the 26 species observed were present with more than 1 individual and 13 species were represented with only one unique specimen. *Terminalia catappa*, *Cordia subcordata*, and *Barringtonia asiatica* were significantly more abundant out of the 11 species along natural coastline shown through Wilcoxon rank sum tests (Table 1).
Crab hole and seedling analysis

No correlation was found between crab hole abundance and seedling abundance using linear regression ($R^2=0.015$) ($p > 0.05$) (Fig. 7).

Soil texture analysis

A total of 9 different soil textures were characterized from 64 soil samples. Seven out of 9 soil texture types contained seedlings within the same quadrat. Eight different species of seedlings were measured (Fig. 7). *Hibiscus tiliaceus* and *Thespesia populnea* were most abundant throughout all soil types, but no relationship was found between *H. tiliaceus*

Table 1. A list of p-values for species specific analysis using Wilcoxon rank sum test. Ocean-dispersed species are labeled with an (OD). Species with significant results are marked with an asterisk (*).

<table>
<thead>
<tr>
<th>Taxa</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Hibiscus tiliaceus</em> (OD)</td>
<td>$p &gt; 0.05$</td>
</tr>
<tr>
<td><em>Inocarpus fagifer</em> (OD)</td>
<td>$p &gt; 0.05$</td>
</tr>
<tr>
<td><em>Thespesia populnea</em> (OD)</td>
<td>$p &gt; 0.05$</td>
</tr>
<tr>
<td><em>Terminalia catappa</em> (OD)*</td>
<td>$p &lt; 0.05$</td>
</tr>
<tr>
<td><em>Cocos nucifera</em> (OD)</td>
<td>$p &gt; 0.05$</td>
</tr>
<tr>
<td><em>Callophyllum inophyllum</em> (OD)</td>
<td>$p &gt; 0.05$</td>
</tr>
<tr>
<td><em>Cordia subcordata</em> (OD)*</td>
<td>$p &lt; 0.05$</td>
</tr>
<tr>
<td><em>Barringtonia asiatica</em> (OD)*</td>
<td>$p &lt; 0.05$</td>
</tr>
<tr>
<td><em>Vigna marina</em></td>
<td>$p &gt; 0.05$</td>
</tr>
<tr>
<td><em>Wedelia trilobata</em></td>
<td>$p &gt; 0.05$</td>
</tr>
<tr>
<td>Grasses</td>
<td>$p &gt; 0.05$</td>
</tr>
<tr>
<td><em>Phyllanthrus urinaria</em></td>
<td>$p &gt; 0.05$</td>
</tr>
<tr>
<td><em>Merremia aegyptia</em></td>
<td>$p &gt; 0.05$</td>
</tr>
</tbody>
</table>

Fig. 4. Stacked bar plot showing plant type and abundance per coastal type.

Fig. 5. Natural coastline is represented in green and rock wall coastline is blue. 1-dimension.

Crab hole and seedling analysis

No correlation was found between crab hole abundance and seedling abundance using linear regression ($R^2=0.015$) ($p > 0.05$) (Fig. 7).

Fig. 6. No correlation or significance between crab hole abundance and seedling abundance.

Soil texture analysis

A total of 9 different soil textures were characterized from 64 soil samples. Seven out of 9 soil texture types contained seedlings within the same quadrat. Eight different species of seedlings were measured (Fig. 7). *Hibiscus tiliaceus* and *Thespesia populnea* were most abundant throughout all soil types, but no relationship was found between *H. tiliaceus*...
and *T. populnea* and soil type using Kruskal Wallis. There is no relationship between seedling abundance and soil type tested in the PERMANOVA test for community composition across soil types (*p* > 0.05) (Fig. 7).

**DISCUSSION**

Seed richness and abundance showed significance along natural coastlines than rock wall coastline. Because all seeds found were from native, ocean-dispersed woody plants, the high difference of seeds may be due to compounding factors of geomorphological effects and shoreline armoring. Because rock walls disrupt and deter sediment deposition, inundation occurs in front of the rock wall. While surveying rock walls on Moorea, it was observed that there was no beach shore fronting these stabilized coastal types, consistent with the physical effects of armored shorelines documented in Hawaii (Fletcher et al. 1997, Ruggiero 2009). Due to this inundation and constant flooding of the substrate fronting rock walls, the lower abundance of seeds may be due to constant mobility as it cannot lodge or deposit along or behind rock walls. Moreover, there is no aggressive wave action in Cook's Bay and Opunohu Bay to potentially wash seeds over the rock wall. These results suggest rock walls are affecting coastal ecology by inhibiting ocean-dispersed seed deposition and therefore plant establishment.

Lack of strong difference found in species richness and abundance comparing woody and herbaceous plants and seedlings in the Wilcoxon rank sum tests is likely due to difference in types of plants found between coasts. The species richness and abundance metric does not take the type of species into account. Natural coastline was found to contain more woody plant species and artificial coastline contained more herbaceous plant species. This difference in types of plants is further supported by significant results of woody versus herbaceous plant groups found along natural and rock wall coast (Fig. 3). Herbaceous plants that were more abundant along rock walls are more readily dispersed by cars, humans, and animals than ocean-dispersed seeds.

However, the lack of difference in mature, woody plants between natural and rock wall coast may be due to already existing woody plants when the rock wall was installed. Moreover, seedling abundance may also be due to nearby woody species that are depositing seeds that subsequently turn into seedlings.

Furthermore, the significance of three native, coastal strand woody plant species along natural coastline than rock wall coastline also suggest a barrier effect of rock walls. The three species include *Terminalia catappa*, *Cordia subcordata*, and *Barringtonia asiatica*, all species that have ocean-dispersed seeds.

The presence of eight different seedlings in seven different soil texture types suggest that certain species may have certain soil texture types needed to grow. However, *Hibiscus tiliaceus* and *Theopsemblia populnea* had the highest abundance across all soil types, but *Hibiscus tiliaceus* was dominantly most
abundant, indicating H. tiliaceus readily establishes on most soil texture types.

No correlation between crab hole abundance and seedling abundance suggests that land crabs may not be predating on the coastal strand seedlings as was hypothesized and resulted in Green et al. (1997).

Historically, the coast of Moorea has been socially linked and valuable because the main road is positioned along the coastal perimeter of the island. Results documented above are consistent with effects observed for the past 50 years (Hinano Murphy, pers. com.), further supporting that rock walls and human development have considerably altered the coastal landscape in a relatively short time, physically and ecologically.

Artificial shorelines were initially installed on Moorea to stabilize coastline that was partially removed for material to create the old main road, especially if the coastline was in close proximity to the main road about 50 years ago before the road changed to pavement. Moreover, especially in Cook’s Bay, land fill was incorporated to artificially create land for coastal commercial and housing development. To protect this development, shorelines were armored. Existing plants along these man-made coastal platforms were typically human planted. Human planted vegetation may explain why surveyed rock walls did not show strong difference.

Over the years armored shorelines became increasingly implemented. Rock walls were initially implemented as personal use for property protection, but with smaller boulders. However, some rock walls had more boulders added to the existing walls to accommodate increases in wave erosion. As the French government installed a paved main road, large boulders were afforded and installed. The main road has had elevation added to it throughout the years to adjust for increased wave erosion. As a result, larger boulders were also implemented to maintain the structural strength of the elevated road. Furthermore, this information provides explanation in variability of degree of rock wall. Overall, the physical build of how impenetrable, large, or small the rock wall is can affect seed and seedling recruitment.

Ultimately, the observed inundation fronting armored shorelines and its lower seed abundance both provide evidence of one kind of abiotic and biotic response, respectively. In the case of rock walls and natural coastlines alike, its abiotic characteristics are important in also anticipating the biotic responses. Moreover, it is important to note that observed results do not suggest an explicit decline in total vegetation, but do show differences in type of vegetation that is more dominantly supported between natural and armored coasts.

**Future studies**

A continuation of monitoring biotic responses to coastal armoring will help describe its effects more accurately. In addition, the upcoming El Niño during early 2016 may yield different results where more wave and wind action from cyclone activity could result in higher seed deposition and potential seedling recruitment along armored shorelines. Due to the dynamic nature of coastlines, consistent monitoring is valuable in understanding ecological impacts of armored shorelines. In the long-term, decreases in biodiversity may result if new ocean-dispersed plants are unable to successfully establish, deeming armored shorelines unsustainable for physical and biologic processes.

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LITERATURE CITED


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APPENDIX A

Location information and GPS coordinates of surveyed sites in this study.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Bay</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Near St. Joseph</td>
<td>17°30'14.31&quot;S</td>
<td>149°49'25.82&quot;W</td>
<td>Cook's</td>
</tr>
<tr>
<td>2 West Opunohu Bay</td>
<td>17°30'55.38&quot;S</td>
<td>149°51'14.94&quot;W</td>
<td>Opunohu</td>
</tr>
<tr>
<td>3 Mari Mari's Yacht Club</td>
<td>17°30'43.44&quot;S</td>
<td>149°50'59.10&quot;W</td>
<td>Opunohu</td>
</tr>
<tr>
<td>4 East entrance to Cook's Bay</td>
<td>17°29'8.22&quot;S</td>
<td>149°49'1.38&quot;W</td>
<td>Cook's</td>
</tr>
<tr>
<td>5 Canoe docking area</td>
<td>17°30'24.96&quot;S</td>
<td>149°49'15.78&quot;W</td>
<td>Cook's</td>
</tr>
<tr>
<td>6 West Opunohu Bay</td>
<td>17°30'37.26&quot;S</td>
<td>149°51'29.19&quot;W</td>
<td>Opunohu</td>
</tr>
<tr>
<td>7 Gump Station</td>
<td>17°29'27.66&quot;S</td>
<td>149°49'35.58&quot;W</td>
<td>Cook's</td>
</tr>
<tr>
<td>8 Canoe docking area</td>
<td>17°29'38.65&quot;S</td>
<td>149°49'32.74&quot;W</td>
<td>Cook's</td>
</tr>
</tbody>
</table>
Below are identified mature plants, seedlings, and seeds of coastal strand species that were encountered during surveys.

All photos were taken by the author.
<table>
<thead>
<tr>
<th>Cocos nucifera</th>
<th>Calophyllum inophyllum</th>
<th>Calophyllum inophyllum</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Cordia subcordata</td>
<td>Cordia subcordata</td>
<td>Cordia subcordata</td>
<td>Barringtonia asiatica</td>
</tr>
<tr>
<td>Vigna marina</td>
<td>Wedelia trilobata</td>
<td>Grasses</td>
<td>Guettarda speciosa</td>
</tr>
<tr>
<td>Indigofera hendecaphylla</td>
<td>Cordyline fruticosa</td>
<td>Acacia farnesia</td>
<td>Phyllanthrus urinaria</td>
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