Short-Term Consequences of Nourishment and Bulldozing on the Dominant Large Invertebrates of a Sandy Beach

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ABSTRACT


Biological responses of the dominant beach macro-invertebrates to beach nourishment and bulldozing, two widely practiced structure-free methods of responding to shoreline erosion, were evaluated along Bogue Banks, North Carolina. Sediments taken from maintenance dredging of a channel in Bogue Sound and used for beach nourishment in a replicated design were substantially finer (3.67 vs 2.33 μm) than those of untreated beaches and contained large concentrations of shell hash. In response to nourishment, densities of Emerita talpoida and Donax spp. were lower by 86–99% on nourished beaches in early-mid July, 5–10 weeks after cessation of the nourishment project. Beach bulldozing done to augment the primary dune reduced the width of the intertidal beach by about 7 m and replaced it with a wedge of coarser, shellier sand taken from the lower beach. In late July–early August about 3 months after termination of bulldozing, counts of active burrows of ghost crabs Ocypode quadrata were 55–65% lower on bulldozed beaches, with most of the reduction occurring on the 7 m of high beach occupied by the newly formed dune face. Despite no detectable difference in slope of the lower beach, Emerita talpoida densities were 35–37% lower on bulldozed beach segments of 0.5- and 3-km, and, while Donax spp. exhibited no consistent residual response to bulldozing, two of three contrasts showed increased abundances of >100% on bulldozed segments. Failure of Emerita and Donax to recover from nourishment by mid summer when they serve as a primary prey base for important surf fishes, ghost crabs, and some shorebirds may be a consequence of the poor match in grain size and high shell content of source sediments and/or extension of the project too far into the warm season. Effects of bulldozing on ghost crabs may conceivably be mitigated by measures to stabilize the dune face after bulldozing, but the effects on Emerita and Donax are not easily interpreted so potential mitigation measures for mole crabs and bean clams are unclear.

ADDITIONAL INDEX WORDS: Beach nourishment, beach bulldozing, coastal erosion, beach macro-invertebrates.

INTRODUCTION

The likely ecological, economic, and social implications of rising sea level associated with global warming are far-reaching and not yet fully anticipated by scientists or adequately contemplated in social policy (BARTH and TITUS, 1984). One major consequence of rising sea level is enhancement of the rate of shoreline erosion (e.g., LEATHERMAN, 1987). Although predicting the degree of shoreline retreat associated with a given rise in sea level is difficult, the consequences of three likely scenarios of rise in eustatic sea level of 0.5, 1.0, and 1.5 m by 2100 (NRC, 1987) to the erosion of sedimentary shorelines are nothing short of disastrous to coastal communities. Because of the unprecedented rate of development on coastal barriers along the southeast United States during the past quarter century and the vulnerability in this region to hurricane damage, there is growing public demand for management intervention to combat shoreline erosion. The often least economically costly and least ecologically damaging response, moving structures as shoreline retreats (e.g., NRC, 1988), is made difficult when barriers become so densely built upon that there is no room to transplant oceanfront structures.

The threat and reality of shoreline erosion have prompted development of several engineering responses designed to protect coastal development. For sandy beaches, these engineered responses can be divided into those that represent “hardening” of the shoreline with addition of structures, such as seawalls, groins, or breakwaters, and those not involving structure, primarily beach replenishment by importing sediments and beach bulldozing to restore dunes by moving sediments from low to high on the beach. The use of hardened structural responses to shoreline erosion creates an enhanced threat of loss of the intertidal beach to erosion (e.g., WALTON and SENSEBAUGH, 1979; PILKEY and WRIGHT, 1989), and is therefore discouraged by coastal management programs in some states, such as North Carolina. On the other hand, the
The growing demand for application of beach nourishment and beach bulldozing to protect beachfront development raises challenging questions about the ecological consequences of these disturbances to the beach and how those consequences can be minimized by design modifications to the projects. These questions are not new: there are numerous studies of the ecological consequences of beach nourishment, but results of this work rarely find their way into peer-reviewed literature (NELSON, 1993). Assessment of ecological consequences of beach bulldozing is far less common (WELLS and McNINCH, 1991). The sand beach ecosystem not only possesses intrinsic value but also has important use and non-use values to human society that make its protection even more vital (BROWN and McLACHLAN, 1990). This ecosystem is characterized by dense populations of burrowing macro-invertebrates, whose high production is sustained by the wave energy (LEIGH et al., 1987), which transports particulate foods to feeding animals in the swash zone, and the high microalgal (especially diatom) productivity of the surf zone, driven in part by efficient nutrient retention (McLACHLAN et al., 1981). These macro-invertebrates, typically mole crabs, bivalve molluscs, amphipods, and polychaetes in warm oceans, represent the prey base for surf fishes, shorebirds, and predatory crabs (BROWN and McLACHLAN, 1990). In many areas, such as the southeast United States, surf fishes make a substantial contribution to the coastal economy and to coastal property valuation by provision of the amenity of recreational surf and pier fishing. Protection of migratory shorebirds is also an important component of natural resource conservation in coastal policy. Furthermore, the Endangered Species Act in the United States requires consideration of any activity that threatens the five species of endangered or threatened sea turtles that nest on barrier beaches of the southeast.

The likelihood of dramatic growth in demand for beach nourishment and beach bulldozing in the coming decades and the paucity of information on ecological impacts compelled us to design and conduct this study of short-term biological consequences of these two measures of combating shoreline erosion on coastal barriers. We chose to assess the effects of these two physical disturbances on the dominant burrowing macro-invertebrates of the sand beach system (mole crabs, bean clams, and ghost crabs) for two reasons. First, benthic invertebrates in general lend themselves well to studies of environmental impacts because they are sufficiently sedentary that they can capture and retain a spatial imprint of perturbation (WARWICK, 1993). Second, these animals represent the fundamental prey base for the food web of the entire beach system (WOLCOTT, 1978; LEBER, 1982; DELANCEY, 1989) and thus can dictate the response of the system.

METHODS

Study Site and Beach Ecosystem

Our study was conducted on the ocean beaches of Bogue Banks, North Carolina, a 28-km long barrier island on the central coast of the state (Figure 1). Although this coastline is generally considered to be a high-energy environment, Bogue Banks is oriented such that the ocean beach faces toward the south and south-southeast. Consequently, wave heights are lower on average than on east-facing beaches and net longshore sediment transport is estimated at only 22,500 m³ per year, as compared to 115,000 at Ocean City, Maryland, 57,000 at Hillsboro Inlet, Florida (WIEGEL, 1964), and 1,700,000 m³ at Cape Hatteras (LANGFELDER et al., 1968). Nevertheless, due to its position near one of the major capes,
KARLSON, Dry weights category were determined and mean, median, standard deviation, and skewness of the particle size distribution were calculated (FOLK, 1980). Biological samples were also taken to 10 cm were collected from each transect: at its beginning, end, one-quartile, and three-quartile marks. Each sample was dry-sieved for 12 min on a series of sieve sizes (−3, −2.5, −2, −1.75, −1, 0, 1, 2, 3, 6, and 10φ). Dry weights of each φ category were determined and mean, median, standard deviation, and skewness of the particle size distribution calculated (FOLK, 1980). Biological samples were also taken from the low tide mark at low tide to the base of the dune scarp at 1-m intervals using a cylindrical corer with internal diameter of 10.2 cm covering a surface area of 82 cm² to a depth of 20 cm. Contents of each core were sieved through 3-mm mesh to isolate the large macrofauna. The procedure used during resampling of the large macrofauna on 18 July at the Holiday Inn nourished site and the Iron Steamer control site differed somewhat. The same corer, coring procedure, and sieving methods were used, but the transects ran from the high-tide mark to a distance where water depth was 1 m at low tide, sampling interval was chosen to be 5 m, and each sample was comprised of a composite of two adjacent cores (doubling area sampled). This resampling was done to provide increased coverage of the shallow subtidal zone. In addition, three replicate transects separated by 50 m were sampled at each site at low tide. For the control site, an additional sampling of three more transects was conducted at high tide. During this 18 July sampling, the control site actually sampled was located about 1.5 km east of the original Iron Steamer site.

Beach Bulldozing

Beach bulldozing (or scraping) is the process whereby sand is pushed from the low intertidal zone towards the back of the beach to enhance the size of the primary dune at the back
of the beach in hopes of providing protection for beachfront development to reduce risk of damage during subsequent storms (Wells and McNinch, 1991). We took advantage of beach bulldozing that occurred on Bogue Banks during April 1993 in response to a damaging northeaster storm on March 13. The pattern of beach bulldozing allowed tests of ecological impacts on two different spatial scales. First, a continuous stretch of 3 km of beach was bulldozed centered around the Ramada Inn. Second, a stretch of 0.5 km was bulldozed starting about 1.5 km east of the Iron Steamer pier. Thus, although these two differing treatment lengths were not replicated, we could sample at control, unmanipulated sites close to each of them as a means of testing for ecological impacts.

For the 3-km treatment, we sampled benthic macrofauna from 20 July through 4 August 1993 on 20 replicate transects spaced at intervals throughout the bulldozed shoreline and compared densities to 20 similarly spaced replicate transects sampled in control areas, 10 on each side of the bulldozed stretch (Figure 1). For the 0.5-km treatment, we sampled benthic macrofauna on 15 July 1993 on three replicate transects spaced at 50-m intervals within the bulldozed stretch and compared densities to six replicate transects, also spaced every 50 m, sampled in a control area about 300 m east. Three of the control transects were sampled at low tide and three at high tide, whereas all three transects in the bulldozed stretch were sampled at low tide. Transformation of the natural beach profile by hotel and condominium development to the west prevented establishment of control transects on that side of the 0.5-km treatment.

Beach profiles and densities of large macro-invertebrates were assessed on bulldozed and control beaches to evaluate impacts of treatment. For the 3-km scale treatment, elevation profiles were measured from the base of the major dune scarp at the back of the beach to the water level at low tide at ten randomly selected sites within the bulldozed stretch and at ten (five on each side) control sites. Methods were identical to those used in the profiling done to assess effects of nourishment, except that measurement stations were set at 0.5-m intervals. Abundances of the dominant macro-invertebrates of the beach system were estimated by two different types of sampling, one designed for Donax and Emerita, the other for Ocypode. The sampling for Donax and Emerita was similar to methods used in the assessment of nourishment. Identical cylindrical cores of 10.2-cm diameter were taken during low tide to a depth of 15 cm at 5-m intervals along each sampling transect extending from the wrack line at the previous high-tide mark to a location where water depth was 1 m. Each sample was a composite of two adjacent cores. Contents were sieved through nested meshes of 1 and 3 mm. The sampling for ghost crabs involved counting the numbers of active burrows (indicated by tracks of crabs around the opening) on 2-m-wide transects (with densities converted to a 4-m swath for consistency in the results) extending from the low water line to the top of the primary dune scarp. Wolcott (1978) confirmed the accuracy of this method of estimating of ghost crab abundance. The ghost crab transects were located at the same sites as the Donax-Emerita transects. For the 0.5-km scale treatment, sampling was conducted for Donax-Emerita and for ghost crabs along the three replicate transects in treated and control areas in a similar fashion, differing only in that sample contents were sieved through 3-mm mesh only and the ghost crab burrow counts were made along 4-m-wide transects (doubling the area sampled). In addition, two samplings of the same coring transects were conducted, one at low and one at high tide of the same day. For both the 3-km and 0.5-km scale samplings, counts of active ghost crab burrows were partitioned on each transect into two numbers: those on the face of the bulldozed dune (or on the corresponding segment of the control beach that would have been covered by bulldozing had it occurred there) vs. those on the segment of intertidal beach that for both bulldozed and untreated beaches rises from the low-water line to where the base of the bulldozed dune scarp begins (or would begin, if present). This partitioning was done to address how the crabs responded to these two actions of bulldozing, burial of the back beach and replacement of intertidal beach with a constructed dune face vs. extraction of sands from the lower, intertidal beach.

RESULTS

Beach Nourishment

The surface appearance of the intertidal beach at renourished sites was substantially different from the appearance of the untreated beaches in early July. Our observations were made 5 and 10 weeks after cessation of nourishment in that the two beaches were nourished in sequence, with the Holiday Inn beach completed before the Ramada Inn beach. During our observations in the first week of July 1990, the nourished beaches were gray in color, as compared to a brownish white on control beaches, and they possessed extensive shell hash, especially consisting of blackened oyster shell, concentrated both on the upper intertidal and the swash zone at low tide. No similar accumulations of shell were evident on control beaches. The nourished beach possessed several mud balls, absent from the untreated beaches, and the sediments were more compacted making the surface of the beach harder.

The topographic and sedimentary measurements made on the four beaches revealed large effects of nourishment. Profiling on each beach showed that replenished beaches extended 6–12 meters further away from the dune base than control beaches (Figure 2), reflecting the immediate success of widening the beach. This sediment addition also had an effect of necessarily reducing and smoothing the slope of the intertidal beach, evident in contrasting the profiles of the four beaches (Figure 2). The average slope of the entire intertidal beach profile was 2.86° and 2.92° at the two control beaches, as compared to 2.06° at both nourished beaches. Sediment grain size analysis revealed the untreated beaches to possess a mean grain size of 2.33 μm (fine sand), with a standard deviation of 0.55 (well to moderate sorting), and a skewness of 0.5 (very positive—toward finer grain sizes). These values were identical on both control beaches (Table 1). In contrast, nourished beaches exhibited a mean grain size of 3.67 μm (very fine sand almost coarse silt), with standard deviations of 2.06 and 2.21 (poorly sorted), and skewness of 0.18 and 0.13 (positively skewed but less than at control beaches). These sedi-
component parameters did not differ much between the two nourished beaches, but the contrast between nourished and control beaches was striking (Table 1).

Core sampling for large macro-invertebrates revealed dramatically lower densities of both *Donax* spp. and *Emerita talpoida* on nourished beaches (Figure 3). Average density of *Donax* spp. on control beaches ranged from 264–334 m$^{-2}$ as compared to 40–42 m$^{-2}$ on nourished beaches in the late June-early July sampling. This represents a reduction of 86%. Similarly, *Emerita* density on control beaches on those same dates varied between 137 and 159 m$^{-2}$, compared to 0–4 m$^{-2}$ on nourished beaches. This represents an even sharper 99% decline. While elevation on the beach surely represents a factor that causes some variation in counts among samples, such that a stratified analysis would be more powerful, a simple one way ANOVA on 4th-root-transformed counts serves to show for each species that beaches differed significantly at $p < 0.0001$ and subsequent Bonferroni contrasts revealed that the significance was a consequence of differences between all pairs of nourished and control beaches for each species. Resampling in mid July 2–3 weeks later with a design that included the shallow subtidal zone from 0–1 m water depth produced a virtually identical pattern of differences in *Donax* and *Emerita* densities between nourished and untreated beaches (Figure 3). Average density of both *Donax* and *Emerita* on the nourished beach was 97% lower than on the control beach in this sampling ($p < 0.01$ and $p < 0.05$ in respective t-tests for unequal variances, using transect totals as the sampling unit: $n = 6$ for controls and 3 for nourished beaches). No sampling was conducted for ghost crabs.

### Beach Bulldozing

Sampling of the intertidal beach profiles yielded no remaining evidence of bulldozing on intertidal beach topography in late July about three months after cessation of the treatment. Averaging of the elevation profiles taken along ten bulldozed and ten control transects revealed no differences in the topography of the intertidal beach face between bulldozed and control transects (Figure 4). Despite the iden-

![Comparative Beach Profiles](image)

**Figure 2.** Elevation profiles in late June-early July 1990 for four intertidal beaches from the base of the primary dune scarp to the waterline at low tide. Two beaches (Iron Steamer [IS] and Salter Path [SP]) were untreated natural control beaches. Two beaches (Holiday Inn [HI] and Ramada Inn [RI]) were nourished with dredge spoils, with projects ending five (RI) and ten (HI) weeks prior to sampling.
Ecological Impacts of Beach Nourishment and Bulldozing

Figure 3. Average densities (+1 SE) across the intertidal zone of the two dominant macro-invertebrates of the intertidal beach (*Donax* spp. and *Emerita talpoida*) on nourished (white bars) beaches (Holiday Inn [HI] and Ramada Inn [RI]) and on untreated control (gray bars) beaches (Iron Steamer [IS] and Salter Path [SP]) on two dates. For the first set of dates, means and SEs were calculated over 28 (IS), 29 (SP), 38 (HI), and 33 (RI) composite core samples (2 adjacent cores of 82 cm² each, taken every 5 m from the high-tide wrack line to 1-m water depth and sieved through 3-mm mesh). For the second date, means were calculated over 72 (IS) and 37 (HI) composite core samples. P-values comparing mean densities of each species among (between) sites are derived from one-factor ANOVAs on 4th-root-transformed counts for the first set of dates and from t-tests for unequal variances performed on replicate transects, totaling 6 (IS) and 3 (HI), for the second date.

Vertical slopes of the low intertidal zones, the width of the intertidal beach from the waterline at low tide to the base of the major dune at the back of the beach, the distance over which the profiles were taken, was about 7 m less on bulldozed beaches, changing from 29 to 22 m (Figure 4). This reflects the deposition of sands against the scarp by the bulldozer to increase the dune mass. Observation of the face of the dune scarps revealed that bulldozed faces were characterized by looser, more mobile, and less vegetated sediments made up of coarser particles with more shell fragments than the very fine sands of the faces of untreated dune scarps. The slope of the face of bulldozed dune scarps was shallower, at about 45°, than the steep almost 90° slope of the natural dune scarp of the control beaches.

Biological sampling data from the 3-km scale treatment revealed substantial differences between bulldozed and control sites in average abundance per transect for *Ocypode*, *Donax*, and *Emerita* (Figure 5). Active *Ocypode* burrows were on average 65% lower on the bulldozed beach transects. This reduction was a consequence of almost complete elimination of ghost crab burrows from the face of the bulldozed dune and over a 60% reduction on the lower beach (Figure 5). Total *Emerita* (both size classes pooled) showed a reduction of 37%, whereas total *Donax* abundance per transect on bulldozed beaches was more than five times that of control beaches. Each of these differences is statistically significant at p < 0.0001 in a t-test comparing the means of bulldozed and control transect counts (variances were not significantly different except for *Donax*, which even after log and square-root transformation remained heteroscedastic at p < 0.05 in an F-max test). Separate analyses of the large (>3 mm) and small (between 1 and 3 mm) animals (Figure 5) shows that for *Emerita* only the smaller size class differed significantly (p < 0.05) between bulldozed and control beaches, but for *Donax* both large and small animals were more abundant on bulldozed beaches. Results of sampling the 0.5-km scale treatment and an adjacent control area in mid July demonstrate a similar set of biological differences (Figure 5). Average counts of active *Ocypode* burrows were 55% lower on bulldozed than on control transects (p < 0.0001 in a t-test). The partitioning of counts of ghost crab burrows by location on the beach revealed that essentially all of the effect of the
Figure 5. Average (+1 SE) abundance per beach transect of Donax spp., Emerita talpoida, and Ocypode quadrata on two scales in summer 1993 as a function of bulldozing. The bulldozed treatment was applied and evaluated on two separate spatial scales, over 3-km and over 0.5-km. Bulldozed transects are indicated by white bars and untreated beaches by gray shading. Transects for Donax spp. and Emerita began at the high-tide wrack line and extended to a water depth of 1 m at low tide, whereas transects for Ocypode extended continuously over a 4-m swath from the low tide mark to the top of the primary dune. Counts of active Ocypode burrows were split into the lower beach (hatched bars) and the upper beach (unhatched bars), defined by the position where the base of the bulldozed dune began (bulldozed beaches) or would have begun (untreated control beaches) had bulldozing been applied similarly. Sampling on the 0.5-km scale for Donax spp. and Emerita talpoida was done twice, at peak high and at minimum low tides. Transects consist of two consolidated adjacent cores of 82 cm² each, taken every 5 m, and passed through 1- and 3-mm meshes (small and large, respectively) for the 3-km sampling and 3-mm mesh for the 0.5-km sampling. P-values comparing effects of bulldozing on mean total densities for each species, spatial scale, and (where relevant tidal stage) are derived from t-tests (equal variances).
bulldozing on ghost crab burrow counts at this 0.5-km scale can be explained by the absence of burrows on the artificially constructed dune face. Burrow counts on the intertidal beach from the water line at low tide to the elevation where the scarp face begins on bulldozed transects were essentially identical to the counts over that same rise of beach on control transects: the difference arises from the virtual absence of ghost crab burrows on the bulldozed dune face compared to the large number of active burrows on the high intertidal portion of the untreated control beach that would have been buried if bulldozing had been done there (Figure 5). Almost half of the ghost crab burrows occurred on untreated beaches on the high beach in the segment which becomes buried when bulldozing is done. Emerita counts per transect were lower on the bulldozed transects by 55% in the high-tide sampling and 35% in the low-tide sampling (< 0.01 and p < 0.05 in each of two t-tests). In contrast, Donax counts appeared higher on the bulldozed transects by over 100% in the high-tide sampling and lower by 32% in the low-tide sampling, but only the high-tide difference was statistically significant (p < 0.0001 in a t-test).

**DISCUSSION**

Our studies of the ecological consequences of beach nourishment and bulldozing demonstrate large short-term effects on dominant species of beach macro-invertebrates. Abundances of both Emerita talpoida and Donax spp. were 86–99% lower on nourished beaches in late June-early July, 5 and 10 weeks after cessation of nourishment (Figure 3). This is a season of the year when abundances of both of these dominant species of burrowing macro-invertebrates are typically at their maximum (Diaz, 1980; Leber, 1982) and when they are providing the important ecosystem service of feeding abundant surf fishes (Lever, 1982; Delancey, 1989) and ghost crabs (Wolcott, 1978). This transfer of energy to higher trophic levels was almost certainly dramatically reduced by nourishment. Our short-term observation period does not suffice to allow estimation of the length of time over which this tertiay production was diminished. Beach bulldozing caused reduction of densities of Emerita in the intertidal zone and ghost crabs on the high shore by 35–37% and 55–65%, respectively (Figure 5). This effect was evident in July three months after termination of the bulldozing project. The magnitude of the impacts was similar on each of two spatial scales of treatment, a 3-km and a 0.5-km bulldozing project. Bulldozing did not exhibit any negative effect on Donax abundance by this date and appeared to have enhanced its local abundance on bulldozed segments. Consequently, the negative impact of beach bulldozing on production of higher trophic levels was presumably not as large as for the beach nourishment.

The causes for the sensitivity of Emerita to both of these types of "soft" response to beach erosion probably differ between the two projects because the physical effects on the environment were not at all similar. Reilly and Bellis (1983) showed that nourishment of a nearby Bogue Banks beach from December into June caused complete loss of Emerita when sediment deposition began but that the population density recovered by mid June with only a one-month time lag in the timing of its seasonal reappearance compared to a control beach. Recolonization of the nourished beach occurred, however, only through larval recruitment not from migration of adults, as normally occurs in spring (Diaz, 1980) and as took place on the untreated beach. Our data on Emerita response to beach nourishment differ sharply in that by mid July recovery of Emerita had not occurred on the nourished beaches. This difference may be a consequence of the poor match in sediment grade in the 1990 project that we investigated. A φ size of 3.67 corresponds to an average grain size of 0.08 mm, just barely larger than the size limit for acceptable sand in nourishment projects (U.S. Army Corps of Engineers, 1989). This very fine sand differed by over one φ unit from the 2.33φ for the average grain size of the natural beach sands. Emerita appears to prefer a size range of 0.25–0.50 mm (Bowman and Dolan, 1985), substantially larger than 0.08. From previous studies of impacts of beach nourishment (Hayden and Dolan, 1974; Dolan et al., 1992), Emerita is thought to be sensitive to sediment grade because of either implications for burrowing and or effects of turbidity on feeding (e.g., Turner, 1990). Because Reilly and Bellis (1983) report a good match between natural and dredged sand in that earlier project (although without providing any actual sedimentological data as evidence), it is reasonable to hypothesize that the greater impact on Emerita in our study is a consequence of the use of very fine sand that poorly matched existing beach sediments. This interpretation is consistent with the conclusion of Nelson (1989), who reviewed available information on effects of nourishment and concluded that significant mortality is induced only when the match in grain size or organic content of nourished sediments is poor. Like our study, the study of Reilly and Bellis (1983) also reported extensive introduction of shell hash, so while this could have negative impacts on burrowing and thus abundance of Emerita and other beach invertebrates, it cannot explain the difference in recovery rates of Emerita between the two projects. Similarly, the presence of clay balls was reported in both studies. It is also reasonable to hypothesize that stopping nourishment projects in early spring before onset of the warm season in May when Emerita returns to the intertidal beach would greatly reduce this impact on a major forage species.

The cause of the reduced Emerita density and the possible increase in Donax density on bulldozed beaches three months after termination of the projects is not clear. There was no apparent residual difference between bulldozed and adjacent untreated beaches in beach slope (Figure 4), grain size, or wave and tidal energy, the major determinants of biological variation among sandy beach communities (McLachlan, 1983; McArdle and McLachlan, 1992; Jaramillo et al., 1993). The North Carolina Coastal Resources Commission allows only 30 cm of sediment to be removed from the lower beach in a bulldozing project, an amount that is usually rapidly replaced by natural sediment transport (Wells and McNinch, 1991). It is possible that the bulldozing affected the natural cuspatate morphology of the shore and thereby altered its suitability for Emerita and Donax (e.g., McLachlan and Hesp, 1984), but we made no observations to test this
hypothesis. It is also possible that the reduction in width of the intertidal beach (Figure 4) caused by bulldozing affects *Emerita* and *Donax*, but the mechanism is not obvious.

Not enough is known about the physiology and ecology of *Donax*, especially in its larval and early postlarval stages, to be able to explain the causes of its response to beach nourishment (NELSON, 1989; 1993) and only one study (REILLY and BELLIS, 1983) has previously assessed its response to nourishment in any detail. *Donax* had clearly not recovered on either of the nourished beaches, which differed in the timing of when nourishment projects had ended. This lack of recovery matches the observations of Reilly and Bellis (1983), who showed no *Donax* at all on the nourished beach until late July, more than 2 months after cessation of the project. In addition, the colonists were young of the year immigrants in their study: unlike *Emerita*, no larval recruitment occurred on the nourished beach in that first summer. Consequently, understanding the recovery dynamics of *Donax* requires some further knowledge of larval ecophysiology and ecology. Future nourishment projects should be designed to end before onset of the warm season (April or May in North Carolina) when *Donax* and *Emerita* return to the intertidal beach so as to test the reasonable hypothesis that seasonal timing of nourishment affects the rate and timing of recovery. No negative impacts of bulldozing on *Donax* population density was evident from our study three months after completion of the projects.

Separation of the ghost crab burrow counts by location on the beach (Figure 5) helps explain the cause of the negative impact of beach bulldozing on this dominant predator of the system. The counts of active *Ocypode* burrows on the lower beach below the location of the wedge of newly placed sand at the face of the major dune on bulldozed beaches were virtually identical to the counts over that same stretch of lower beach on untreated beaches on the 0.5-km scale and were reduced by over 50% on the 3-km scale bulldozing treatment (Figure 5). However, on the upper portion of the beach where the new dune face was created by bulldozing, ghost crab burrows were virtually eliminated for both the 0.5-km and 3-km scale projects (Figure 5). This upper zone of the beach of about 7 m (Figure 4) was converted from a gradually sloping intertidal beach of fine sand sediments to a steeply sloping berm face composed of coarser, shellier materials that were unconsolidated and incapable of holding a burrow when we tried to excavate by hand into it. The natural berm face that was comprised of finer sediments, less shell, and a greater degree of vegetative cover held the shape of our hand excavations much better. It is not clear which of the many physical differences between the natural flat intertidal beach and natural berm face and the artificial berm face were responsible for the virtual absence of ghost crabs. A mechanistic understanding of this inhibition would be valuable if the responsible feature could be manipulated during the project in such a way as to reduce the negative impacts on *Ocypode*. It is possible that some measures to consolidate the sediments of the dune face, perhaps by planting dune grass, may mitigate for the bulldozing effects. The similar (0.5-km) or reduced (3-km) numbers of observed ghost crab burrows on the lower portions of bulldozed and untreated bulldozed beaches suggests that the bulldozing did not merely displace the ghost crabs to lower levels of the beach. It is possible that the ghost crabs were displaced laterally by bulldozing, but this seems rather unlikely given the probable difficulty in reburying toward the beach surface after burial by a bulldozer and given the similar magnitude of the impact of bulldozing on total ghost crab burrow counts on 3- and 0.5-km segments of bulldozing. Successful lateral displacement would presumably imply higher densities in nearby untreated beaches relative to bulldozed beaches the longer the bulldozed segment. That was not observed in our study. The additional reduction in ghost crabs that was detected on the lower beach at the 3-km scale that was not evident at the 0.5-km scale is not readily explained, but may be a consequence of unmeasured differences in the intensity of bulldozing in the two projects.

While the general depiction of the organization of sand beach macrofaunal communities identifies the physical processes of waves and tides and the physical variables of sediment grade and beach slope as the primary determinants of biological pattern and dynamics (e.g., Mclachlan, 1983; Jaramillo et al., 1993), there is growing evidence that biological interactions, including human intervention, play an important role. WOLCOTT'S (1978) calculations suggesting that ghost crabs on North Carolina barriers consume most of the annual production of *Emerita talpoida* and *Donax* spp. implies a large role for predation, although this has not been experimentally evaluated. Fishing on beach clams has been identified as a factor affecting dynamics of beach bivalves in Uruguay (Defeso and Alava, 1995). In addition, several previous studies of beach nourishment have demonstrated impacts on macro-invertebrates (reviewed in Nelson, 1989; Hackney et al., 1996). We too showed a huge local depression of the normally dominant macrofauna about 5 and 10 weeks after nourishment. Our demonstration of the negative effects of beach bulldozing represents results of the first assessment of how this human intervention influences beach biota. While impacts on the biota from human activities designed to combat erosion do exist, and have serious implications in the case of beach nourishment to the tertiary production of valuable surf fishes, we were able to evaluate those impacts only over short-term time scales. Yet our observations of both *Donax* and *Emerita* well into what should normally be the summer season of peak abundance, when these benthic animals should be playing the valuable ecosystem function of feeding surf fishes, imply that nourishment may have caused the loss of a full season of energy transfer to these fishes at the nourished sites. Furthermore, longer-term impacts are also possible arising from persistent modifications of the physical environment, either of the topography or the sedimentology. For example, if removal of sand to enhance dunes or to nourish beaches creates higher wave heights onshore, then modified wave energy could have a lasting impact on beach biology. Similarly, alterations offshore from borrow sites outside the normal range of the sediment transport system could be much more long-lasting (e.g., Rakocinski et al., 1996). Further study is required to provide mechanistic understanding of impacts of beach manipulation so as to allow development of means of mitigating those impacts and to assess long-term
modifications in physical processes, which can have substantial biological implications.

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