Ecological Effects of Coastal Armoring: A Summary of Recent Results for Exposed Sandy Beaches in Southern California

Jenifer E. Dugan[1] and David M. Hubbard[1]

Introduction

The use of coastal armoring is already widespread on developed coastlines and is expected to escalate in response to the combination of expanding human populations, coastal erosion, and sea level rise. Although there is an extensive literature on the physical effects of armoring on open coast beaches (see reviews by Kraus and McDougal, 1996; Griggs, 2005a, 2005b; Weigel, 2002a, 2002b, 2002c), relatively few studies have investigated the ecological implications. This is true even though sandy beaches harbor distinctive ecological communities and provide critical foraging and nesting areas for threatened wildlife, such as sea turtles and shorebirds (for example, Schlacher and others, 2007). Consequently, ecological impacts of armoring have been largely overlooked in coastal management and conservation and rarely are considered in decision-making or policy (Dugan and others, 2011a). However, results from recent studies suggest that the ecological effects of armoring and other coastal defense structures on open coast beaches could be important (Martin and others, 2005; Dugan and Hubbard, 2006; Dugan and others, 2008).

In this paper, we provide a summary of the conceptual model we developed for predicting potential ecological responses to coastal armoring. Our model framework incorporates the presence, extent, and functioning of multiple intertidal zones, as well as changes in beach width in general. Using available information on ecological communities of exposed sandy beaches, we hypothesized that changes in the width and extent of intertidal zones could affect the diversity, abundance, and structure of the intertidal community with strongest effects on the upper zones of the beach. We predicted that these effects could in turn reduce the prey resources available to shorebirds and their use of beach habitats. We summarize the results of our investigations of a number of the ecological responses expected from the loss of intertidal and supralittoral beach habitat associated with coastal armoring, including the reduction or loss of intertidal zones and associated invertebrates, reduced accumulation of macrophyte wrack and decreased shorebird use.

Conceptual Framework

Coastal armoring, including seawalls and rock revetments, has been shown to reduce intertidal beach widths through the processes of placement loss, passive erosion, and increased erosion directly seaward of structures (Griggs, 1998, 2005b; Hall and Pilkey, 1991; Tait and Griggs, 1990). The most widely documented initial effect of coastal armoring is placement loss, whereby the footprint of the armoring structure and any backfill material covers or replaces existing coastal habitat (Griggs 2005a, 2005b). The magnitude and relative importance of passive erosion and active erosion effects on beach widths are subject to more debate. To provide a conceptual framework for assessing biological effects of armoring, we developed hypotheses concerning patterns of beach habitat loss associated with coastal armoring and its consequent effects on biota (table 1). We propose that a number of ecological impacts of coastal armoring could be predicted using changes in the widths of different zones of the beach (for example, McLachlan and Jaramillo, 1995) as proxies for habitat loss (fig. 1). As beaches become narrower in front of armoring structures and as the intensity of interaction between structures and coastal processes (for example, wave reflection) increases, our model predicts habitat is lost disproportionately from the upper beach. Our model predicts the effects of armoring to be greatest on the landward-most coastal strand (for example, Feagin and others, 2005; Dugan and Hubbard, 2010) and supralittoral “dry sand” zones of the beach (fig. 1) in response to placement loss and passive erosion. Habitat near the driftline (fig. 1) also may be greatly reduced or eliminated; this is the primary zone for a diversity of wrack-associated and scavenging invertebrates, such as burrowing talitrid amphipods, ghost crabs, isopods and beetles, as well as for grunion, sea turtle and shorebird nesting. As the driftline shifts from the sandy beach to the armoring structure, the rich, three-dimensional habitats characteristic of this zone are replaced with the steep, reflective, two-dimensional habitat of the seawall. Although this manmade hard substrate may support a low diversity of rocky shore organisms (for example, Chapman, 2003; Chapman and Bulleri, 2003; Moreira and others, 2006), foraging opportunities for shorebirds would be greatly reduced.

[1]Marine Science Institute, University of California, Santa Barbara, California 93106, j_dugan@lifesci.ucsb.edu.

Table 1. Framework of hypotheses on the ecological effects of coastal armoring.

As beach width narrows in response to armoring structures:
Upper intertidal, supralittoral and coastal strand zones are lost disproportionately,
Loss of upper beach zones decreases number of habitat types available and room for migration of habitats/zones and macroinvertebrates with changing ocean conditions,
Reduction in habitat types reduces diversity and abundance of macroinvertebrates, particularly on the upper shore,
Loss of upper beach habitat eliminates nesting habitat for sea turtles, fish, birds etc.,
Lack of dry sand habitat and increased wave reflection associated with structures alters deposition and retention of buoyant materials, (e.g., macrophyte wrack, driftwood) further affecting upper shore biota and processes, including nutrient cycling,
Intertidal predators, such as shorebirds, respond to the combination of habitat loss, decreased accessibility at higher tides, and reduced prey resources.

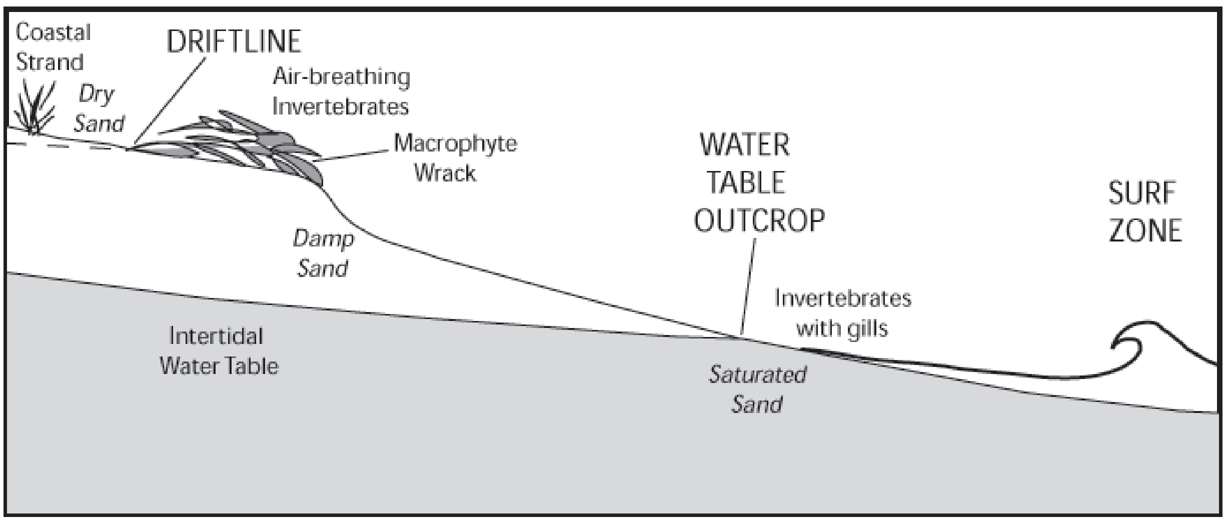

Figure 1. Profile of an exposed sandy beach showing the intertidal and supralittoral zones investigated. The relative locations of invertebrate types, driftline, macrophyte wrack and coastal strand vegetation are indicated.

Increased wave reflection and the loss of upper beach zones also could affect the retention of macrophyte wrack and other drift material in front of seawalls (Dugan and Hubbard, 2006), thereby reducing the primary support for the wrack-based component of the beach food web (see review by Colombini and Chelazzi, 2003; Dugan and others, 2003). The distribution and survival of mobile invertebrates of the lower shore (for example, donacid bivalves, whelks, isopods and hippid crabs) also may be reduced by restrictions on tidal migration (Klapow, 1972; McLachlan and others, 1979; Jaramillo and others, 2002b) imposed by seawalls. In addition, changes in concentrations of suspended sediment and altered littoral current velocities and sediment transport rates in front of seawalls (Miles and others, 2001) could affect the distribution of intertidal animals as well as that of sand. These projected ecological effects of armoring on invertebrates, wrack, and beach zones could reduce prey resources, accessibility, and the amount of foraging and nesting habitat available to shorebirds, thus diminishing the value of armored beaches for wildlife.

Research Approach

To investigate predictions from the conceptual model outlined above, we compared (1) widths of intertidal zones, including the distance to the driftline and the water table outcrop (see fig. 1), (2) standing crop of macrophyte wrack, (3) distribution and abundance of mobile upper beach invertebrates, and (4) distribution and abundance of birds on paired armored and unarmored segments of four beaches in southern California (Dugan and Hubbard, 2006; Dugan and others, 2008). These studies were conducted on wave-exposed intertidal beaches in Santa Barbara County, California, where the coastline consists primarily of narrow, bluff-backed beaches perched on wave-cut bedrock platforms. At each of the four study beaches we studied (1) a segment of shoreline immediately seaward of an intertidal concrete seawall (hereinafter armored segment) and (2) an adjacent unarmored bluff-backed segment of shoreline of the same length and with similar orientation (hereinafter unarmored segment). The seawalls we studied are 60-plus-year-old massive concrete structures ranging from 170 to 1,050 m long, with nearly vertical concave faces that interacted with high tides year-round (for example, waves were reflected off the seawalls at least daily) during our studies. The toes of all the seawalls were located at a low intertidal level but the degree of interaction of the seawalls with waves and tides on any particular sampling date depended on the sand levels. The elevations of the sand surface at the seawalls varied by an average of 0.98 m (range: 0.83 to 1.16 m) during the 1-year study with an average change of 0.36 m between subsequent months. When sand levels were low and waves were large, swashes or surf interacted with the seawalls even during low tides. Our study methods and statistical analyses are described in more detail in Dugan and Hubbard (2006) and Dugan and others (2008).

Results

Study results generally supported the predictions of our conceptual framework and revealed some unexpected effects of armoring on roosting birds (gulls, seabirds and others; table 2; see Dugan and Hubbard, 2006, and Dugan and others, 2008, for more details). Overall, armored shoreline segments supported significantly less habitat area, lower macrophyte wrack biomass, and fewer invertebrates and birds than did unarmored segments (table 2). Intertidal zone widths on armored beach segments were narrower than on adjacent unarmored segments. The uppermost zones, from the driftline to the upper beach limit, were lacking altogether, and mid beach zones (upper beach limit to the water table outcrop) were narrower (greater than two times) year-round on armored than on adjacent unarmored segments. The biomass of macrophyte wrack was significantly lower (1 to approximately 3 orders of magnitude) on armored segments. The abundance, biomass, and size of upper intertidal invertebrates (including talitrid amphipods and isopods) were significantly lower on armored segments. No difference was detected in the species richness of upper shore invertebrates between armored and unarmored shoreline segments; however, only a few species were found and sampling effort was relatively limited. Foraging shorebirds and roosting birds, including gulls and a variety of other species, responded with significantly lower species richness and abundance on armored segments. The result for roosting birds was not predicted by our model.

As hypothesized, the scale of effects we observed was strongest for the upper shore (table 2). Large differences (greater than tenfold) were found for extent of upper beach zones, macrophyte wrack, and the abundance and biomass of upper shore macroinvertebrates. The scale of effects for other ecological variables we measured ranged from 1.6 to 7.7-fold.

Table 2. Scales of ecological effects of armoring detected on open coast beaches, expressed as the ratio of mean values from the pairs of unarmored and armored beach segments for each parameter listed.

[* p≤0.05, **p≤0.01, ***p≥0.001, n.d. not detected]

Ecological characteristic	Scale of effect
Intertidal zone widths	
Upper beach: upper beach limit to driftline	36x***
Mid beach: upper beach limit to water table outcrop	2.1x***
Macrophyte wrack (standing crop)[1]	374x*
Macroinvertebrates (upper shore)	
Species richness	n.d.
Abundance	10.6x*
Biomass	16.1x***
Mean individual size	1.6x*
Shorebirds	
Species richness	2.0x***
Abundance	3.7x*
Gulls	
Species Richness	2.0x
Abundance	4.8x***
Other birds	
Species richness	3.3x***
Abundance	7.7x***

[1] Values from Dugan and Hubbard, 2006; Dugan and others, 2008.

Discussion

Habitat loss resulting from coastal armoring structures and the narrowing of beaches in front of such structures was evident year-round for the seawalls we studied in on open coast beaches of southern California. Our results supported the prediction that upper intertidal beach zones would be lost and mid-intertidal zones reduced in front of coastal armoring structures. Armoring affected the “dry” upper beach zones most strongly, with all the zones above the driftline missing on armored segments in almost every survey. The reduction in width of the highest beach zones (above the driftline) observed for the armored segments compared to adjacent unarmored segments (average = 3.5 m) was consistent with the scale of placement loss expected for the seawalls in the study and demonstrates the relative importance of this armoring impact on narrow beaches. However, the overall narrowing of the mid beach above the water table outcrop (see fig. 1) on armored segments (11.4 m) was much greater than expected from placement loss alone, suggesting that the effects of passive erosion were also present in this zone. The contrast between our results on armoring effects on the widths of mid-beach zones and those of Jaramillo and others (2002a) for a newly constructed seawall may be related in part to the differences in age of the armoring structures studied (20 months versus 60-plus years). No comparisons are possible for upper beach zones because their study did not compare zone widths above the driftline.

Predicted ecological effects of the observed loss and reduction in beach zones, including declines in intertidal invertebrate communities, were supported by the differences in abundance and biomass of mobile upper beach invertebrates that we observed on open coast beaches. In a study of sheltered beaches on Puget Sound, the abundance of talitrid amphipods and insects also was significantly higher on natural beaches than on armored beaches (Sobocinski, 2003; Sobocinski and others, 2010). In contrast, a well-designed study of short-term responses (20 months) of beach invertebrates to a newly constructed seawall in Chile did not find significant effects of armoring on the overall macroinfaunal invertebrate community (Jaramillo and others, 2002a) or on populations of two abundant invertebrates (the cirolanid isopod, *Excirolana hirsuticauda* and the anomuran decapod, *Emerita analoga*) that inhabit lower intertidal zones of open coast beaches. However, upper beach invertebrates, such as talitrid amphipods, were not compared separately in their analyses. This contrasting result is quite valuable in the context of understanding ecological effects of armoring because it indicates that additional factors, including the age and the position of the structure on the beach profile, may be important in predicting impacts.

Effects of armoring on upper beach invertebrates may be associated in part with impacts to wrack retention on armored beaches. As found here for open coasts, wrack abundance also was significantly lower on sheltered beaches with armoring (Sobocinski, 2003). The majority of invertebrates in our samples were talitrid amphipods, a group known to respond to wrack availability on beaches (for example, Dugan and others, 2003) and which play a major role in the processing and breakdown of wrack (Lastra and others, 2008). Therefore, the significant reductions in wrack biomass associated with armoring are likely to affect abundance and distribution of these key taxa, as well as wrack breakdown and nutrient cycling on beaches (for example, Dugan and others, 2011b). Impacts to wrack-associated invertebrates, which make up more than 35 percent of the species on most beaches in the region (Dugan and others, 2003) have clear implications for intertidal biodiversity. In addition, wrack-associated invertebrates, such as talitrid amphipods, often are an important prey resource for shorebirds and, importantly, are available to avian predators on a wider range of tide levels than many of the suspension-feeding invertebrates found lower on the beach. Declines in the abundance of upper-intertidal invertebrates thus results in reduced prey availability and reduced foraging windows for shorebirds on armored beaches.

In addition to the macroinvertebrates we studied, the high intertidal zone around the driftline is nesting habitat for several ecologically and commercially important marine fish and invertebrate species, including the California grunion (*Leuresthes tenuis*) on open coastlines, and surf smelt (*Hypomesus pretiosus*), Pacific sand lance (*Ammodytes hexapterus*), and American horseshoe crabs (*Limulus polyphemus*) on protected shores. These animals lay their eggs in this zone during spring high tides to incubate in the sand through the neap tides and hatch on a subsequent spring tide series. Negative effects of armoring on embryo survival already have been reported for the surf smelt in Puget Sound (Rice, 2006, 2010) and could be expected for California grunion on open coasts. The reduction or loss of this high intertidal zone resulting from coastal armoring has clear consequences for the success of reproduction in beach-dependent fish and crab species. The importance of Pacific sand lance and surf smelt as forage fish for salmon and seabirds and of horseshoe crab eggs to migrating shorebirds (for example, Red Knot) has stimulated efforts to identify and protect spawning beaches from coastal armoring and other human impacts in the Puget Sound area (Reeves and others, 2003; Rice, 2006, 2010; Krueger and others, 2010) and in Delaware Bay (Jackson and others, 2010).

The prediction that shorebirds would respond to the presence of coastal armoring was strongly supported by our results. Of note, the significant effects of armoring on shorebirds were found during low-tide surveys when the greatest amount of intertidal habitat was available to the birds. During higher tides, bird use including foraging and roosting would be eliminated in front of these seawalls. The response of shorebird abundance to coastal armoring (greater than threefold) exceeded that predicted by the overall loss of beach habitat area alone (twofold) (table 2), suggesting that other factors, including prey abundance, availability of high tide feeding habitat, and refuges, as well as other landscape factors, may have contributed to the observed responses. Shorebird diversity and abundance have been correlated with prey availability on California beaches (for example, Dugan and others, 2003). The habitat and invertebrate prey resources of sandy beaches may be increasingly critical to the survival and success of these avian predators in developed coastal regions (Hubbard and Dugan, 2003). Our results suggest that further investigations of relationships between coastal armoring and shorebird conservation are worthy of consideration on open coasts.

Our finding that gulls and seabirds also responded negatively to armoring indicates ecological implications that extend beyond prey resource availability for coastal birds. In fact, the responses of gulls and other birds (both greater than fourfold) to armoring were stronger than that of shorebirds overall (greater than threefold) (table 2). This result suggests that armoring affects the use of beach habitat preferred for roosting or loafing by gulls and seabirds that are not using the beach for foraging. The addition of effects of armoring on roosting habitat to the suite of predictions in the conceptual framework is supported.

Significant ecological impacts to several components of the beach community were associated with the old, nearly vertical seawalls that interacted daily with tides and waves in our study (table 2). Ecological responses to other types of coastal armoring structures may differ (for example, Martin and others, 2005) and likely would scale with the physical effects of these structures on beach zones; however, further investigation is needed. An important consideration relative to our results is the location of the armoring structure on the beach profile, which affects the amount of interaction with waves and tides. Generally, the lower the structure on the beach profile, the greater the physical impacts associated with that structure (Weigel, 2002a, 2002b, 2002c). The ecological impacts of any armoring structure would be expected to be similar, whether location on the profile is a result of initial placement of the structure or subsequent erosion of the beach. Predicted sea level rise will not only increase beach erosion and lead to expansion of the use of coastal armoring, it will effectively shift the location of existing armoring structures to lower positions on the beach profile, hence increasing the physical and ecological impacts of existing armoring to beach ecosystems.

Conclusions

The combination of rising sea levels predicted by climate change models and the increasing extent of coastal development and armoring (for example, Griggs, 1998) will accelerate beach erosion and loss and increase ecological impacts to sandy beach ecosystems on a scale that is unprecedented. Loss of habitat resulting from coastal armoring was associated with significant impacts to mid- and upper-beach zone widths, macroinvertebrates, foraging shorebirds, and roosting gulls and seabirds on open coast beaches (table 1). Further investigation of ecological responses to coastal armoring is needed to inform the management and conservation of these threatened ecosystems. We suggest that this research include studies designed to evaluate the effects of extreme events, which may have important interactive effects on morphodynamics and ecological processes. Longer term studies that lead to a greater knowledge of the trade-offs between the quantifiable and immediate impacts of placement loss and other potential impacts occurring over longer time scales, including passive and active erosion, clearly are needed. In addition to developing a better understanding of the potential ecological impacts of individual structures, it is crucial to develop an approach for evaluating the cumulative impacts of coastal armoring for coastal regions.

Relevance to Puget Sound Ecosystems

This review summarizes our recent research on the effects of large (greater than 100 m), old (greater than 60 years) seawalls on the ecology of open coast, sandy beaches. Although it may not be possible to apply the results of this research directly to the various types and sizes of armoring structures constructed on the tide-dominated sheltered shores in Puget Sound, the framework we developed for investigating ecological effects may be of use. The ecology of all soft sediment shoreline habitats, sheltered and open-coast, is strongly affected by sediment supply, wave-energy, exposure and tidal regime. In all systems, the installation of coastal armoring structures can directly alter shore habitats through placement loss, passive erosion, and perhaps other mechanisms (for example, active erosion, depth of activation). Assessments of possible ecological impacts of armoring to open coast and sheltered soft shore ecosystems may be more effective if the relative widths and distributions of key shore zones are quantified. Impacts may be most immediately apparent and strongest in high shore zones where the direct effects of placement loss reduce or eliminate habitats and high tide refugia and alter physical or biological processes (for example, retention and processing of wrack). Large armoring structures may also fragment habitats, reduce connectivity with adjacent habitats, and inhibit significant ecotone processes and exchanges. Animals at higher trophic levels (for example, shorebirds, seabirds, turtles, fish) that use soft shores may be affected by alterations or reductions in habitat availability and quality (for example, area and type of habitat available, nesting areas, roosts, high tide refuges) and by bottom-up effects resulting from changes in prey assemblages (food resources) associated with habitat alteration as a consequence of coastal armoring.

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