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Utilization of Sandy Beaches by Shorebirds: Relationships to Population Characteristics of Macrofauna Prey Species and Beach Morphodynamics

Final Technical Summary

Final Study Report

U.S. Department of the Interior
Minerals Management Service
Pacific OCS Region

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FINAL TECHNICAL SUMMARY

STUDY TITLE: Utilization of sandy beaches by shorebirds: relationships to population characteristics of macrofauna prey species and beach morphodynamics

REPORT TITLE: Utilization of sandy beaches by shorebirds: relationships to population characteristics of macrofauna prey species and beach morphodynamics

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KEY WORDS: Southern California, Ventura County, Santa Barbara County, Santa Barbara Channel, intertidal ecology, exposed sandy beaches, shorebirds, invertebrate macrofauna, beach morphodynamics, macrophyte wrack

BACKGROUND: Little information exists on the potential risk from oil related impacts to shorebirds and to resources which they depend upon on exposed sandy beaches of Southern California. To address this gap in information needed for oil spill contingency planning and damage assessment, the distribution and abundance of shorebirds on Ventura County beaches was studied by Minerals Management Service personnel. The present study was undertaken to complement that project by examining factors which could affect the distribution and abundance of shorebirds on beaches, including prey availability and beach morphodynamics. The combined results of the Minerals Management Service study and the present study address a major gap in our understanding of the vulnerability of sandy beach resources to oil related impacts.

OBJECTIVES: The present study was designed to provide new information on beach morphodynamics and other factors affecting shorebirds and macrofauna community structure on exposed sandy beaches on the Southern California coast. We examined relationships between shorebirds and their invertebrate macrofauna prey, macrophyte wrack, and physical attributes of sandy beaches using the results of field surveys of sandy beaches in Ventura and Santa Barbara counties in combination with the results of a study of shorebird distribution. Specifically we investigated relationships between: 1) the abundance and species richness of shorebirds on sandy beaches and the abundance, biomass and mean individual size of macrofauna prey species, 2) the abundance, biomass and mean individual size of macrofauna prey species on sandy beaches and physical factors, such as beach morphodynamics and 3) the distribution and abundance of shorebirds on a beach and physical factors, such as beach morphodynamics, beach size, landward boundary and other factors such as macrophyte wrack.

DESCRIPTION: To determine the species richness, abundance, biomass and population size structure of the macrofauna community and selected species we conducted quantitative sampling at each of the Ventura County sandy beach sites (12) in the MMS shorebird study (McCrary and Pierson 1997) and at 3 additional Santa Barbara County beaches chosen to expand the range of morphodynamic beach types represented in the study. The physical characteristics and macrofauna communities of 15 beaches were sampled in September and October of 1996.

Macrofauna community samples were collected in daylight on spring low tides on fifteen days between September 12 and October 13, 1996. On each beach, three transects were established extending from the landward boundary of the beach to below the lowest swash level. Each transect was sampled with 150 uniformly spaced cores of 10 cm diameter and 20 cm depth. At each of 15 tidal levels, 10 consecutive cores were grouped and rinsed through a 1 mm sieve, retaining the macrofauna. Macrofauna were preserved for analysis. This sampling design yielded a total sampling area of 3.5 m^2 and a total of 45 biological samples at each beach.

The cover and composition of macrophyte wrack was measured on the three transects at the 15 sites. Amounts of accumulated macrophyte wrack were estimated (as % cover and total cover) using point-contact transects across the intertidal zone from the lowest edge of the terrestrial vegetation or base of the sea bluff to the high swash zone.

To estimate beach morphodynamic state, physical parameters including wave height and period, sediment grain size and beach slope at three beach levels, swash width and period and beach width were measured on the three transects at all sites.

From November of 1996 through November 1997, surveys of shorebirds, macrophyte wrack and physical characteristics were conducted monthly during spring low tides on the three Santa Barbara County study beaches using the MMS techniques for shorebirds and the protocols above for beaches. Dates of those surveys were selected to coincide with the monthly surveys of shorebirds on the Ventura County study beaches by MMS biologists. Monthly shorebird surveys of the 14 Ventura County study beaches by MMS biologists were completed in May 1997 yielding 3 years of data on shorebirds and 20 months of data on sediments and wave climate. For comparisons, data from months in which both the Ventura and Santa Barbara County study sites were surveyed were used in analyses.

In March 1997, the 15 study beaches were resurveyed using the protocols above to determine physical characteristics and macrophyte cover. In addition, a census of shorebirds and detailed observations of shorebird zonation were made at each beach.

All sediment samples from the macrofaunal, winter, and monthly surveys were rinsed, dried and analyzed with standard testing sieves by a MMS/CMI student intern. Mean grain size, sorting, skewness and kurtosis were calculated for each sample.

Wave height and wave period data were compiled from data collected by MMS biologists from that period by the student intern. Dean's parameter for each month and site were calculated from the wave and sediment data and used to estimate the modal morphodynamic state of the study beaches.

To examine hypotheses concerning shorebirds, their macrofauna prey, and the physical characteristics of sandy beaches, data from the macrofauna community and beach surveys and from the shorebird surveys were analyzed using univariate and multivariate statistics.

SIGNIFICANT CONCLUSIONS: Species richness, abundance, and biomass of macrofauna inhabiting exposed sandy beaches in Southern California were high compared to values reported for similar beaches of other regions. Species richness and abundances of selected taxa were positively correlated with macrophyte wrack cover. Beach grooming practices that remove wrack may have significant impacts on macrofauna communities. The results of our study in conjunction with those of the MMS shorebird study in Ventura county indicate that large numbers and high densities of shorebirds utilize exposed sandy beaches on the southern California coast. Our results suggest the standing crop and production of macrofauna prey may be important to understanding spatial variation in the abundance of shorebirds on exposed sandy beaches.

STUDY RESULTS: The majority of the beaches we surveyed were modally intermediate morphodynamic types with values of Dean's parameter between 0.6 (reflective) and 5.5 (high intermediate to dissipative). The values for most of the study beaches in that period were between 1.5 and 4.4 (intermediate). Average values of Dean's parameter for the study beaches obtained from monthly surveys during the study ranged from 0.7 to 3.6 and were similar to those obtained in the September/October 1996 surveys, indicating primarily intermediate beach types. Although values of Dean's parameter >6 were obtained during some of the monthly surveys, no modally dissipative beaches were studied and none occur in the study region. Only one modally reflective beach was studied.

Mean overall beach widths varied from 52 m to over 200m, while intertidal widths varied from 29 m to 77 m. Mean swash zone widths varied from 5.8 m to 36.3 m and were negatively correlated with beach slope at the water table outcrop and the low swash level, and with Dean's parameter ($p<0.05$). Intertidal slopes at the water table outcrop ranged from 1.1 to 7.1 degrees in the 1996 surveys. The slopes at the low swash level ranged from 0.8 to 7.0 degrees and were positively correlated with the slope at the water table outcrop. The slope of the beach at the high tide strand line was quite variable both within and between study sites and mean values ranged from -3.0 to 20.7 degrees. Mean sediment diameters varied among sites and intertidal levels, mean values ranged from 0.24 to 0.50 mm for the high tide strand, 0.20 to 0.71 mm for the water table outcrop and 0.26 to 0.87 for the low swash zone. Sediment sorting varied more than sediment diameter among sites and intertidal levels. At the water table outcrop, sediment sorting ranged from well sorted, 0.40, to poorly sorted, 0.74. At the high tide strand, sorting varied over a similar range, between 0.38 and 0.79. Sorting was poorest at the low swash level, ranging from 0.49 to 1.31.

The majority of the macrophyte wrack cover on the study beaches consisted of giant kelp, *Macrocystis pyrifera*. and surfgrass, *Phyllospadix*. The mean intertidal cover of marine wrack on ungroomed beaches varied over 2 orders of magnitude among beaches ranging from 0.03 m^2 to 5.03 m^2 per running meter of beach. On groomed beaches, the total cover of marine wrack was generally lower and varied from 0.08 m^2 to 0.39 m^2 per running meter of beach.

More than 60 species of free-living macrofauna occurred in our surveys. Species richness of macrofauna ranged from 12-37 species among sites. More than 24 species of macrofauna occurred in samples at 7 of the 15 sites.

Mean abundance of macrofauna varied more than 25-fold among the study beaches, ranging from 3,360 to 88,500 individuals m^{-1}. The most abundant and widespread species was the common sand crab, *Emerita analoga*, which varied over two orders of magnitude, ranging from 1,278 to 79,000 individuals m^{-1} among beaches. Sand crabs, *E. analoga* composed the majority of animals on many of the beaches sampled, ranging from 7 to 94% of the total macrofaunal abundance.

Mean biomass (wet) of the macrofauna was more variable than abundance and varied over more than an order of magnitude, ranging from 660 to 22,000 gm^{-1} among the study beaches. Sand crabs, *Emerita analoga* were the dominant component of the biomass at all but two beaches and accounted for 31 to 99% (580 to 19,200 gm^{-1}) of the biomass. The mean individual sizes of macrofauna varied over an order of magnitude among beaches, ranging from 0.10 to 1.11g.

The most commonly observed species of shorebirds were sanderlings (*Calidris alba*), willets (*Catoptrophorus semipalmatus*), marbled godwits (*Limosa fedoa*), black-bellied plovers (*Pluvialis squatarola*) and whimbrels (*Numenius phaeopus*). Western snowy plovers (*Charadrius alexandrinus nivosus*) were abundant at selected beaches and occurred at 7 of the 15 beaches during the study period. The average number of shorebirds per km of shoreline varied over an order of magnitude among beaches, ranging from 9 to 177 individuals km^{-1}. In the March 1997 surveys, the majority of shorebirds (average = 87%) occurred on saturated sand (below the water table outcrop) and in the swash zone.

Beach morphodynamics as estimated by Dean's parameter did not provide good predictions of macrofauna community attributes or shorebird abundance. Macrofauna species richness was negatively correlated with mean sediment sorting at the water table outcrop ($p < 0.005$). The abundance and biomass of macrofauna other than *Emerita analoga* were negatively correlated with sediment sorting at the water table outcrop ($p < 0.001$).
Species richness of the macrofauna was positively correlated with the amount of marine macrophyte wrack ($p < 0.05$). The abundance of beachhoppers, *Megalorchestia* spp., varied over four orders of magnitude, from 85 to 10,200 individuals m^{-1} and was positively correlated with the cover of marine wrack ($p < 0.001$).

The abundance of wintering shorebirds was significantly correlated with some beach and prey characteristics measured at the study beaches, including wrack cover and prey biomass. The average abundance of wintering shorebirds was positively correlated with mean macrofaunal biomass ($p < 0.001$) in this study. The average abundance of a widely distributed shorebird, black-bellied plover, was positively correlated with the cover of macrophyte wrack ($p< 0.001$). The abundance of the western snowy plover, a threatened shorebird species, was also positively correlated ($p < 0.05$) with wrack cover .

STUDY PRODUCTS:

Presentations:

Dugan, J.E. 1997. Community and population responses of macrofauna to sandy beach morphodynamics and other environmental parameters. Invited seminar, California State University Cal Poly.

Dugan, J.E., D.M. Hubbard, J.M. Engle, D.L. Martin, K.D. Lafferty, R.F. Ambrose, D.M. Richards, and G.E. Davis. 1999. Macrofauna communities of exposed sandy beaches on the Southern California mainland and the Channel Islands. Fifth California Islands Symposium, Santa Barbara Museum of Natural History. Santa Barbara, CA

Dugan, J.E. 1999. Studies of sandy beach macrofauna in southern California. Invited seminar, Universidad Austral de Chile, Valdivia, Chile

Dugan, J.E. 2000. Effects of grooming on the ecology of exposed sandy beaches. Presented at the California Shore and Beach Preservation Society/ CalCoast conference, Monterey, CA.

Dugan, J.E. 2000. Macro-scale patterns in sandy beach communities in California and Chile. Presented at Marine Macroecology and Conservation Workshop**,** Vina del Mar, Chile

Dugan, J.E. 2001. Ecological impacts of grooming on exposed sandy beaches in southern California. Invited symposium presentation, Western Society of Naturalists, Ventura, CA

Dugan, J.E. 2002. Riddles in the sand: Ecological patterns and processes on exposed sandy beaches. Invited Seminar, Sonoma State University.

Dugan, J.E. 2002. Ecological impacts of grooming on exposed sandy beaches in southern California. Paper presentation, California and the World Ocean ’02, Santa Barbara, CA

Dugan, J.E. 2002. Ecological effects of grooming on exposed sandy beaches in southern California. Invited Seminar, California State University Northridge.

Dugan, J.E. 2002. Effects of beach grooming on sandy beaches in California. Presented to San Diego City Council, Natural Resources and Culture Committee, San Diego, CA

Dugan, J.E. 2003. Ecology of sandy beaches. Invited presentation and field trip for the NOAA Damage Assessment Center Rapid Assessment Program meetings, September 2003, Monterey, CA.

Dugan, J.E., D.M. Hubbard, and H.M. Page. 2003. Response of sandy beach ecosystems to macrophyte wrack subsidies from coastal reefs. Poster for 2003 LTER All Scientists Meeting, Seattle WA.

Publications:

Dugan, J.E., D.M. Hubbard, J.M. Engle, D.L. Martin, K.D. Lafferty, R.F. Ambrose, D.M. Richards, and G.E. Davis. 2000. Macrofauna communities of exposed sandy beaches on the Channel Islands and southern California mainland. Proceedings of the 5th California Islands Symposium. OCS Study, MMS 99-0038: 339-346.

Dugan, J.E., D.M. Hubbard, and M. Lastra. 2000. Burrowing abilities and swash behavior of three crabs, *Emerita analoga* Stimpson, *Blepharipoda occidentalis* Randall and *Lepidopa californica* Efford (Anomura, Hippoidea), of exposed sandy beaches. J. Exp. Mar. Biol. Ecol. 255(2): 229-245.

Dugan, J.E., D.M. Hubbard, M. McCrary, and M. Pierson. 2003. The response of macrofauna communities and shorebirds to macrophyte wrack subsidies on exposed sandy beaches of southern California. Estuar. Coastl. Shelf Sci. 58S: 133-148.

Dugan, J.E., D.M. Hubbard, and H.M. Page. 2005. Ecological effects of grooming on exposed sandy beaches in southern California. Pp. 824-826 In: California and The World Ocean '02: Revisiting and Revising California's Ocean Agenda: proceedings of the conference. O. T. Magoon, H. Converse, B. Baird, B. Jines and M. Miller-Henson (eds.). American Society of Civil Engineers. 1431 pp.

FINAL STUDY REPORT

INTRODUCTION

Sandy beaches comprise approximately three-quarters of the world's shorelines (Bascom 1980). In southern California, 74, 93, and 66% of the coasts of Santa Barbara, Ventura and Los Angeles Counties, respectively, are sandy beaches (Smith et al. 1976; Dugan et al. 1998a).
This high prevalence means that sandy beaches are likely to receive the majority of contamination from a spill or other impact associated with coastal and offshore oil and gas activities

Exposed sandy beaches in California are inhabited by an abundant invertebrate macrofauna community (Straughan 1982, 1983; Dugan et al. 1995, 1999), which is an important food resource for vertebrate predators such as shorebirds, seabirds, marine mammals and fishes. Sandy beaches of the region are also nesting sites for two federally listed birds: the threatened western snowy plover (*Charadrius alexandrinus nivosus*) and the endangered least tern (*Sterna antillarum brownii*). A unique fish, the California grunion (*Leuresthes tenuis*), deposits eggs for incubation in the high intertidal zone of sandy beaches.

Sandy beaches are also considered extremely valuable as recreational and scenic resources for humans, both residents and tourists (Leatherman 1997). Although human use varies considerably among beaches, the majority of the shores of the Southern California Bight are heavily used, disturbed, developed and managed. Many beaches in the region are also subject to regular grooming, where trash, debris and drift macrophytes are removed with heavy equipment.

Exposed sandy beaches are dynamic habitats and have been difficult to classify using single physical parameters such as slope and sediment size. The use of Dean's parameter, a dimensionless index of sediment fall velocity and wave height and period that expresses the dynamic interaction between the wave regime and available sediments (Short and Wright 1983; Short 1996), has provided a more functional classification of beaches. Using this morphodynamic classification, three major categories of exposed sandy beaches can be identified: reflective, intermediate and dissipative. Reflective beaches (Dean's parameter < 1) are characterized by small waves (<0.5 m), narrow surf zones, coarse sediments and steep slopes and are a harsh environment for intertidal fauna. Dissipative beaches (Dean's parameter >6) are characterized by large waves (>2 m), wide surf zones, fine sand and flat slopes, and are the most physically benign sandy beach habitat for fauna. Intermediate beaches (Dean's parameter 1 - 6) exhibit characteristics that fall between those extremes (Short and Wright 1983) and are the most variable type. Information on the morphodynamics of sandy beaches on the California coast is limited compared to other parts of the worl, such as. Australia (Short 1996, Dugan et al. 1998b).

The use of Dean's parameter and other morphodynamic indices to ordinate exposed sandy beaches for comparisons of macrofauna community structure has allowed predictions of community attributes to be made with respect to beach characteristics (e.g., McLachlan 1990, McLachlan et al. 1993). Several general trends have been identified for macrofauna communities of exposed sandy beaches: 1) species richness increases, 2) total abundance increases, 3) total biomass increases and mean individual body size decreases across the spectrum from reflective to dissipative beach types and with increasing values of Dean's parameter (McLachlan 1990, McLachlan et al. 1993). Macrofauna community abundance and biomass could also be affected by surf zone productivity and wrack input. Dean's parameter may be also useful in predicting population characteristics of macrofauna species (Jaramillo and McLachlan 1993, Dugan and Hubbard 1996, Dugan and Hubbard in prep.).

Many shorebirds utilize sandy beaches for feeding, roosting and breeding in Ventura and Santa Barbara counties. Shorebirds occurring on sandy beaches consist of migrant, wintering, and breeding or resident species. The distribution, abundance and utilization patterns of shorebird species on a beach may be related to a variety of factors, including prey availability, beach morphodynamic type, width and condition, macrophyte wrack cover, time of year, and human activity.

Shorebirds have high metabolic rates and relatively high daily energy expenditures (Kersten and Piersma 1987), hence rich and productive food resources are critical to the survival of breeding and nonbreeding shorebirds. The abundant macrofaunal invertebrate community (Straughan 1982, 1983, Dugan et al. 2000) inhabiting exposed sandy beaches of Southern California may represent an important prey resource for shorebirds, including federally listed species such as the western snowy plover. Shorebirds feed on a variety of sandy beach invertebrate species, including polychaete worms, insects, amphipods, isopods, hippid crabs, and bivalve mollusks. Some shorebird species forage opportunistically on exposed sandy beaches, but several species of shorebirds, including sanderlings, feed primarily on sandy beaches during the nonbreeding season.

The abundance, biomass and mean individual size of macrofauna prey species (Dugan and Hubbard 1996, Dugan et al. 1995, 2000) and the distribution and abundance of their shorebird predators (Shuford et al. 1989, Webster et al. 1980) can vary on a variety of spatial and temporal scales in California (McCrary and Pierson 2002). The distribution and abundance of shorebird species on sandy beaches may be related to the distribution and abundance of their macrofauna prey as well as other factors.

Macrophyte wrack is an important source of carbon for the semi-terrestrial upper intertidal macrofauna, including several species of talitrid amphipods, two species of isopods, two species of kelp flies and numerous beetle species, all of which are preyed upon by shorebirds. The distribution and abundance of shorebirds that feed on the upper beach could thus be related to the abundance of wrack.

Relationships between sandy beach macrofauna and beach morphodynamics similar to those reported elsewhere in the world may well occur on California beaches. However, relationships between species occupying higher trophic levels that prey upon the macrofauna, such as shorebirds, and the physical characteristics of beaches, such as beach morphodynamics, but have not been studied. If such relationships exist, they could provide a valuable tool for understanding and predicting shorebird use patterns on sandy coasts.

Despite the high prevalence of exposed sandy beaches along the coast of southern California, macrofauna communities and shorebirds of this important coastal habitat have received relatively little attention from marine ecologists. As such, little information exists on the potential risk from oil related impacts to shorebirds and to resources which they depend upon on exposed sandy beaches of southern California. To address this gap in information needed for oil spill contingency planning and damage assessment, the distribution and abundance of shorebirds on Ventura County beaches was studied by Minerals Management Service personnel (McCrary and Pierson 2002). The present study was undertaken to complement that project by examining factors which could affect the distribution and abundance of shorebirds on beaches, including prey availability and beach morphodynamics. The combined goal of the Minerals Management Service study and the present study was to address a major gap in our understanding of the vulnerability of sandy beach resources to oil-related impacts.

In this study, we examined relationships between shorebirds and their invertebrate macrofauna prey, macrophyte wrack, and physical attributes of sandy beaches, as outlined in Figure 1, using the results of field surveys of sandy beaches in Ventura and Santa Barbara counties in combination with the results of the concurrent MMS study of shorebird distribution (McCrary and Pierson 2002). Specifically we investigated relationships between: 1) the abundance and species richness of shorebirds on sandy beaches and the abundance, biomass and mean individual size of macrofauna prey species; 2) the abundance, biomass and mean individual size of macrofauna prey species on sandy beaches and physical factors, such as beach morphodynamics; and 3) the distribution and abundance of shorebirds and physical factors, such as beach morphodynamics, beach size, landward boundary and other factors, including the cover of macrophyte wrack..

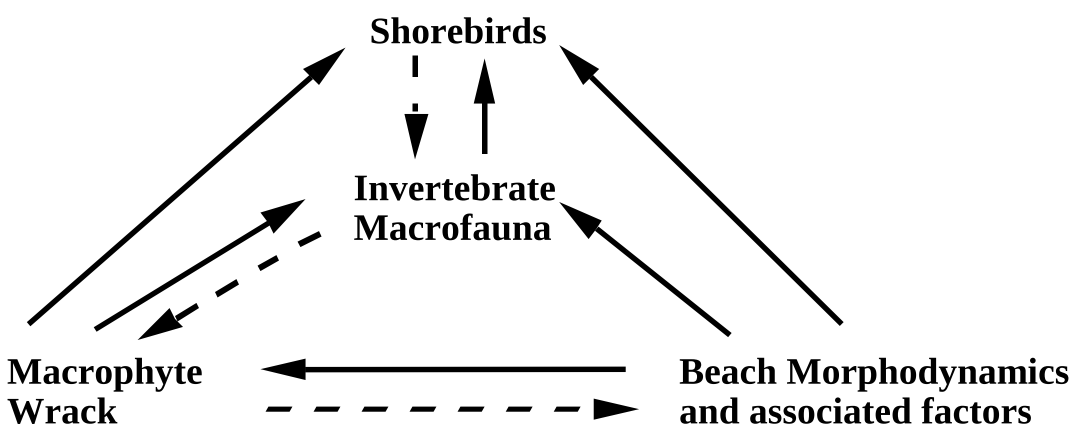

Figure 1. Possible relationships between shorebirds, macrofauna prey, macrophyte wrack, and beach morphodynamics. Solid arrows indicate relatipnships we are currently investigating, dashed arrows indicate other potential relationships.

MATERIALS AND METHODS

To determine the species richness, abundance, biomass and population size structure of the macrofauna community and selected species, we conducted quantitative sampling at 12 of the Ventura County study beaches surveyed in the MMS shorebird study (McCrary and Pierson 2002) and at 3 additional Santa Barbara County beaches chosen to expand the range of morphodynamic beach types represented in the study. Table 1 contains a list of the study beaches and sampling/survey dates. Two of the MMS shorebird study beaches (Hobson Park and Mugu Rock) which either are washed completely at high tide or contain significant amounts of rocky habitat, were not sampled in the present study and are not included in this report. The physical characteristics and macrofauna communities of 15 beaches were sampled in September and October of 1996 (Table 1, Figure 2).

Table 1. Survey dates and locations of study beaches from north to south.
* MMS study sites not sampled, ** additional sites surveyed in this study

Beach Location	Macrofauna Sampling Date	Winter Survey Date	Shorebird surveys
SANTA BARBARA COUNTY			
Sands Beach**	10/13/96	3/16/97	monthly
East Campus**	9/27/96	3/16/97	monthly
Santa Claus Lane**	9/15/96	3/17/97	monthly
VENTURA COUNTY			
La Conchita	9/16/96	3/17/97	monthly
Rincon	9/13/96	3/6/97	monthly
Hobson Park*	not sampled	not sampled	monthly
Solimar	9/12/96	3/6/97	monthly
Marina Park	9/26/96	3/11/97	monthly
Surfer's Knoll	10/12/96	3/7/97	monthly
5th Street	10/10/96	3/7/97	monthly
Silver Strand	10/11/96	3/11/97	monthly
Ormond Beach 3	9/28/96	3/19/97	monthly
Ormond Beach 2	9/25/96	3/19/97	monthly
Ormond Beach 1	9/25/96	3/19/97	monthly
Point Mugu*	not sampled	not sampled	monthly
Deer Creek	9/29/96	3/10/97	monthly
Leo Carrillo	9/24/96	3/10/97	monthly

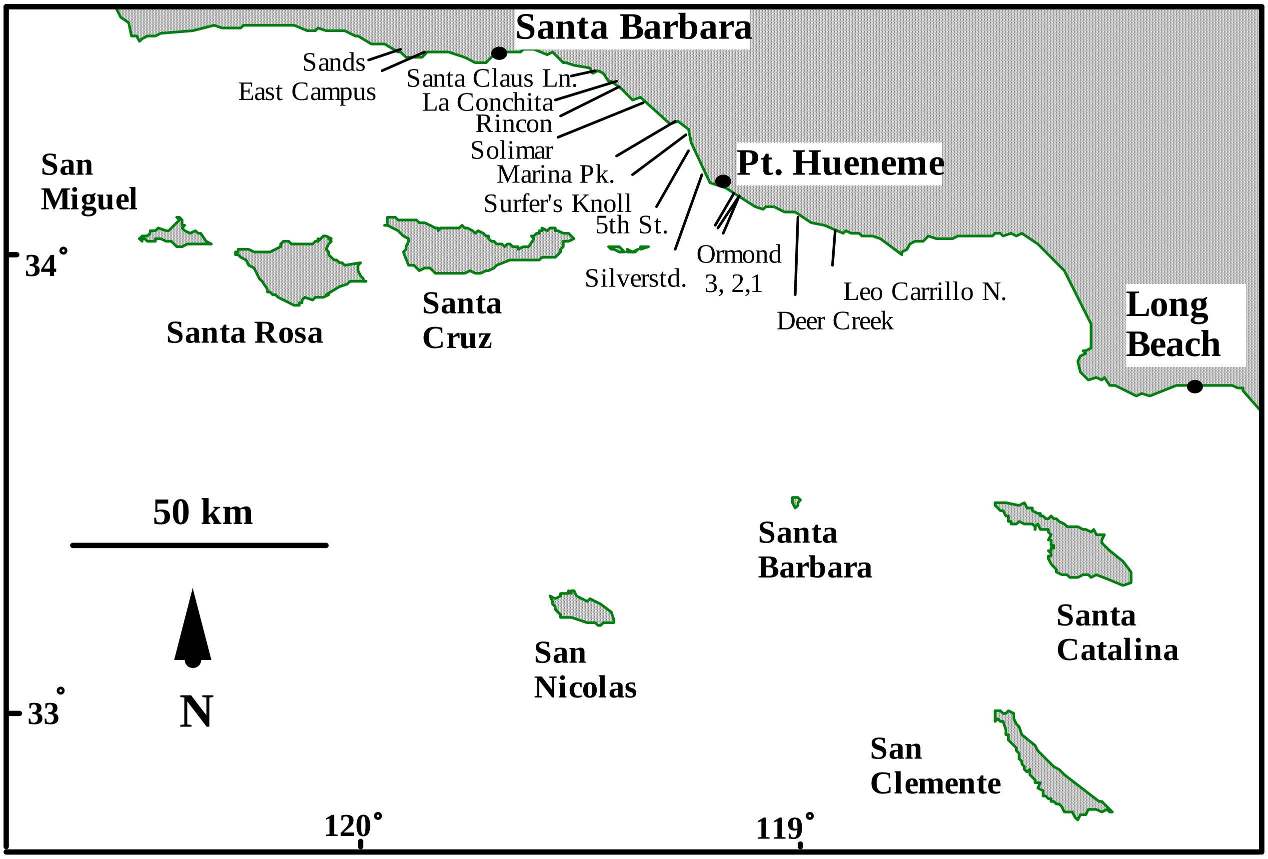

Figure 2. Locations of the study beaches.

Macrofaunal community samples were collected in daylight on spring low tides on fifteen days between September 12 and October 13, 1996. On each beach, three transects were established extending from the landward boundary of the beach to below the lowest swash level. When possible, we sampled an area of the beach with a natural landward boundary and a measurable supralittoral zone. The distances between transects were randomly selected, but a minimum distance of at least 10 m between transects was used to avoid disturbance of mobile macrofauna , such as *Emerita analoga*, in adjacent transects.Each transect was sampled with 150 uniformly spaced cores of 10-cm diameter and 20-cm depth. At each of 15 tidal levels, 10 consecutive cores were grouped and rinsed through a 1-mm sieve, retaining the macrofauna. All macrofauna were preserved for later analysis in buffered formalin in seawater. This sampling design yielded a total sampling area of 3.5 m^2 and a total of 45 biological samples at each beach.

To estimate the standing crop of macrophyte wrack, the cover and composition of wrack were measured using a line intercept method along each of the three transects sampled for macrofauna (see above). All wrack, debris, driftwood, carrion, or tar of 0.01 m or more in width that intersected the transect line was measured, categorized, recorded. The total width of wrack encountered was then totaled for each transect. Means of wrack cover were calculated for the three transects at each site and expressed as square meters of wrack m^{-1} of beach. The percent cover of wrack was calculated by dividing the total wrack intersected (m) by the intertidal width (m) of each transect. Means of percent cover were also calculated for the three transects at each beach.

To estimate beach morphodynamic state, physical parameters, including wave height and period, sediment grain size and beach slope at three beach levels (driftline or high tide strand, water table outcrop, and low swash limit), swash width and period, and beach width, were measured on the three transects at all study beaches.

From November 1996 through November 1997, surveys of shorebirds, macrophyte wrack and physical characteristics were conducted monthly during spring low tides on the three Santa Barbara County study beaches using the MMS techniques for shorebirds (see McCrary and Pierson 2002) and the protocols above for beaches. In both studies, shorebirds were counted monthly along standard one kilometer transects on each of the 15 beaches from November 1996 to May 1997. The 15 one kilometer transects were surveyed for shorebirds on low tides (0 to 0.75 m MLLW) during a three to four day period in the same tide sequence each month. All birds were counted and identified to species using binoculars by a single observer on each transect. Mean shorebird abundance was calculated for each beach. The dates of the Santa Barbara County surveys were selected to coincide with the monthly surveys of shorebirds on the Ventura County study beaches by MMS biologists. Monthly shorebird surveys of the 14 Ventura County study beaches by MMS biologists were completed in May 1997, yielding three years of data on shorebirds and 20 months of data on sediments and wave climate. For comparisons, data from months in which both the Ventura and Santa Barbara County study beaches were surveyed for shorebirds were used in the analyses.

In March 1997, the 15 study beaches were resurveyed using the protocols above to measure physical characteristics and macrophyte cover (Table 1). In addition, a census of shorebirds and detailed observations of shorebird zonation were made at each study beach.

All sediment samples from the macrofaunal, winter, and monthly surveys were rinsed in distilled water, dried and shaken through standard sieves by an MMS/CMI student intern. The fraction in each sieve was weighed to determine grain size distribution. Mean particle size and the inclusive graphic standard deviation (IGSD), an estimate of sediment sorting was calculated for each sample (Folk 1968). Sediment diversity was calculated using the Shannon Weiner diversity index (Zar 1984) as in Etter and Grassle (1992). Sand fall velocity was calculated using the conversion for mean particle size given by Gibbs et al. (1971) for each sample. Dean's parameter was calculated from the breaker height divided by the wave period and sand fall velocity (Short and Wright 1983) for each site.

Wave height and wave period data were compiled by student interns from data collected by MMS biologists from that period. Dean's parameter values for each month and study site were calculated from the wave and sediment data then used to estimate the modal morphodynamic state of the study beaches.

To examine hypotheses concerning shorebirds, their macrofauna prey, and the physical characteristics of sandy beaches, data from the macrofauna community and beach surveys and from the shorebird surveys were analyzed using linear regression analyses..

RESULTS

General Characteristics

We observed considerable spatial and temporal variation in physical characteristics of the study beaches. Most of the beaches sampled are subject to prevailing west winds and large winter swells from the west or northwest. Beaches in the central and southern portion of Ventura County are regularly exposed to southern swells in the summer months.

The degree of human alteration and disturbance differed among the 15 study beaches. Several of the beaches (Santa Claus, Solimar, La Conchita, Marina Park, and Deer Creek) had artificially narrow upper beach zones due to the presence of riprap or seawalls in front of former foredunes or bluffs, while several other beaches (Surfer's Knoll, 5th Street and Silverstrand) had abnormally wide, flat upper beach zones that were groomed regularly and may have been enhanced with imported sand. In addition, piers and groins altered the wave regime at several of the study beaches (Rincon, Marina Park, Surfer's Knoll and Silverstrand). Large scale sand-bypassing activities has influenced beach conditions at Ormond 1, 2, and 3 for decades. The most physically unaltered and natural beach types were Sands, East Campus, and Leo Carrillo. Human use of the study beaches, including numbers of dogs, varied spatially and temporally.

Morphodynamics and other physical factors

The majority of the beaches we surveyed were modally intermediate morphodynamic types with values of Dean's parameter between 0.6 (reflective) and 5.5 (high intermediate to dissipative) measured during the surveys in September/October 1996 (Figure 3) and in other periods. The values of Dean’s parameter for the majority of the study beaches during that period were between 1.5 and 4.4 (intermediate). Those surveys followed a period of strong southern swells.

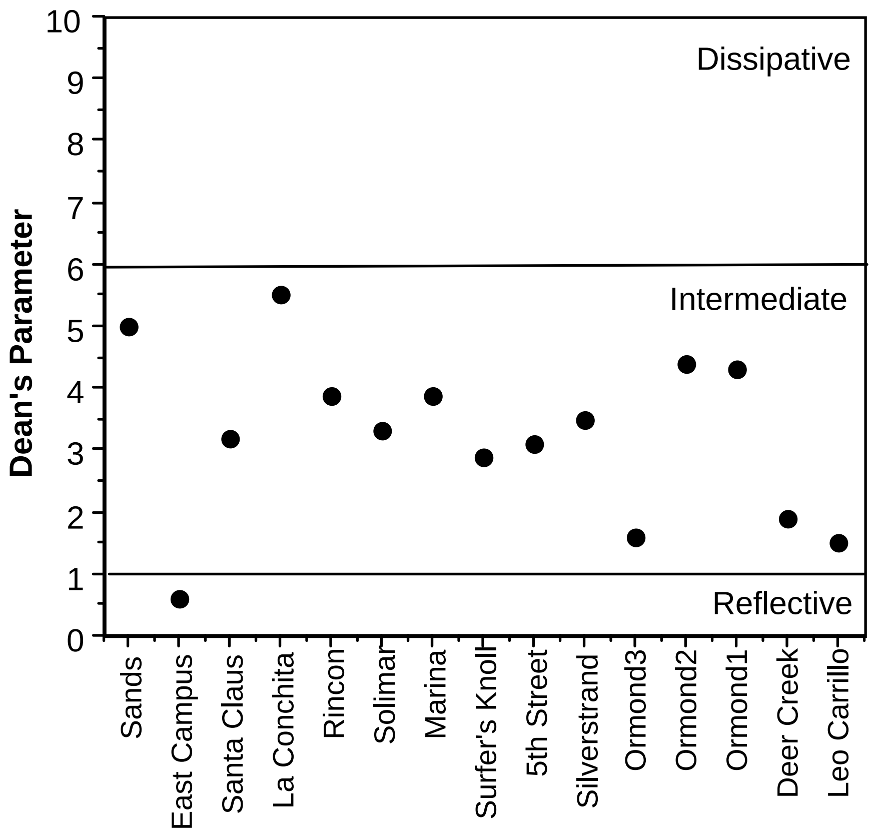

Figure 3. Morphodynamic state of the study beaches estimated by Dean's parameter in September/October 1996 surveys.

In the winter (March 1997) surveys, values for Dean's parameter were lower for most of the study beaches, ranging from 0.1 to 4.7, and four of the beaches had values of <1, indicating reflective conditions. These surveys coincided with a period of unseasonably low swell activity, which could have resulted in the reflective conditions observed at some beaches.

Average values of Dean's parameter for the study beaches obtained from monthly surveys during the study period ranged from 0.7 to 3.6 and were similar to those obtained in the September/October 1996 surveys, indicating primarily intermediate beach types. Although values of Dean's parameter > 6 were obtained during some of the monthly surveys, no modally dissipative beaches were studied and none occur in the study region. Only one modally reflective beach was studied (East Campus, Santa Barbara County, values of Dean's parameter ranging from 0.2 to 1.2, average = 0.7).

In the September-October surveys, mean overall beach widths varied from 52 to over 200 m, while intertidal widths varied from 29 to 77 m among the 15 study beaches (Figure 4). Mean swash zone widths varied from 5.8 to 36.3 m and were negatively correlated with beach slope at the water table outcrop and the low swash level, as well as with Dean's parameter ($p < 0.05$).

During the winter (March 1997) surveys, mean intertidal widths (Figure 4), swash widths and slopes were comparable to the late summer values for the majority of the beaches.

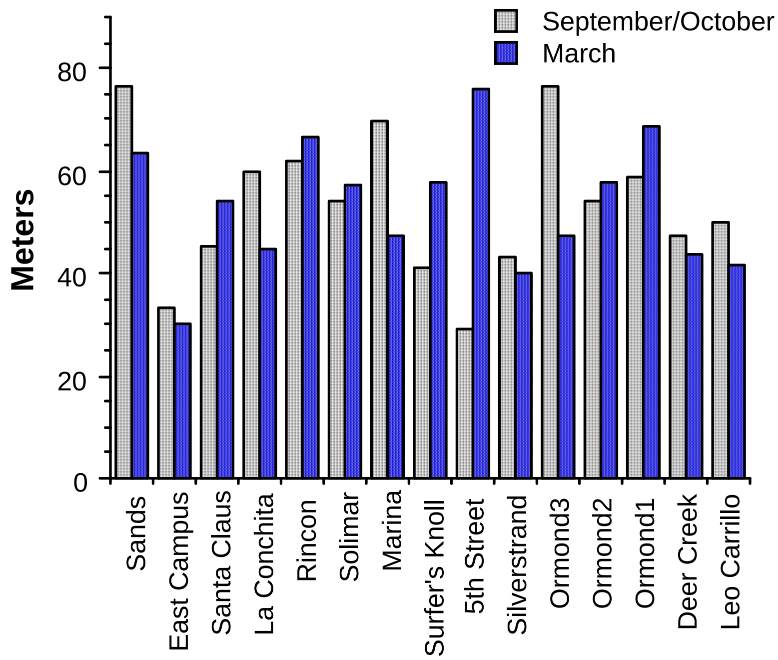

Figure 4. Mean intertidal widths of the study beaches in the September/October 1996 and the March 1997 surveys.

Intertidal slopes at the water table outcrop ranged from 1.1 to 7.1 degrees in the September/October 1996 surveys. The slopes at the low swash level ranged from 0.8 to 7.0 degrees and were positively correlated with the slope at the water table outcrop ($p < 0.05$). The slope of the beach at the high tide strand line was quite variable both within and among study beaches, with mean values ranging from -3.0 to 20.7 degrees. Mean intertidal widths were significantly negatively correlated with the slope at the water table outcrop ($p < 0.05$).

Sediment diameter varied among beaches and intertidal levels: mean values ranged from 0.24 to 0.50 mm for the high tide strand, 0.20 to 0.71 mm for the water table outcrop, and 0.26 to 0.87 mm for the low swash zone (Figure 5). In general, the coarsest sediments occurred at the low swash level at most beaches. The mean sediment diameter at the water table outcrop was relatively consistent among the study beaches, with mean values between 0.20 and 0.30 mm. None of the study beaches had sediments with grain sizes < 0.20 mm, and only two of the beaches, Silverstrand and Leo Carrillo, had mean values for sediment size > 0.30 mm at the water table outcrop level.

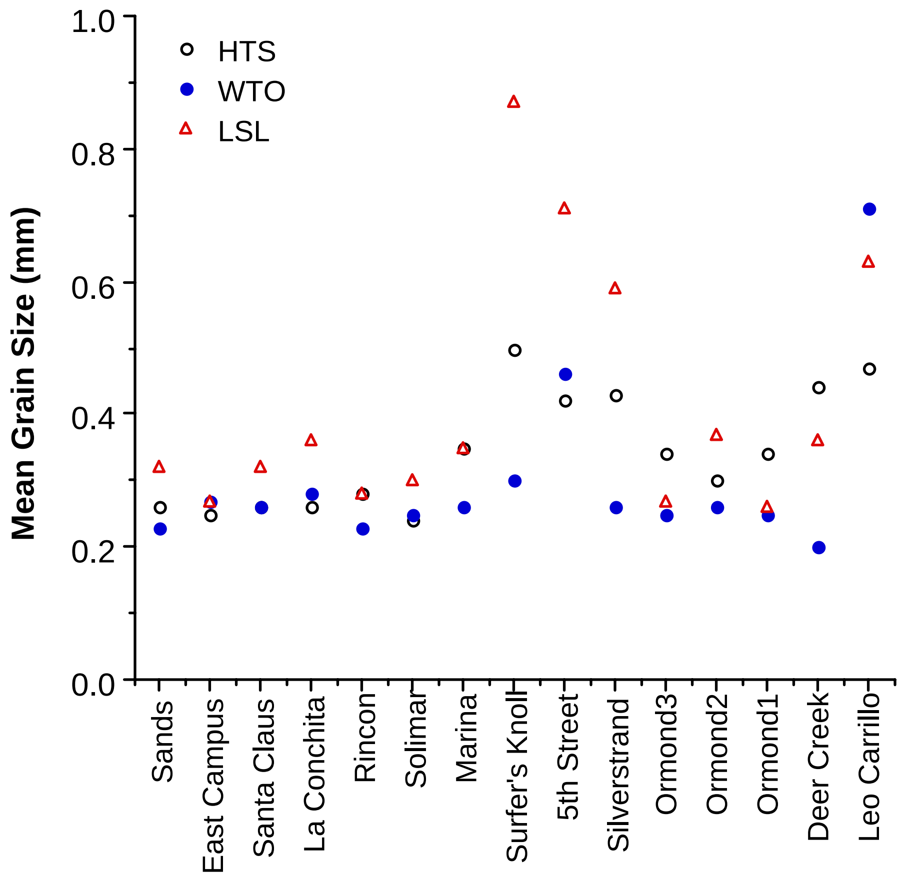

Figure 5. Mean grain sizes of sediments at three intertidal levels (HTS- high tide strand, WTO- water table outcrop and LSL- low swash level) at the study sites during surveys in September/October 1996.

Sediment sorting varied more than sediment diameter among beaches and intertidal levels. At the water table outcrop, sediment sorting ranged from well sorted, 0.40, to poorly sorted, 0.74. At the high tide strand, sorting varied over a similar range, between 0.38 and 0.79. Sorting was poorest at the low swash level, ranging from 0.49 to 1.31. In the March 1997 survey, sediments were distinctly coarser and less well sorted at most of the study beaches.

Macrophyte Wrack

The majority of the macrophyte wrack cover on the study beaches consisted of giant kelp, *Macrocystis pyrifera*. and surfgrass, *Phyllospadix* spp. Three of the beaches sampled were subject to regular grooming to remove accumulated trash and macroalgal wrack (Silverstrand, 5th Street and Surfer's Knoll).

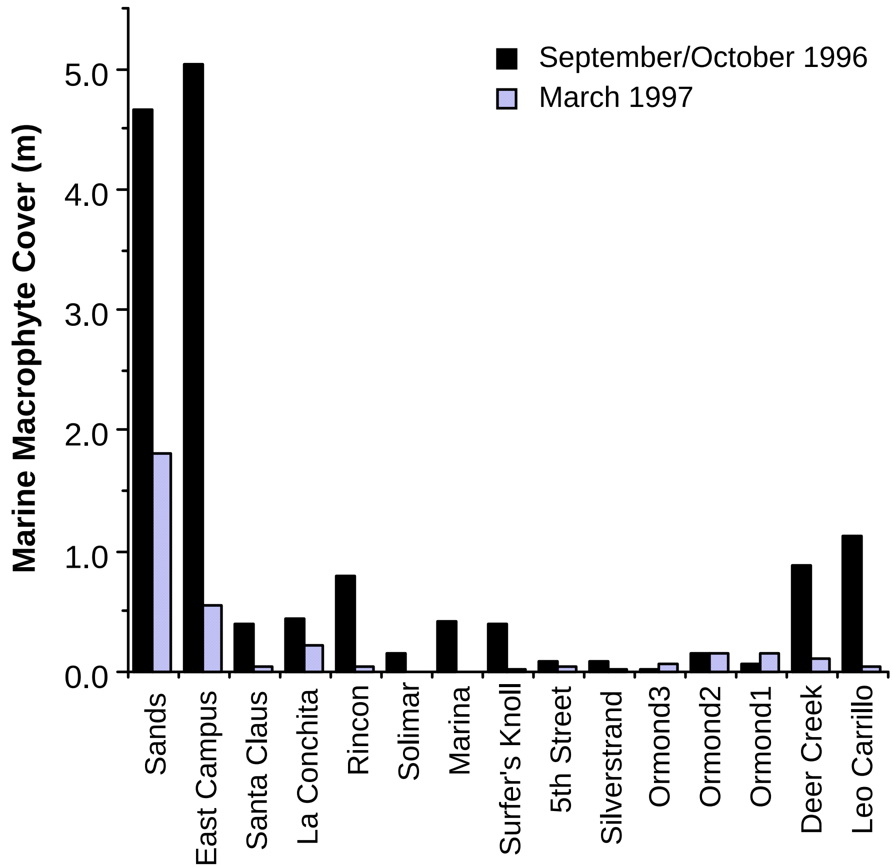

Figure 6. Mean macrophyte wrack cover on the study beaches in September/October 1996 and March 1997 surveys.

The mean intertidal cover of marine wrack on ungroomed beaches varied over two orders of magnitude among beaches ranging from 0.03 to 5.03 m^2 per running meter of beach (Figure 6). On groomed beaches, the total cover of marine wrack varied from 0.08 to 0.39 m^2 per running meter of beach. The lowest cover was found on the three groomed beaches and on the Ormond beaches. Estimates of the mean percent cover of marine macrophyte wrack on the study beaches varied from 0.0 to 9.7%. On the three beaches subject to regular grooming, the mean percent cover of marine wrack was generally <0.2%. Mean cover of macrophyte wrack was lower in March 1997 than in September/October 1996 at most of the study beaches, ranging from 0.0 to 1.81m^2 per running meter of beach (Figure 6).

Regional variation in the cover of wrack were also apparent. Cover of wrack was generally low (<1%) on the Ventura County study beaches. The only two Ventura County beaches with wrack cover greater than 1% were the easternmost beaches, Leo Carrillo and Deer Creek, which are located in areas with adjacent subtidal rocky habitat. Two of the Santa Barbara County beaches had moderately high cover of wrack, 5-10% (Sands and East Campus), while the third had <1% cover (Santa Claus).

Invertebrate Macrofauna

Species Richness

More than 60 species of free-living macrofauna occurred in our surveys of 15 beaches. Species richness of macrofauna ranged from 12 to 37 species among the study beaches, not including incidental and commensal species (Figure 7). More than 24 species of macrofauna occurred in our samples at 7 of the 15 study beaches. The greatest number of species of macrofauna (37) occurred on an intermediate type beach protected by oil piers, Rincon, and the second greatest number of species (35) occurred on a modally reflective beach, East Campus.

Species richness was lowest on the three beaches subject to regular grooming and wrack removal, with ≤15 species in those samples (range 11 to 15 species; Surfer's Knoll, 5th Street, Silverstrand). That depression in species richness was particularly noticeable in the upper intertidal sampling levels. Beaches with naturally low amounts of wrack also had lower species richness (17 to 22 species; e.g., Ormond 1, 2, 3, Leo Carrillo) than those with abundant wrack.

Eggs and newly hatched larvae of the California grunion, *Leuresthes tenuis*, occurred abundantly in upper beach samples from Solimar Beach. High numbers of a small staphylinid beetle, *Bledius fenyesi*, were associated with the grunion eggs at that site.

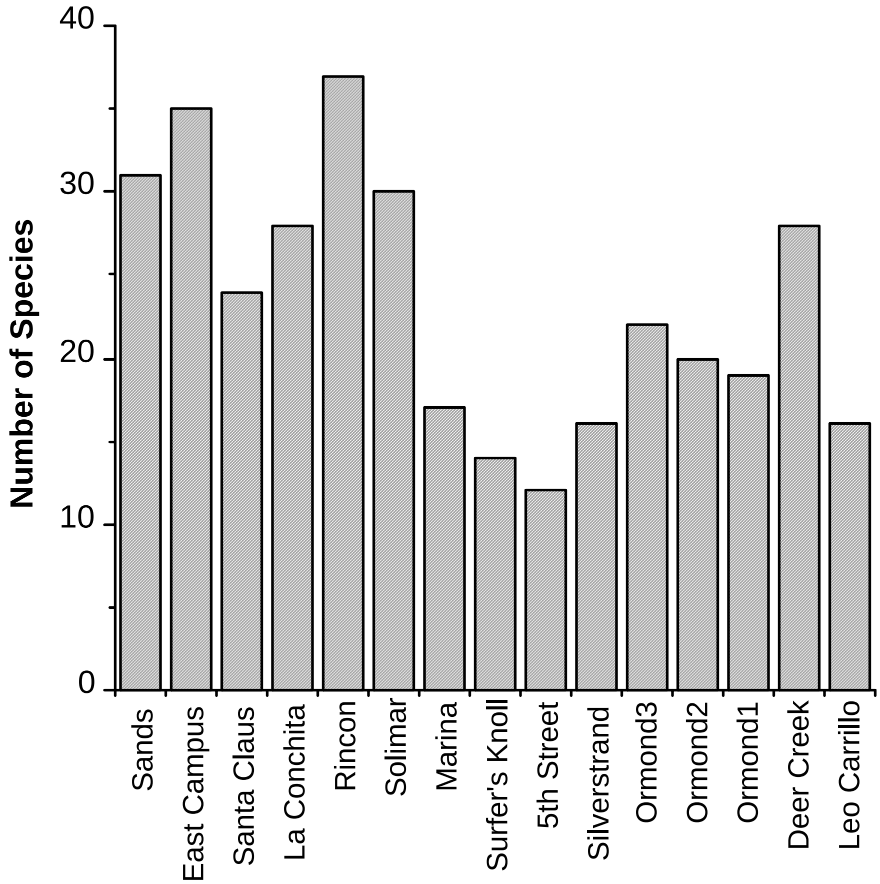

Figure 7. Estimated species richness of the macrofauna on the study beaches from the September/October 1996 surveys.

Abundance

The mean values of total macrofaunal abundance varied more than 25-fold among study beaches, ranging from 3,360 to 88,500 individuals m^{-1} among the 15 beaches sampled (Figure 8). The estimated mean abundance of macrofauna exceeded 12,000 individuals m^{-1} at all but three of the study beaches. Mean abundance of macrofauna was >20,000 individuals m^{-1} at six of the study beaches (Figure 8). Macrofaunal abundance was generally lower on groomed beaches than on ungroomed beaches. This was particularly noticeable in the upper beach sampling levels. The lowest mean value of macrofaunal abundance occurred on a groomed beach (3,360 individuals m^{-1}; 5th Street).

The most abundant and widespread species was the common sand crab, *Emerita analoga*. This species occurred on every beach sampled and was the most abundant species on 11 of the 15 beaches surveyed (Figure 8). Mean abundance of this species was >10,000 individuals m^{-1} in samples from three of the beaches. Abundance of this decapod species ranged over two orders of magnitude, from 1,280 to 79,000 individuals m^{-1} of shoreline, among the study beaches. The presence of high densities of *E. analoga* in the swash zone accounted for the majority of the animals (>50%) on four of the study beaches, with sand crabs making up 7% to 94% of the total macrofaunal abundance across all the study beaches.

Other macrofauna species for which mean values of abundance exceeded 10,000 individuals m^{-1} at one or more beaches included, talitrid amphipods, *Megalorchestia* spp. (up to 10,200 individuals m^{-1}), and the deposit-feeding polychaete, *Euzonus mucronata* (up to 23,000 individuals m^{-1}). Talitrid amphipods, *Megalorchestia* spp., were widespread and occurred at every study beach. These amphipods were the most abundant wrack-associated species present in samples from all but three of the study beaches, with mean values for abundance ranging from 85 to 10,200 individuals m^{-1}. The high beach isopod, *Tylos punctatus*, was found in samples from five of the study beaches and was the most abundant wrack-associated species at two of those beaches with mean abundance values of 890 and 8970 individuals m^{-1}.

Two free-living bivalve species, the Pismo clam, *Tivela stultorum*, and the bean clam, *Donax gouldii*, occurred at 10 and 8 of the study beaches, respectively. These two clam species co-occurred at 9 of the study beaches. When present, values for mean abundance of these clams ranged from 89 to 800 individuals m^{-1} for *T. stultorum* and 83 to 1,940 individuals m^{-1} for *D. gouldii*.

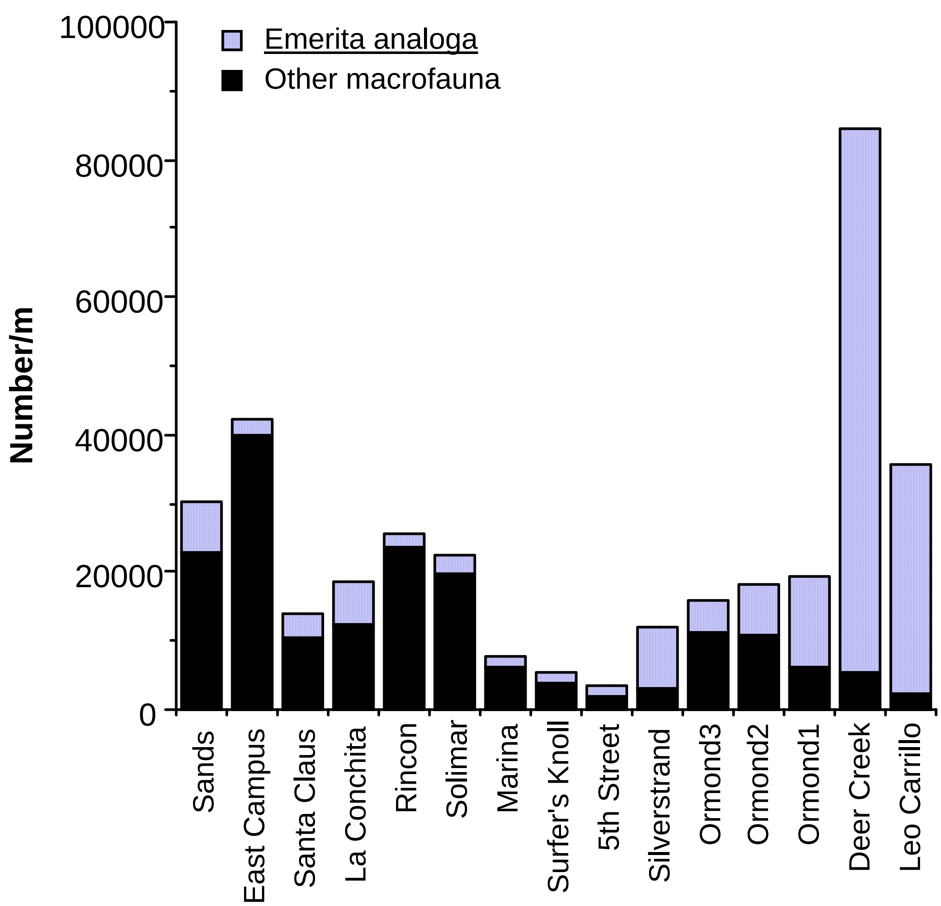

Figure 8. Estimated abundances of *Emerita analoga* and other macrofauna on the study beaches from the September/October 1996 surveys.

Biomass

Mean biomass (wet) of the macrofauna was more variable than abundance and ranged over more than an order of magnitude, from 660 to 22,000 gm^{-1} (Figure 9). All but four of the study beaches had biomass values of >4,000 gm^{-1} and total biomass exceeded 10,000 gm^{-1} at four of the study beaches. The lowest biomass values (<1,000g m^{-1}) occurred in our surveys of two groomed beaches. The sand crab, *E. analoga,* was the dominant component of the biomass at all but two beaches (Figure 9). This species alone accounted for 31 to 99% (580 to 19,200 gm^{-1}) of the biomass at the study beaches. The biomass at one beach (Ormond 2) was dominated by the Pismo clam, *T. stultorum* (6,590 gm^{-1}), and that of second beach (East Campus) by the spiny sand crab, *Blepharipoda occidentalis* (1,821 gm^{-1}).

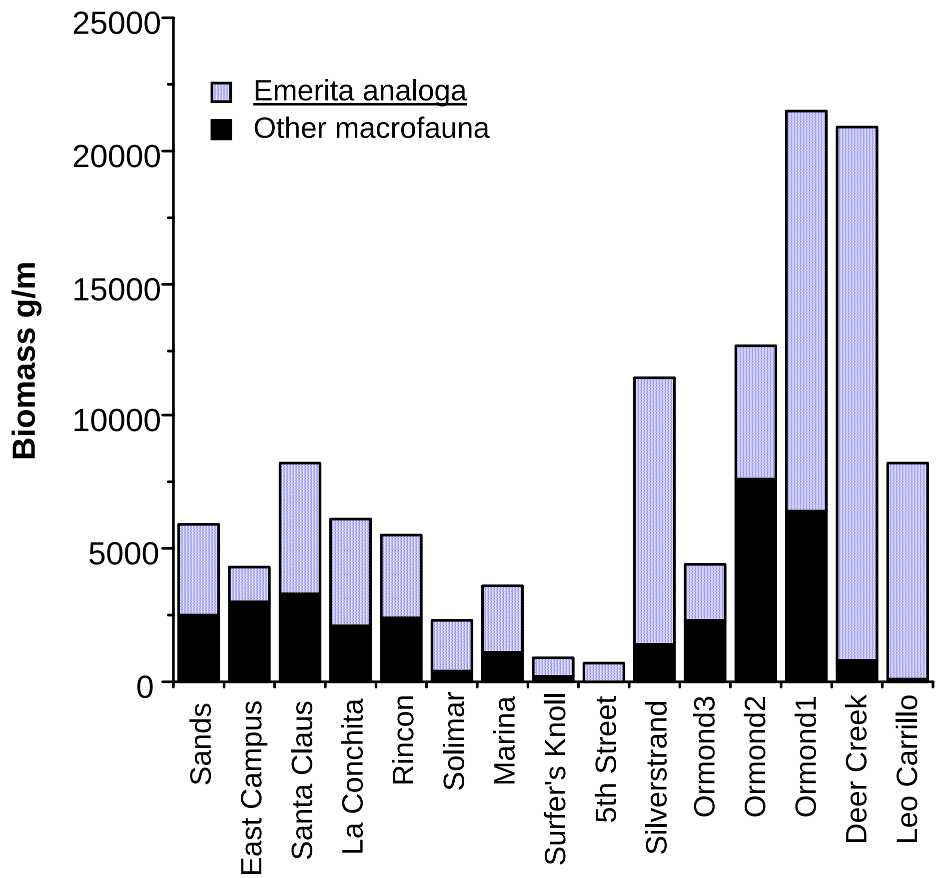

Figure 9. Mean values for wet biomass of *Emerita analoga* and for other macrofauna at the study beaches from the September/October 1996 surveys.

Mean Individual Size

The mean individual sizes of macrofaunal invertebrates varied over an order of magnitude among the study beaches and ranged from 0.10 to 1.11g (Figure 10). The largest animals in our samples were several Pismo clams, *T. stultorum,* weighing over 700 g (live wt.) each, which occurred at a single site (Rincon). However, because the size of those animals exceeded the

0.1m core diameter, their masses were reduced accordingly. The smallest individual species weighed <0.001 g wet weight. The largest crustacean in the samples was the spiny sand crab, *Blepharipoda occidentalis,* which weighed more than 47 g wet weight. Mean individual weights of *Emerita analoga* ranged from 0.25 to 1.99 g among the study beaches.

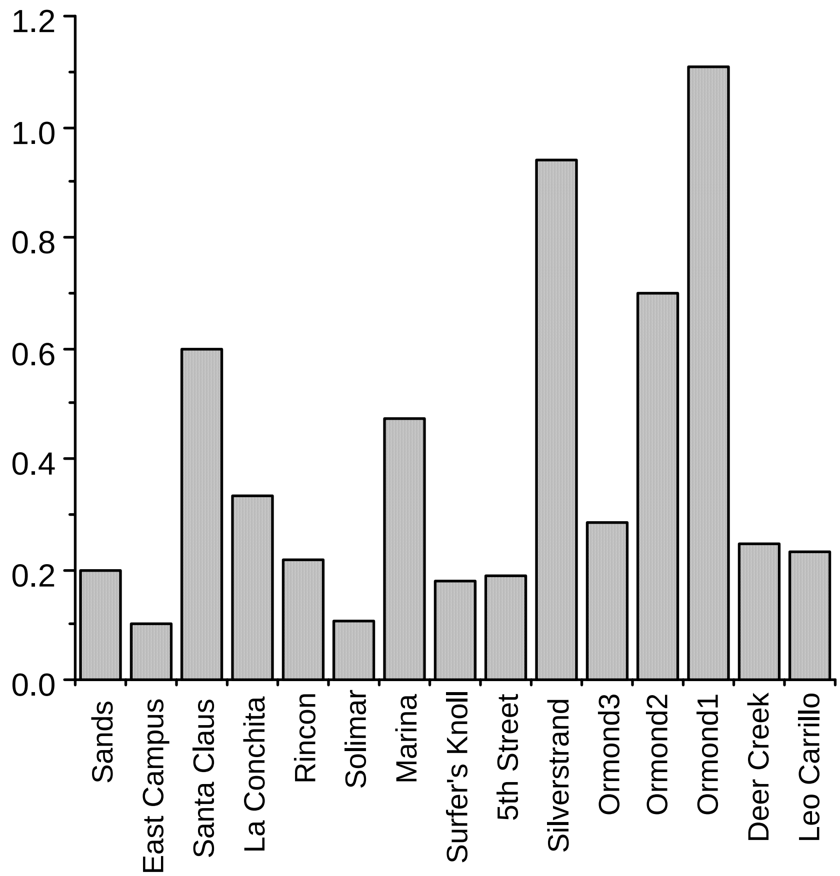

Figure 10. Mean individual size of macrofaunal invertebrates on the study beaches from the September/October 1996 surveys.

Shorebirds

Shorebirds were present on the study beaches during all of our surveys. The most commonly observed species of shorebirds were: sanderlings (*Calidris alba*), willets (*Catoptrophorus semipalmatus*), marbled godwits (*Limosa fedoa*), black-bellied plovers (*Pluvialis squatarola*) and whimbrels (*Numenius phaeopus*). Western snowy plovers (*Charadrius alexandrinus nivosus*)were abundant at selected beaches (e.g. Sands, Ormond 1, 2, 3) but did not occur at 8 of the 15 study beaches during the study period. The average number of shorebirds km $^{-1}$ (per kilometer of shoreline) varied over an order of magnitude among beaches, ranging from 9 to 177 individuals km^{-1} (Figure 11). The highest average numbers of shorebirds occurred on Ormond 1 and the lowest at Solimar. In the winter (March 1997) surveys, the majority of shorebirds (average = 87%) occurred on saturated sand (below the water table outcrop) and in the swash zones of the study beaches.

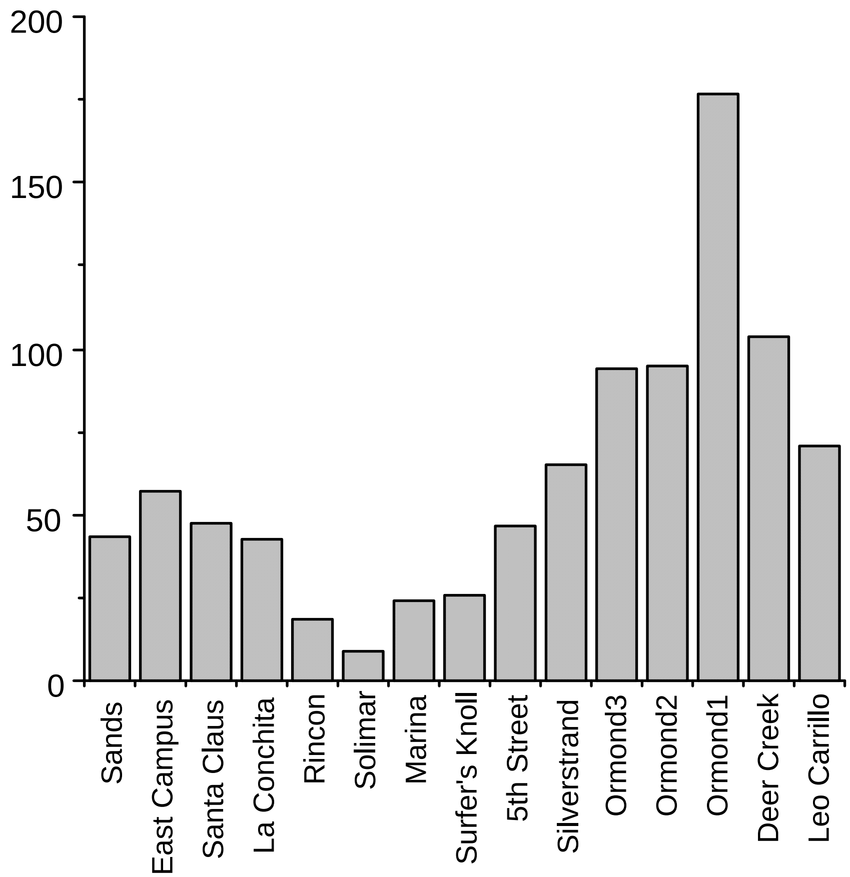

Figure 11. Average number of shorebirds km^{-1} on the study beaches from monthly surveys conducted between November 1996 and May 1997.

Relationships between Shorebirds, Macrofauna, Morphodynamics and Macrophyte Wrack

<u>Associations with Beach Morphodynamics and Physical Factors</u>

Beach morphodynamics as estimated by Dean's parameter did not provide useful predictions of macrofaunal community attributes or shorebird abundance. Sediment sorting was the only physical parameter that was correlated with macrofaunal community attributes. Macrofauna species richness was negatively correlated with sediment sorting at the water table outcrop ($p < 0.005$, Figure 12). The abundance and biomass of the macrofauna other than *E. analoga* were also negatively correlated with sediment sorting at the water table outcrop (abundance- $r = 0.800$, $p < 0.001$; biomass- $r = 0.790$, $p < 0.001$, $n = 15$).

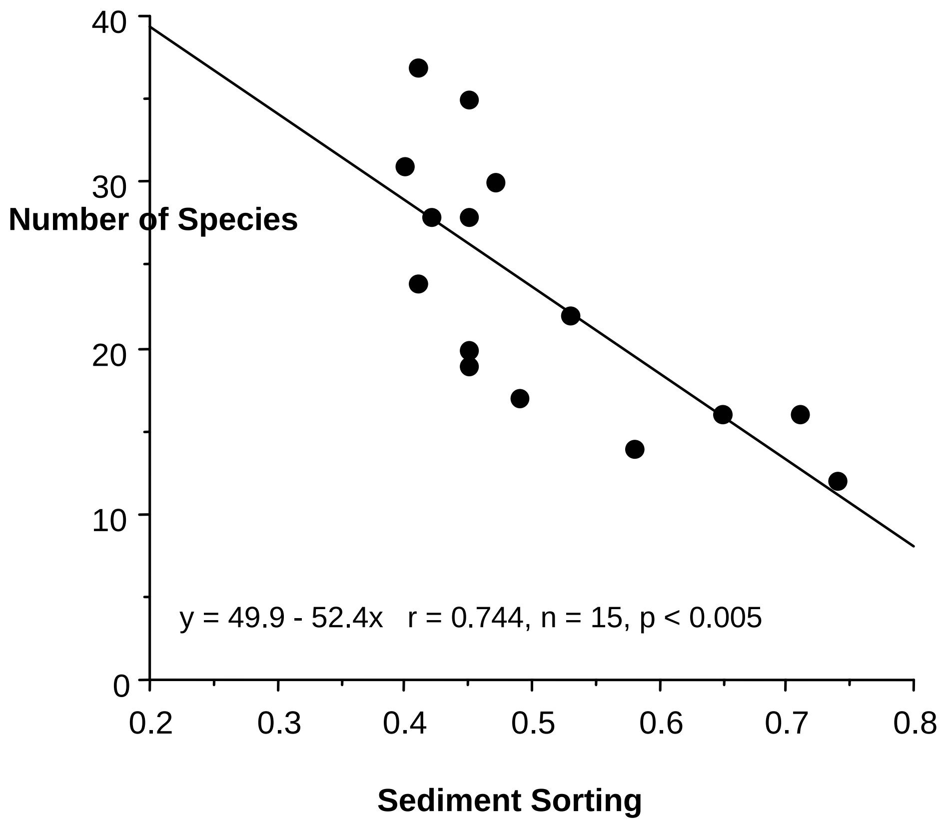

Figure 12. Relationship between macrofauna species richness and mean sediment sorting at the water table outcrop for the 15 study beaches sampled in September/October 1996.

<u>Associations with Macrophyte Wrack</u>

Species richness of the macrofauna was positively correlated with the amount of marine macrophyte wrack as estimated by cover ($r = 0.533$, $p < 0.05$, $n = 15$). This is due primarily to the presence of a number of species of insects and crustaceans associated with stranded drift algae and macrophytes. Beetle species included a carabid, *Dyschirius marinus*, a tenebrionid, *Phalaria rotundata*, a hydrophilid, *Cercyon luniger*, several histeriids, *Neopachylophus sulcifrons* and others, a curculionid, *Emphyastes fucicola*, and several species of staphylinids, including *Thinopinus pictus*. Larvae and pupae of two species of kelp fly, *Coelopa vanduezei* and *Fucellia costalis*, occurred in association with macrophyte wrack. Two species of isopods, *Alloniscus perconvexus* and *Tylos punctata*, and four species of talitrid amphipods, *Megalorchestia* spp. were often abundant on ungroomed beaches with accumulated macrophyte wrack.

Upper beach macrofaunal invertebrates, including talitrid amphipods (*Megalorchestia* spp.), kelp flies, and a variety of beetles, were widespread. Talitrid amphipods or beachhoppers, *Megalorchestia* spp. occurred at all beaches and were generally the most abundant upper beach species. The abundance of beachhoppers ranged over four orders of magnitude, from 85 m^{-1} to 10,200 individuals m^{-1} and was positively correlated with the cover of marine wrack ($p < 0.001$). The mean abundance of beachhoppers was generally higher on ungroomed beaches (594 to 10,200 individuals m^{-1}) than on groomed beaches (85 to 654 m^{-1}). The mean abundance of intertidal beetles was also generally higher (50 m^{-1} to 5,160 m^{-1}) on ungroomed beaches than on groomed beaches (0 to 60 individuals m^{-1}).

The average total abundance of shorebirds was not correlated with the cover of macrophyte wrack. However, the average abundance of one common species of shorebird, black-bellied plover, was positively correlated with the cover of macrophyte wrack ($r = 0.865$, $p < 0.001$, $n = 15$). The abundance of the western snowy plover, *Charadrius alexandrinus nivosus*, was also positively correlated with wrack cover ($r = 0.564$, $p < 0.05$, $n = 15$).

Shorebirds and Macrofauna Prey

The average abundance of shorebirds (all species combined) was not significantly correlated with species richness or mean macrofaunal abundance in this study. Average abundance of shorebirds was positively correlated with mean macrofaunal biomass (g wet weight) ($r = 0.822$, $p < 0.001$, $n =15$) (Figure 13). A positive but non-significant relationship was found between the average abundance of shorebirds and the mean individual size (g wet weight of the macrofauna) on the study beaches.

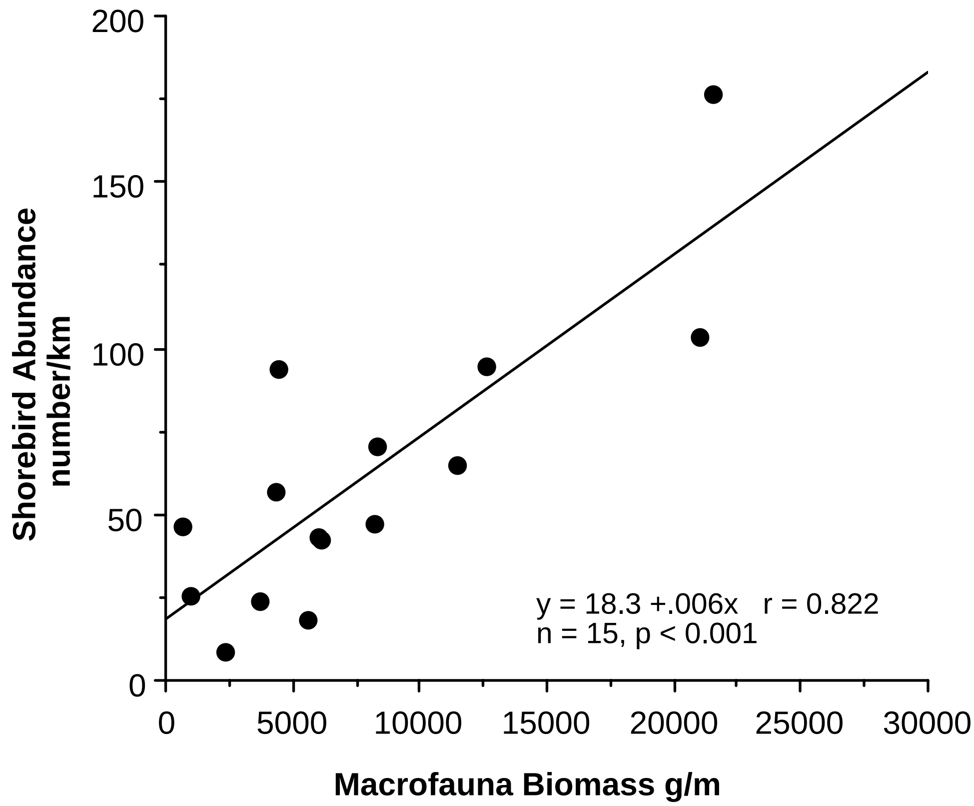

Figure 13. Relationship between mean macrofaunal biomass and average shorebird abundance at study beaches in Ventura and Santa Barbara Counties. Shorebird abundance is the average number of birds per km in surveys from November 1996 through May 1997. Macrofaunal biomass is from the macrofauna surveys of September/October 1996.

DISCUSSION

Exposed sandy beaches of the coast of southern California harbor a surprisingly high diversity, abundance and biomass of macroinvertebrate species for modally reflective and intermediate beaches. Modally dissipative beaches were not present in the study region (see Dugan et al. 1998b). The lack of macrofaunal data from dissipative beaches in our dataset precludes a definitive evaluation of possible relationships between community structure and morphodynamics in the Southern California Bight. However, our results suggest that other factors, including sediment sorting; recruitment dynamics for species such as *Emerita analoga* (e.g. Dugan and Hubbard 1996), *Donax gouldii* and *Tivela stultorum* (Coe 1955); disturbance; human activities; and the input of macrophyte wrack may strongly influence the structure of macrofaunal communities inhabiting exposed sandy beaches in southern California.

The results of our surveys and of earlier studies (Straughan 1982, 1983) indicate that the macrofaunal invertebrate communities of exposed sandy beaches of southern California are generally much richer in species than reported for beaches of similar morphodynamic type elsewhere in the world. For example, in a synthesis of studies of macrofaunal community structure of beaches in Australia, South Africa, Chile and Oregon using survey techniques similar to those used in our study, the greatest number of macrofaunal species reported from a single beach was 30 on a macrotidal ultradissipative beach in Australia (McLachlan et al. 1996). Species richness ranged from 5 to 19 macrofauna species per beach for ten intermediate beaches in New South Wales, Australia (Hacking 1998). In Chile, where a number of congeners of the species found here occur, species richness for ten beaches ranged from 1 to 14 species, with the greatest number of species occurring on a dissipative beach and the lowest numbers (1 to 4) on reflective beaches (McLachlan et al. 1993; Jaramillo and McLachlan 1993). In addition, on three fully dissipative beaches in Oregon, macrofaunal species richness ranged from 17 to 21 species (McLachlan 1990), a value lower than we found on many of the intermediate and even the reflective beach surveyed in our study.

Our surveys of exposed sandy beaches in Ventura and Santa Barbara Counties also found the abundance of macrofauna to be high relative to that reported for reflective and intermediate type beaches in other parts of the world. For macrofauna of exposed sandy beaches, abundance values of greater than 10,000 individuals m^{-1} are considered high and have been reported primarily on dissipative beaches (McLachlan et al. 1996). Values of macrofaunal abundance greater than 10,000 individuals m^{-1} were reported for only 13 of 75 beaches from around the world, those 13 were high energy intermediate to dissipative types (McLachlan et al. 1996). Mean values of total abundance less than 10,000 individuals m^{-1} occurred on only three of the 15 beaches surveyed in the present study, two of those beaches were subject to regular grooming and macrophyte wrack removal. Macrofaunal abundance values of an order of magnitude greater (100,000 individuals m^{-1}) have been reported only for dissipative beaches in Oregon (McLachlan 1990).

On many of the beaches we surveyed, the majority of individuals were sand crabs, *Emerita analoga*. High values for macrofaunal abundance (>10,000 m^{-1}) were also reported for intermediate to dissipative state beaches in Chile where *E. analoga* occurs (Jaramillo and McLachlan 1993, McLachlan et al. 1993).

The biomass of macrofauna on the sandy beaches we sampled was variable, but generally high relative to that reported for intermediate type beaches in other parts of the world. McLachlan et al. (1996, 1993) considered dry biomass values greater than 1,000 gm^{-1} to be high and a value of 5,000 gm^{-1} a ceiling value for macrofaunal communities of exposed sandy beaches. Macrofaunal biomass greater than 1,000 gm^{-1} was reported for only 13 of 75 beaches from around the world; those 13 were high intermediate to dissipative types (McLachlan et al. 1996). We estimated (dry biomass = 25% of wet biomass, McLachlan personal communication) mean dry biomass values greater than 1000 gm^{-1} for surveys at ten of our 15 study beaches and a maximum value greater than 5,000 gm^{-1} for modally intermediate beaches in southern California.

Again, on many of the beaches we surveyed, the sand crab, *Emerita analoga*, composed the majority of the macrofaunal biomass. Relatively high macrofaunal biomass (>1000 gm^{-1}) was also reported for four intermediate to dissipative state beaches in Chile where *E. analoga* occurs (Jaramillo and McLachlan 1993, McLachlan et al. 1993).

Macrofaunal communities inhabiting sandy beaches are supported primarily by allocthonous sources of carbon as little or no primary production occurs on the beach itself (Brown and McLachlan 1990). In southern California, the main sources of primary production are drift macrophytes and phytoplankton. Drift macrophyte input was estimated as 473 kg wet weight $m^{-1}y^{-1}$ for an exposed sandy beach in southern California (Hayes 1974). Macrofaunal communities of sandy beaches depend upon the production of nearshore kelp forests, seagrass and macroalgal beds and oceanographic processes for food subsidies. Drift macrophyte consumers, including talitrid amphipods and insects, inhabit the upper beach and move down to the mid and low intertidal to feed. Suspension feeders that utilize phytoplankton and associated particulate organic material, including hippid crabs and bivalves, inhabit the lower intertidal zone. Scavengers and predators, such as albuneid crabs, isopods, polychaetes and beetles, prey upon primary consumers of both types and feed on drift carrion. Vertebrate predators, such as shorebirds and fishes, can utilize all of the trophic levels of this intertidal food web as prey. Changes in either wrack input or phytoplankton production may shift community structure and energy flow in the infaunal community and at higher trophic levels.

Many beaches on the southern California coast are subject to grooming, the regular removal of trash, macrophyte wrack and other debris with heavy equipment. The ecological effects of this widespread management practice have rarely been examined, and no direct studies exist for California beaches. The fact that several of the beaches we surveyed were subject to regular grooming allowed an opportunity to make comparisons with less disturbed beaches. In general, macrofauna species richness, abundance and biomass were lower in surveys from groomed beaches and those with low amounts of wrack, particularly for upper intertidal species, than in samples from beaches with abundant wrack. In addition, the significant relationships between the abundance of selected upper beach taxa and species richness, and the cover of wrack found in our study suggest that some aspects of the community structure of sandy beach macrofauna are closely linked with the input and fate of marine macrophyte wrack. The positive correlation we found between the average abundance of two visually searching shorebird species, the black-bellied plover and the western snowy plover, and the cover of macrophyte wrack suggests that wrack dynamics could also affect the distribution of prey for shorebirds. Human alteration of wrack dynamics through beach grooming appears to be associated with substantial alteration in macrofauna community structure and potential reduction of prey resources for shorebirds on exposed sandy beaches in southern California.

Predictions of shorebird densities using physical factors, such as sediment characteristics, have been made in protected soft sediment marine habitats (e.g. Yates et al. 1993). The distribution of shorebirds on exposed sandy beaches could be potentially related to physical factors, such as beach morphodynamics and sediments, through effects on prey densities, swash climate and roosting sites. On South African beaches, the density of white-fronted plovers was inversely correlated with median sand grain size (Hockey et al. 1983). The lack of correlations between shorebird abundance and physcial factors including beach morphodynamics in the present study is not conclusive, but does not support this idea in the study area. However, other factors not examined in the present study, such as the presence of alternative foraging habitats, could also be important and potentially confound the above comparisons. For example, on the Pacific coast of North America, densities of sanderlings were highest on beaches linked to estuaries; away from estuaries, densities were higher on extensive beaches than on shorter beaches, (Myers et al. 1984 as cited in Shuford et al. 1989).

The correlations we found between the abundance of shorebirds and the total biomass of macrofauna suggest that shorebirds may also frequent beaches with more favorable conditions for the growth and survival of macroinvertebrae prey. The majority of the macrofaunal biomass on many of the study beaches was composed of suspension feeding species, such as clams and hippid crabs, a result which suggests that many common shorebird species, particularly tactile feeders, may prey upon those species or that the presence of these species might be a proxy for favorable conditions for other prey species. Some common suspension feeding species, including clams and hippid crabs, also reach the largest individual sizes among the macrofauna, and many older individuals can be too large to be ingested by a shorebird. In addition, the observation that the majority of shorebirds (average = 87%) occurred on saturated sand and in the swash zones of the study beaches supports the idea that lower intertidal macrofauna such as sand crabs, the two clam species and other species may be important prey for shorebirds on exposed sandy beaches in the Southern California Bight. This is further supported by the observation that *Donax gouldii* and *Emerita analoga* were major components of shorebird pellets collected at the study beaches (Dugan and Walling unpublished).

The lack of correlations between shorebird abundance and the abundance of macrofaunal prey raises interesting questions and may be related to the overwintering survival and recruitment dynamics of dominant macrofauna species, such as *Emerita analoga*. Beaches that are favorable for the recruitment of the planktonic larvae of *E. analoga* may not provide good overwintering habitats, and intraspecific competition may reduce growth rates and ultimately overwintering success (Dugan and Hubbard 1996, Dugan et al. 1991, 1994, Wenner et al. 1993). In addition, large numbers of wintering and migratory shorebirds may be capable of reducing the total abundance and standing crop of macrofaunal prey on beaches they frequent. Our study measured the standing crop of invertebrate macrofauna to estimate prey availability for shorebirds. Measuring macrofaunal production would provide a useful approach to refine this estimate and to better understand the dynamics of shorebird predators and prey communities. For example, a study of South African sandy beaches estimated that migrant and resident shorebirds consumed 2 to 65% of the standing crop and 10 to 49% of the annual invertebrate production (Hockey et al. 1983).

The results of this study in conjunction with those of the MMS shorebird study in Ventura county indicate that large numbers and high densities of shorebirds use exposed sandy beaches on the southern California coast. In addition, beaches in the study area support rich macrofaunal communities with high abundance and biomass of potential prey species for shorebirds. Our results suggest the standing crop and production of macrofaunal prey may be important to understanding spatial variation in the distribution and abundance of shorebirds on exposed sandy beaches.

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As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Royalty Management Program** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.