

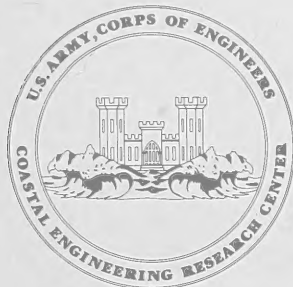
The Ecological Impact of Beach Nourishment with Dredged Materials on the Intertidal Zone at Bogue Banks, North Carolina

by
Francis J. Reilly, Jr., and Vincent J. Belmont



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<p>During the winter and spring of 1977-78 approximately 1600 meters of high-energy sandy ocean beach at Fort Macon State Park was nourished with sediments dredged from Morehead City State Port Harbor. This report is the result of a 20-month study of the nourished beach and a comparable unnourished beach. Shannon-Weaver's Species Diversity Indexes ranged from 0.00 to 0.64 on both beaches during the 6 months before nourishment. Generally, Shannon-Weaver values were higher on the nourishment beach before nourishment due to the</p> <p>(continued)</p>		

higher numbers of species present. High species number is attributed to the close proximity of the nourishment beach to Beaufort Inlet. After nourishment began the unnourished beach maintained the same diversity and density patterns that both beaches had displayed before nourishment although there was seasonal variation. The species diversity on the nourished beach became undefined at the onset of nourishment because the density of all species dropped to zero. This situation remained at the nourished beach until nourishment activities ceased. During the nourishment activities, the Fort Macon beach was subdivided into two segments (the area already nourished and the area not yet nourished). While all organisms in the nourished area disappeared, no increased population densities were noted from the adjacent unnourished area. Near the end of nourishment activities this unnourished area showed both a drastic reduction in diversity and a change in species composition, thus indicating a certain edge effect of nourishment. A special transect designed to monitor rate of recovery after nourishment indicated that a speedy recovery largely depended on recruitment from pelagic larval stocks. It also seemed to indicate that high turbidities associated with nourishment can prevent this recruitment. Lastly it showed that those species unable to recolonize through pelagic larval recruitment returned to the area much more slowly.

A comparison of the before-and-after nourishment data at Fort Macon showed little evident change in the densities of the most dominant secondary producer the mole crab, *Emerita talpoida*; however, when comparing before-and-after size class data with the comparison beach the effects of nourishment are obvious. While a complex age and size class array was evident before nourishment at Fort Macon and after nourishment at the comparison beach, only young of the year age classes were observed for any intertidal species present at Fort Macon. This lack of older and larger individuals and consequently biomass was reflected in lower densities of important migrating consumers at the study site. Although the populations of these consumers were probably not affected, they were noticeably absent from the nourished area during and after nourishment; they probably had moved to adjacent areas. The beach showed signs of recovery. Only *Emerita talpoida* returned in near-normal density; all other numerically important species also returned but in significantly lower density.

PREFACE

This report provides coastal engineers the results of a study on the effects of beach nourishment activities on the intertidal zone at Bogue Banks, North Carolina. This research was funded by the State of North Carolina, Division of Marine Affairs, and the U.S. Army Engineer District, Wilmington, and published under the U.S. Army Coastal Engineering Research Center's (CERC) Environmental Impact Program, Environmental Quality Area of Civil Works Research and Development.

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Comments on this publication are invited.

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TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins ¹

¹To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9) (F - 32)$.

To obtain Kelvin (K) readings, use formula: $K = (5/9) (F - 32) + 273.15$.

THE ECOLOGICAL IMPACT OF BEACH NOURISHMENT WITH DREDGED MATERIALS
ON THE INTERTIDAL ZONE AT BOGUE BANKS, NORTH CAROLINA

by

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I. INTRODUCTION

The National Shoreline Inventory (U.S. Army, Corps of Engineers, 1971) showed that more than 4350 kilometers of the nation's shorelines is "critically eroding." Investment in beach property continues to rise. New developments are often forced to utilize more erosion-prone property, because most of the relatively stable shoreline has already been developed. For these reasons the priority given to stabilizing waterfront property and controlling beach erosion can be expected to increase markedly during the next decade.

A variety of erosion control methods have already been developed and tested. Structural control methods including groins, seawalls, and bulkheads have frequently been found to be unsatisfactory due to hazards to beach users, lack of esthetic appeal, and high cost coupled with limited effectiveness. Because of these limitations, beach nourishment or replenishment (the addition of borrowed sediments to the beach) is fast becoming the preferred method for dealing with shoreline erosion. Major advantages of beach nourishment have been summarized by Walton and Purpura (1977). They include emphasis upon non-structural methods which approximate the shape and visual aspect of a natural beach, fast results at a cost competitive with other erosion control methods, and beneficial use of dredged materials obtained from activities that are undertaken to maintain navigation channels.

An Army Corps of Engineers publication dealing with beach nourishment summarized its geological effect as follows: "It's hard to hurt an eroding area by adding material to it" (Richardson, 1976). This generalization may or may not apply to the sediment budget of an eroding beach and should not be extended to include effects on the beach biota. Since passage of the National Environmental Policy Act in 1969 and the Federal Water Pollution Control Act of 1972, it has become both a practical and a legal necessity to determine the ecological impact of proposed erosion control projects.

Although the ecological consequences of dredge and fill projects are well documented for estuaries (Ingle, 1952; Hellier and Kornicker, 1962; Sykes, 1971; Rosenberg, 1977) and marshlands (Pomeroy, 1959; Odum, 1961; Clark, 1967), few studies have considered the ecological effects of beach construction or nourishment. Most studies on beach nourishment have dealt either with effects at the borrow site (Cronin, Gunter, and Hopkins, 1971; Courtenay, Hartig, and Loisel, 1980; Culter and Mahadevan, 1982; Saloman, Naughton, and Taylor, 1982; Turbeville and Marsh, 1982) or offshore effects (Holland, Chambers, and Blackman, 1972; Parr, Diener, and Lacy, 1978; Courtenay, Hartig, and Loisel, 1980; Marsh, et al., 1980; Saloman, Naughton, and Taylor, 1982; Culter and Mahadevan, 1982). Only one previous study of beach nourishment was located that actually dealt with the ecological effects on the upper beach (Dolan, 1974; Hayden and Dolan, 1974). This study described the response to beach nourishment of a group of mature mole crabs, *Emerita talpoida* (Say), occurring in the center of the swash zone at Cape Hatteras National Seashore. The study

reported a redistribution of *E. talpoida* away from the impacted zone during nourishment rather than an increase in mortality. Parr, Diener, and Lacy (1978) reported on the nourishment of Imperial Beach, California. Their study sites differed in that either seawalls or stone revetments backed their beach, and the dominant fauna was amphipods. However, they also reported a slight redistribution of organisms away from the nourishment and no long-term effects. Two other studies (Marsh, et al., 1980; Culter and Mahadevan, 1982) mentioned the beach intertidal zone in their studies; however, both found the area to be biologically depauperate and concentrated on offshore sampling stations in their evaluations.

This study evaluates the effects of beach nourishment on an intertidal sandy beach macrofaunal community. Specific objectives of this study were:

- (1) To establish base-line quantitative data on the community structure and seasonal variation among the biota inhabiting the intertidal zone of a high-energy sandy beach;

- (2) to determine the effects of beach nourishment using dredged materials on the intertidal macrofaunal community of a high-energy sandy beach; and

- (3) to make recommendations concerning the implementation and environmental advisability of beach nourishment with dredged materials.

The study is based on observations of community dynamics on two similar beaches located on Bogue Banks in Carteret County, North Carolina (Fig. 1). One beach, located at Fort Macon State Park on the eastern tip of Bogue Banks, received nourishment with dredged sediments from December 1977 to June 1978. The other beach was located at Emerald Isle on the western end of Bogue Banks; this beach, which was called the comparison beach, received no nourishment. Both beaches were sampled repeatedly before, during, and after nourishment.

II. SITE DESCRIPTION

Both the beaches monitored during this study are located on Bogue Banks, a south-facing barrier island in North Carolina (Fig. 1). It is relatively stable historically (Pilkey, Pilkey, and Turner, 1975), but is subject to local overwash (Fisher, 1967) especially when high-energy conditions exist during storms. The actual study sites, however, are not subject to storm overwash.

Both beaches are similar in that the land immediately shoreward of the beaches is relatively undeveloped. At the nourished beach (Fort Macon), the only development is a bathhouse and parking area behind the primary dune at the far western boundary of the park. The unnourished beach (Emerald Isle) has a single row of houses parallel to the primary dune and behind it. A series of road cuts run perpendicular to the primary dune at approximately 100-meter intervals.

The dune at both beaches was 3 to 4 meters high and, at least at the unnourished beach, was accretionary (Leber, 1977). The dune in both cases is stabilized by sea oats, *Uniola paniculata*; American beachgrass, *Ammophila breviligulata*; seacoast blue stem, *Andropogon littoralis*; bitter panicum, *Panicum amarum*; seaside goldenrod, *Solidago sempervirens*; and sea rocket, *Cakile edentula*.

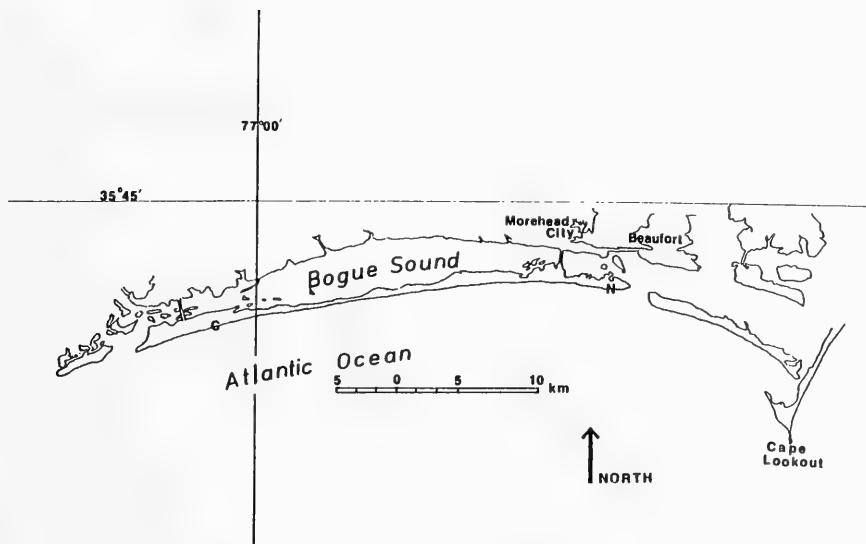


Figure 1. Location of study sites at Bogue Banks, North Carolina. The nourished beach (N) is located at Fort Macon State Park and the comparison beach (C) is located at Emerald Isle.

Behind the dune at both beaches is a relict dune and swale system covered by maritime forest. Several of the swales contain freshwater in enough quantity to support small mammals. Fort Macon is the site of a partially restored pre-Civil War brick fort. The Fort Macon beach is subject to fairly heavy usage by bathers during the summer months. Fort Macon State Park is a favorite spot for sport fishing, but no commercial seining is allowed from the beach.

The nourished beach at Fort Macon (Fig. 2) consisted of a segment of ocean-facing beach stretching from the park's western boundary marker east to a point on the beach even with the Coast Guard station, or a distance of approximately 1460 meters. The slope of the beach was gentle, averaging less than 3 percent (3 meters of drop per 100 meters of run), but during high-energy conditions, storm scarps were prevalent. This beach has been described previously by Pearse, Humm, and Wharton (1942).

The unnourished comparison beach was the same beach described by Leber (1977). It is located approximately 20 kilometers west of the Fort Macon beach (Fig. 3). The study area begins near the end of James Street in Emerald Isle and stretches east a distance of 1460 meters. The beach slope here was also gentle averaging 2 to 3 percent (2 to 3 meters of drop per 100 meters of run) and was also subject to storm scarping during high-energy situations.

Both beaches are typical high-energy sandy beaches as described by Pratt (1973) and Riedl and McMahan (1974). Both received waves averaging 0.3 to 1.0 meter from crest to trough during this study. Semidiurnal tidal fluctuations

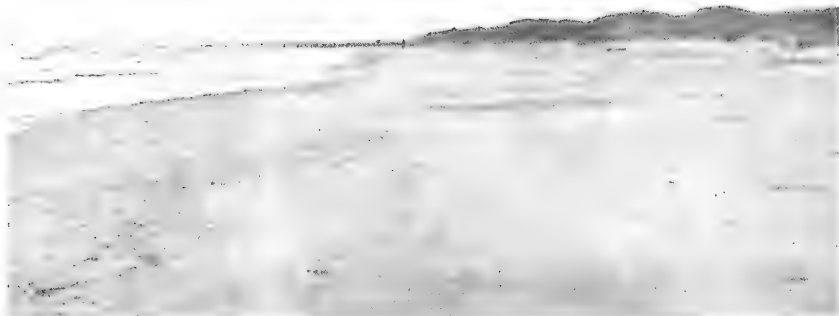


Figure 2. Fort Macon beach after nourishment had begun, but before nourishment had proceeded to this point. The coarse materials in the swash zone were washed into this area from the nourished beach segment by littoral drift. The jetty in the background is the same one shown in Figure 6 being buried. This photo was taken facing southwest along the beach. The jetty in the photo use to exist in front of the bathhouse and parking area.



Figure 3. The Emerald Isle beach at low tide. Note the gradual slope and fine sediments. This photo was taken facing southeast about half way from the start of the comparison beach segment or approximately 0.5 kilometer northeast of James Street in Emerald Isle.

vary from 0.7 to 1.25 meters (National Oceanic and Atmospheric Administration, 1975). Both beaches were composed mainly of quartz sand with some shell hash.

Tidal Zonation.

Several investigators have attempted to delineate the sandy beach into tidal zones (Dahl, 1953; Pratt, 1973). Leber (1977) adapted a scheme from Wade (1967) that consisted of spray, damp, wash and surf zones. This scheme has been refined further to facilitate sampling in the intertidal zone. These zones are defined and briefly described below (See Fig. 4):

(a) Upper Beach - The area between the high tide mark left from the previous high tide and the primary dune. This area is inhabited mainly by ghost crabs, *Ocypode quadrata*; talitrid amphipods, *Talorchestia megalocephala*; insects; and a few pioneer plants such as sea rocket, *Cakile edentula*.

(b) High Tide Drift Line - A band of detritus that marks the highest point to which the preceding high tide advanced. It does not harbor a specific fauna; however, many organisms such as amphipods, ghost crabs, insects, and birds visit the area in search of food.

(c) Wet Zone - The area between the high tide drift line and the saturated zone where the sand remains moist between high tides. An amphipod, *Haustorius canadensis*, and a polychaete worm, *Scolecopsis squamata*, can be found here most of the time. In addition, coquinas, *Donax variabilis* and *E. talpoida* can sometimes be found in the wet zone during late summer.

(d) Saturated Zone - The area between the wet zone and the swash zone where the sand remains saturated with water. Biotically it is a depauperate version of the swash zone, but there is no feeding here by the secondary producers.

(e) Swash Zone - The area of the beach alternately covered with water by wave uprush and exposed to air by wave downrush. It is the most biologically active zone on the beach. Every organism found on the beach can be found in the swash zone during some phase of the tide or time of day; however, the dominant organisms here are *E. talpoida* and *Donax* spp.

(f) Surf Zone - The surf zone was defined as that part of the beach between the waterline and the breakers that remained submerged during sampling. This is the zone where feeding by offshore migrating consumers is most prevalent. (Because of the difficulty of sampling in the surf zone, samples were obtained by wading rather than by using a boat. Thus, samples were taken only from the shallow part of the surf zone.)

III. PHYSICAL CHANGE RESULTING FROM NOURISHMENT

Deposition of an estimated 1.18 million cubic yards of dredged materials onto the beach at Port Macon began in December 1977. Nourishment continued, with several interruptions, until June 1978. Nourishment materials were obtained from the deepening and widening of the Morehead City State Port Harbor. The dredged material was obtained by the use of a cutterhead placed in the

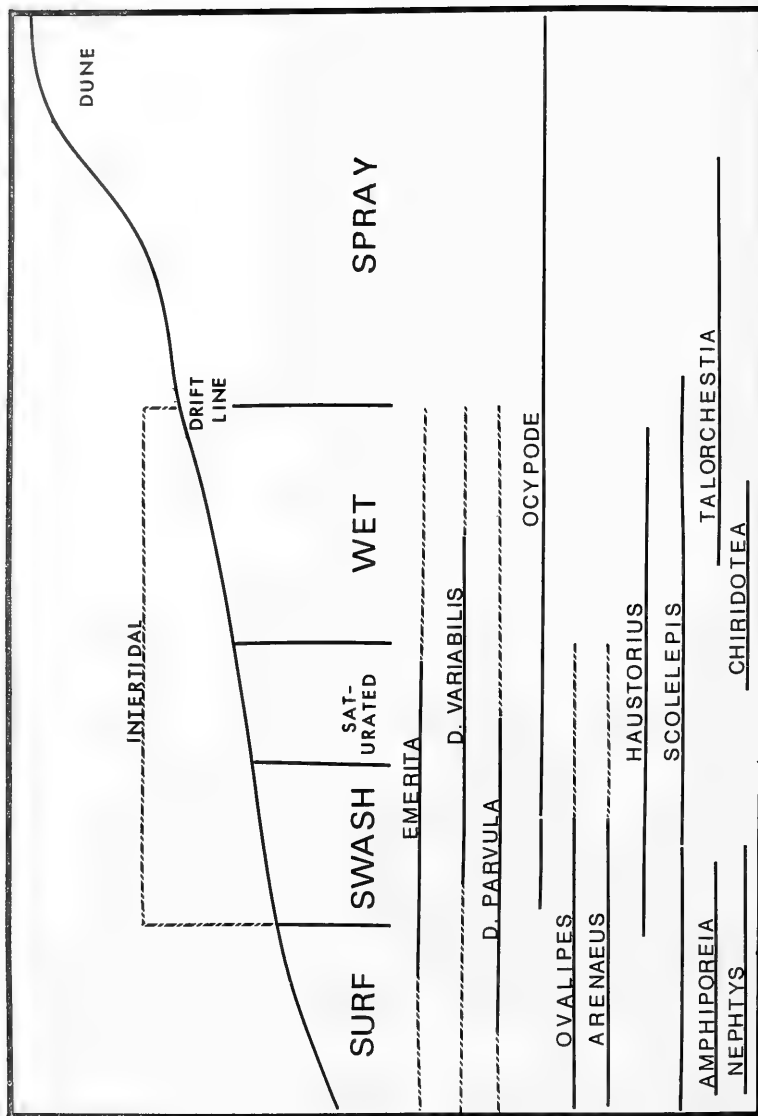


Figure 4. Tidal zonation of sandy beach macrofauna. (Solid lines indicate the zones most frequently used by a given species and broken lines indicate the zones used less frequently.)

channel. Sediment was pumped as water slurry via a pipeline across the island to the beach. Figure 5 is a map showing the nourished area and the pipeline route. The sediment-water slurry was released alternately from one of two diffuser heads branching from the end of the pipeline. Figure 6 shows the sediments coming from the diffuser head.

The material deposited by the pipeline consisted of harbor sediments. These sediments were generally gray to black, indicating that they came from a reducing environment. Park rangers reported at times the smell of hydrogen sulfide (a product of anaerobic respiration).

A series of corings of the harbor sediments were obtained before nourishment by Alpine Geophysical Associates, under contract to the U.S. Army Engineer District, Wilmington (U.S. Army Engineer District, Wilmington, 1976). An analysis of these cores revealed that the average grain size of the sediments was slightly larger than that of Fort Macon beach. However, a much larger proportion of fossil shells and fossil shell hash was present in the nourishment material than was originally present on the Fort Macon beach. Coarser material was quickly sorted out of the intertidal zone and deposited farther up on the beach by tidal action. Concentration of coarse materials on Fort Macon beach is shown in Figure 7.

At times a high proportion of the materials being deposited came from clay lenses. This material was formed into large numbers of clay balls by the action of the pipeline. These clay balls remained on the beach until they were worn down either by drying and fracturing or abrasion in the surf zone (Fig. 8).

Nourishment extended the original width of the beach an average of about 75 meters. This caused the beach slope in the intertidal zone to increase from 3 to 5 percent. Following nourishment the eastern half of the beach exhibited a 0.2- to 1.5-meter-high scarp located where the highest high tide since nourishment had scoured. This scarp moved and changed shape and size daily in some places but remained a persistent feature of the beach for several months following nourishment.

IV. METHODS

1. Fieldwork.

The beach at Fort Macon was monitored from January 1977 to September 1978. Quantitative biological samples were collected twice monthly from the intertidal zone at Fort Macon between June 1977 and September 1978. Quantitative biological samples from the intertidal zone of the comparison beach at Emerald Isle were taken twice monthly between September 1977 and September 1978. Sample collecting was timed to coincide as nearly as possible with low tide.

a. Physical Measurements. Water and air temperatures were measured at each beach using a centigrade glass mercury thermometer whenever samples were collected. Temperatures were recorded to the nearest 0.5° Celsius. At the same time, windspeed was measured using a Simms Electronic Anemometer (model number BT), and salinity was measured using an American Optical Goldberg refractometer. Wind direction and wave height of the surf were estimated. On two occasions beach slope was measured in the intertidal zone using a tape measure, meter stick, and carpenter's level. Several replicate profiles at different locations on each beach were measured on each of these occasions.

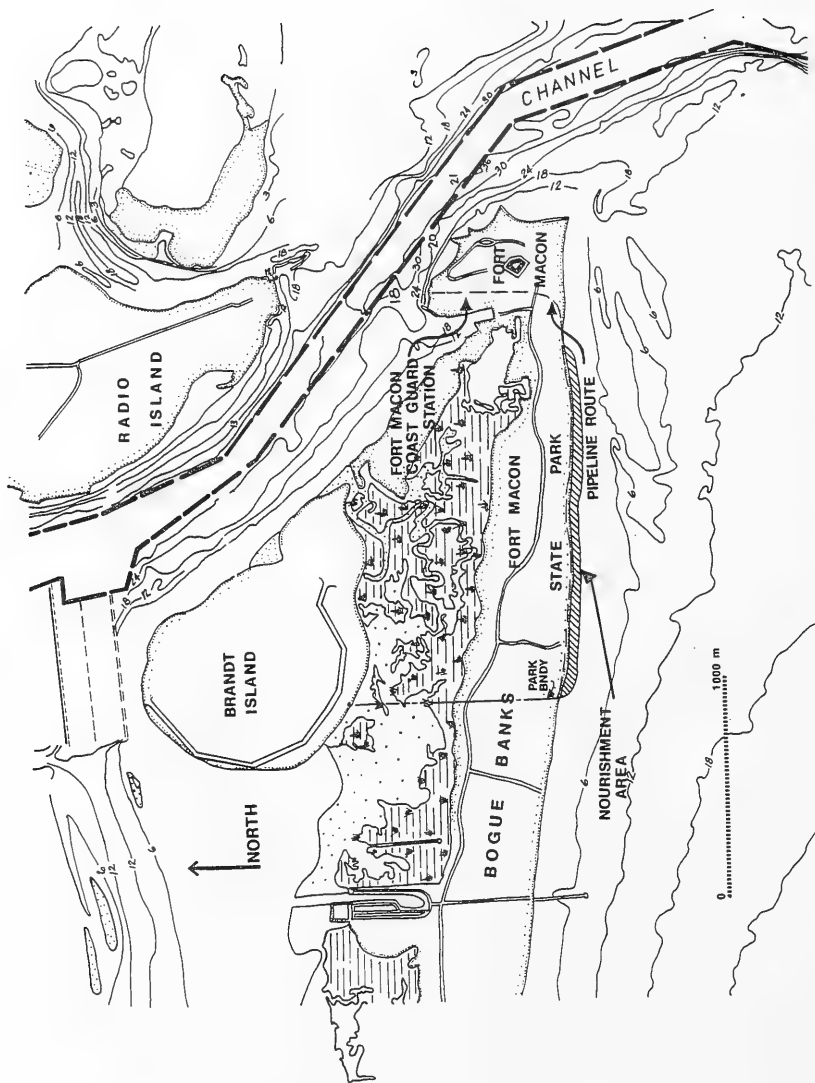


Figure 5. Fort Macon State Park and surrounding area showing the nourished beach area and the pipeline route. Depth contour lines are expressed in feet below mean sea level (MSL).



Figure 6. Sediments coming from the diffuser head at the beach end of the pipeline. (Compare with Fig. 2 which shows the same general area before nourishment.) This photo was taken facing southeast from a point located where the jetty had existed in front of the Fort Macon bathhouse and parking area. The public bathing beach is in the background.



Figure 7. Upper beach at Fort Macon showing the high proportion of fossil shell material present on the postnourishment beach. This photo was taken facing southwest along Fort Macon beach about 1000 meters north of the public bathing beach.

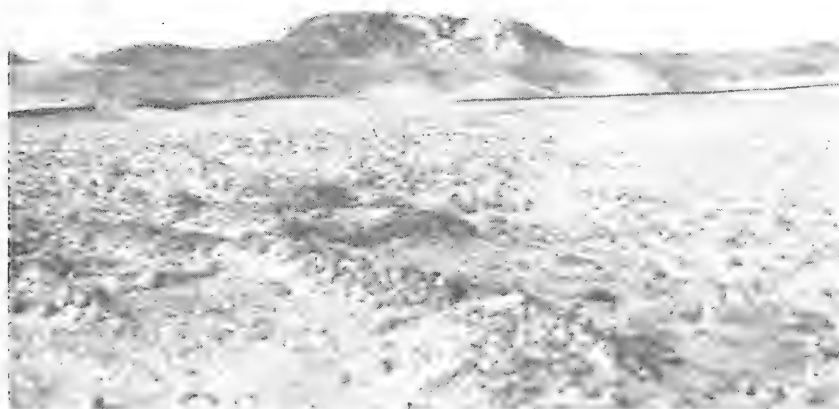


Figure 8. The beach at Fort Macon showing the balls of clay deposited during nourishment with materials dredged from Morehead City Harbor. This photo was taken facing northwest toward the dunes at Fort Macon beach. An abandoned World War II coastal observation station is shown in the dune at the back of the photo.

b. Biological Sampling. Three main strategies were employed to obtain biological samples: (1) Epipsammic microalgal communities occupying the beaches were sampled and identified during four sampling periods. (2) Quantitative sampling of intertidal macrofauna was carried out twice monthly during daylight hours at both beaches. (3) At night, a semiquantitative transect method was employed at the Fort Macon beach to evaluate the interaction between the intertidal, supratidal, and subtidal systems.

(1) Intertidal Microalgal Sampling. The intertidal flora of the study beaches was sampled during the spring, summer, and fall of 1977, and during the winter of 1978. The spring sample of 1977 was obtained by coring to a 3-centimeter depth with a 7-centimeter-diameter plastic coring device. The cores were taken at 5-meter intervals on a sunny morning at low tide along a transect from the previous high tide mark to the surf zone. At least one sample was taken from each tidal zone (wet, saturated, swash, and surf; see Fig. 4). The samples were placed in plastic bags and transported to the laboratory for microalgal analysis.

The summer, fall, and winter samples were also taken on sunny mornings at low tide to evaluate the diatom populations. However, rather than using a corer, 1.0-meter-long troughs were scraped from the top 0.5 to 1.0 centimeter of sand in a strip 2 centimeters wide. The troughs were dug 4 meters apart along a transect from the previous high tide mark to the swash zone. The troughing method did not lend itself to sampling in the surf zone, so the surf zone sampling was abandoned. The change in method was intended to increase the amount of surface area sampled while still keeping the sample size manageable. The sand surface has been reported to harbor the greatest amount of microflora (Meadows, 1965).

(2) Intertidal Macrofauna Sampling. Intertidal macrofaunal sampling consisted of collecting a series of sediment cores which included organisms. These samples were then sieved in the field using a 1-millimeter mesh box sieve. The organisms were then handpicked and preserved with 10 percent glycerin, 45 percent ethanol, and 45 percent water mixture for transport back to the laboratory.

Sampling was quantitative. An experiment was performed (in triplicate) to determine the optimum sampling effort with respect to core diameter and number of cores taken. Three different coring devices were tested: a 5-centimeter inside diameter (i.d.) clear plastic coring tube, a 10-centimeter i.d. aluminum coring tube, and a square wooden box that was 31.4 centimeters on a side. Core samples were taken to a 15-centimeter depth in the sand. The effect of putting several cores in one sieve box and treating them as one sample was also tested. The effect of combining the cores was tested for 1, 5, and 10 cores of the 5-centimeter size and 3 cores of the 10-centimeter size.

Results of those experiments are given in Figures 9, 10, and 11. Figure 9, which shows the average number of species collected per sampling effort, indicates that the optimum sampling effort (the greatest number of species obtained with the least work) is ten 5-centimeter cores treated as one sample. Figure 10, however, shows that the average number of organisms continues to increase sharply from ten 5-centimeter cores to three 10-centimeter cores. Indexes of community stability are shown in Figure 11. These values take into account not only the number of organisms and species, but also the number of organisms of

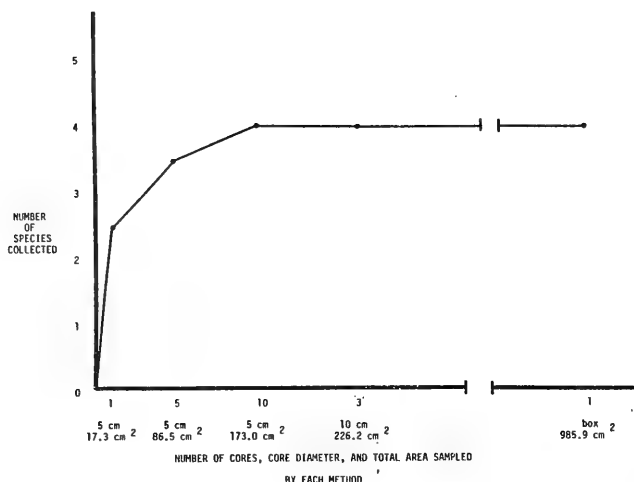


Figure 9. Average number of macrofaunal species collected per sampling effort using various sampling devices (5- and 10-centimeter cores and a box). The numbers next to the X-axis represent the number of cores treated as one sample; the number just below is the interior diameter of the coring device; and the bottom number is the total surface area sampled. All cores were taken to a depth of 15 centimeters.

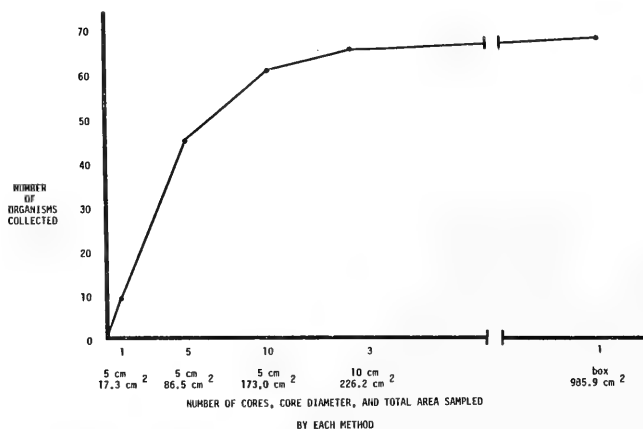


Figure 10. Average number of macrofaunal organisms collected per sampling effort using various sampling devices (5- and 10-centimeter cores and a box). The numbers next to the X-axis represent the number of cores treated as one sample; the number just below is the interior diameter of the coring device; and the bottom number is the total surface area sampled. All cores were taken to a depth of 15 centimeters.

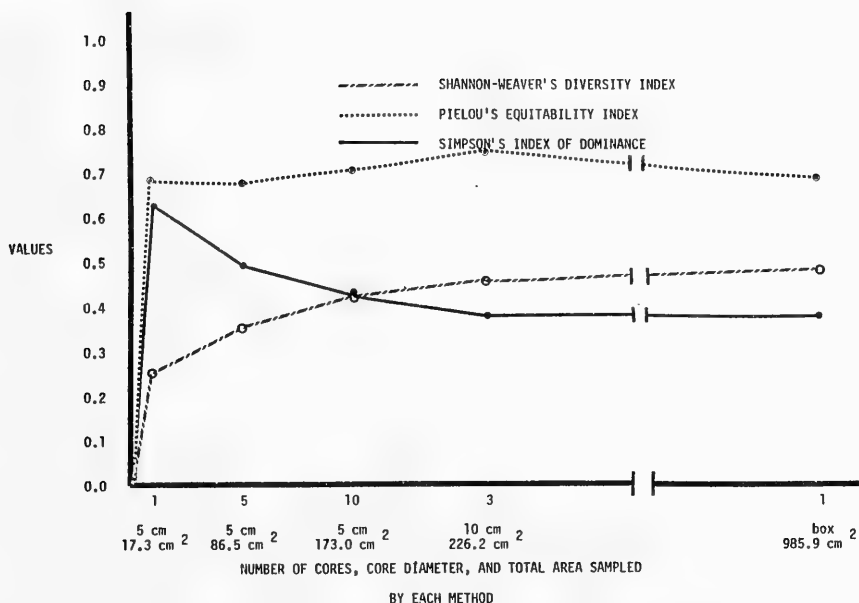


Figure 11. Measures of macrofaunal community structure per sampling effort using various sampling devices (5- and 10-centimeter cores and a box). The numbers next to the X-axis represent the number of cores treated as one sample; the number just below is the interior diameter of the coring device; and the bottom number is the total surface area sampled. All cores were taken to a depth of 15 centimeters.

each species. Figure 11 shows no change after three 10-centimeter cores for Simpson's (1949) Index of Dominance, and little change for Shannon-Weaver's (1963) Index of Diversity or Pielou's (1966) Index of Equitability. Since the box method was unwieldy in the swash zone, impossible in the surf zone, and very time consuming, the method of sampling selected was three 10-centimeter cores taken to a depth of 15 centimeters and treated as one sampling unit. Coring was chosen over other sampling methods such as trenching because cores represent discrete sampling units and make statistical analysis more meaningful (Cox, 1976).

Figure 12 represents a schematic cross section of a typical sandy beach. The X-axis indicates distributional variations perpendicular to the waterline and is usually related to tidal flux. Faunal zonation due to tidal influence has been well documented by Dahl (1953), Cox (1976), and Leber (1977). Therefore, each tidal zone was sampled in order to establish a complete concept of the distribution of the macrofauna and any changes that may occur with time or changing beach configuration.

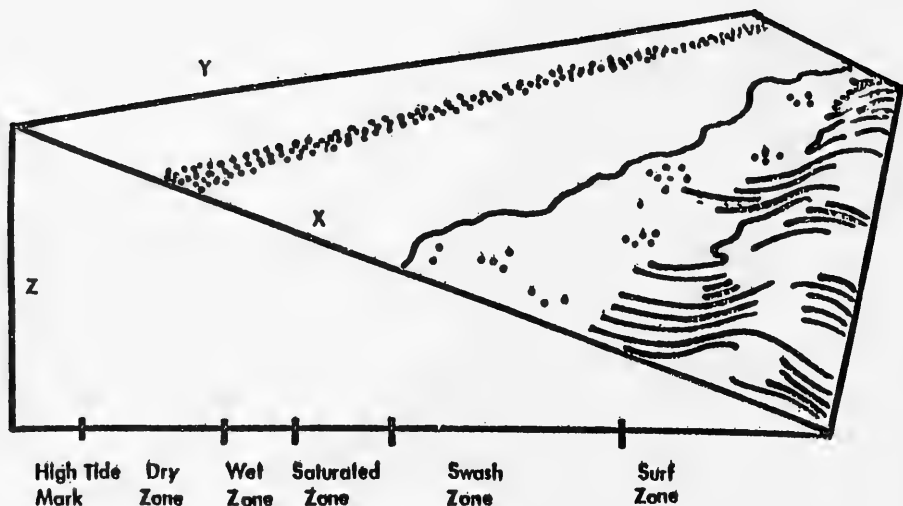


Figure 12. Components of possible spatial variation in macrofaunal distributions on a sandy beach (tidal zonation, X-axis; parallel to the waterline, Y-axis; and depth, Z-axis).

Slight distributional variation with depth (Z-axis) is evident. Macrofauna is generally located entirely within the top 10 centimeters of beach substrate. All cores were, therefore, made to a constant depth of 15 centimeters. At no time during this study did any animals exhibit an avoidance reaction to the coring devices.

Variation in distribution patterns along the length of the beach (Y-axis) also occurs. Such variation has been well documented (Meadows, 1965; Saloman, 1976; Matta, 1977; Leber, 1977), although its cause has been disputed. Some claim that aggregations of macrofauna result from purely physical factors (Dillery and Knapp, 1970). Regardless of the cause of this variation sampling was performed at several transects along the beach in order to minimize the effects of such aggregations.

On any given sample date transects were selected by use of a random number table. All numbers not corresponding to actual beach coordinates were discarded. The random number was then paced out in meters along a base line established parallel to the waterline. When the designated transect point was reached, one sample unit (three 10-centimeter cores) was taken from each tidal zone (high tide mark, wet, saturated, swash, and surf zones; see Fig. 4) along the transect from the high tide drift line to the surf zone. On each sample date three transects were worked on each beach. This number of transects allowed a good statistical evaluation and represented about the maximum amount of work that could be performed during the time when the tide was low enough to allow access to the intertidal zone.

Temporal and seasonal variations in macrofaunal distribution on the sandy beach have been described by Holland and Polgar (1976), Matta (1977), and Leber

(1977). Sampling was begun in January 1977 and continued until September 1978, well after the nourishment actually took place. Sampling was performed every 2 weeks because this regime coincided with a tidal cycle in which low tide occurred during daylight hours.

(3) Night-Migrating Consumer Sampling. Approximately every 2 weeks, usually on the same day as the macrofaunal sampling, two transects were observed on the Fort Macon beach. Each transect was 500 meters long and parallel to the waterline. The transects always covered the same beach segment and their beginning and end were marked by posts driven into the primary dune. This was done to observe and enumerate on a semiquantitative basis the migrating consumers that visited the intertidal zone at night to feed. The enumerating procedure was as follows: A fluorescent camp lantern was suspended from the neck of the investigators who then walked each transect, counting all the animals in the field of vision covered by the light. A representative sample was captured using a hand net, but animals were not chased out of the field of vision. As individuals were encountered, they were enumerated using a hand-operated counting device.

The first transect was walked at or near the high tide drift mark left by the preceding high tide. This transect was established primarily to measure the influx of ghost crabs, *Ocypode quadrata*, and talitrid amphipods.

The second transect was walked in the surf zone at a water depth of 20 to 50 centimeters, where the bottom could be viewed clearly. On this transect mainly portunid crabs and fish were observed, but ghost crabs were occasionally encountered. Crabs and fish were taken whenever possible, and crabs were enumerated even when not caught. It was generally impossible to enumerate the numerous fast-moving fish; however, when fish were taken, their gut contents were examined and identified.

2. Laboratory Work.

a. Biological Methods.

(1) Analyses of Microalgal Samples. Several different methods of analysis were tried to obtain results. None of them produced any organisms for study. The first set of samples taken during the spring of 1977 was placed in finger bowls in the laboratory. Glass microslide cover slips were placed on the surface of each sample. Each sample was then covered with 0.5 centimeter of filtered seawater. The following morning one cover slip from each sample was removed, dried on a hotplate, and ashed in a muffle furnace at 450° Celsius for 1 hour. The cover slips were then mounted, using HyraxR mounting medium, and viewed under several magnifications including oil immersion. On the second and third days another cover slip was removed and the process repeated.

The second set of samples taken during the summer of 1977 was first swirled with freshwater and decanted to remove free-swimming or epipelagic forms (Round, 1965). Each sample was then placed in a finger bowl. Two cover slips were placed on the surface and, in addition, small pieces of lens tissue were placed on each sample. The lens tissue was later teased apart under magnification and searched for diatoms or other algae. After removal of the last cover slips, the samples were stained with a vital stain (rose bengal) and individual sand grains were examined using a microscope.

The third set of samples taken during the fall of 1977 was washed in filtered seawater and decanted as before. Cover slips were used as before. After the last of the cover slips were processed, 10 grams of each sample was placed in 50 millimeters of acidified distilled water. Each sample was then sonicated using an E/MC Corporation Sonicator (model No. BP-1) according to the procedure described by Hickman (1969). Both the sand and the elutriate from each sample were examined. The sand was examined as before, and the elutriate was added drop by drop to individual cover slips on a hotplate and allowed to dry. The cover slips were then cleared and mounted as before, and observed under magnification.

The fourth and final samples taken during the winter of 1978 were not washed as in sample sets 2 and 3. Cover slips were placed on the surface of each sample, and again sand grains were examined. Additionally, a second set of cover slips was left in place for 2 weeks before processing. During this time, the samples were exposed to a 12/12 light-dark cycle with light provided by four 40-watt Gro-lux^R fluorescent lamps.

(2) Intertidal Macrobenthos Methods. Identifications were made with the aid of several taxonomic references (Pettibone, 1963; Williams, 1965; Schultz, 1969; Gosner, 1971; Bousfield, 1973; Gardiner, 1975). Identification of the species in the genus *Donax* was made by H. Porter (University of North Carolina, Institute of Marine Science, Morehead City, North Carolina, personal communication, 1977).

Specimens were counted and measured to the nearest 0.1 millimeter (except worms, which were not measured). *Donax* spp. and *Emerita* were divided into size classes according to length. For *Donax* spp., length was defined as the longest anterior-posterior distance. For *E. talpoida*, length was measured from the tip of the rostrum to the posterior end of the carapace.

(3) Migrating Consumer Methods. Gut contents were examined for all fish taken and identified to the extent possible, labeled, and preserved. All crabs taken were identified, using the monograph of Williams (1965), and measured (carapace width from point to point).

b. Statistical Methods. The experimental design of this project allowed all parametric data (population and density estimates) to be analyzed using a nested analysis of variance. Several measurements of community structure were employed:

Shannon-Weaver's Diversity Index (Pielou, 1966)

$$H^1 = - \sum_{i=1}^S P_i \log P_i$$

where P_i is the proportion of individuals of the i^{th} species.

Species Richness Index (Pielou, 1969)

$$H_{\text{max}} = \log S$$

where S is the number of species present.

$$J = H^1/H_{\max}$$

Dominance Index (Simpson, 1949)

$$C = (n_i/N)^2$$

where n_i is the importance value (number of individuals, biomass, etc.) for each species. N is the sum of all the importance values.

3. Special Methods During Nourishment.

a. Physical Methods. During the nourishment operations, replicate 1-liter grab samples of water were taken from the comparison beach at Emerald Isle, from the jetty in front of the bathhouse at Fort Macon, and from the flume of the diffuser head. These samples were collected in acid-washed Nalge^R bottles, iced, and transported to the laboratory. In the laboratory, the samples were filtered using oven-dried and weighed Gellman AE glass-fiber filters. The filters with residue from the filtration were again oven-dried and weighed to determine the total suspended solids load in the water column.

The filtrate was preserved with hydrochloric acid, refrigerated, and saved for metals analysis. Each of the replicates was split. Part of the split was analyzed by Dr. J. Bray, East Carolina University (ECU) School of Medicine, using a Jarrell Ash Atom Comp (Inductively Coupled Argon Plasma Emission Spectrometer). Another part of the split was analyzed by M. Jones, ECU Department of Biology's Water Quality Laboratory. This part was run both with and without background correction on a Perkins Elmer Atomic Absorption Spectrophotometer in the flame mode. Samples were analyzed on both machines, using the method of additions for cadmium, copper, iron, lead, and zinc.

b. Biological Methods. During the nourishment procedure, additional quantitative intertidal macrobenthic samples were taken both from the nourished area and from the unnourished area (that area not yet reached by the nourishment procedure) at Fort Macon. This method allowed the comparison of the nourished areas with a valid control rather than simply the comparison beach at Emerald Isle.

A sampling regime was established to record the recovery rate of the post-nourishment beach. A fixed point was marked 1070 meters from the western boundary of the park. This point was the site of a fixed transect. This transect was sampled just like the other quantitative transects. Sampling was begun on 19 March 1978, the day this segment of beach was first nourished, and continued every 2 weeks till the end of the monitoring project.

V. RESULTS AND DISCUSSION

1. Summary of Physical Data for Study Sites.

Seasonal variations in air and water temperatures for both beaches are given in Figures 13 and 14. Generally, water temperatures lagged behind air temperatures and never quite reached the extremes that the air temperatures reached. The range of measured air temperatures was 1° to 34° Celsius. Water temperatures ranged from 5° to 33° Celsius.

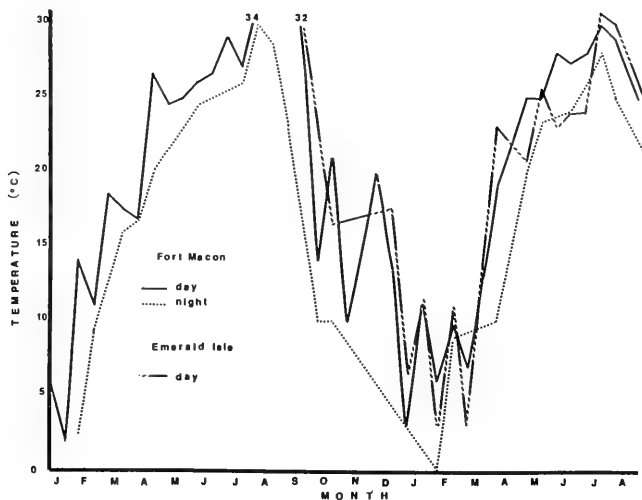


Figure 13. Air temperatures at Fort Macon and Emerald Isle beaches, January 1977 to September 1978.

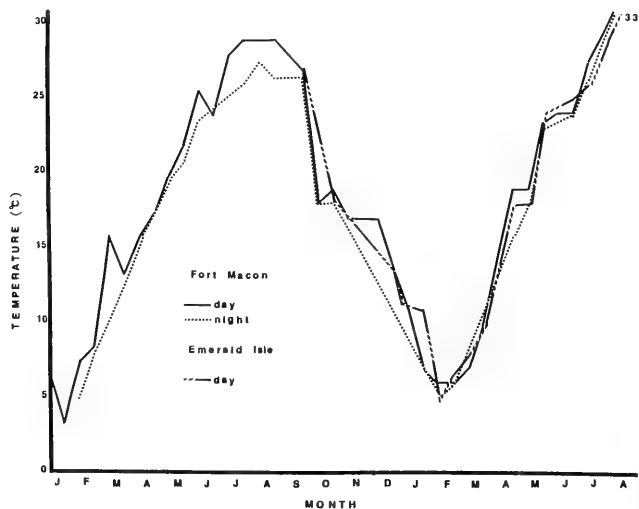


Figure 14. Water temperatures at Fort Macon and Emerald Isle beaches, January 1977 to September 1978.

Salinities at both beaches were similar. They were lower (averaging around 33 parts per thousand) in late winter, and higher (ranging between 36 and 38 parts per thousand) during summer. In February and March 1978, while nourishment was in progress, salinities at Fort Macon reached their lowest (27 parts per thousand). This compares with a salinity of 30 parts per thousand at Emerald Isle during this time. It could not be determined whether this decreased salinity was due to the close proximity of Fort Macon beach to Beaufort Inlet or the nourishment activities.

2. Summary of Analyses of Microalgal Communities.

Large numbers of living microalgae were never recovered from beach sediments by any of the methods tried. No diatoms were located on any of the cured cover slips, not even cover slips prepared with the elutriate after sonication. In fact, the only living microalgae seen during these observations were a few naviculoid diatoms noted on one cover slip before it was cured. These few diatoms were lost during the curing procedure and could not, therefore, be identified to species.

Results of these observations indicate that the epipsammic diatom population of these two beaches was very low and was of minor consequence as a food energy source for the beaches. These results confirm the reports of others who have attempted to quantify the productivity of epipsammic diatoms on ocean beaches. Cox (1976) reported that most sandy beaches on exposed coasts support a mesopsammic (or interstitial) community and that the biomass of this community is low compared to most other littoral and sublittoral systems. Steele and Baird (1968), in their studies of production ecology on a sandy beach in Scotland, reported that the sublittoral part of a sandy beach produced only 4 to 9 grams of organic carbon per square meter per year. Production on the intertidal portion of the Scottish beach was only measured once, but the resulting value was so low that they terminated that part of their studies. Leach (1970) found sand to be the least productive substrate in the Ythan estuary, and estimated its organic carbon production at less than 5 grams per square meter per year.

Even though Steele and Baird's (1968) production estimates were low, they found viable populations of diatoms to a depth of 20 centimeters, well below the euphotic zone for sand. Amspoker (1977) found interstitial diatoms on the beach at La Jolla, California, to be unstratified and uniformly distributed with high diversity. Both sets of researchers attributed the observed distribution of the diatoms to the constant sorting and mixing of wave action.

Neither Amspoker (1977) nor Steele and Baird (1968) gave any indication of the concentration of interstitial diatoms; however, Steele and Baird (1968) did state that the amount of organic carbon under 1 square meter of sand (to a depth of 20 centimeters) was 50 grams, 40 percent of which were diatoms. Thus, the total production available for cropping was only that part of the 20 grams of plant material that could be taken without causing the plant population to become depleted.

Both Amspoker (1977) and Steele and Baird (1968) obviously found more diatoms than were found in this study. It may be significant that their studies took place on beaches that were slightly more sheltered than the beaches at Bogue Banks. Additionally, their beaches were at the base of fjords that were

backed by steep cliffs, while the present study took place on a barrier island of low relief. These factors may have influenced the diatom populations somewhat.

Quantification of the algal community indicated its population was small, leading to the conclusion that it is of minor consequence as a food energy source for the beaches studied.

3. Summary of Analysis of Data from Migrating Consumers.

a. Migrating Consumers from the High Tide Drift Line. Two organisms were observed commonly along the high tide drift line. *Talorchestia megalopthalma*, talitrid amphipods, were encountered sporadically, but never in great numbers. This amphipod seemed to be more prevalent during times when the normally dominant ghost crabs (*Ocypode quadrata*) were absent.

Ghost crabs were the most prevalent higher order consumer above the swash zone except during winter when they remained quiescent in their burrows. The density of ghost grabs increased as temperatures rose in spring (Fig. 15). The peak pre-nourishment population estimate of 280 crabs per linear kilometer of beach occurred in July 1977. Counts gradually decreased until winter when the crabs became quiescent.

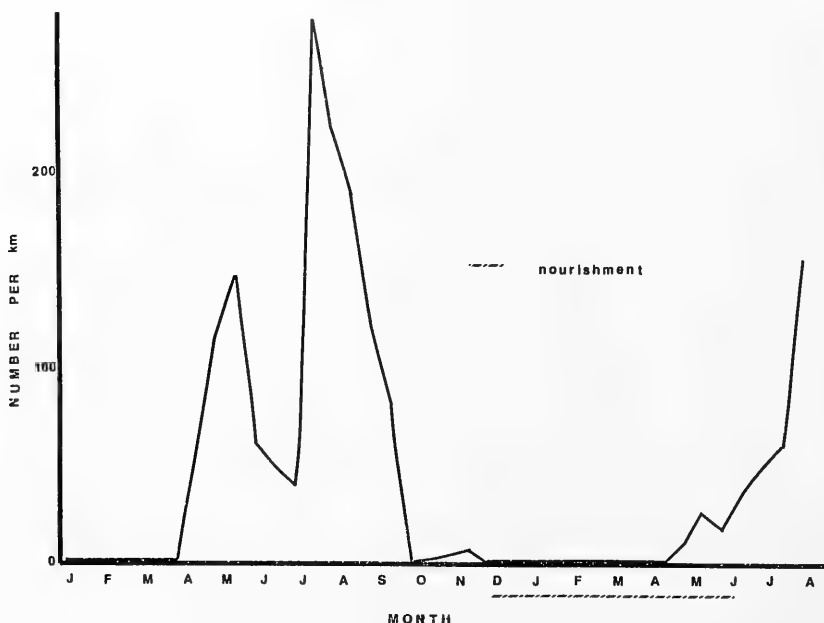


Figure 15. Annual pattern of ghost crab (*Ocypode quadrata*) abundance at Fort Macon, January 1977 to August 1978.

The emergence of ghost crabs from their burrows seemed to be keyed more to temperature than to season. Figure 16 plots the number of ghost crabs found against temperature. It is obvious from this figure that ghost crab activity is triggered when temperatures reach about 15° Celsius. Landy (1977), using controlled temperature chambers, has established that the critical temperature is 16° Celsius. The fact that temperature serves as the activity trigger rather than day length or some other seasonal factor is borne out by the fact that ghost crabs were found on a particularly warm night in early December 1977 after several weeks of inactivity (Fig. 15).

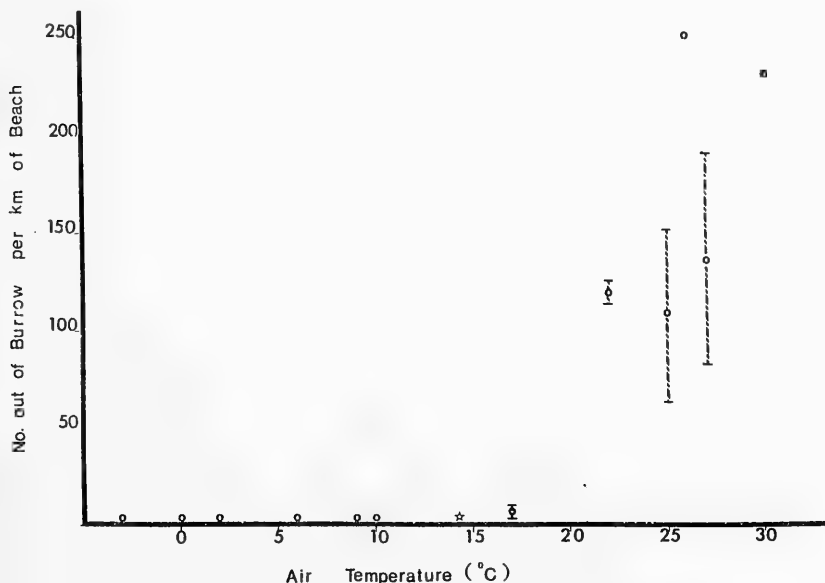


Figure 16. Ghost crab (*Ocypode quadrata*) densities at Fort Macon as they correspond with air temperature. Points are represented by small circles. No activity was recorded at temperatures below 15° Celsius. At 15° Celsius burrow activity was evident (noted by a star) but no crabs were seen. The study was repeated three times, and the points in the center of slashed vertical lines represent the mean number of crabs. The lines represent the range.

Density of ghost crabs was depressed following nourishment. The postnourishment summer population peak was nearly 50 percent lower and came nearly a month later than the peak the summer before nourishment (Fig. 15). This would seem to be a significantly greater difference than can be explained by the simple yearly variation. The mechanism responsible for the decrease is not clear, but one of the following seems likely:

- (1) The ghost crabs could have been buried in their burrows during their winter dormancy period.

(2) The pipeline used to carry the sediments to the beach ran parallel to the base of the dunes and could have acted as a physical barrier to the crabs' movement to the beach, thus preventing them from acquiring needed food and water.

(3) Spring recruitment to the ghost crab stock from pelagic sources could have been prevented by the increased load of suspended solids in the surf zone during nourishment.

(4) Ghost crabs may have emigrated from the area in response to lowered densities of their major prey species, *E. talpoida* and *Donax* spp.

It is not likely that the crabs would be severely affected by the direct deposition of beach nourishment materials. Most overwintering burrows lay beyond the nourishment zone and thus would not have been covered by the nourishment. Ghost crabs that were buried would probably have been able to dig through the material to the surface since burrows are probably covered naturally by winter storms.

Leber (1977) and Wolcott (1978) have established that the normal behavior of ghost crabs is to emerge from their burrows in the upper dunes at dusk and then move down to the swash zone to moisten their gills and feed. The pipeline (the route shown in Fig. 5) could have acted as a physical barrier to the active ghost crabs; however, several nighttime surveys of the pipeline did not reveal aggregations of trapped ghost crabs. Instead it was discovered that windblown sand had provided a natural bridge over the pipeline in many places, while elsewhere the crabs had simply tunneled under the pipe. Numerous crabs were encountered during these surveys, and several were observed to escape over the pipeline with no difficulty when they were frightened. These factors, coupled with the fact that ghost crabs were collected at the high tide drift line, seemed to indicate that the pipeline did not act as an effective deterrent to ghost crab nocturnal activities.

Insufficient information concerning the ghost crab breeding cycle is available to postulate whether the turbidity associated with nourishment may have prevented ghost crab larvae from pelagic sources from colonizing the beach. In fact, very few larvae were collected during the entire study and none were found following nourishment. (Those found were usually taken during corings.)

A plausible explanation for the decreased number of ghost crabs on the nourishment beach is that the crabs left the area in search of food. Ghost crabs have been reported to travel great distances in a single night in search of food (Wolcott, 1978). Their major food source during warm weather is *E. talpoida* and *Donax* spp., and populations of these were severely reduced during and after the nourishment.

b. Migrating Consumers of the Surf Zone. Migrating decapods found in the surf zone were: speckled crabs, *Arenaeus cribrarius*; the lady crab, *Ovalipes ocellatus*; the ghost crab, *Ocypode quadrata*; and the blue crab, *Callinectes sapidus*. The blue crab was found infrequently and never represented by more than one individual per transect. The speckled crab was reported as the most important surf zone decapod by Leber (1977) and by Anderson, et al. (1977); but at Fort Macon its abundance was markedly lower than that of the lady crab.

The first appearance of the three portunid crabs appeared to be linked to water temperatures rising above 16° Celsius; however, the numbers varied widely throughout the year (Fig. 17). The cause of this variation was not clear. Certainly some variation was related to difficult collecting conditions (in turbid waters the crabs are difficult to see), but steepness of the beach slope, grain size, food availability, predation, and current velocity are also possible controlling factors.

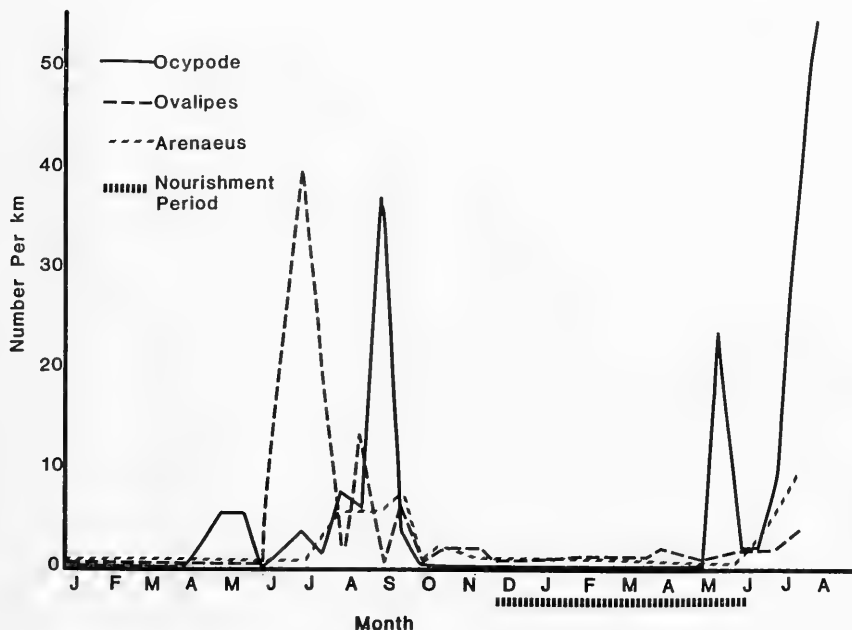


Figure 17. Densities of *A. cribrarius*, *O. ocellatus*, and *O. quadrata* in the surf zone at Fort Macon, January 1977 to August 1978. The slashed line below the X-axis represents the actual duration of the nourishment.

Regardless of what factors normally control the densities of these three species of surf zone consumers (*O. ocellatus*, *A. cribrarius*, and *C. sapidus*), the nourishment at Fort Macon severely reduced their abundance. Collections during nourishment were more difficult due to increased turbidity and greater beach slope and could have prevented detection of some crabs. However, poor collecting conditions are not believed to fully explain the low numbers observed because, even after nourishment had ceased and collecting conditions had improved, the number of crabs present remained markedly lower compared to densities recorded before nourishment. Several explanations for the reduced numbers of crabs in the surf zone are possible:

(1) Resident populations of the crabs in the nearshore could have been buried or forced to leave the area in response to greater turbidity associated with the nourishment procedure.

(2) Changes in the offshore bar system and beach slope could make approach to the beach physically difficult or hazardous due to increased exposure to predators.

(3) Reduced availability of prey organisms may have caused the crabs to move elsewhere in search of food.

If the resident populations of these large, highly mobile crabs were destroyed or forced to move as a result of beach nourishment, recruits from Bogue Banks and Shackleford Banks or from pelagic larval stocks would be expected to recolonize soon after nourishment ended. In fact, recruitment from elsewhere did not occur. Population estimates for all portunid crabs remained low even 2 months after nourishment had ceased. Thus, although resident populations of portunid crabs were lost as a result of beach nourishment, some factor other than the direct effects of nourishment prevented rapid recovery.

The beach slope became much steeper after nourishment, and the plunge zone for the waves was often directly adjacent to the swash zone thus making feeding portunids in the swash zone easier prey for nearshore predators. Also, the high concentrations of large shells and shell hash in this zone would have made burrowing by the larger crabs almost impossible. These changes in the surf zone would have produced conditions generally unfavorable to portunid crabs and may have caused them to move elsewhere in search of better habitat.

The most likely explanation for the low density of portunid crabs in the surf zone after cessation of nourishment is that their principal food source (*E. talpoida* and *Donax* spp.) had been severely depleted.

The following young adult fish and fry were encountered in high numbers in the surf zone throughout the study period: silversides, *Menidia menidia*; whiting, *Menticirrhus* spp.; summer flounder, *Paralichthys dentatus*; pompano, *Trachinotus carolinus*; croaker, *Micropogon undulatus*; spot, *Leiostomus xanthurus*; and cravelle jack, *Caranx hippos*. Although the importance of fish as carnivores in the surf zone has been firmly established (Anderson, et al., 1977), the scope of this project did not allow detailed study of these fish. However, more than 100 examinations of gut contents were performed during this study, and all fish examined had either *E. talpoida* or *Donax* spp. present in significant amounts in their stomachs. Leber (1977) has reported similar results for the same study area.

Although a number of ghost crabs were encountered in the surf zone (Fig. 17), their actual feeding activity there was minimal. Most feeding by the ghost crabs occurred in the swash zone and those ghost crabs found in the surf zone were usually wetting their gills.

4. Special Studies During the Nourishment Process.

a. Physical Studies. Rosenberg (1977) reported that one of the effects of dredging was an increase in concentration of mercury, cadmium, copper, lead, nickel, and zinc both in the water column and in the benthic fauna. Three

different methods were employed in the present study to determine the concentration of cadmium, copper, iron, lead, and zinc in the nearshore due to the nourishment activities. Results showed that the levels of these metals never significantly exceeded background levels for seawater (Table 1). That these results do not parallel Rosenberg's (1977) is not surprising in that the drainage system that ultimately provided the sediments for this nourishment project did not contain significant anthropogenic sources for any of these metals.

Table 1. Concentrations of cadmium, copper, iron, lead, and zinc in seawater using a Jarrell Ash Atom Comp (Inductively Coupled Argon Plasma Emission Spectrometer), Perkins Elmer Atomic Absorption Spectrophotometer with and without background correction.

Jarrell Ash Atom Comp						
Metal	Nourishment Pipeline effluent ($\mu\text{g}/\ell$)	Surf zone				
		Nourished beach ($\mu\text{g}/\ell$)		Comparison beach ($\mu\text{g}/\ell$)		
Cadmium	<0.01	<0.01		<0.01		
Copper	<0.02	<0.02		<0.02		
Iron	0.21	0.97		0.02		
Lead	<0.2	<0.2		<0.2		
Zinc	0.03	0.06		<0.02		
Perkins Elmer Atomic Absorption Spectrophotometer with and without background correction						
	With	Without	With	Without	With	Without
Cadmium	<0.02	0.06	---	0.06	---	0.05
Copper	<0.02	0.03	<0.02	0.06	<0.02	0.03
Iron	<0.02	0.7	<0.02	2.7	<0.02	0.7
Lead	<0.5	0.3	<0.5	0.3	<0.5	0.5
Zinc	---	0.04	---	0.1	---	0.04

Total suspended solids load in the nearshore water column was many times that of normal seawater (Table 2). A comparison of the water from the surf zone at Fort Macon with the water from the surf zone at Emerald Isle reveals that on two occasions when the solids were measured, the waters from the nourishment beach held at least an order of magnitude more suspended solids than those of the unnourished comparison beach. High loads of suspended solids have been implicated previously as a cause of larval death during dredging and disposal activities (Mileikovsky, 1970) and were likewise probably responsible for much of the adverse impact of the beach nourishment at Fort Macon.

b. Biological Changes During Nourishment. The beach at Fort Macon was nourished gradually from the eastern end of the study area to the western end. Thus, at any given time during nourishment, the beach at Fort Macon could be divided into a nourished part and an unnourished part. Population data for

Table 2. Total suspended solids during nourishment in the water from the surf zone at Fort Macon, the surf zone at Emerald Isle, and from the nourishment pipeline effluent.

Sample location	Total suspended solids (g/l)	
	Trial 1	Trial 2
Emerald Isle (comparison beach)	0.096	0.086
Fort Macon surf zone (nourished beach)	1.76	4.70
Nourished pipeline effluent	34.18	15.03

E. talpoida and measures of community structure could then be compared for the two sections (Figs. 18 and 19). Thus, direct comparison of recently nourished, longer term nourished, and unnourished beach was possible. This provided a better control than the comparison beach more than 20 kilometers away at Emerald Isle. The densities and Shannon-Weaver indexes for this study are plotted for the three segments of beach (nourished, prenourished or unnourished beaches at Fort Macon, and the control or comparison beach at Emerald Isle) in Figures 18 and 19.

Densities of *E. talpoida* on all three beach segments were of similar magnitude the week before nourishment began. By the end of the first week of nourishment, all *E. talpoida* had disappeared from the nourished zone. They remained absent from this area as well as all subsequently nourished areas throughout the nourishment operations. By comparison the prenourishment beach and the control beach exhibited gradually decreasing numbers of *E. talpoida*. This late winter decline was also reported by Leber (1977) and was considered to be a normal event, unrelated to the nourishment operation. Leber suggested that these animals simply move offshore to overwinter. This suggestion is supported by Saloman (1976) and Matta (1977) who reported increased numbers of psammolittoral organisms during winter in the offshore points of their transects.

Emerita talpoida was not the only organism affected by the nourishment activities. Figure 19 shows the Shannon-Weaver Species Diversity for the three segments of beach. Species diversity is undefined when no organisms are found. No living macrofaunal organisms were ever found on nourished areas of the beach while nourishment operations were in progress. The prenourishment beach and the control beach exhibited the gradual decline in species diversity that was to be expected with the onset of winter.

Under winter conditions, there were no spare adults to colonize the newly formed beach and there were no available larvae to fill the void. The effect of beach nourishment on indigenous populations was profound. All the infauna in the nourished area was probably destroyed and the area did not recover until recruitment from outside occurred.

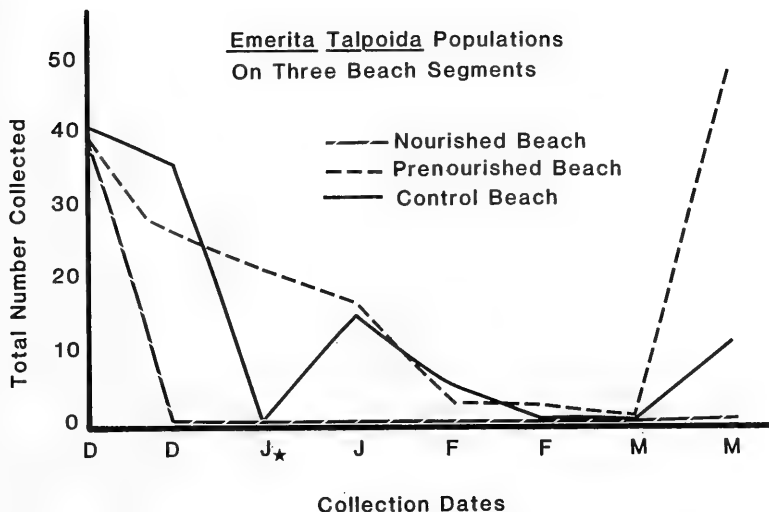


Figure 18. *Emerita talpoida* population densities along three segments of beach during the nourishment period, December 1977 to March 1978. The nourished segment was located in the north-eastern part of Fort Macon and the prenourishment segment was located in the southwestern part of Fort Macon. By March there was no longer any part of the prenourishment segment left because nourishment activities had progressed that far. The control beach was located at Emerald Isle. On the starred date in January no sampling was performed in the surf zone due to rough water. Thus values for that date probably represent lower estimates of organism density than were actually present.

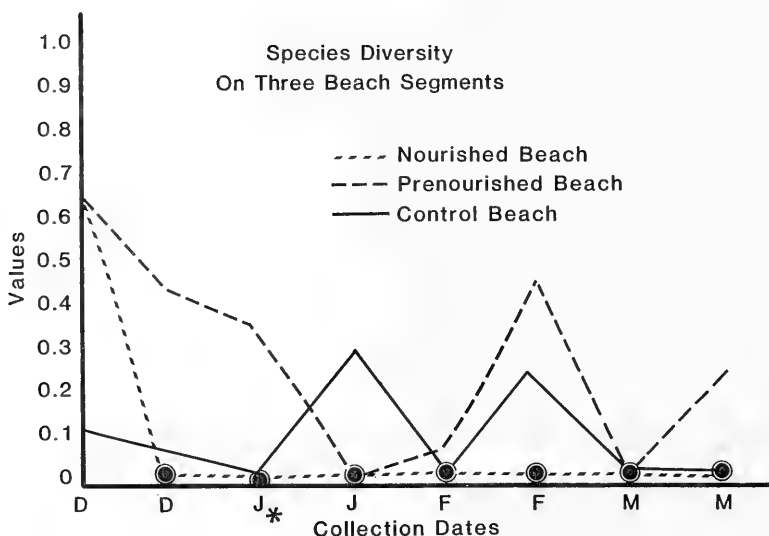


Figure 19. Average Shannon-Weaver Species Diversity on three segments of beach during the nourishment period, December 1977 to March 1978. The nourished segment was located in the northeastern part of Fort Macon and the prenourishment segment was located in the southwestern part of Fort Macon. By March there was no longer any part of the pre-nourished segment left because nourishment activities had progressed that far. The comparison beach was located at Emerald Isle. On the starred date in January, no sampling was performed in the surf zone due to rough water. Thus values for that date probably represent lower estimates of organism density than were actually present. The "bull's-eye" symbol represents periods when species diversity was undefined because no organisms were found.

c. Rate of Recovery. A special study was carried out to determine the rate of recovery of a particular spot on the beach following nourishment. On 19 March 1978, a fixed study transect was established in the center of the beach segment nourished on that day. This transect was located 1070 meters west of the eastern park boundary.

No living organisms were found in any of the tidal zones on the day of nourishment; however, this situation was expected since the entire intertidal macrofauna had just been buried by about 2 meters of sediment and the effective intertidal zone had been transposed 75 meters seaward of its former position. Colonizers would have had insufficient time to become established.

The first recruits to the area arrived between 15 and 30 days after establishment of the study transect. On 16 April *Scolecopsis squamata* were found at the high tide drift line and seven juvenile *E. talpoida* were found in the swash zone. On 14 May only one juvenile *Emerita* was found; therefore, species diversity was 0.00. No organisms were found 29 May; thus species diversity was undefined.

Nourishment activities stopped on 12 June and by 15 June 260 juvenile *E. talpoida* were taken from the swash and surf zones. This number represents an average density of 2,080 individuals per square meter. Species diversity, however, remained 0.00. All these individuals were postmegalops larvae or young juveniles. The fact that they appeared so quickly and in such great numbers immediately after the cessation of the nourishment activities indicates that the increased turbidity (suspended solids load) in the water probably acted as an effective block to larval recruitment.

The first report of an organism other than *E. talpoida* occurred on 29 July 1978, nearly 2 months after the nourishment stopped. On that day 9 juveniles and 1 adult *E. talpoida*; 2 *H. canadensis*; 15 *Donax variabilis*; 6 *Donax parvula*; and 1 *S. squamata* were found. This brought the species diversity up to 0.56 which was actually higher than the average Shannon-Weaver Species Diversity at the Emerald Isle comparison beach. Fort Macon usually had higher diversity estimates before nourishment due to a greater number of species than were present at Emerald Isle. The unnourished comparison beach at Emerald Isle still far surpassed the nourished beach in terms of organism density.

The special transect study was useful because it indicated that the effects of beach nourishment are not limited to the beach. Pelagic larvae were prevented from colonizing the beach. Inhibition of pelagic larval recruitment may have resulted from the high turbidity of nearshore water associated with beach nourishment. However, some *E. talpoida* juveniles were able to overcome this stress and occupied the beach although in lesser density than nearby unnourished beaches. Larval recruitment of *Donax* spp. occurred during nourishment, but because *Donax* spp. larvae were not as fit as the *E. talpoida* larvae, the appearance of this clam on the beach was prevented until a few young adults could colonize. The first clams found on the nourished beach were larger than normal young of the year and were recruited by means of littoral drift from the adult population of a neighboring beach. If nourishment continues beyond a period of larval recruitment, the only mechanism that the beach has for regaining these species before the next year's larval recruitment is via chance diffusion and littoral drift.

d. Edge Effects During Nourishment. Animals near the nourishment activity but not subject to actual burial were also subjected to stress. Three special transects were established in an attempt to evaluate this stress. On 19 March one transect was established near the nourishment activity but outside the area actually receiving materials that day. This special study transect yielded two small *E. talpoida* from the swash zone but no other organisms. This yield was low in relation to the following average densities per transect obtained from the unnourished part of the beach that same day: 16 *E. talpoida*, 1 *H. canadensis*, 2 *D. variabilis*, and 1 *D. parvula*.

Two more special study transects were established on 5 May 1978. By that time nourishment had proceeded to near the park's western boundary. Thus, no "prenourishment" section remained on the Fort Macon beach. The results of these special transects were compared to the data obtained the same day from the unnourished comparison beach at Emerald Isle. The special transects were worked, but no organisms were recovered. An attempt was then made to determine if any organisms were present by carrying out an intensive, nonquantitative digging and sieving effort. No *E. talpoida* were recovered; however, a few *Donax* spp., some amphipods (*H. canadensis* and *T. megalopthalma*), and a small number of *S. squamata* were found. The Emerald Isle comparison beach that day yielded an average of 14 *E. talpoida*, 38 *D. parvula*, 45 *D. variabilis*, 3 *H. canadensis*, 4 *Amphiporeia virginiana*, and 1 *T. megalopthalma* per transect.

This special study is useful because it serves to further implicate the increased turbidity associated with nourishment activities as a prime environmental stress factor during nourishment. This part of the study proves that impacts to the adjacent beach and nearshore waters can be profound, and it demonstrates that organisms in the nourishment area may not always simply move to adjacent unnourished areas during nourishment, as was observed by Dolan (1974) and Hayden and Dolan (1974). Organisms are either killed or they are driven from the nourishment area and its immediate vicinity.

5. Prenourishment and Postnourishment Population Dynamics.

a. *Emerita talpoida*. This common mole crab is the dominant organism on high-energy psammolittoral beaches in North Carolina (Matta, 1977; Leber, 1977). During this study, *E. talpoida* densities reached a prenourishment maximum density of 1,416 individuals per square meter in late summer 1977. At this time, *E. talpoida* completely dominated the swash and saturated zones, and were present in every other tidal zone. The autumn maximum density of 976 individuals per square meter which occurred at Fort Macon, closely matched the autumn maximum recorded at the comparison beach (1,096 individuals per square meter). Both populations declined rapidly as winter approached (Fig. 20).

Nourishment started in December, causing the mole crab population at Fort Macon to fall to zero. Meanwhile, the mole crab population at Emerald Isle continued its steady decline. From the onset of nourishment to April, no crabs were found on the nourished area of the beach (Fig. 18). All crabs reported from the Fort Macon beach during this time were found on the unnourished part of the beach.

Both beaches showed a rapid recovery in mole crab density with the onset of spring (Fig. 20); however, the population at Fort Macon lagged behind that of Emerald Isle by 1 month in April when recolonization began, and by 2 weeks

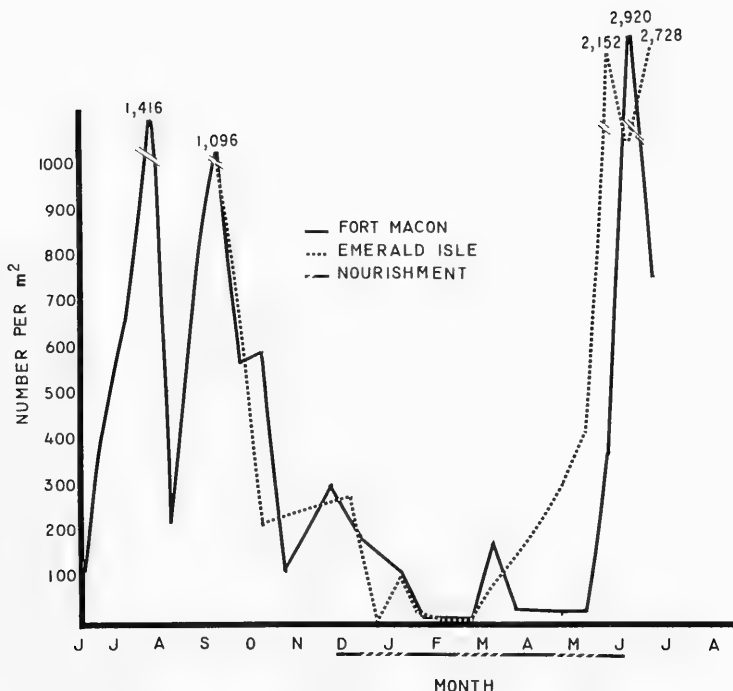


Figure 20. Seasonal variation in the density of *E. talpoida* populations at the nourishment beach at Fort Macon, June 1977 to August 1978, and the comparison beach at Emerald Isle, September 1977 to August 1978. The actual period of nourishment is represented by a slashed line below the X-axis.

in May when repopulation was well underway at both beaches. This recruitment lag resulted from the failure of adult *Emerita* to recolonize at Fort Macon (Fig. 21). Only adult *Emerita* were present on the Emerald Isle beach when repopulation began in April. These individuals had overwintered offshore and were returning to the beach where they would breed. As spring progressed, a greater proportion of the population was contributed by new recruits in the lower size classes. These smaller individuals represented recruitment cohorts from pelagic larval stocks or the young of the year. The first individuals to arrive on the Fort Macon beach were not the overwintering adults but the young of the year juveniles from pelagic larval stocks. While comparative density data for June (Fig. 20) indicated that mole crab densities were similar for both beaches, the size class composition was drastically different (Fig. 21). Where the Emerald Isle demographic table (Fig. 21) displays a complex assortment of size classes representing at least two year classes, the Fort Macon table (Fig. 21) shows only several cohorts of young of the year crabs.

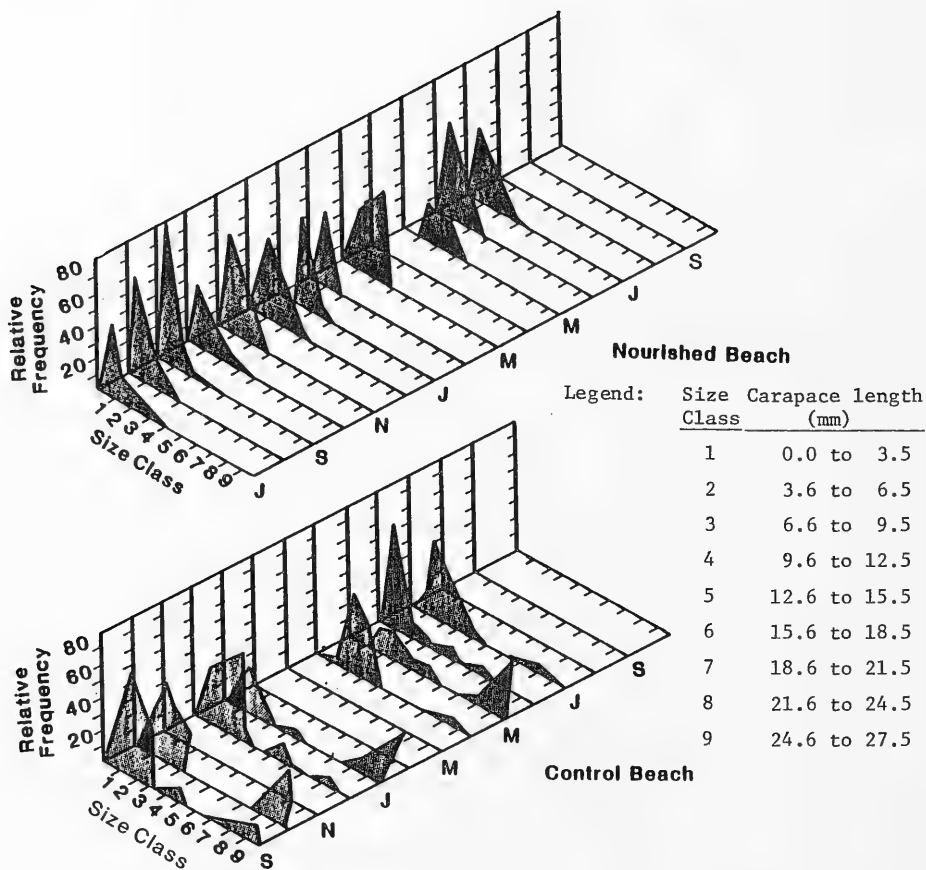


Figure 21. Size class distributions for *E. talpoida* populations at the nourishment beach at Fort Macon, June 1977 to August 1978, and the comparison beach at Emerald Isle beach, September 1977 to August 1978.

Differing demographic structures had a direct effect on the total available biomass at the two beaches. Absence of larger size classes at the nourished beach therefore resulted in a drastic reduction in available biomass. In any event, the adult population of overwintering *E. talpoida* never returned to the beach at Fort Macon following nourishment. They could have been (1) forced to move out of the nourished area due to the nourishment activities, (2) killed in their offshore overwintering grounds, or (3) killed on the beach as they attempted to recolonize in early spring while nourishment was underway.

Hayden and Dolan (1974) suggested that *E. talpoida* responds to beach nourishment by relocating in adjacent but unimpacted areas until nourishment is over and then returns to the nourished area. This seems an unlikely explanation for the failure of *E. talpoida* to repopulate the Fort Macon beach because no increased densities were observed in areas immediately adjacent to the nourishment area (Fig. 18); few adult *E. talpoida* ever returned to the beach. It is also possible that adult *E. talpoida* were killed on the beach during the nourishment process. The diffuser head shown in Figure 6 gives an idea of the volume and speed of the material being laid down. However, at any given time only a small fraction of the total beach front was being nourished, and it seems likely that at least some of the adult *E. talpoida* would have survived.

The most likely explanation for failure of adult crabs to return to the Fort Macon beach is that they were killed in their nearshore-offshore overwintering grounds. The probable cause of this mortality was increased turbidity. The mole crab is a fairly unselective filter feeder (Efford, 1966), and its stomach could have easily been clogged with undigestable inorganic matter from the turbid waters. Mortality of offshore macrofauna by such a mechanism has been attributed to turbidity and siltation by Courtenay, et al. (1974).

b. *Donax parvula* and *Donax variabilis*. *Donax parvula* were slightly more abundant than *D. variabilis* at Fort Macon, while the reverse was true at Emerald Isle. These differences, although not statistically significant, do suggest the possibility that *D. parvula* may prefer the slightly less rigorous environment provided by the partially protected beach at Fort Macon (C. Lytle, Department of Zoology, North Carolina State University, Raleigh, North Carolina, personal communication, 1978) or beaches near inlets (H. Porter, personal communication, 1977).

During the study period *D. parvula* and *D. variabilis* reached their highest densities at Fort Macon in late June and early August 1977 (Figs. 22 and 23); however, Leber (1977) reported that population peaks for *Donax* spp. occurred much earlier in the year. The data from the Emerald Isle beach for the spring of 1978 (Figs. 22 and 23) support Leber's observations. Therefore, it is concluded that the peak populations of *Donax* spp. in 1977 for Fort Macon were probably missed by starting the sampling in June.

After the peaks were reached, populations of *Donax* spp. decreased somewhat as summer progressed and began to decline steadily during fall. Adult *Donax* spp. were rarely encountered on the beaches between December and March. Recruitment began in March at Emerald Isle and, in contrast to the pattern exhibited by mole crabs, the first recruits to the beach were young of the year from pelagic larval stocks (Figs. 24 and 25).

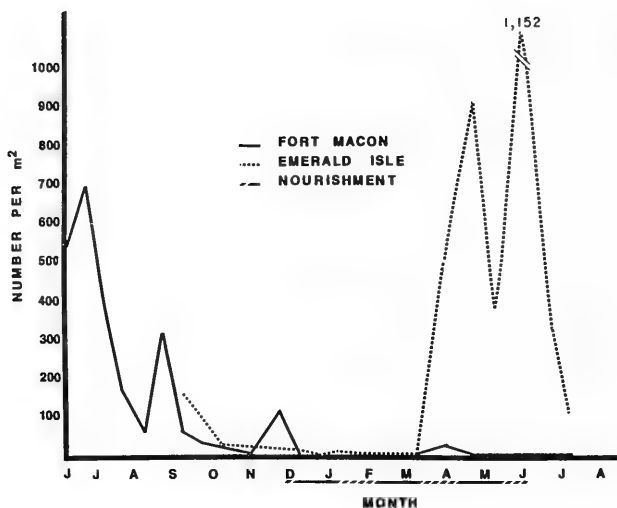


Figure 22. Seasonal variations in density of *D. parvula* at the nourishment beach at Fort Macon, June 1977 to August 1978, and the comparison beach at Emerald Isle, September 1977 to August 1978. The actual period of nourishment is represented by a slashed line below the X-axis.

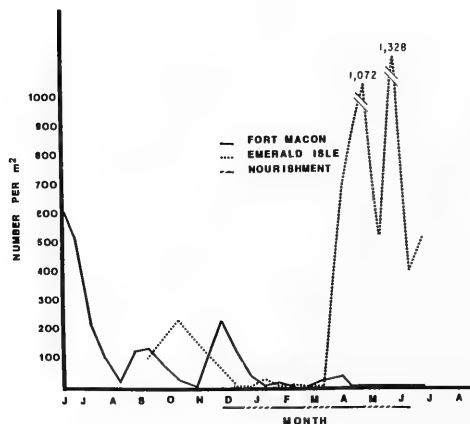
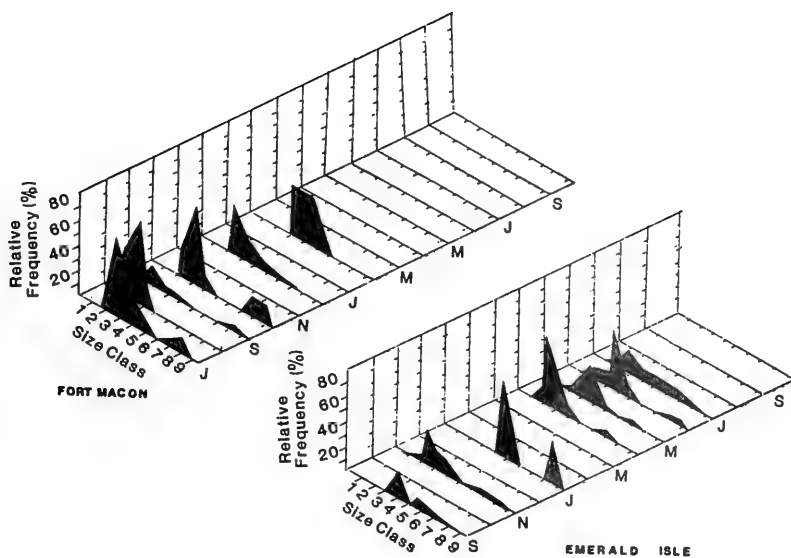
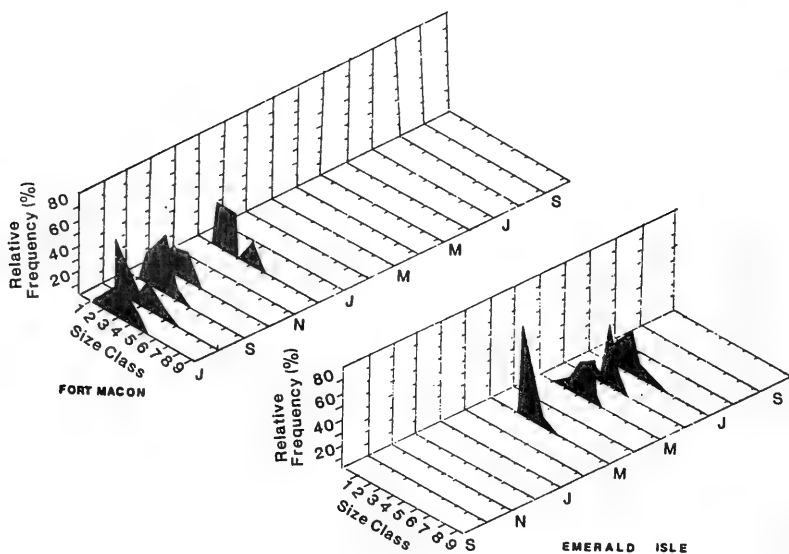


Figure 23. Seasonal variations in density of *D. variabilis* at the nourishment beach at Fort Macon, June 1977 to August 1978, and the comparison beach at Emerald Isle, September 1977 to August 1978. The actual period of nourishment is represented by a slashed line below the X-axis.



Legend:	Size Class	Shell length (mm)
	1	0.0 to 2.5
	2	5.1 to 7.5
	3	5.1 to 7.5
	4	7.6 to 10.0
	5	10.1 to 12.5
	6	12.6 to 15.0
	7	15.1 to 17.5
	8	17.6 to 20.0
	9	20.1 to 22.5

Figure 24. Size class distributions for *D. parvula* at the nourishment beach at Fort Macon, June 1977 to August 1978, and the comparison beach at Emerald Isle, September 1977 to August 1978.



Legend:	Size Class	Shell length (mm)
	1	0.0 to 2.5
	2	2.6 to 5.0
	3	5.1 to 7.5
	4	7.6 to 10.0
	5	10.1 to 12.5
	6	12.6 to 15.0
	7	15.1 to 17.5
	8	17.6 to 20.0
	9	20.1 to 22.5

Figure 25. Size class distribution for *D. variabilis* at the nourishment beach at Fort Macon, June 1977 to August 1978, and the comparison beach at Emerald Isle, September 1977 to August 1978.

The fact that young of the year *Donax* spp. constituted the earliest recruits is significant in that it establishes that this clam breeds offshore in its overwintering grounds. Chanley (1969) reported that although adult *D. variabilis* displayed ripe gonads all during the summer, the time of breeding had not been established. He reported that the pediveliger metamorphosed at a length of approximately 270 to 350 micrometers and at an age greater than 22 days. Results of the present study indicate that the *Donax* spp. breeding season begins in early March when water temperatures first begin to rise (Fig. 14).

Neither adult *Donax* or their young stages were observed at Fort Macon beach during the first spring recruitment following beach nourishment. In fact, no *Donax* spp. were found on the Fort Macon beach until 29 July, nearly 2 months after the cessation of nourishment. Those individuals that did return were young of the year, but were not from pelagic larval stocks. They were post-metamorphal adults which had diffused from another beach via littoral drift into the Fort Macon area. The transport of 1.3- to 3.9-millimeter-long post-metamorphal *Donax* spp. in the plankton was observed by Williams and Porter (1971). *Donax* spp. are able to "leap" from the substrate (Ropes, 1967; Ansell, 1969) and be carried by the current to a suitable new substrate.

The results of this study indicate that adult *Donax* spp. were killed in their offshore overwintering ground and that beach nourishment activities, probably greater turbidity, prevented the normal recruitment of pelagic larvae.

Adult *Donax* are not as mobile as *E. talpoida*, and therefore, probably could not relocate to any great extent. Thus adult individuals in the intertidal zone were destroyed by burial, while adults overwintering in the nearshore-offshore were probably eliminated by high turbidity and burial. The effects of burial on *Donax* spp. are unknown, although death resulting from burial of other bivalves has been well documented (Needler and Ingallie, 1944; Glude, 1954; Smith, 1960; Medcof and MacPhail, 1964; Gallucci and Kawaratani, 1975).

Absence of *Donax* spp. from the beach for any extended length of time could result in serious ecological consequences. Leber (1977) pointed out that *Donax* spp. contributed up to an order of magnitude greater biomass than any migrating consumer, and up to 12 percent of the total available secondary productivity.

c. *Haustorius canadensis*. *Haustorius canadensis* was more important in the Fort Macon beach community than in the Emerald Isle beach community before nourishment. However, it was present and important to both beaches (Fig. 26). Population density at the Fort Macon beach was fairly constant before nourishment, while the Emerald Isle beach exhibited a single population peak.

The *H. canadensis* is a burrowing amphipod that normally inhabits wetter parts of the beach. Unlike the invertebrates previously mentioned, the *H. canadensis* broods its eggs and young and has no pelagic larval life history. It is a poor swimmer but a good burrower. The significance of these characteristics was evident in the slow recovery displayed by this species on the nourished beach. No amphipods had been found on the nourished part of the beach until two were discovered along the permanent transect being sampled to determine the rate of recovery of a segment of beach. They were discovered along a part of the beach close to Beaufort Inlet. Possibly these individuals

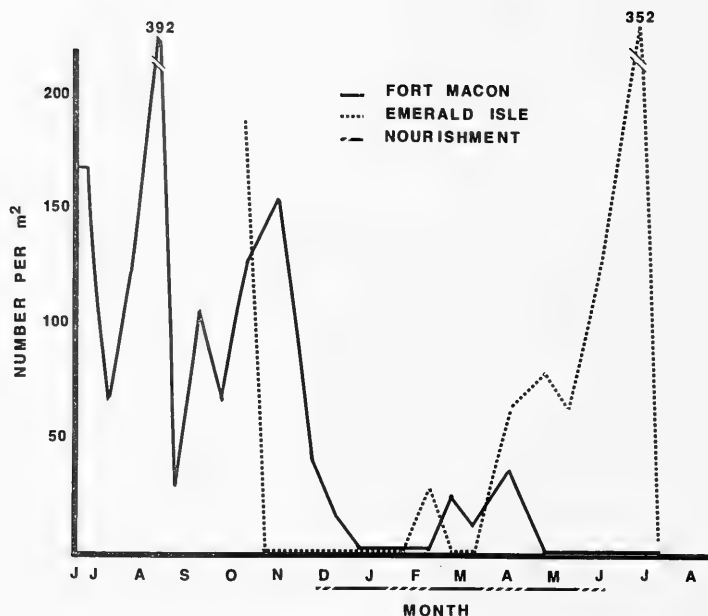


Figure 26. Seasonal variations in *H. canadensis* densities from the nourishment beach at Fort Macon, June 1977 to August 1978, and the comparison beach at Emerald Isle, September 1977 to August 1978. The actual period of nourishment is represented by a slashed line below the X-axis.

were recruited from the calmer inlet waters or sound beaches. Dexter (1967, 1969) indicated that *H. canadensis* were very abundant on the protected Radio Island beach inside the inlet. This could explain the disparate densities between the study beach and the comparison beach before nourishment.

This amphipod remained absent from any nourished part of the beach once nourishment began. It first reappeared on the nourished beach at a point very near the inlet. No other *H. canadensis* had been found at any other location by the end of this study. The life history and behavior of this organism does not favor a quick return to the nourished area. Density will remain low until enough of a "seed" population of *H. canadensis* can diffuse into the area.

d. *Scoelelepis squamata*. This indirect selective deposit-feeding spionid worm has widespread distribution (J. McDermott, Franklin Marshall College, Lancaster, Pennsylvania, personal communication, 1978) and has been reported as important in the lower swash zone (Matta, 1977). Results of this study indicate that while it was an important member of the Fort Macon macrofauna, it was virtually absent from the Emerald Isle beach. The *S. squamata* density at Fort Macon declined from a prenourishment maximum of 120 individuals per square

meter in June 1977, until the onset of nourishment when the population fell to zero (Fig. 27). This pattern may be misleading in that *S. squamata* was the only organism found in a nourished zone during the nourishment process. The absence of the worm at the onset of nourishment may have been due to normal seasonal variation in relative abundance rather than to the impact of nourishment.

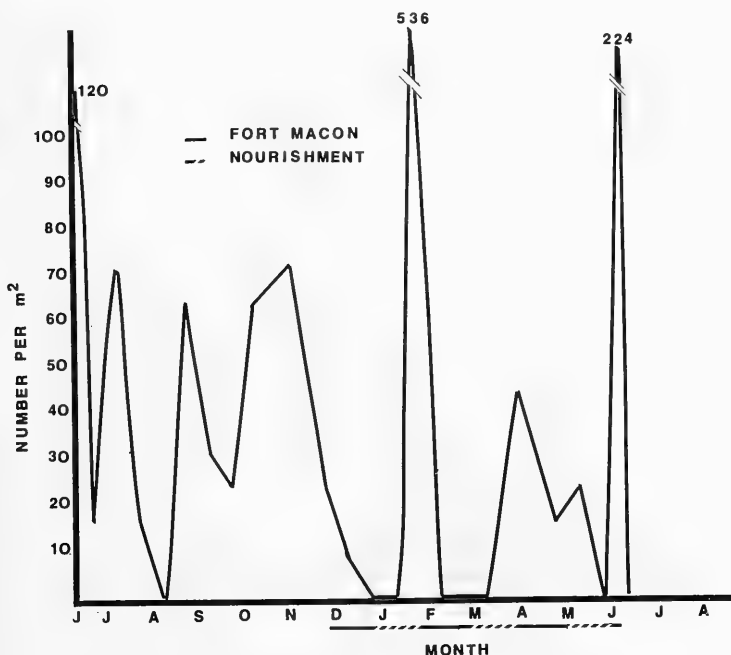


Figure 27. Seasonal variation in the density of *S. squamata* at the nourishment beach at Fort Macon, June 1977 to August 1978. Very few *S. squamata* were found at Emerald Isle. The actual period of nourishment is represented by a slashed line below the X-axis.

Little is known about the ecology of this worm; however, previous studies have reported worms to be the first organisms to recolonize sites of dredged spoil disposal. Stone (1972) reported the polychaete *Nephtys incisa* as the first colonizer of spoil banks in the lower Chesapeake; Pfitzenmeyer (1970), while reporting a 71 percent reduction in the total number of individuals other than polychaetes due to a disposal project in the upper Chesapeake Bay, noted that the first colonizers of this material were *S. viridis*.

e. Other Intertidal Organisms. A variety of other intertidal organisms was found on both beaches during the study; however, their occurrences were infrequent and their numbers were low. The talitrid amphipod, *T. megalopthalma*,

was found on less than half of the sample days. Another amphipod, *A. virginiana*, was found even less frequently. Both amphipods were less abundant following nourishment, but the actual magnitude of the nourishment effect was difficult to evaluate due to their generally sporadic appearance and low numbers.

Other organisms encountered (in decreasing order of importance) included the polychaete, *N. picta*; ghost crab, *O. quadrata* (megalops and young adults); the idoteid isopod, *Chiridotea coeca*; the albuneid crab, *Albunea gibbesii*; and unidentified decapod larvae. Although these animals never formed an important component of the biomass, they are mentioned here because of the inordinate effect their presence or absence had on some measures of community structure. Both the Shannon-Weaver and Pielou Indexes are known to respond significantly to the presence or absence of a single category (species) when the number of categories (species) is low. None of these animals had been found on any nourished section of beach by the end of this study.

6. Statistical Results.

The population densities for *E. talpoida*, *Donax* spp., and *H. canadensis* were the only data suitable for Analysis of Variance (ANOVA); ANOVA requires a large sample size and parametric data (Zar, 1974).

A nested analysis of variance was performed with the following results:

(a) There was no significant difference between transects of a single beach on any given sample date. Thus, individual transects on the same beach could be treated as replicates of one another on any given sample date.

(b) There was no significant difference between most consecutive sample dates on a particular beach.

(c) There was a significant difference between tidal zones on the beach.

(d) There was a significant difference on each beach between widely separated sample dates.

(e) The comparison beach and the nourished beach had significantly different population densities both before and after nourishment.

(f) There was a significant difference between population densities at the nourished beach before, during, and after nourishment.

7. Community Relationships.

a. Measures of Community Structure. Parametric statistics are not in order when comparing individual measures of diversity (Fig. 28), equitability (Fig. 29), species richness (Fig. 30), and dominance (Fig. 31), because these measures are only ratios and not from a normally distributed data population (Zar, 1974). There are ways to compare a single index value for one date to another value on another date; however, when values are as different as they are in this study, a graphic analysis is sufficient.

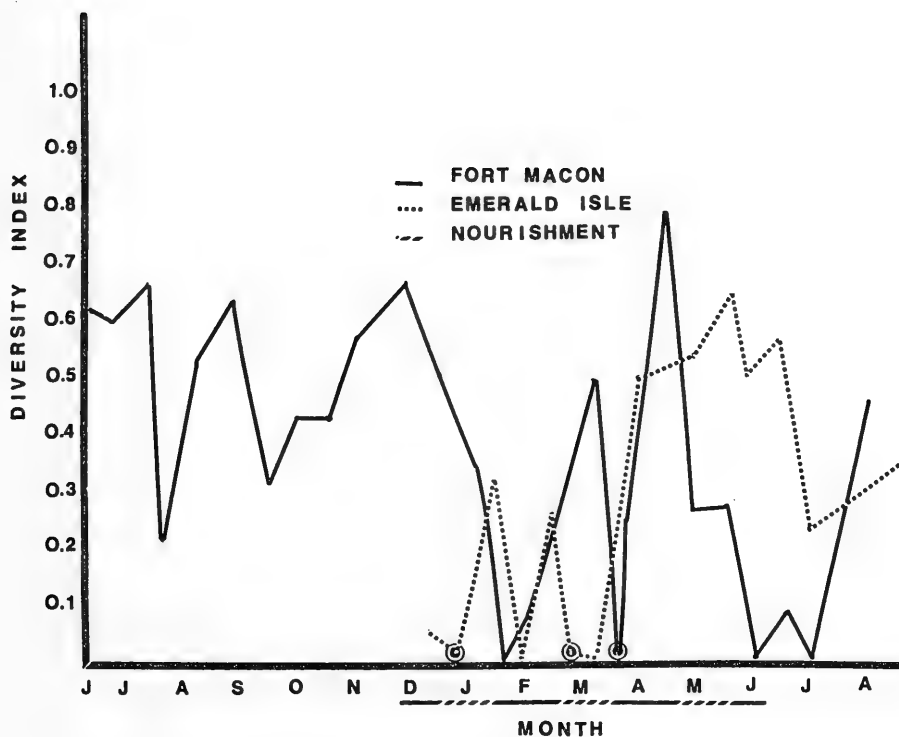


Figure 28. Seasonal variation in Shannon-Weaver's Species Diversity for the intertidal zone at Fort Macon (nourishment beach), June 1977 to August 1978, and the comparison beach at Emerald Isle, December 1977 to September 1978. The actual period of nourishment is represented by a slashed line below the X-axis. The bull's eye symbol represents a species diversity that is undefined because no organisms were found.

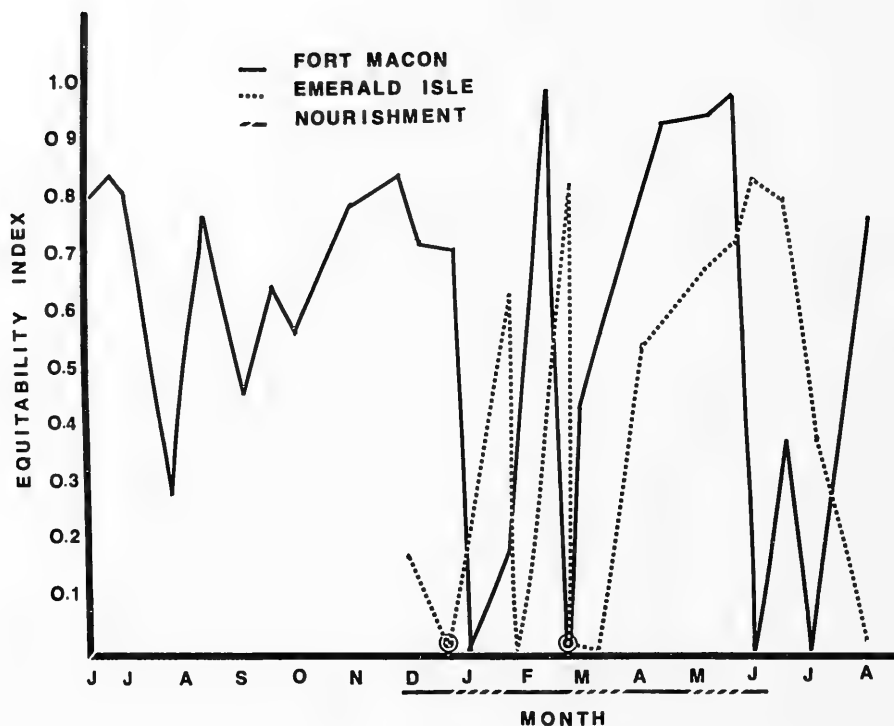


Figure 29. Seasonal variation in the Pielou's Equitability Index for the intertidal zone at the nourishment beach at Fort Macon, June 1977 to August 1978, and the comparison beach at Emerald Isle, December 1977 to August 1978. The actual period of nourishment is represented by a slashed line below the X-axis. The bull's eye symbol represents an equitability index that is undefined because no organisms were found.

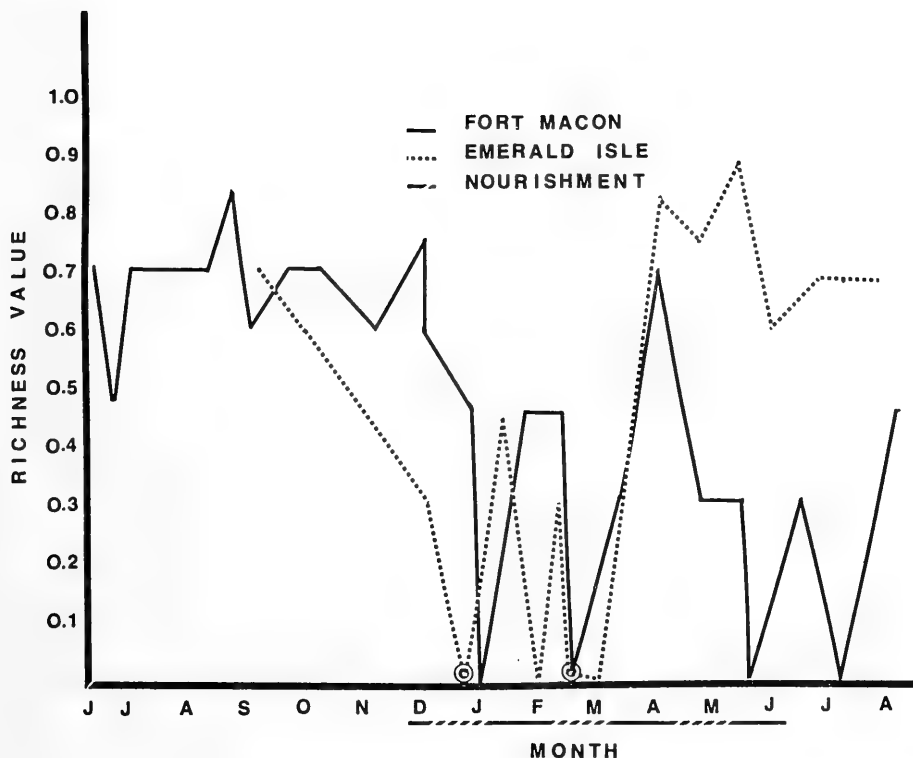


Figure 30. Seasonal variation in species richness for the intertidal zone at the nourishment beach at Fort Macon, June 1977 to August 1978, and the comparison beach at Emerald Isle, September 1977 to August 1978. The actual period of nourishment is represented by a slashed line below the X-axis. The bull's eye symbol represents a species richness that is undefined because no organisms were found.

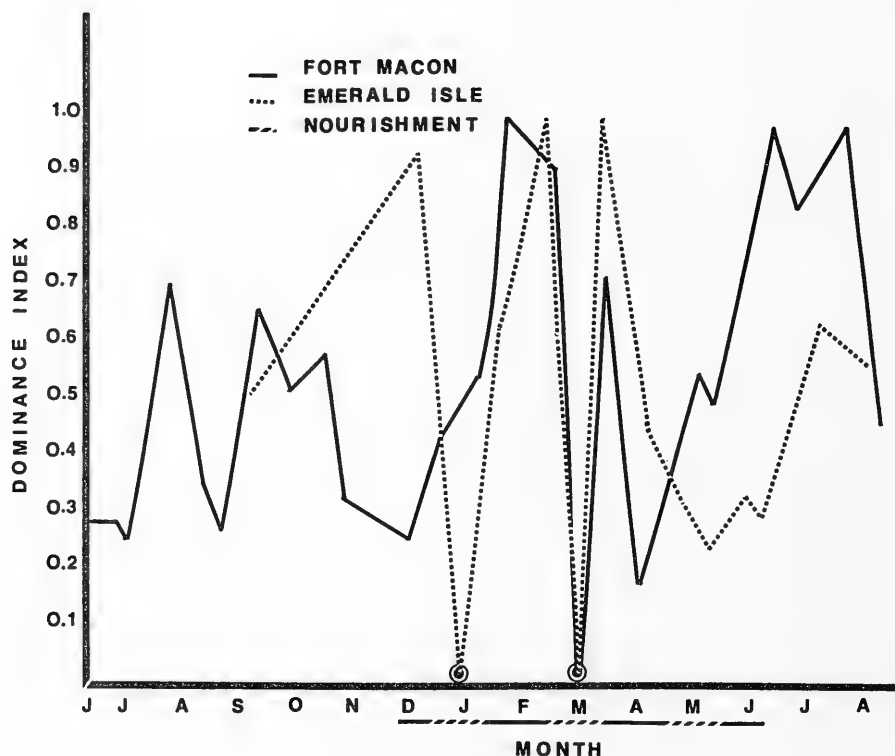


Figure 31. Seasonal variation in Simpson's Index of Dominance for the intertidal zone at the nourishment beach at Fort Macon, June 1977 to August 1978, and the comparison beach at Emerald Isle, September 1977 to August 1978. The actual period of nourishment is represented by a slashed line below the X-axis. The bull's eye symbol represents an index of dominance that is undefined because no organisms were found.

An examination of the Shannon-Weaver Diversity (Fig. 28) and Pielou's Equitability (Fig. 29) Indexes for both beaches indicated that the most diverse community present was that of the Fort Macon beach before nourishment. When the maximum possible diversity or species richness (Fig. 30) is considered, it can be seen that the reason for this was the high species number associated with the Fort Macon beach. The dominance criterion (Fig. 31) is less affected by species number and indicates that the before nourishment beach at Fort Macon closely resembled the Emerald Isle beach.

The effects of nourishment are evident in all the community measures. There was a decrease in diversity to near zero when nourishment began, and this situation continued throughout the study. At one point in March no organisms were found, and all measures of community structure were therefore undefined. On two separate occasions (in June and July), only *E. talpoida* were found on the beach; thus diversity was 0.00 and dominance was complete (1.00). The species richness value dwindled because the total number of species decreased to one or two at the Fort Macon beach during nourishment.

b. Community Functional Relationships. Community organization has two components: structural and functional. Structural properties are easily seen and measured, whereas functional properties cannot be as easily discerned. The mathematical relationships of diversity, equitability, etc. generally describe the structural aspects of a community. Examples of the functional relationships of a community can often be represented qualitatively in trophic level or energy flow diagrams (see App., Figs. A-1, A-2, and A-3); however, the quantification of such models is time consuming, costly, and often unmanageable. For this reason most environmental assessments contain the purely structural measurements of a community.

Deevey (1969) suggested that species diversity (a measure of the structure of a community) is related in an unclear, complex way to the functional relationships within a community. Peterson (1977) suggested that in order to explore the relationship between structure and function, the behavior of the species diversity function in "neutral communities" should first be examined. Caswell (1976) defined a "neutral community" as a community in which there are no species interactions and, thus, structural representations of the community very closely reflect functional relationships.

c. Competition. The intertidal sandy beach macrobenthic community is probably a good example of a neutral community. There is no predation from within, and there does not appear to be resource or space competition. Thus, according to Peterson's (1977) model for predicting the possible effect of a perturbation, if the probability of each species being affected is equal (which it was for beach nourishment) and the proportion of reduction due to the stress for each species is the same (which it was, because all species were removed from the nourished zone), species diversity will decrease due to the perturbation without any one species having an advantage. Because the high-energy psammolittoral community represented a basically "neutral community," species diversity did decrease and no single species garnered an advantage.

The rapid recovery of *E. talpoida* populations was due to the chance finish of nourishment activities just as the main cohort of *E. talpoida* larvae began to arrive. The *Donax* spp. were probably no more disadvantaged by nourishment than the *E. talpoida*, but because their larvae arrived while nourishment was still underway and turbidity high, they were unable to become established.

The results of this study indicate that there is no effective competition between *E. talpoida* and *Donax* spp. There is no competition among other organisms of the beach macrofauna because all are filling different resource niches, except the amphipods who fill different spatial niches. Leber (1977) theorized that the large populations of *E. talpoida* competitively excluded the *Donax* spp. from the swash zone by their large numbers and superior swimming ability. He concluded that as *E. talpoida* populations grew in late summer, *D. variabilis* compensated by remaining stranded at the higher tidal levels by the receding tide, while *D. parvula* compensated by leaving the intertidal zone until the following spring. This migration pattern was not noted by Matta (1977) or in the present study. Thus, it would appear that interspecific competition is not the controlling factor in mediating the coexistence of these three species.

This leaves two possible mediators to explain why one of these three species has not completely overridden the other two. The extreme physical variation in the intertidal zone makes the high-energy sandy beach a perfect example of Sanders' (1968) physically controlled community. Such a community is typified by low species diversity. Physical stress is likely to be a factor in species coexistence when severe weather conditions or major perturbations such as beach nourishment deplete the breeding stock to the extent that not enough young of the year are produced to fill the spatial or resource niche. Physically mediated coexistence is unlikely to be of major significance on the beaches studied here because of the low frequency of major perturbations.

d. Predation. A much more likely explanation for coexistence among the macrofaunal species is predator mediation; i.e., predators utilizing this community are responsible for structuring it. The predators in this case were migrating consumers from supralittoral and sublittoral sources. This type of mediation was first theorized by Darwin (1859) and has been postulated for many systems since then. Wolcott (1978) postulated that ghost crabs are responsible for cropping most of the secondary production of *E. talpoida* and *Donax* spp. Thus, he believes that ghost crabs are the primary structuring force in the intertidal community.

Wolcott (1978) arrived at his conclusion largely by calculation rather than by measurement. He failed to consider predation by subtidal consumers. Leber (1977) found subtidal portunid crab densities to be of the same order of magnitude as *Ocypode* at Emerald Isle. Anderson, et al. (1977) reported that one subtidal crab *A. cribrarius*, also Leber's most important species, was the second most important species by weight in the surf zone of Folly Beach, South Carolina. Night surveys of the surf zone during this study always turned up large numbers of fish feeding on *E. talpoida* and *Donax* spp. Another factor Wolcott failed to consider was that while ghost crabs can only feed on *E. talpoida* and *Donax* spp. during summer when they are on the beach, subtidal fishes and crabs feed on them during the summer, by migrating to the surf and swash zones, and also feed on them in the winter while they are located offshore.

Several models for predator-mediated coexistence have been postulated; however, most fall short of their goal of explaining natural systems by assuming them to be closed (cells) or by solving for the equilibrium state, which has a low probability of occurring (Caswell, 1978). Gurney and Nisbet (1978) proposed a model for predator-prey fluctuations in patchy environments.

Their model involves random colonization of empty spaces compensating for random local extinction in other spaces. Prey species become established first followed by predator species. The predator then proceeds to drive the prey to local extinction just as a new "patch" is being formed. Although patchiness is well known in *E. talpoida* and *Donax* spp. populations, the patches are generally fairly discrete and long lived (Efford, 1965, Dillery and Knapp, 1970; Diaz, 1974). In addition, C. Peterson (University of North Carolina, Institute of Marine Science, Morehead City, North Carolina, personal communication, 1978) noted that ghost crab populations (as determined by daytime burrow counts) did not correlate at all with clumps of *Donax* spp., *E. talpoida*, or *H. canadensis*. Thus the community discussed here does not fit the Gurney-Nisbet model exactly. Caswell (1978) however postulated a nonequilibrium model for predator-mediated coexistence in which no equilibrium condition is reached, and no local extinction is required. A combination of the two models and a degree of physical moderation probably most clearly explains the community structure on the high-energy sandy beach intertidal. When clumping is present it is probably the result of physical parameters on the beach. This clump is not a static group of individuals but an aggregation that gains and loses new members constantly via littoral drift (Dillery and Knapp, 1970). These groups are never preyed upon to extinction; as populations increase the patches meld together until the populations of both *E. talpoida* and *Donax* spp. completely fill the swash zones for the entire length of the beach (Leber, 1977). When this condition is reached, predation by migrating consumers is greatest, and population numbers of the intertidal organisms are kept from exceeding the spatial carrying capacity of the intertidal zone.

e. Symbiosis. There was one visible example of symbiosis on the sandy beach during the study. It consisted of a colonial hydroid which was found occasionally on the posterior ridge of both species of *Donax* spp. The infestation was distributed equally between the two species on both beaches and affected up to 10 percent of the samples collected in late spring and early summer. The hydroids generally disappeared by late summer and were never found in individuals collected during the winter. Leber (1977) tentatively identified this hydroid as *Clytia bakeri*; however, it is more likely a new species of *Lovenella* (C. Lytle, personal communication, 1978).

Leber (1977) called the relationship commensalism. T. Wolcott (North Carolina State University, Raleigh, North Carolina, personal communication, 1977) originally thought that the relationship was more mutualistic, the benefit to *Donax* spp. being that nematocysts of *Lovenella* sp. might prove to be a deterrent to predators. Wolcott's feeding experiments revealed that ghost crabs are not affected by the nematocysts and, if anything, are better able to catch the *Donax* spp. because the large growth of *Lovenella* sp. impairs the digging efficiency of *Donax* spp. If this is so the *Lovenella* sp. and *Donax* spp. association is parasitic.

Lovenella sp. was always low in colony number and, due to its diminutive size, small in biomass. It was not apparent on the beach after nourishment, but neither was its host. For that reason the impact of nourishment upon this relationship and upon the *Lovenella* sp. was not determined.

IV. SUMMARY

The beach at Fort Macon State Park was nourished with dredged materials obtained from the Morehead City State Port Harbor deepening and widening project.

The study monitored this beach (Fort Macon) and a comparison beach which did not receive nourishment (Emerald Isle) before, during, and after the Fort Macon nourishment activities. The primary objectives of this study were:

- (1) To establish base-line quantitative data on community structure and seasonal variation among the biota inhabiting the intertidal zone of a high-energy sandy beach;
- (2) to determine the effects of beach nourishment using dredged materials on the intertidal macrofaunal community of a high-energy beach; and
- (3) to make recommendations concerning the implementation and environmental advisability of beach nourishment with dredged materials.

The high-energy sandy beach environment is harsh, characterized by great variations in various abiotic ecofactors. The fauna of the intertidal zone is highly mobile and responds to stress by displaying large diurnal, tidal, and seasonal fluctuations in population density. Biological diversity is kept low and, thus, community structural and functional relationships are kept simple. The high-energy psammolittoral community is made up of *Emerita talpoida*, the mole crab; *Donax parvula* and *Donax variabilis*, coquina clams; *Haustorius canadensis*, an amphipod; *Scolecopsis squamata*, an indirect selective deposit-feeding spinoid worm; *Talorchestia megalopthalma* and *Ampiporeia virginiana*, amphipods; *Chirodotea caeca*, an isopod; and *Nephyts picta*, a deposit-feeding polychaete (listed in order of decreasing abundance). There is little chance for competition because every member of this community except *E. talpoida* and *Donax* spp. occupies a different trophic or spatial niche. *Emerita talpoida* and *Donax* spp. are the dominant organisms in the intertidal zone where they are major sources of secondary production. The coexistence of these two species within the same trophic and spatial niche is mediated both by the rigorous environment and by predation. Migrating consumers responsible for this predation include: fishes of both commercial and sport interest, subtidal portunoid crabs, shore birds, and ghost crabs.

1. The Environmental Significance of Beach Nourishment.

Beach nourishment was found to affect organism density and community structure both during and after nourishment. Organisms on the beach at the time of nourishment were killed; however, the effects of nourishment were not limited solely to the beach or to the nourishment area. Other effects included: failure of adult intertidal organisms to return from their nearshore-offshore overwintering refuges, reductions in organism densities on adjacent unnourished beaches, and inhibition of pelagic larval recruitment effort. The nourished beach recovered slowly. During this period, secondary productivity remained low and measures of community structure indicated low diversity. Low secondary productivity resulted in a reduced utilization of nourished beach by migrating consumers of commercial and sport interest.

2. Recommendations.

Larval recruitment appeared to be inhibited by the greater water turbidity associated with the nourishment operations. Further study is needed to determine the mechanism of larval inhibition by suspended materials and threshold

levels at which turbidity becomes harmful. In the interim, materials utilized in beach nourishment should be selected to minimize turbidity and nourishment should be carried out before the onset of larval recruitment in spring.

Beach nourishment virtually destroys existing intertidal macrofauna; however, recovery is usually rapid once the pumping operation ceases if the nourishment material is compatible with the natural beach sediments. In most cases, recovery should occur within one or two seasons following the project. Harmful consequences to the intertidal macrofauna and subsequent reduction in surf-feeding fish populations can be reduced or avoided by carrying out nourishment operations during the winter after adult *Donax* spp. and *E. talpoida* leave. Small nourishment projects, of 0.8 kilometer or less, should recover faster than larger projects since the speed of recovery is dependent upon recruitment from nearby beaches. A succession of small projects carried out in nonsequential order should have less long-term impact than a single grand-scale nourishment project.

There are two types of biological associations found on sandy beaches. There are beaches dominated by organisms recruited from pelagic larval stocks, and there are beaches where the entire life history of the dominant organism is within the beach system. Results of this study indicate that on beaches where the major organism is recruited from pelagic larval stocks (as is the case with *E. talpoida* and *Donax* spp. in North Carolina), the impact of beach nourishment will be drastic but ephemeral. However, on beaches where the major organism is one whose entire life history is within the beach system (as is the case with *H. canadensis*, the dominant species on northern beaches), recovery of secondary production biomass will be very slow, thus local sport and commercial fishing may also be affected.

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GENERAL BEACH ECOLOGY

The pioneer work on sandy beaches is *Biologiske Studier Over Sand-strands-faunen, Saerlig Ved De Danske Kyster* by Mortensen in 1923, as cited by Dahl (1953). Mortensen is credited by Dahl with first posing the main problems in sandy beach ecology. The earliest study in this country of species assemblages on sandy beaches was conducted at Beaufort, North Carolina (Pearse, Humm, and Wharton, 1942). This Beaufort study also constituted the first description of the fauna at Fort Macon. Although it was not a quantitative study, it did note the intertidal zonation and general abundance of *E. Talpoida* and *Donax* spp.

There are few other studies of high-energy sandy beaches. Leber (1977) studied the community ecology of the beach at Emerald Isle. This same beach was used as a comparison beach in the present study. He monitored the intertidal macrofauna for 14 months and established a qualitative energy flow model for the macrofaunal community. Matta (1977) performed a quantitative survey of the organisms located on transects from the swash zone to a distance of 60 meters offshore at Duck, North Carolina.

Other studies of sandy beach macrofaunal communities have been of beaches exposed to lower wave energies. Dexter (1967) reported the distribution and niche diversity of haustoriid amphipods; Dexter (1969) reported the faunistics of the sandy beach community of Radio Island at Beaufort, North Carolina. In addition she compared the fauna of Pacific and Atlantic sandy beaches of Panama (Dexter, 1972), Costa Rica and Columbia (Dexter, 1974), and described the sandy beach fauna of Mexico (Dexter, 1976). Croaker (1967) studied the amphipods of sandy beaches in Georgia. Pamatmat (1968) carried out a quantitative faunistic study of the beaches in Washington. Grant (1965) studied the fauna of protected beaches in Massachusetts. Whithers (1977) compared the faunal communities of a series of sand and sand-mud beaches in Wales, and McLachlan (1977a, 1977b) described both macrofaunal and meiofaunal communities on a series of protected beaches in South Africa. Saloman (1976) reported the effects of a hurricane on the beach and the nearshore beach fauna of Panama City Beach, Florida. Holland and Polgar (1976) studied the ecology of a high-energy intertidal sandflat in Georgia. All these investigators concluded that sandy beach macrofaunal communities generally are: (1) low in measures of community structure such as species diversity (Shannon and Weaver, 1963), species richness (Pielou, 1969), and species evenness (Pielou, 1966); and (2) dominated by one or two species which are particularly well adapted to the environmental stresses of the habitat in which they live (Sameoto, 1969). This type of low diversity system is thought by some (Holland and Polgar, 1976; Leber, 1977) to constitute a classic example of a physically controlled community as defined by Sanders (1968). The physically controlled sandy beach is subjected to large fluctuations in various abiotic ecofactors including temperature, salinity, oxygen availability, redox potential, water movement, and pH (Hartwig, Gluth, and Wieser, 1977).

In general, ecological communities are composed of primary producers, first-order consumers (sometimes called secondary producers), predators (sometimes called second-order consumers), and decomposers. The high-energy sandy beach is an exception, however, in that it lacks any important primary production.

1. Primary Production.

Primary production on sandy beaches is very low. Cox (1976) reported that plant biomass was low compared to most littoral and sublittoral systems, and that diatoms were of small consequence as a food energy source. Leach (1970) measured primary production of intertidal sediments and found the sand beach to be the least productive substrate in the Ythan estuary. He estimated total annual primary production of the sand beach to be less than 5 grams organic carbon per square meter per year. Steele and Baird (1968) measured the primary production occurring in the top 20 centimeters and estimated subtidal sand beach production to be only 4 to 9 grams organic carbon per square meter per year. When they measured the total production for the intertidal part of the beach, they found negligible production. Low productivity was attributed to constant sorting and mixing of the substrate, which buried diatoms or otherwise kept them out of the photic zone.

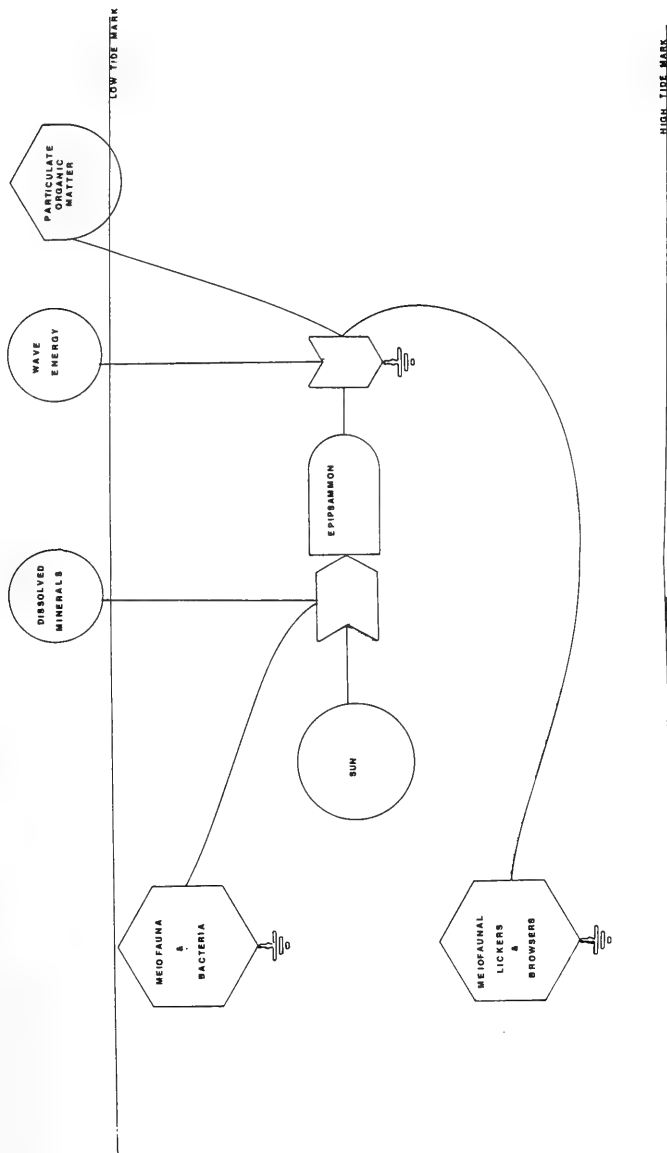
Amspoker (1977) found diatoms on Scripps Beach at La Jolla, California, to have high diversity, uniform distribution, and no stratification. He attributed this distribution pattern to tidal mixing. Pearse, Humm, and Wharton (1942) found diatoms associated with sandy beaches inside the Beaufort Inlet; however, they reported none from the sands at Fort Macon. Although production seems to be low, a wide range of primary producers have been reported for sandy beaches, including blue-green algae, diatoms, and early stages of brown algae (Meadows, 1965).

Figure A-1 presents an energy flow diagram for primary production on a sandy beach. The producers are dependent on input of mineral nutrients from offshore sources, and remineralization of organic compounds by the meiofauna decomposer-bacteria complex. The greatest loss of energy from this system results from the sorting, mixing, and scouring action of the surf. Primary production is inherently low, and most of what is produced is lost as near-shore particulate matter. Only a small fraction of the total production becomes available to epistrate browsers and lickers in the meiofaunal community. Virtually none of the primary production on sandy beaches is available to macrofauna.

2. Bacteria.

Bacteria serve an important function on sandy beaches where they constitute an important food source for the meiofauna (McIntyre and Murison, 1973; Cox, 1976). The major input into the bacterial community of the sandy beach is dissolved organic matter derived from tidal influx from coastal waters which is either absorbed to substrate or formed into microparticles by bubbling and surface phenomena (Cox, 1976).

Elmgren (1976) and Gerlach (1978) demonstrated that bacterial production is enhanced by the mechanical and metabolic activities of the meiofauna, although bacteria and meiofauna compete for the same food resources. At the same time the meiofauna utilizes this increased bacterial production as a food source. Thus, the meiofauna-bacteria community represents an essentially closed or self-contained system having minimal interaction with surrounding communities.



- Passive energy storage. No new potential energy is generated and some work must be done in the process of moving the potential energy in and out of the storage by some other unit.
- Energy source. A reservoir of energy.
- Self-maintaining consumer population. A combination of active storage and an energy multiplier.
- Plant population. A combination of a consumer unit and a pure energy receptor.
- Stress. Defines the drain of calories of potential energy flow when the system is stressed.
- Workgate. Module at which a flow of energy (control factor) makes possible another flow of energy (input-output).

Figure A-1. Energy flow diagram for primary production on a sandy beach. For a more thorough explanation of the symbols used in energy flow diagrams, see Odum (1971).

3. Meiofauna.

In the past, meiofauna has been distinguished from macrofauna merely on the basis of relative size. Macrofauna was defined as those animals retained by a 500-micrometer mesh, and meiofauna as those metazoan animals passing through a 500-micrometer mesh, but being retained by a 64-micrometer mesh (McIntyre, 1964; Muus, 1967; Hulings and Gray, 1971). However, McIntyre (1968) and Cox (1976) noted that macrofauna and meiofauna fill different ecological niches. Macrofauna are generally burrowers that feed on particulate organic matter (detritus and plankton), whereas meiofauna is generally interstitial and feeds on dissolved organic matter that has become particlized (microdetritus) and epipsammic bacteria (Cox, 1976).

There are other differences, especially in community structure. Whereas sandy beaches usually possess impoverished macrofauna, they display abundant, stable, and diverse meiofauna (McIntyre, 1968, 1969; McIntyre and Murison, 1973; McLachlan, 1977b). The number of species of meiofauna is generally an order of magnitude greater than the number of species of macrofauna. The numerically dominant meiofaunal groups are usually nematodes and copepod crustaceans (McIntyre, 1971; Sikora, Erkenbrecher, and Coull, 1977); the macrofauna is usually dominated by mollusks, and either amphipod or decapod crustaceans (Dexter, 1969; McIntyre, 1971; Cox, 1976). There are other indications that these communities remain ecologically separate. These include nonnormal size array and differences in habitat, migratory behavior, and reproduction. Sanders (1960) theorized that when a normal community is divided into size classes, the largest groups (according to biomass measurements) should be those members of the community with the smallest size. Conversely, as the size of individual organisms increases, the relative proportion of total biomass should decrease. However, in actual situations frequency polygons for meiofauna compared to macrofauna always show that the macrofaunal groups constitute far more of the biomass than meiofaunal groups (McLachlan, 1977a). Thus on the basis of size class distribution, macrofaunal and meiofauna evidently represent different communities. The meiofauna occupies a different spatial niche than the macrofauna. The most diverse group of macrofauna on any beach is most likely occupying the surface in the intertidal zone, whereas most of the meiofauna will likely be found deeper in the sands above the high tide mark. Because of this difference in habitat migratory differences are also common. Macrofauna generally migrates directly with the tide; meiofauna migrates with fluctuations in the water table, if at all. If the meiofauna migrates with the tide, it is done only after a lag of up to 4 hours (Riedl and McMahan, 1974). There is generally no seasonal migration of the meiofauna, whereas the macrofauna often leaves the beach during winter (Saloman, 1976; Matta, 1977; Leber, 1977). Finally there are likely to be differences in reproduction. Meiofauna generally reproduces all year long, bears few young, broods them, and displays interstitial larval life histories. The macrofauna generally only breeds for a short time, has large numbers of eggs, and exhibits free-swimming pelagic larval life histories (Riedl and McMahan, 1974).

Figure A-2 indicates that the meiofaunal community is composed of detritus feeders, epistrate browsers and lickers, and meiofaunal predators (Cox, 1976), however, the meiofauna appears to be at the top of a food web separate from the macrofauna (McIntyre and Murison, 1973; Cox, 1976; McLachlan, 1977a). Although meiofaunal community structure is evolutionarily advanced, meiofauna

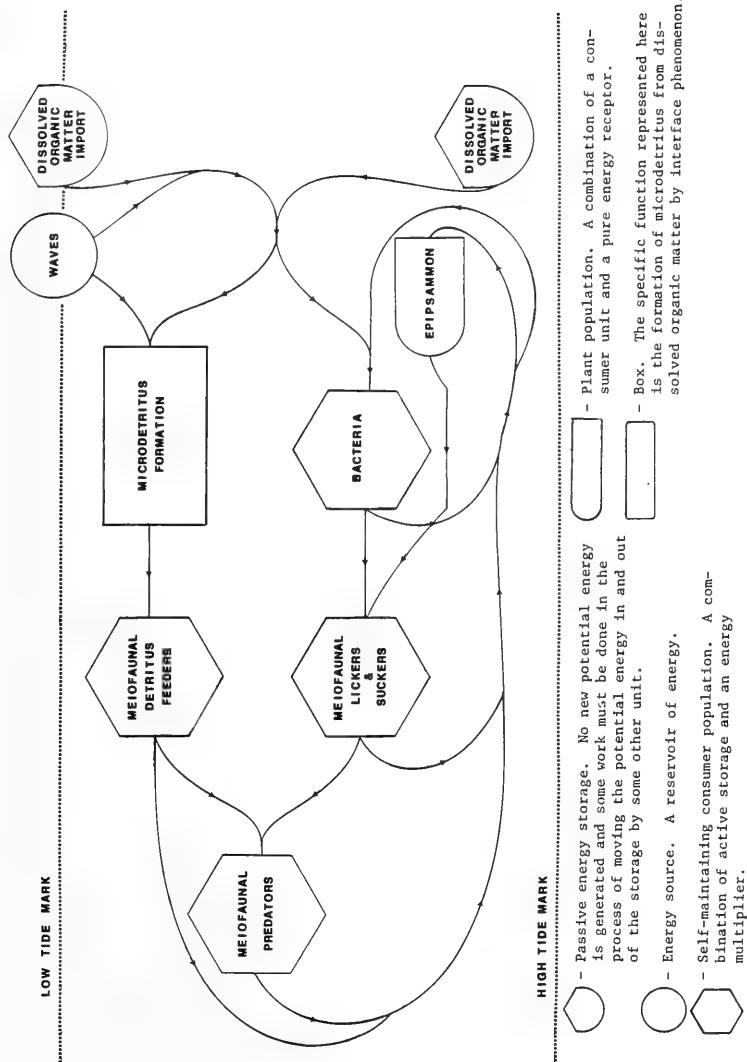


Figure A-2. Energy flow diagram for the bacteria-meiofauna community on a sandy beach. For a more thorough explanation of the symbols used in energy flow diagrams, see Odum (1971).

is not available to macrofauna as food in sufficient amounts (Gerlach and Schrage, 1969; McIntyre, 1969, 1971; McIntyre and Murison, 1973; McLachlan, 1977a; Gerlach, 1978) because biomass remains low due to the diminutive size of the individual meiofaunal organisms (McLachlan, 1977a).

The importance of the meiofaunal system to the nearshore environment seems to be restricted to the recycling of nutrients (McIntyre, 1969; Elmgren, 1976).

Meiofauna was not monitored during the present study because of the:

(a) Relative insignificance of the meiofaunal system as a direct food source for any important sport or commercial species, and the unclear ecological importance of the meiofauna;

(b) extreme difficulty of meiofauna taxonomy (R. Rieger, Department of Zoology, University of North Carolina, Chapel Hill, North Carolina, personal communication, 1977) coupled with the widespread occurrence of endemic forms (Cox, 1976); and

(c) serious problems of sample reproducibility due to extreme microscale variation (Cox, 1976).

4. Macrofauna.

The macrofauna system was chosen to monitor the effects of beach nourishment because:

(a) The importance of the macrofauna is well established both as a direct and an indirect food source to both commercial and sport species;

(b) there are no difficulties with taxonomy, and the organisms represented on a sandy beach are generally fairly widespread biogeographically;

(c) sample reproducibility is possible even though there is a great deal of variation within any given beach in the distribution of the macrofauna; and

(d) the larval life histories are fairly well known.

The intertidal zone macrofauna of a high-energy sandy beach in North Carolina is dominated by the mole crab, *E. talpoida*, and coquina clams, *Donax* spp. (Pearse, Humm, and Wharton, 1942; Matta, 1977; Leber, 1977). According to Porter (personal communication, 1977) previous workers have not differentiated between two species of *Donax* occurring south of Cape Hatteras, *D. variabilis* and *D. parvula*. Although both species of *Donax* look somewhat alike (Emerson and Jacobson, 1976) and occur together during certain times of the year, Leber (1977) suggested that they occupy different niches. He stated that during late summer when *E. talpoida* populations occupy all the available space in the swash zone, *D. parvula* compensates by moving offshore till early the following spring, but *D. variabilis* compensates by remaining stranded on the upper beach. Figure A-3 is an energy flow diagram for the sandy beach macrofauna. Figure 4 in the text shows tidal zonation on the sandy beach with the locations most occupied by each species encountered on North Carolina beaches.

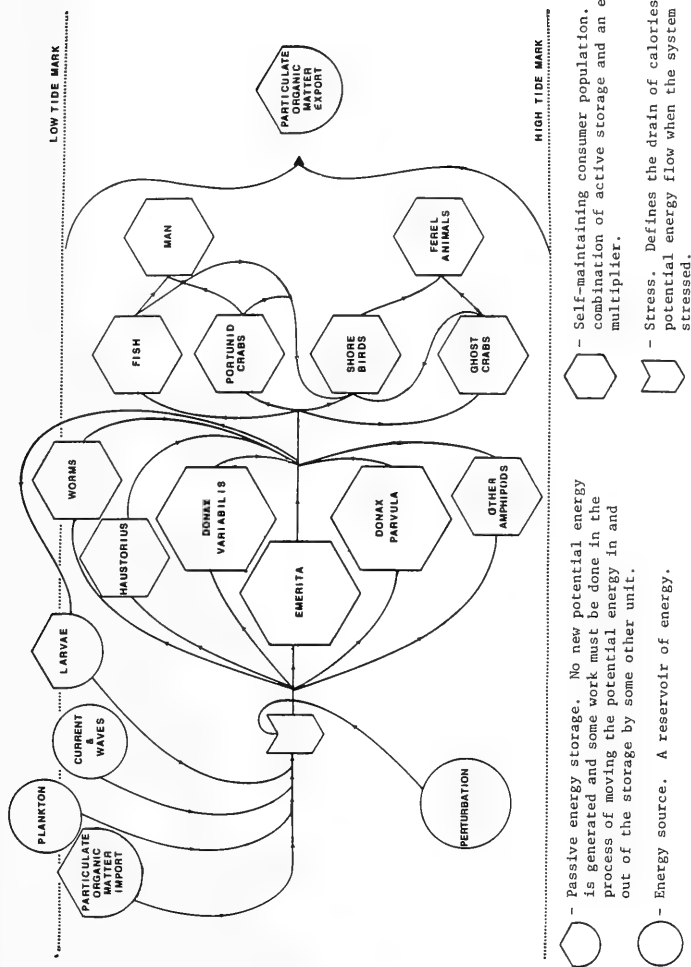


Figure A-3. Energy flow diagram for the macrofaunal community of a sandy beach. For a more thorough explanation of the symbols used in energy flow diagrams, see Odum (1971).

The distribution pattern of the three dominant species (i.e., *E. talpoida* in the swash zone, *D. parvula* absent from the beach, and *D. variabilis* present on the upper reaches of the intertidal zone) remains until falling temperatures in winter force both *E. talpoida* and *D. variabilis* into deeper nearshore waters (Leber, 1977). The fact that these animals do not just die at the end of the season is demonstrated by the total absence of empty carapaces and shells during the time when the population starts to dwindle. In addition, several investigators have reported increased numbers of the animals in the nearshore-offshore waters at this time (Saloman, 1976; Matta, 1977), and the return in spring of adults rather than juveniles (Leber, 1977).

Emerita talpoida, *D. parvula*, and *D. variabilis* are the three most important organisms in the intertidal zone on these beaches. They are numerically dominant (Cox, 1976; Saloman, 1976; Matta, 1977; McLachlan, 1977a; Leber, 1977) and they also represent the largest component of the total biomass of the system (Leber, 1977). Functionally, they provide an efficient system for harvesting planktonic primary production and other forms of particulate organic matter for higher level consumers. Thus, they constitute the important first link in energy flow through the intertidal system (Matta, 1977; Leber, 1977).

The high-energy sandy beach intertidal zone has no indigenous higher order consumers, and the great amount of secondary production there is largely untouched during the daylight hours. After dark, several different migrating consumers enter the area to feed. Ghost crabs, *O. quadrata* (Fabricius), move from their burrows in the upper beach and dune areas. Wolcott (1978) stated that the ghost crabs are the top carnivores in a simple food chain based on filter feeding. However, Leber (1977) asserted that there are other equally important consumers. He stated that the predation by two portunid crabs (*A. cribrarius* and *O. ocellatus*) that migrate in from the nearshore is nearly as important as that of ghost crabs.

The importance of the nearshore and surf zone as recreational areas for sport fishermen and as nursery grounds for both sport and commercial species, such as pompano, *Trachinotus* spp., mullet, *Mugil* spp., whiting, *Menticirrhus* spp., and flounder, *Paralichthys* spp., has been established (Tagatz and Dudley, 1961; Miller and Jorgenson, 1969; Dahlberg, 1972; Cupka, 1972; Anderson, et al., 1977). Anderson, et al. (1977) showed the importance of these species of fish in terms of biomass, and Leber (1977) demonstrated by gut content analysis that these fishes, at least when in the surf zone, consume *E. talpoida* and *Donax* spp. almost exclusively. The studies cited above indicate that *E. talpoida* and *Donax* spp. serve as important food sources for other consumers in addition to ghost crabs.

Other organisms that occur less frequently than either *E. talpoida* or *Donax* spp. include three species of amphipods: *H. canadensis*, a fairly abundant burrowing amphipod inhabiting the wetter parts of the beach; *T. megalopthalma*, a very active amphipod inhabiting the drier sands near the high tide drift line; and *A. virginiana*, an uncommon inhabitant of the lower swash zone. Two species of polychaetes occur commonly on the sandy beach in North Carolina also. One is the selective indirect deposit-feeding spionid worm, *S. squamata*, which occurs interstitially on all parts of the intertidal zone (J. McDermott, personal communication, 1978). The other is a slightly larger deposit-feeding polychaete, *N. picta*, which Leber (1977) reported as occurring at times in the swash and surf zones. The idoteid isopod, *C. coeca* is the only isopod found on the beach.

<p>Reilly, Francis J., Jr. The ecological impact of beach nourishment with dredged materials on the intertidal zone at Bogue Banks, North Carolina / by Francis J. Reilly, Jr. and Vincent J. Bellis.--Fort Belvoir, Va. : U.S. Army, Corps of Engineers, Coastal Engineering Research Center ; Springfield, Va. : available from NTIS, 1983. [74] p. : ill. ; 28 cm.--(Miscellaneous report / Coastal Engineering Research Center ; no. 83-3). Cover title. "March 1983." Report provides results of a 20-month study of beach nourishment effects on the intertidal zone at Bogue Banks, North Carolina. Fort Macon State Park beach was nourished with sediments dredged from Morehead City State Port Harbor for comparison with an unnourished beach. 1. Beach nourishment. 2. Bogue Banks, North Carolina. 3. Ecology. 4. Macrobenthos. 5. Macrofauna. 6. Macroinvertebrate. I. Title. II. Bellis, Vincent, J. III. Coastal Engineering Research Center (U.S.). IV. Series: Miscellaneous report (Coastal Engineering Research Center (U.S.)); no. 83-3. TC203 .J581mr no. 83-3 627</p>	<p>Reilly, Francis J., Jr. The ecological impact of beach nourishment with dredged materials on the intertidal zone at Bogue Banks, North Carolina / by Francis J. Reilly, Jr. and Vincent J. Bellis.--Fort Belvoir, Va. : U.S. Army, Corps of Engineers, Coastal Engineering Research Center ; Springfield, Va. : available from NTIS, 1983. [74] p. : ill. ; 28 cm.--(Miscellaneous report / Coastal Engineering Research Center ; no. 83-3). Cover title. "March 1983." Report provides results of a 20-month study of beach nourishment effects on the intertidal zone at Bogue Banks, North Carolina. Fort Macon State Park beach was nourished with sediments dredged from Morehead City State Port Harbor for comparison with an unnourished beach. 1. Beach nourishment. 2. Bogue Banks, North Carolina. 3. Ecology. 4. Macrobenthos. 5. Macrofauna. 6. Macroinvertebrate. I. Title. II. Bellis, Vincent, J. III. Coastal Engineering Research Center (U.S.). IV. Series: Miscellaneous report (Coastal Engineering Research Center (U.S.)); no. 83-3. TC203 .J581mr no. 83-3 627</p>
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