

# Ecological Responses to Coastal Armoring on Exposed Sandy Beaches

By

Jenifer E. Dugan  
David M. Hubbard

*Marine Science Institute  
University of California  
Santa Barbara, CA 93106  
j\_dugan@lifesci.ucsb.edu*

## ABSTRACT

We develop a conceptual model for assessing potential ecological responses to coastal armoring that incorporates the presence, extent and functioning of multiple intertidal zones, as well as changes in beach width in general. We propose that ecological responses to the narrowing of beaches associated with coastal armoring are related to changes in the widths and the dynamics of the different intertidal zones of the beach and that, as habitat narrows in response to armoring, intertidal zones are lost disproportionately from the upper beach. The reduction and loss of intertidal zones, along with expected changes in the deposition and retention of macrophyte wrack, are predicted to depress the diversity and abundance of macroinvertebrates on armored beaches. The combination of reductions in 1) habitat, 2) accessibility at high tides, and 3) macroinvertebrate prey availability is predicted to reduce biocomplexity and affect the use of armored beaches by shorebirds. We investigated several predictions of our model using comparisons of armored and unarmored segments of narrow bluff-backed sandy beaches in southern California. Our results supported those predictions and revealed some unexpected responses to armoring. Intertidal zones were fewer and narrower where armoring was present compared to adjacent unarmored segments. This was evident in the absence of the upper intertidal zones on armored

segments of coastline and narrower mid-intertidal zones on armored segments. The standing crop of macrophyte wrack was significantly greater (one to nearly three orders of magnitude) on unarmored segments than on armored segments. Shorebirds responded to coastal armoring as predicted by our model with significantly lower species richness (2.3 times) and abundance (>3 times) on armored segments of beach. All 13 species of shorebirds observed were more abundant on unarmored segments than on armored segments. Although not predicted by our model, the three species of gulls observed also responded to coastal armoring with significantly lower abundance (4.7 times) on armored segments. We predict that the amount of interaction between a coastal armoring structure and the coastal processes of waves and tides will affect the ecological responses to the structure. Our model provides a framework that could be used in investigating ecological responses to coastal armoring of other types and tidal heights and in other coastal regions. The accelerated loss of beaches associated with rising sea levels and the implications of our results indicate further investigation of ecological responses to coastal armoring is needed.

**ADDITIONAL KEYWORDS:** biodiversity, California, intertidal zones, seawall, shorebirds, macrophyte wrack

the processes of placement loss, passive erosion, and increased erosion directly seaward of structures (Griggs 1998, 2005, Hall and Pilkey 1991, Tait and Griggs 1990). These effects on the intertidal beach appear to be related to the hardened faces of armoring structures, which act to reflect rather than dissipate wave energy as well as the initial placement loss and the constraints imposed on natural migration of the shoreline by the structures.

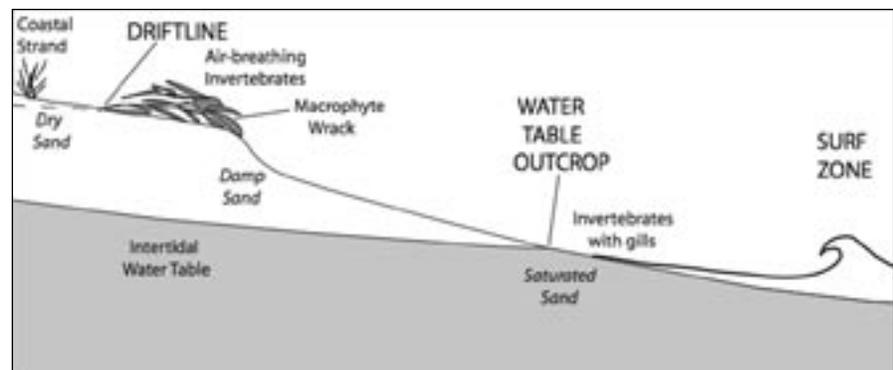
Despite the use of armoring on coastlines for centuries and numerous studies of the physical effects of this form of shore protection, the ecological responses of beach communities to armoring are poorly documented and understood. As a consequence of this lack of information, ecological effects are often not considered in decision-making or coastal policy.

Intertidal zonation on exposed sandy beaches is extremely dynamic due to the highly mobile nature of the sandy substrate, the intertidal animals and the resources on which these animals depend (McLachlan and Jaramillo 1995, Brown and McLachlan 1990). In general, two to three different intertidal zones inhabited

## INTRODUCTION

Coastal armoring, involving the placement of hard structures and walls constructed of a variety of materials, has been applied to reduce threats to coastal structures for centuries (Charlier et al 2005). The extent of coastal armoring varies regionally, with higher prevalence generally found on populous developed coastlines (Nordstrom 2004). California, where approximately 10 percent of the coastline has been armored with rock, concrete, and wood during the past century (Griggs 1998), illustrates this trend. The application of coastal armoring has not declined over time, as exemplified by California where the extent of coastal armoring increased by over 400 percent in the 21 years between 1971 and 1992 (Griggs 1998).

Coastal armoring, including seawalls and rock revetments, has been shown to reduce intertidal beach widths through



**Figure 1. Profile of an exposed sandy beach showing the intertidal and supralittoral zones investigated in this study. The relative locations of major invertebrate types, accumulations of macrophyte wrack and ephemeral coastal strand vegetation are indicated. Air-breathing invertebrates can include talitrid amphipods, oniscoidean isopods, insects, and arachnids. Invertebrates with gills can include hippid crabs, isopods, amphipods, bivalves, gastropods, and polychaetes.**

by distinct groups of mobile animals are present on most exposed sandy beaches (McLachlan and Jaramillo 1995). These zones generally correspond to the relatively dry sand/substrate of the upper intertidal zone at and above the drift line, the damp sand of the middle intertidal zone and the wet or saturated sand of the lower intertidal zone (Figure 1). In addition, a supralittoral or coastal strand zone exists at the extreme high water level on many beaches (Figure 1). Unlike rocky shores, the location of these zones and of the diversity of organisms that inhabit them changes with the tides, wave conditions, and the seasons.

We propose that ecological responses to the narrowing of beaches associated with coastal armoring can be estimated from the widths and dynamics of the different intertidal zones of the beach. Loss of habitat area alone can have clear ecological consequences in many coastal ecosystems (e.g., wetlands, riparian corridors and reefs). For beaches, we hypothesize that as habitat narrows in response to armoring, intertidal zones are lost disproportionately, resulting in a sequence of ecological impacts. We predict that the loss of intertidal beach habitat caused by coastal armoring proceeds from the upper beach to the lower beach.

The supralittoral zone and sand-stabilizing coastal strand vegetation may be strongly and immediately affected by the placement loss, accelerated erosion and the narrowing of the beach associated with armoring, processes that can result in the rapid elimination of this zone. Below this, the rich zone of drying and damp sand around the drift-line inhabited by air-breathing crustaceans and insects could also be greatly reduced or eliminated. The retention of wrack and other drift material would likely decline as this zone narrows, and depositional dynamics shift, reducing the primary food source for wrack consumers and the wrack-based beach food web. The narrowing and loss of the mid-intertidal zone and associated animals such as isopods, amphipods, and polychaetes is also predicted to occur on armored beaches. The saturated sand of the low intertidal zone would be expected to persist the longest; but impacts on the intertidal species of this zone, such as sand crabs and clams, could also occur. The survival of these mobile animals is likely to be negatively affected by restrictions on their upward migration with tides and wave events (Jaramillo et al 2000) imposed by the narrowing beach in front of the armoring structure.

macroinvertebrates (Dugan et al. 2003) than unarmored beaches.

The rich invertebrate communities of southern California beaches are important as prey for a remarkably diverse and abundant shorebird assemblage, particularly during spring and fall migrations and over the winter months with over 26 different species observed in numbers that can exceed 1000 individuals  $\text{km}^{-1}$  (McCrary and Pierson 2000, Hubbard and Dugan 2003, Dugan et al. 2003). The diversity and abundance of shorebirds on southern California beaches has been positively correlated with the diversity and abundance of macroinvertebrate prey and with macrophyte wrack in this region (Dugan 1999, Dugan et al. 2003) and others (Tarr and Tarr 1987).

Using existing 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 most distinct effects on the upper zones of the beach. These effects could in turn reduce the prey resources available to shorebirds and their use of beach habitats. Based on this conceptual model, we investigated several ecological responses predicted from the loss of intertidal and supralittoral beach habitat associated with coastal armoring, including the reduction or loss of intertidal zones and associated organisms, reduced accumulation of macrophyte wrack and reduced shorebird use. We tested these predictions using paired observations of intertidal zones, wrack and shorebird use of armored and unarmored coastal segments of beaches in southern California.

## METHODS

### Study area

This study was conducted on wave-exposed intertidal beaches at four sites located between Gaviota and Goleta in southern Santa Barbara County, California. The coastline of this region consists primarily of narrow, bluff-backed beaches perched on wave-cut platforms that are interspersed with stream mouths, rocky points and a variety of coastal armoring structures (e.g., Habel and Armstrong 1978). The study region experiences a mixed semi-diurnal microtidal regime. Seasonal and episodic variation in wave climate and strong longshore transport drive changes in sand levels altering mixtures of sand, cobbles, boulders, and rocky substrates in the intertidal zone (e.g., Hubbard and Dugan 2003). These beaches are

in the Santa Barbara Littoral Cell where estimated average net longshore transport rates of sand range from 400 to 900 yards<sup>3</sup> per day from west to east for this portion of this cell (Bascom 1980). Many beaches on this coast experience large inputs and high standing crops of macrophyte wrack from nearshore kelp forests reefs, and surfgrass beds (Dugan et al. 2003).

All of the study sites were narrow, bluff-backed open coast beaches as described above and would be considered intermediate in morphodynamic state (e.g., Short 1996) with seasonally variable wave heights (significant breaker heights = 0.3 to 2.5 m) and moderately fine sand (mean grain sizes = 0.216 to 0.256 mm) (Dugan and Hubbard 2004). None of the study sites are subject to beach grooming.

Each of the four study sites consisted of two segments: 1) a segment of shoreline immediately seaward of an intertidal concrete seawall (hereafter the armored segment) and 2) an unarmored bluff-backed segment of shoreline adjacent to the armored segment of the same length and with similar orientation (the unarmored segment). The unarmored segments were either upcoast or downcoast of the armored segments, depending on coastal orientation and presence of other structures. During the study period, the four seawalls chosen for study interacted with the majority of high tides but were out of range of the wave wash on most low tides. The lengths and mean heights of the four seawalls used in the study are given in Table 1. The concrete seawalls chosen for study were all massive, nearly vertical structures, with some gentle landward slope near the bases, that have been in place for at least 60 years. The study sites were surveyed and all data collected during August and September 2005, a time of year when sand levels are generally at their annual maxima in this region and shorebird visitation is high (Hubbard and Dugan 2003).

We collected data on three ecological aspects on each armored and unarmored segment of beach: 1) width and extent of intertidal zones, 2) standing crop (wet biomass) of accumulated macrophyte wrack, and 3) diversity and abundance of shorebirds, gulls and other birds. To avoid possible end effects associated with armoring structures, we only measured habitat zones and wrack in the middle 50 percent of each segment.

For each segment, we measured the distance (to the nearest 0.1 m) from the landward limit of intertidal habitat (seawall or bluff) to the high tide strand or

Beach	Segment	Length (m)	Mean height (m)
El Capitan	Seawall	370	2.0±0.6
	Adjacent	370	-
Refugio	Seawall	170	3.2±0.5
	Adjacent	170	-
Arroyo Quemado	Seawall	760	2.8±0.5
	Adjacent	760	-
Arroyo Hondo	Seawall	1050	2.7±0.4
	Adjacent	1050	-

**Table 1. Lengths and mean heights (± standard deviation) of seawalls and adjacent unarmored shoreline segments used in the study (mean heights are based on measurements from five to seven locations in the middles 50 percent of each armored segment in September 2005). Seawalls are listed from east to west as in the figures. Beach names indicate locations of nearby landmarks, not the names of seawalls or their owners.**

driftline and to the water table outcrop on five to seven transects during low tide in September 2005 (Figure 1). The hypothesis that intertidal zone widths differed between armored and unarmored segments was examined with two-way analysis of variance (ANOVA).

To estimate the standing crop of wrack, we measured the mass of macroalgae and seagrass deposited on three randomly located shore-normal transects located within the central 50 percent of each segment on a single sampling date in September 2005. We collected all exposed and buried wrack in a 1-m wide strip across the intertidal zone and sorted it by type including: fresh and dried *Macrocystis pyrifera*, *Egria menziesii*, *Phyllospadix* spp., *Zostera* spp., red algae, green algae and other brown algae. All wrack was weighed in the field with a spring scale. The hypothesis that the standing crop of wrack differed between armored and unarmored segments was examined with two-way ANOVA. We also noted the presence or absence of driftwood on each segment.

We counted and identified all birds present, including shorebirds, gulls, and other birds, on intertidal sand or rocks, or on seawalls on the armored and unarmored segments at each site during low tides on eight dates between Aug. 19 and Sept. 30, 2005. Counts of paired segments of coast were always made on the same tide and date. Data were summarized as abundance and species richness for all birds observed. Means and standard errors of species richness and abundance of shorebirds, gulls and other birds were calculated for each segment and shoreline type. Raw abundance data were adjusted to densities per km of shoreline for comparisons. The hypothesis that the species richness and abundance of shorebirds and gulls varied

water table outcrop ranging from 4.1 m to 15.4 m on armored segments and 6.5 m to 28.7 m on unarmored segments of beach. No coastal strand zone was present on the study beaches in 2005. We also observed fewer intertidal boulders (large naturally occurring rocks of greater than 256 mm diameter) seaward of the armored segments compared to unarmored bluff-backed segments.

Intertidal zones were fewer and narrower where armoring was present compared to adjacent unarmored segments (Figure 2). This was manifested in the absence of the upper intertidal zones on armored segments of coastline (Figure 2, 3a). In every comparison, the driftline occurred at the base of or on the seawall itself on armored segments, indicating the elimination of the upper and supralittoral intertidal zones on armored segments (Figure 2, 3a). On unarmored sections, at least a narrow upper intertidal zone was present at every site (Figure 3a).

The distance from the upper beach limit to the water table outcrop was narrower (47 percent to 60 percent) for armored compared to adjacent unarmored segments (Figure 2, 3b). This distance differed significantly among armored and unarmored segments and among the four sites (two-way ANOVA, n = 40: Type: F = 98.41, p < 0.001, Site: F = 14.51, p < 0.001, Type x Site: F = 1.19, p = 0.330).

with armoring was tested with repeated measures ANOVA. The distribution of shorebird species relative to coastal armoring was examined with the Sign test (Zar 1984).

## RESULTS

### Intertidal Zonation

The intertidal zones of all beach segments we measured were relatively narrow with overall widths from the upper beach limit to the

### Wrack

The distribution of drift material, wrack, and driftwood, present during our surveys varied between armored and unarmored segments. The macrophyte wrack in our surveys consisted primarily of brown macroalgae and surfgrass and amounts varied considerably among the four sites and among transects. Driftwood deposits were present on the four unarmored segments studied, but no driftwood was observed along any of the armored segments during the study period.

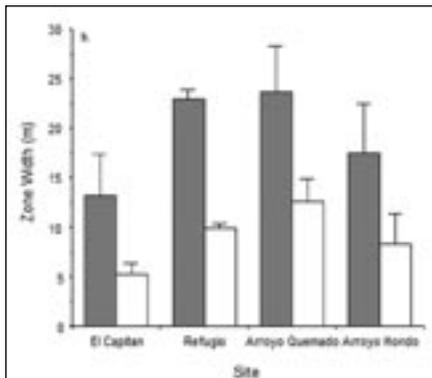
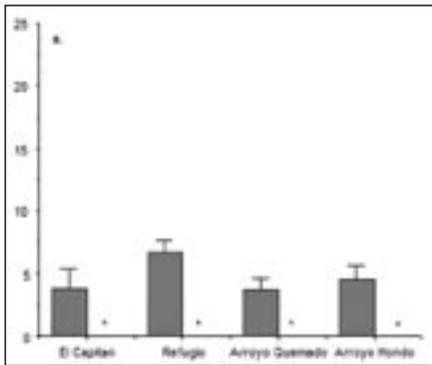
The standing crops of macrophyte wrack (wet biomass per meter of shoreline) were very low on all the armored segments during the study period. The standing crop of wrack was one to nearly three orders of magnitude greater on unarmored segments (881 g m<sup>-1</sup> to 9351 g m<sup>-1</sup>) than on armored segments (6 g m<sup>-1</sup> to 37 g m<sup>-1</sup>) (Figure 4). The standing crop of wrack was significantly greater on unarmored bluff-backed segments than on armored segments but did not differ significantly among the four beach sites (2 way ANOVA, n = 24, Type: F = 5.60, p = 0.031, Site: F = 0.88, n = 24, p = .474, Type x Site: F = 0.88, p = 0.47).

### Birds

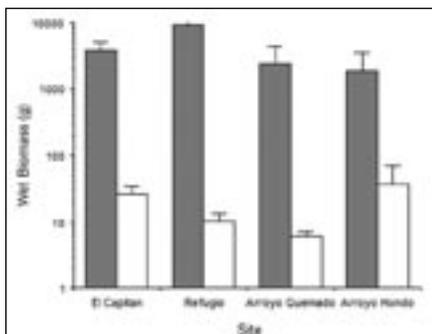
Overall, we observed a total of 3,961 birds of 27 species, including shorebirds, gulls and other birds, in eight counts at each of four sites (4.7 km of shoreline total per count) (Table 2). Birds were more abundant and more diverse on unarmored segments than on armored segments with seawalls. Mean abundance was 4.3 times higher on the unarmored segments (164 ± 234 individuals km<sup>-1</sup>) than on the armored segments (38 ± 83 individuals km<sup>-1</sup>). The mean species richness of birds (per count) was 2.1 times higher for unarmored segments than for armored segments.



**Figure 2. This view looking east along an old concrete seawall on the Gaviota coast at low tide illustrates the attenuation of intertidal zones on a beach seaward of coastal armoring.**



**Figure 3.** Mean widths (+ one standard error, n = 5) of intertidal zones in meters at low tide for unarmored (grey bars) and armored (white bars) segments of coastline at four beaches: (a) mean widths of the zone between the driftline and the upper beach limit, (\* indicates the absence of this zone) (b) mean widths of the beach between the upper beach limit and the water table outcrop (wet/dry line). The names of the beaches given on the x axis indicate nearby landmarks.



**Figure 4.** Mean wet biomass of macrophyte wrack (+ one standard error, n =3) in grams at low tide for unarmored (grey bars) and armored (white bars) segments of coastline at 4 beaches.

### Shorebirds

Shorebirds responded to coastal armoring as predicted by our model. We observed a total of 514 shorebirds of 13 species in the 8 surveys (Table 2). Most of the shorebirds observed were foraging actively. A total of 13 species of shorebirds were recorded on unarmored segments, while only eight species were seen on ar-

mored segments (Table 2). The mean species richness (per count) of shorebirds was 2.3 times higher for unarmored segments than for segments with seawalls (Figure 5). Overall, the abundance of shorebirds was more than three times greater on unarmored segments ( $24.3 \pm 12.6$  individuals  $\text{km}^{-1}$ ) than on armored segments ( $7.5 \pm 7.5$  individuals  $\text{km}^{-1}$ ) (Figure 6). The species richness and abundance of shorebirds was significantly greater on unarmored segments than on armored segments of beach (Repeated Measures ANOVA, n = 8, Richness:  $F = 15.971$ ,  $p = 0.007$ ; Abundance:  $F = 13.194$ ,  $p = 0.011$ ).

All 13 species of shorebirds observed were more abundant on unarmored segments than on armored segments (Sign Test,  $p < 0.001$ ) (Table 2). The four most

abundant species of shorebirds accounted for 90 percent of the total shorebird abundance: Spotted Sandpiper, *Actitis macularia*, 51 percent; Willet, *Catrophorus inornatus*, 15 percent; Wandering Tattler, 13 percent; and Killdeer, *Charadrius vociferus* 11 percent. Of these species, large proportions of all individuals observed were found on unarmored segments (70 percent, 91 percent, 85 percent, and 95 percent respectively).

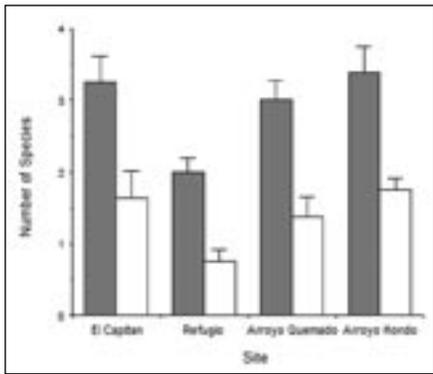
### Gulls

Although not predicted by our model, gulls also responded to coastal armoring. We observed a total of 3,378 gulls of three species in the eight surveys (Table 2). All three species of gulls were recorded on armored and unarmored segments of beach (Table 2); most of them were loafing. Mean

**Table 2.** Abundance (as counts) and occurrence (number of times present) of shorebirds, gulls, and other birds in paired surveys of armored and unarmored segments of beach between Aug. 19 and Sept. 30, 2005. (Not adjusted to per km densities.)

COMMON NAME	SPECIES	ABUNDANCE			OCCURRENCE		
		Unarmored	Armored	Total	Unarmored	Armored	Total
<b>SHOREBIRDS</b>							
Spotted Sandpiper	<i>Actitis macularia</i>	185	78	263	31	25	56
Willet	<i>Catrophorus semipalmatus</i>	68	7	75	10	4	14
Wandering Tattler	<i>Heteroscelus incanus</i>	57	10	67	18	8	26
Killdeer	<i>Charadrius vociferus</i>	55	3	58	16	2	18
Sanderling	<i>Calidris alba</i>	13	10	23	2	1	3
Whimbrel	<i>Numenius phaeopus</i>	9	4	13	7	2	9
Long-billed Curlew	<i>Numenius americanus</i>	5	1	6	3	1	4
Black-bellied Plover	<i>Ploveris squatarola</i>	2	1	3	1	1	2
Western Sandpiper	<i>Calidris mauri</i>	2	0	2	1	0	1
Semipalmated Plover	<i>Charadrius semipalmatus</i>	1	0	1	1	0	1
Black Turnstone	<i>Arenaria melanocephala</i>	1	0	1	1	0	1
Long-billed Dowitcher	<i>Limnodromus scolopaceus</i>	1	0	1	1	0	1
Surfbird	<i>Aphriza virgata</i>	1	0	1	1	0	1
<b>ALL SHOREBIRDS</b>		<b>400</b>	<b>114</b>	<b>514</b>			
<b>GULLS</b>							
Heermann's Gull	<i>Larus heermanni</i>	1715	472	2187	16	8	24
Western Gull	<i>Larus occidentalis</i>	770	404	1174	23	11	34
Ring-billed Gull	<i>Larus delawarensis</i>	14	3	17	5	1	6
<b>ALL GULLS</b>		<b>2499</b>	<b>879</b>	<b>3378</b>			
<b>OTHER BIRDS</b>							
Black Phoebe	<i>Seiornis nigricans</i>	22	13	35	19	10	29
Song Sparrow	<i>Melospiza melodia</i>	5	1	6	3	1	4
Great-blue Heron	<i>Ardea herodias</i>	4	0	4	4	0	4
American Crow	<i>Corvus brachyrhynchos</i>	4	5	9	3	3	6
Great Egret	<i>Ardea alba</i>	3	0	3	2	0	2
Pelagic Cormorant	<i>Phalacrocorax pelagicus</i>	2	4	6	2	3	5
Rock Dove	<i>Columba livia</i>	2	0	2	1	0	1
Brown Pelican	<i>Pelicanus occidentalis</i>	1	0	1	1	0	1
Double-crested Cormorant	<i>Phalacrocorax auritus</i>	1	0	1	1	0	1
California Towhee	<i>Pipilo californicus</i>	1	0	1	1	0	1
Green Heron	<i>Butorides virescens</i>	0	1	1	0	1	1
<b>ALL-OTHER BIRDS</b>		<b>45</b>	<b>24</b>	<b>69</b>			
<b>TOTAL BIRDS</b>		<b>2944</b>	<b>1017</b>	<b>3961</b>			

**Table 2.** Abundance (as counts) and occurrence (number of times present) of shorebirds, gulls, and other birds in paired surveys of armored and unarmored segments of beach between Aug. 19 and Sept. 2005. (Not adjusted to per km densities.)



**Figure 5. Mean species richness of shorebirds (+ one standard error, n = 8) during fall migration for unarmored (grey bars) and armored (white bars) segments of coastline at four beaches.**

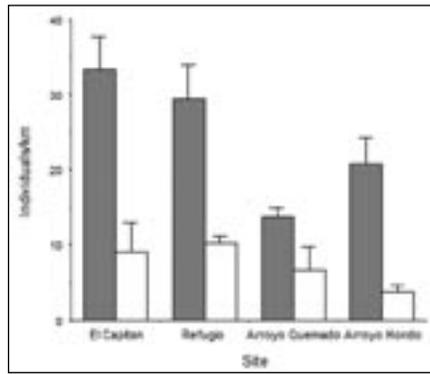
species richness did not vary significantly between armored and unarmored segments. Overall, the mean abundance of gulls was 4.7 times higher for unarmored segments ( $136.7 \pm 234.8$  individuals  $\text{km}^{-1}$ ) than for armored segments ( $29.3 \pm 83.8$  individuals  $\text{km}^{-1}$ ) (Table 2). The species richness of gulls did not vary significantly with coastal armoring (Repeated measures ANOVA, n = 8, F = 2.7, p = 0.151). The abundance of gulls was significantly greater on unarmored segments than on armored segments of beach (Repeated Measures ANOVA, n = 8, F = 18.880, p = 0.005).

### Other birds

A response to armoring was also apparent for a variety of other species of birds observed including seabirds (cormorants, California Brown Pelican), herons (Great Blue Heron, Great Egret, Green Heron) and terrestrial birds (e.g., Black Phoebe, Song Sparrow, American Crow, Rock Dove). Low numbers of other bird species were observed with a total of 69 individuals of 11 species recorded in our surveys (Table 2). Overall, twice as many species of other birds were observed on unarmored segments (10 species) as on armored segments (five species) of beach (Table 2) however, this difference was not statistically significant (Repeated measures ANOVA, n = 8, F = 4.531, p = 0.077). The abundance of other bird species was generally quite low, but varied with coastal armoring. The overall mean abundance of other birds was 2.3 times higher on unarmored segments ( $3.2 \pm 3.0$  individuals  $\text{km}^{-1}$ ) than on armored segments ( $1.4 \pm 2.0$  individuals  $\text{km}^{-1}$ ) but did not differ significantly with armoring (Repeated measures ANOVA, n = 8, F = 3.465, p = 0.112).

### DISCUSSION

Narrowing of beaches in front of coastal armoring was evident in both the upper



**Figure 6. Mean abundance of shorebirds (+ one standard error, n = 8) during fall migration for unarmored (grey bars) and armored (white bars) segments of coastline at four beaches.**

and the middle intertidal zones of the beach. Upper intertidal zones appeared to be most affected by armoring with the zone of the beach located above the driftline eliminated from the armored segments of beach, even in late summer. The effects on intertidal zones would be expected to be stronger during the winter and spring months when intertidal sand levels decline (e.g., Hubbard and Dugan 2003). A well-designed BACI (Before After Control Impact -- e.g., Schroeter et al. 1993) study of the short-term responses (20 months) to a newly constructed seawall did not find a significant effect of the seawall on the distance between the driftline and the low tide level of the beach (Jaramillo et al. 2002). This contrasting result for effects on the intertidal zone may be due in part to the young age of the seawall studied by Jaramillo et al. (2002) compared to the old structures studied here. Importantly, their study did not compare the zone widths above the driftline where the most extreme differences were observed in our study.

The coastal strand zone and associated vegetation did not exist on most of the narrow beaches we studied and was never observed on the armored segments. The effects of coastal erosion and sea level rise on this restricted zone (e.g., Feagin et al. 2005) combined with armoring impacts bode poorly for the survival of the coastal strand zone on coastlines that are both retreating and developed.

The lack of intertidal boulders seaward of the armored segments compared to unarmored bluff-backed segments suggests a reduced supply and/or higher longshore transport of boulders occurs in front of seawalls. This result could be examined in more detail and has important implications for both coastal sediment supply (e.g., Runyan and Griggs 2003) and the biocomplexity of the intertidal zone.

Our results support the prediction that upper intertidal beach zones are lost and mid-intertidal zone are reduced in front of coastal armoring structures. The upper intertidal zone, specifically the driftline, shifts from the beach to the armoring structure with clear consequences for the ecology of the beach, including reduced biodiversity, abundance and prey for shorebirds. Rich, three-dimensional infaunal beds of the driftline are eliminated and are replaced by the steep two-dimensional habitat of the seawall, which may support a low diversity of some rocky shore species (e.g., Chapman 2003, Chapman and Bulleri 2003) but has little or no resource value for shorebirds. The damp sand zone of the beach was also significantly narrower on armored segments of coast compared with adjacent unarmored segments. This result implies reduced habitat for invertebrates and more restricted foraging areas for shorebirds on armored coastlines.

In addition to macroinvertebrates, the high intertidal zone around the driftline is nesting habitat for several species of fish, including the California grunion (*Leuresthes tenuis*) on open coastlines and Surf Smelt (*Hypomesus pretiosus*) and Pacific Sand Lance (*Ammodytes hexapterus*) on protected shores, who lay their eggs in this zone during peak spring high tides to incubate in the sand through the neap tides. Negative effects of armoring on embryo survival have been reported for the surf smelt in Puget Sound (Rice 2003) and might be expected for California grunion. The reduction or loss of this high intertidal zone associated with coastal armoring reported here has clear consequences for reproduction of beach-dependent fish species. The importance of Pacific sand lance and surf smelt as forage fish for salmon and seabirds have stimulated efforts to identify and protect spawning beaches from coastal armoring and other human impacts in the Puget Sound area (Reeves et al. 2003).

Wrack is a key resource for beach invertebrates (Brown and McLachlan 1990). Availability of macrophyte wrack can affect diversity and abundance of intertidal animals including shorebirds (Dugan et al. 2003). An average of 37 percent (range = 14 percent to 55 percent) of the invertebrate species on beaches of the study region were wrack-associated forms and overall species richness of the community was positively correlated with the standing crop of wrack (Dugan et al. 2003). We predict that the loss of this habitat zone observed on armored segments in this study has likely resulted in a significant reduc-

tion of intertidal diversity and an alteration of community structure and function. The abundance of talitrid amphipods was positively associated with wrack cover (Dugan et al. 2003) and this important crustacean can reach densities exceeding 90,000 individuals  $m^{-1}$  on unarmored bluff-backed beaches (Dugan et al. unpublished).

The significant reduction in the standing crop of this key resource found on armored beaches is expected to have strong negative effects on biodiversity and abundance of wrack-associated invertebrates, including talitrid amphipods, isopods, and beetles, as well as the entire intertidal community and food web of the beach. Our results also suggest that the accumulation of wrack may be affected by coastal armoring on other shore types including boulder, cobble, rock shelf, and estuarine shorelines thus affecting a variety of intertidal food webs.

Our results fit our prediction that the distribution of shorebirds on beaches during fall migration responds negatively to the presence of coastal armoring. The significant responses of species richness and abundance of shorebirds to armoring was evident even during low tide surveys when the greatest amount of habitat was available. We expect the differences in shorebird distributions would be greater during high tides and when sand levels are reduced during winter and spring. The response of shorebirds to coastal armoring exceeded that predicted by the loss of habitat area alone, suggesting that other factors -- including prey abundance and diversity, availability of high tide refuges, and other landscape factors -- also contribute to the observed response. Loss of habitat for migration staging, foraging, and wintering has been implicated in the declines of populations of many species of shorebirds in North America and is a

major concern for shorebird conservation planning (Brown et al. 2001).

Our results were also consistent with the prediction that visually searching shorebirds, such as plovers (e.g., killdeer and black-bellied plovers), were strongly affected by beach changes associated with armoring. This may be related to the disproportionate reduction of the zones above and around the driftline where the prey for these species concentrate in stranded wrack.

Although not predicted by our conceptual model, gulls, seabirds, waders, and other birds also responded negatively to coastal armoring in this study. Factors associated with armoring that may be affecting this wider variety of birds require further investigation.

The seawalls observed in this study were old, primarily vertical structures that interacted with tides and waves daily, even in the late summer when sand levels are expected to be greatest on this coastline (e.g., Hubbard and Dugan 2003). These walls were associated with significant depression in several ecological elements of the beach community. Ecological responses to other forms of coastal armoring may differ. Seawalls or other coastal armoring structures that experience more or less interaction with waves and tides could produce different results. We predict that the ecological effects of any armoring structure will increase with the amount of interaction between the structure and the intertidal processes of waves and tides, whether this is due to initial placement or subsequent erosion of the beach.

## CONCLUSIONS

Our study results suggest that the alteration of sandy beaches by coastal armoring causes significant ecological responses

of intertidal beach communities including overall loss of habitat, the loss and reduction of intertidal zones, altered wrack deposition and retention, and reduced diversity and abundance of macroinvertebrates, shorebirds, gulls, and other birds. The combination of rising sea levels predicted by climate change models (e.g., Kendall et al 2004) and the increasing extent of coastal armoring (already >10 percent of the coast in California (Griggs 1998)) will accelerate beach loss and increase ecological consequences for sandy beach communities and shorebirds in many regions. The ecological responses to coastal armoring we found indicate that further and more detailed research is needed on this question. We predict that the amount of interaction between a coastal armoring structure and the coastal processes of waves and tides will affect the ecological responses to the structure. Our conceptual model provides a framework that could be used in investigating ecological responses to coastal armoring of other types and tidal heights and in other coastal regions.

## ACKNOWLEDGMENTS

We gratefully acknowledge S. Bull, M. James, G. Osherenko, and D. Revell for their encouragement and valuable discussions about this study. The deliberations of the Goleta Beach Working Group organized by Santa Barbara County provided the inspiration for this study. We also thank L. Ewing and four anonymous reviewers whose suggestions improved our manuscript. This research was supported by a grant from the A.S. Students Shoreline Preservation Fund of the University of California at Santa Barbara and by the Santa Barbara Coastal Long Term Ecological Research project (NSF Cooperative Agreement #OCE-9982105).

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