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Deposition and Long-Shore Transport of Dredge Spoils to Nourish Beaches: Impacts on Benthic Infauna of an Ebb-Tidal Delta

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ABSTRACT

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Dredged materials from maintenance and deepening of inlets on coastal barriers are typically transported for disposal in deep water or on land. An alternative is to treat dredged materials as a resource, placing them on the ebb-tidal delta or subtidal shoals at depths where they are retained within the long-shore transport system and can nourish eroding down-drift beaches. Deposition of sediments onto subtidal shoals may, however, bury and selectively kill populations of benthic invertebrates, or indirectly alter assemblages by modifying sediment characteristics. Core sampling of the eastern (control) and western (disturbed) sides of Beaufort Inlet, North Carolina, twice before and once 8 months after a large (660,000 m^3) disposal revealed significant coarsening of sediments and associated changes to assemblages of benthic macroinvertebrates in response to the perturbation. Impacts to sediments and macroinvertebrates were closely correlated and, although greatest where sediment was directly deposited, extended over a wider (at least 1 km to the east) area than the deposition. Of the taxa comprising faunal assemblages, spionid polychaetes were most affected by the disposal, declining in abundance. These results, which tie the deposition and dispersal of coarse sediments on an ebb-tidal delta to changes in benthos, imply a biological cost that may be less than that of direct nourishment of biologically productive intertidal beaches.

ADDITIONAL INDEX WORDS: *Bathymetry, disturbance, granulometry, inlet, macroinvertebrate, sediment.*

INTRODUCTION

Maintenance of adequate depths for passage of ships in coastal waterways and inlets requires frequent dredging. Shallow depths result in unsafe working conditions and possible costly damage to vessels. Disposal of dredged materials is, however, a significant challenge. Many land-based sites of disposal are fully utilized, and the filling of salt marshes is now prohibited by land use regulations in many jurisdictions. Thus, most projects in the U.S.A. have disposed of sediments from inlet dredging in deep water. Such disposal removes sediment from subtidal portions of coastal barriers and results in deficits in the sand-sharing budget. This can accelerate rates of erosion of beaches, placing oceanfront development at risk (ROESSLER, 1998: WELLS and PETERSON, 1986).

An appealing alternative to treating dredged materials as spoils to be discarded is to recognize their value in sand-sharing budgets (see COSTA-PIERCE and WEINSTEIN, 2002). Sediment dredged from inlets may be retained in the beach system by depositing it on the adjacent ebb-tidal delta. This method of disposal has received recent attention as a potential strategy of sand management that can nourish beaches (see FOSTER, HEALY, and DELANGE, 1994, 1996; HEALY *et al.,* 2002). Significant onshore movement of sediment onto down-drift beaches has been demonstrated following deposition on ebb-tidal deltas (e.g., FOSTER, HEALY, and DELANGE, 1994, 1996).

Along the barrier beaches of the Atlantic coast of the U.S.A., the demand for beach nourishment is at a historic peak in response to recent increases in storm activity, rising sea levels, and greater numbers of people residing in the coastal zone (see FENSTER and DOLAN, 1993). One of the greatest engineering costs associated with beach nourishment is the transport of sediment from its source to the fill site. This cost may be greatly reduced by using long-shore currents to distribute sediments along the beach. Moreover, sediments transported to the intertidal beach by long-shore currents will presumably be naturally sorted and have dis-

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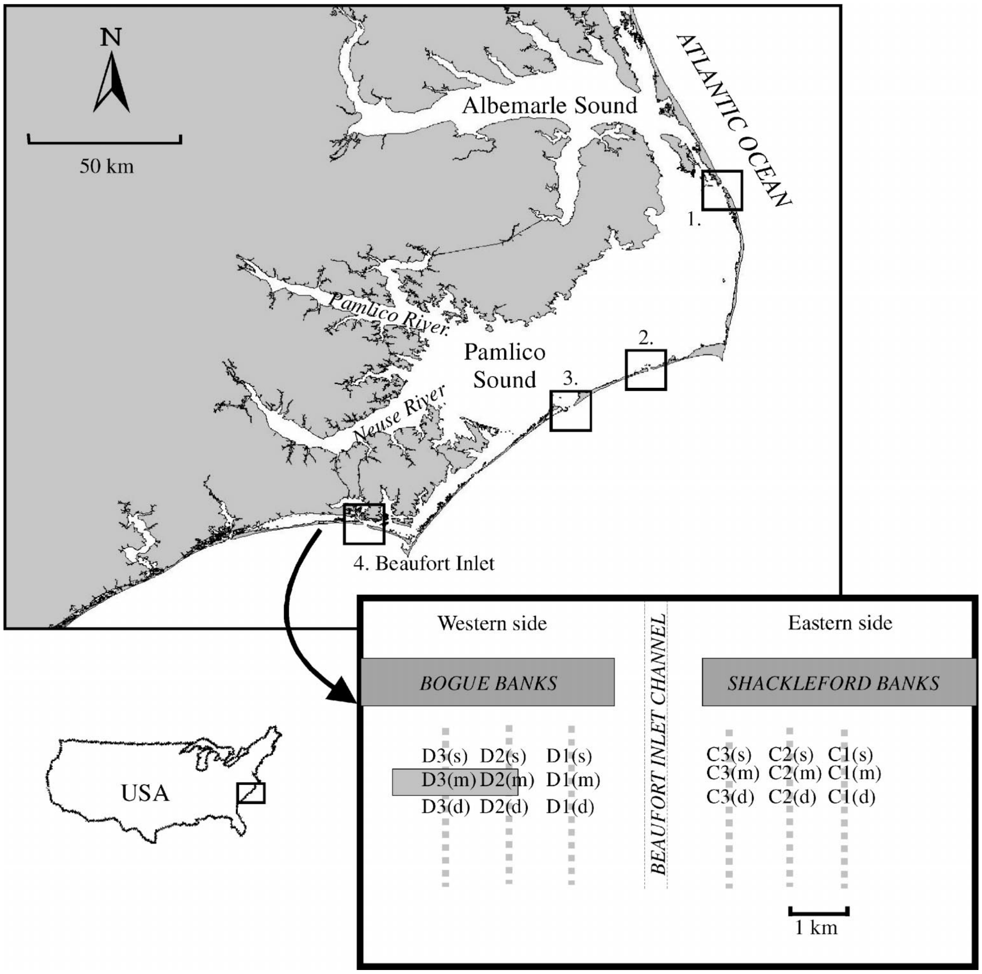


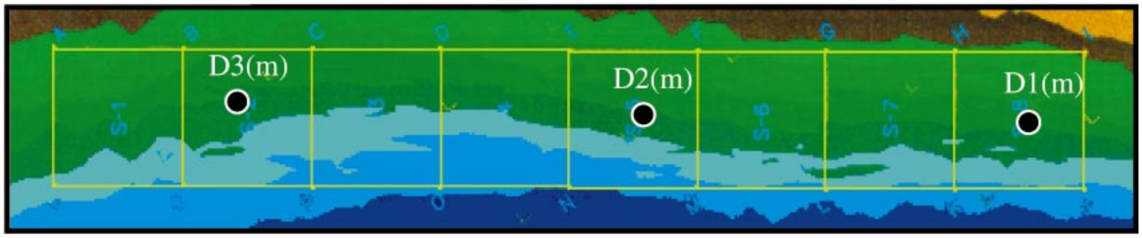
Figure 1. Map of coastal North Carolina, U.S.A., showing the four major inlets (1, Oregon Inlet; 2, Hatteras Inlet; 3, Ocracoke Inlet; and 4, Beaufort Inlet) that connect the Albemarle-Pamlico estuarine system to the Atlantic Ocean. The inset shows to scale the arrangement of sampling station along transects (dotted lines) adjacent to Beaufort Inlet, with the area that directly received dredge spoil in light gray. Transects were separated by 1.05 km. D = disturbed, C = undisturbed, s = shallow depth (5.8 m), m = medium depth (7.9 m), d = deep depth (11.0 m).

tributions of grain sizes that closely match those of the beach. The degree of concordance between native and introduced sediments is considered the most important factor determining the rate of recovery of populations of beach invertebrates following nourishment (Nelson, 1993; Peterson, Hickerson, and Grissom Johnson, 2000). In addition, adding dredged materials to subtidal shoals avoids direct disturbance of the dense benthic assemblages of the intertidal beach. Consequently, the injury to public trust resources of the intertidal beach during beach nourishment may be greatly reduced by allowing natural transport processes to move sediment onto the shore.

Despite the potential benefits of depositing spoil from a dredged inlet on its ebb-tidal delta, this practice represents a considerable perturbation to biota at the site of deposition. Deposition of sediment can smother existing fauna and result in drastic changes in characteristics of the sediment that can slow biotic recovery (Cummings *et al.,* 2003; Norkko *et al.,* 2002). Contour (on the scale of centimeters), grain size, porosity and the organic and chemical content are among the properties of the sediment that are known to influence the recruitment of polychaetes and crustaceans (Gray, 1974; Jones, 1950; Rhoads and Young, 1970; Thorson, 1957), and the distribution and abundance of benthic invertebrates is closely linked to the nature of the sedimentary substratum (e.g., Butman, 1987; Rhoads, 1974; Sanders, 1958; Scheltema, 1974; Snelgrove and Butman, 1994). Infauna may be particularly susceptible to modification of sediment because of low mobility (e.g., Günther, 1992) and intimate physical association with the bottom.

Rhoads, McCall, and Yingst (1978) were among the first to document long-term impacts of the deposition of dredged materials on benthic fauna. Throughout their 26-month study, they observed distinct differences in fauna between sites in the Long Island Sound that received weekly dumps of dredged materials (over 6 mo) and sites that were undisturbed. They hypothesized that modified biogeochemical conditions at the dump site influenced settlement and survival

(a) August 1994



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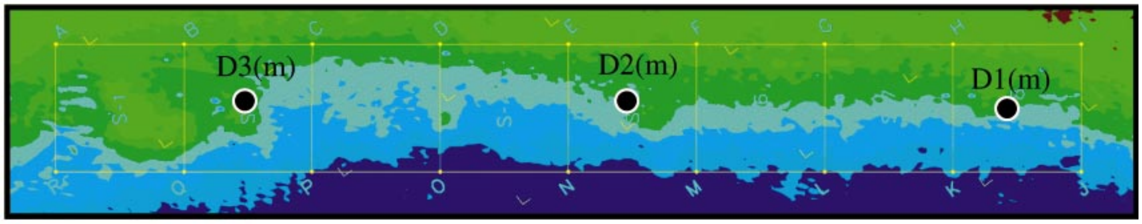
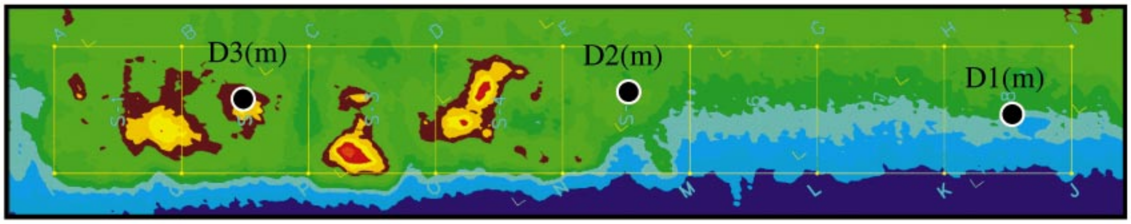


(c) May 1996



(d) February 1997

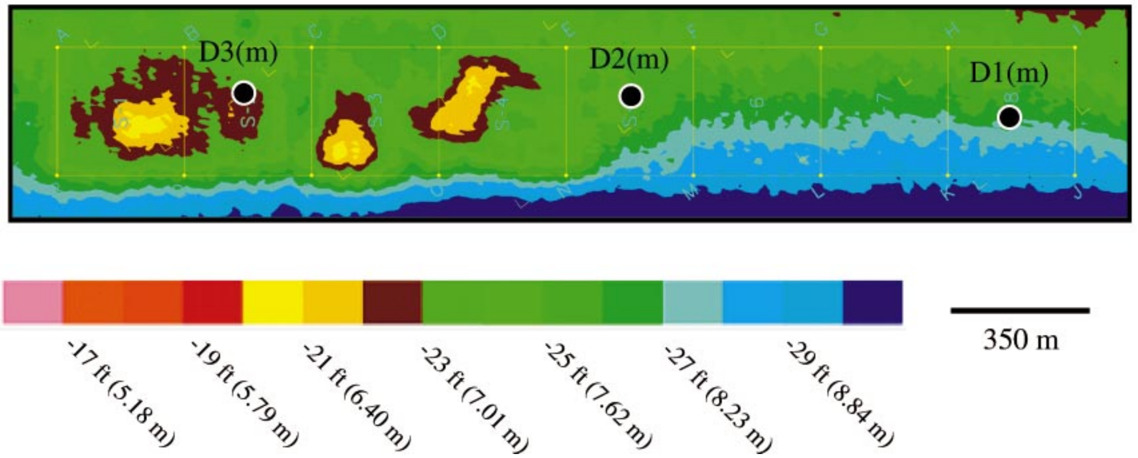


Figure 2. Maps from the US Army of Corps of Engineers, Wilmington District (P. Payonuk and D. Wall, unpublished data) showing the bathymetry, at a medium depth (~7.9 m), of the ebb-tidal delta on the western side of Beaufort Inlet in (a) August 1994, prior to disturbance; (b) February 1996, one year after the minor deposition of sediment that occurred in February–March 1995; (c) May 1996, one month after the major March–April 1996 deposition; and (d) February 1997, one year after the March–April 1996 deposition. The inlet was surveyed using a differential global positioning system, to determine horizontal position, and a fathometer of frequency 200 kHz, to determine depth. The data (ASCII) were processed using Bentley Microstation and Inroads surface modeling software (Bentley Systems, Inc., Exton, Pennsylvania, U.S.A.). D1(m), D2(m) and D3(m) indicate the location of sampling stations at the medium depth.

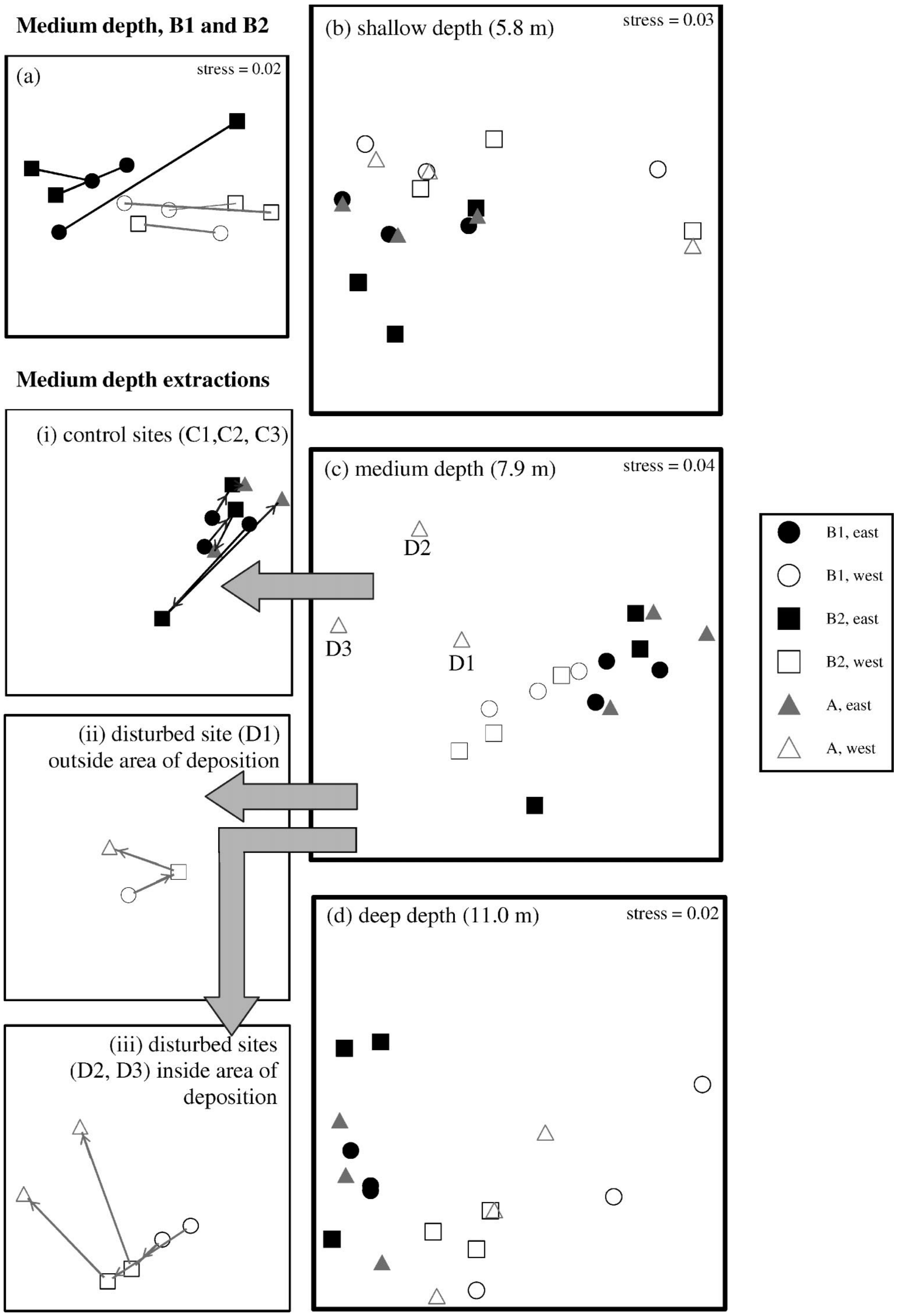


Figure 3. nMDS ordinations of sediment grain sizes at eastern, control transects (filled symbols) and western, disturbed (unfilled symbols) transects at (a) a medium depth before (before-1; circles) and after (before-2; squares) the minor deposition in February–March 1995 and at (b) shallow, (c) medium and (d) deep depths on two dates before (before-1, before-2; black symbols) and one date after (gray symbols) the major deposition of sediment on the western ebb-tidal delta of Beaufort Inlet in March–April 1996. D1, D2 and D3 denote points corresponding to disturbed sites at the after time. (i-iii) are extractions of the plot for the medium depth (c), more clearly depicting temporal trajectories of change for each of the sampling stations by including arrows. Points represent centroids of untransformed data ($n = 3$). Euclidean distances were used.

Table 1. *Results of analysis of variance and post hoc contrasts comparing the magnitude of Euclidean distances in sediment grain size distributions calculated between the two times (before-1, before-2) prior to the major deposition of sediment on the western delta of the Beaufort Inlet with those calculated between times before (before-2) and after the deposition, among the six stations sampled at medium depth. Ti = time comparison (2 levels: before-1 to before-2 [B1B2]; before-2 to after [B2A]), St = station (6 levels: control 1 [C1], control 2 [C2], control 3 [C3], disturbed 1 [D1], disturbed 2 [D2], disturbed 3 [DS]); Sig. = significance level. Data were* $ln(x + 1)$ *transformed prior to analysis.* $n = 9$ *possible pairwise comparisons of cores.*

	DF	MS	F-ratio	Sig.
Ti	1	2.15	11.9	***
St	5	3.54	19.6	***
Ti × St	5	0.84	4.7	***
Residual	96	0.18		
Cochran's test			C = 0.21 NS	
Student-Newman-Keuls contrast Ti × St			C1: B1B2 = B2A	
			C2: B1B2 = B2A	
			C3: B1B2 = B2A	
			D1: B1B2 = B2A	
			D2: B1B2 < B2A	
			D3: B1B2 = B2A	

NS = not significant.
*** $p < 0.001$.

of larvae and that smothering of microbial food sources decreased abundance of deposit feeders. Persistent changes to populations of benthic macroinvertebrates resulting from massive deposition of dredged materials that differ in character from native ebb-tidal sediments could potentially induce trophic cascades and indirectly influence commercially important species of demersal fishes and crustaceans that feed primarily on benthic invertebrates (ARNTZ, 1978; VIRNSTEIN, 1977).

Recovery of benthic assemblages following a perturbation is often closely coupled to recovery of the habitat (see BURD, MACDONALD, and BOYD, 2000; DERNIE *et al.,* 2003; NORKKO *et al.,* 2002). Unlike biogenic habitats such as coral reefs, mussel beds, and sea-grasses, which require relatively long periods of time (several years) to recover following perturbation (HALL-SPENCER and MOORE, 2000; PETERSON, SUMMERSON, and FEGLEY, 1987), sedimentary habitats can recover rapidly from disturbance through natural physical (e.g., wave action and currents) and biological (e.g., bioturbation; see COLLIE *et al.,* 2000; NORKKO *et al.,* 2002) processes. In the case of the disposal of sediment, waves and currents could rapidly disperse sediments from the point of deposition. Although this may facilitate recovery of benthos at the point of deposition, dispersal of sediments may increase the area within which sediments and benthic macroinvertebrates are modified by the deposition.

Here we report results of quantitative bottom sampling of an ebb-tidal delta before and after trial disposals of coarse sediments conducted by the US Army Corps of Engineers (USACE). Our sampling design tests whether and how the benthic macroinvertebrate assemblage changed where bathymetry and sedimentology on the seafloor demonstrated substantial deposition. We also assess whether the sedimentary and benthic biological signals moved over time as physical transport redistributed those initial deposits, and document whether the benthic signals are attenuated with transport away from the point of deposition. This study not only assesses benthic biological impacts of sediment deposition and transport, but also characterizes the lateral asymmetry of bottom habitats and their resident macrobenthos on the two sides of the ebb-tidal delta of Beaufort Inlet, North Carolina.

MATERIALS AND METHODS

Study Area

Beaufort Inlet (34°42′N, 76°40′W) is one of four major inlets (JOYEUX, 2001) connecting the large Albemarle-Pamlico estuarine complex (North Carolina, U.S.A.) with the Atlantic Ocean (Figure 1). The inlet is about 1 km wide at its narrowest, has a length of 0.5 km and an average tidal range of around 1 m. A navigation channel, 140 m wide, runs through Beaufort Inlet, providing deep-draft vessels with access to the commercial port of Morehead City. This channel, which extends about 5 km offshore and 2 km into the port, is routinely dredged to maintain 15 m depth.

Until 1995, dredged materials from the channel were deposited on nearby Brandt Island, a land-based storage site, for later nourishment of beaches of Fort Macon and Atlantic Beach on eastern Bogue Banks. From January to March 1995, 114,690 m^3 of dredged material from deepening the navigation channel was deposited as a test trial on the western, ebb-tidal delta of the inlet. A second disposal of 660,000 m^3 of dredged material occurred in March–April 1996 at the same location (Figure 1).

METHODS

To test the hypotheses that: (i) materials deposited during the first, smaller disposal would have no detectable sedimentological or benthic biological impacts, because of the small volume of sediment deposited; (ii) the second, much larger disposal of sediment would have detectable effects on sedimentology and benthic assemblages of the ebb-tidal delta; and (iii) the area over which faunal assemblages are modified would grow with dispersal of sediments, we conducted quantitative before-after sampling. Specifically, we sampled sediments and macrobenthic invertebrates at stations on the eastern (control) and western (disturbed) sides of the inlet before (before-1, December 1994) and after (before-2, February 1996) the first minor disposal of 1995 and after the large disposal of 1996 (after, December 1996). We designated the second sampling date as before-2 in relation to the second (major) disposal, although we also included tests of potential impacts of this first (minor) deposition. Stations were situated at three depths (shallow, 5.8 m; medium, 7.9 m; deep, 11.0 m) along each of six transects. Three transects were situated on the eastern (control: C1, C2, C3) and three on the western (disturbed: D1, D2, D3) side of the main channel. On each side of the channel, transects were spaced at distances of 1.05 km and were parallel to the channel (Figure 1). One kilometer separated the closest transects (C3, D1) from the channel.

To determine sediment grain size distributions and thereby

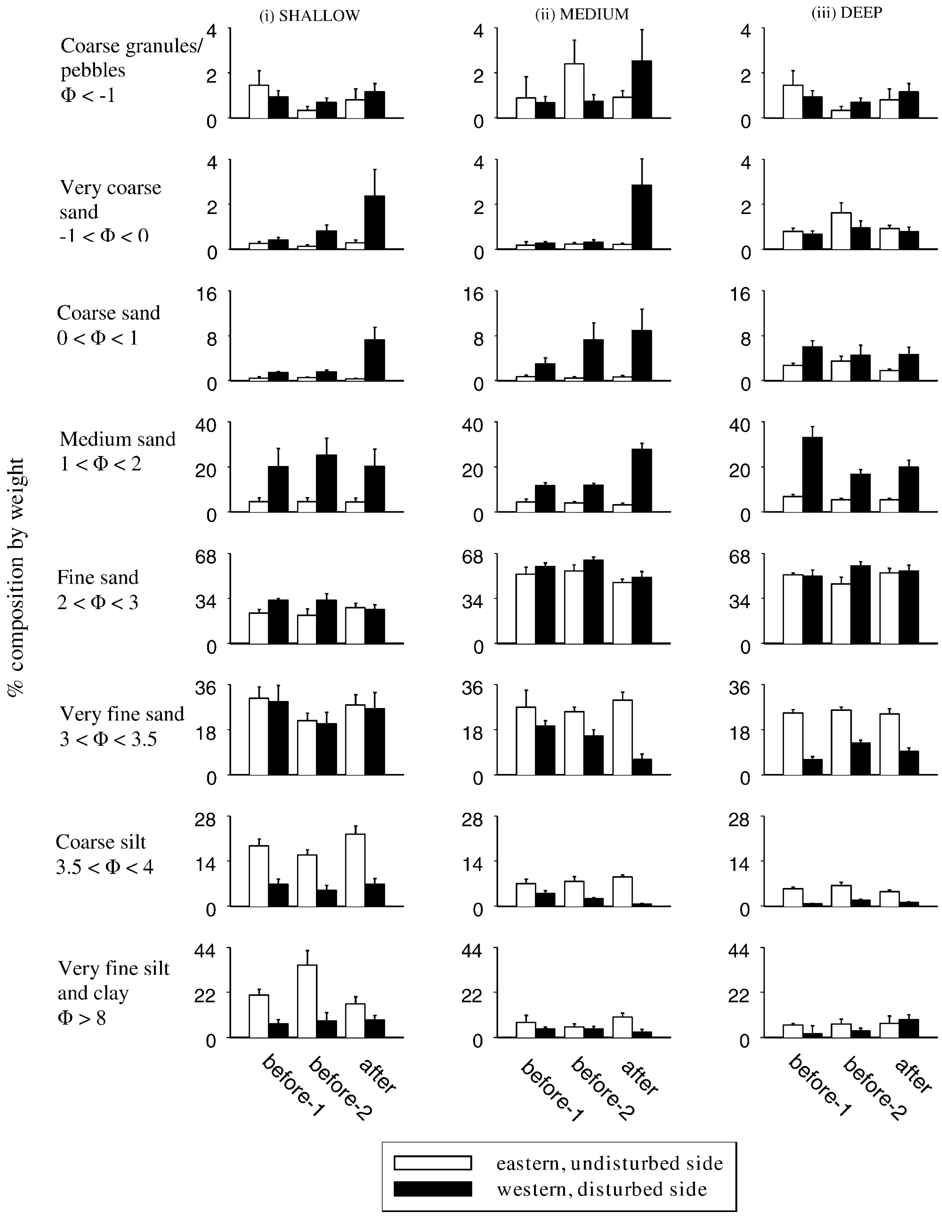


Figure 4. Mean (+SE) proportion, in each size class, of sediments by weight, collected from the eastern, undisturbed (white bars) and western, disturbed (black bars) side of Beaufort Inlet on two dates before (before-1, December 1994; before-2, February 1996) and one date after (December 1996) the major deposition of dredged materials in March–April 1996. $n = 3$, with three transects sampled on each side of the inlet at each time.

characterize the sedimentological signal of deposition, three cores of sediment, 10 cm in depth and 1.3 cm in diameter, were collected by SCUBA from each station at each time using a plastic syringe. Cores were frozen at −40°C until analysis. Upon thawing, sediment samples were homogenized and washed through a 4-ϕ (63-μm) sieve. The fraction that passed through the sieve was diluted to 1000 ml in a graduated cylinder. This fraction was mixed by stirring for exactly 1 min and left to settle for 56 s, at which time a 20-ml sample was taken from a depth of 10 cm to calculate the total amount of sediment less than 63 μm in diameter present in the core (see FOLK, 1974). A full pipette analysis in which the weights of this finest fraction are partitioned further was not done because the >4-ϕ fraction contributed little to the total weight.

Sediment retained on the 4-ϕ sieve was dried to constant weight at 85°C. This sediment was sorted into fractions by mechanically shaking a column of sieves of mesh size 0 ϕ (1 mm), 1 ϕ (500 μm), 2 ϕ (250 μm), 2.5 ϕ (177 μm), 3 ϕ (125 μm), 3.5 ϕ (88 μm), and 4 ϕ (63 μm) for 10 min using a Ro-Tap (Tyler, Mentor, Ohio, U.S.A.) shaker. The dry weight (after 48 h) of each fraction was determined, as was its proportionate contribution to total dry weight.

Table 2. *Results of asymmetrical analyses of variance comparing the proportion (by weight) of sediment fractions in samples between times before (before-1, before-2) and after the major deposition of dredged materials on the western side of the ebb-tidal delta, between eastern (control) and western (disturbed) sides of the inlet. Data were arcsine transformed prior to analysis. Medium depth = 7.9 m; shallow depth = 5.8 m.* n *= 3. Only sediment fractions showning graphical patterns consistent with an impact of the perturbation were analyzed.*

		Coarse Granules ($\Phi < -1$) Medium Depth			Very Coarse Sand ($-1 < \Phi < 0$) Shallow Depth			Very Coarse Sand ($-1 < \Phi < 0$) Medium Depth			Coarse Sand ($0 < \Phi < 1$) Shallow Depth		
Source	DF	MS	F-ratio	Sig.	MS	F-ratio	Sig.	MS	F-ratio	Sig.	MS	F-ratio	Sig.
Time	2	13.8	0.4	NS	18.7	1.7	NS	47.4	3.9	*	34.1	1.5	NS
Side	1	6.6	NO TEST		104.0	NO TEST		70.1	NO TEST		855.3	NO TEST	
Station (side)	4	72.1	2.3	NS	62.7	5.8	*	14.9	1.2	NS	480.3	21.2	***
Time × side	2	33.3	1.1	NS	14.5	1.3	NS	47.0	3.8	NS	47.2	2.1	NS
Before *vs* after × side	1	49.2	2.8	NS	18.8	1.8	NS	94.0	16,215.7	***	33.4	0.5	NS
Among before × side	1	17.3			10.2				0.0			61.0	
Time × station (side)	8	31.3	4.8	***	10.9	7.1	***	12.3	4.5	***	22.7	15.0	***
Residual	36	6.6			5.3			2.7			1.5		
Cochran's test			$C = 0.39$*			$C = 0.72$**			$C = 0.78$**			$C = 0.59$**	

NS = not significant ($p > 0.05$).
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

To determine whether benthic macroinvertebrate assemblages were affected by deposition, on each date we used SCUBA to collect by hand five cylindrical cores of sediment, 10 cm in diameter and 10 cm deep, taken haphazardly from within a 1-m radius of the center of each station. Cores were capped on the sea floor to prevent losses of invertebrates, carried to the surface, placed on ice, and transported to the laboratory, where they were washed over a 500-μm mesh. The portion of the sample retained by the sieve was preserved in 5% formalin and stained with Rose Bengal (Fisher Scientific, Fairlawn, New Jersey, U.S.A.). Polychaetes, bivalves, gastropods, and amphipods were sorted to family, and other crustaceans to order. This approach shortened the time needed to process samples, enabling us to collect a greater number of replicate samples from a greater number of replicate transects. It is unlikely to have affected the usefulness of the data in demonstrating spatial patterns in benthic assemblages; similar patterns of benthic assemblages are often found when coarse or fine levels of taxonomic resolution are used (SOMERFIELD and CLARKE, 1995).

To test for multivariate changes in geology and benthic biology arising from the first and then the second disposal, differences between control and disturbed transects in grain size distributions and in assemblages of macroinvertebrates were examined by depth using nonmetric multidimensional scaling (nMDS; KRUSKAL, 1964; SHEPHARD, 1962) of centroids (averages) for stations. Ordinations of ecological data were based on matrices of Bray-Curtis dissimilarities (BRAY and CURTIS, 1957), calculated from untransformed counts. Euclidean distances were used for ordination of physical data. To evaluate potential impacts of the first disposal, ordinations including only points from times before-1 and before-2 (before and after the first deposition) were plotted for the medium depth, where disposal occurred and any impact would presumably be greatest. These ordinations allowed changes in sediments and macroinvertebrates on the east (control) and west (disturbed) sides of the inlet to be compared between times before and after the first, smaller deposition without the distorting influence of data from after the second, larger disposal. We then performed a second set of ordinations for individual depths that included data from all three times of sampling to evaluate the joint impact of the two disposals (January–March 1995 and March–April 1996) on sediments and fauna. On the resulting plots, greater distances between points representing eastern (control) and western (disturbed) transects after the second disposal than at times before-1 and before-2 would indicate an impact of the second disposal.

To test formally for any impact of the major (second) deposition on the composition of sediments and assemblages of invertebrates, we ran two-way analyses of variance (ANOVAs) on dissimilarity measures using the factors Time Comparison (before-1 to before-2; before-2 to after) and Station (C1, C2, C3, D1, D2, D3). These analyses were applied only to stations from medium depths because the ordination plots implied that impacts were restricted to this depth. A significant impact of the major deposition would be indicated by emergence of a significant interaction between the two factors that is caused by specific patterns of differences among stations. The significant interaction would imply that changes during the two time periods varied among stations. If this interaction were related to disposal, then those stations that received disposal directly and possibly also those that received sediments indirectly would share the same outcome in station-specific *post hoc* Student-Newman-Keuls contrasts by demonstrating significantly greater dissimilarity in the second than in the first time period.

Asymmetrical beyond-Before-After-Control-Impact-(BACI) ANOVAs (UNDERWOOD, 1992) with two times before and one time after the second (major) deposition tested for a significant interaction between time (before *vs.* after) and disturbance (undisturbed east *vs.* disturbed west). Separate tests were done for each depth on sediment particle size classes that, from visual inspection of the data, displayed different patterns of temporal change between the eastern and western sides of the inlet. Additional asymmetrical ANOVAs on

Table 2. *Extended.*

		Medium Sand ($1 < \Phi < 2$) Medium Depth			Very Fine Sand ($3 < \Phi < 3.5$) Medium Depth			Coarse Silt ($3.5 < \Phi < 4$) Medium Depth		
Source	DF	MS	F-ratio	Sig.	MS	F-ratio	Sig.	MS	F-ratio	Sig.
Time	2	152.9	6.0	*	150.7	1.6	NS	28.0	0.7	NS
Side	1	2202.1	NO TEST		1584.0	NO TEST		885.1	NO TEST	
Station (side)	4	36.1	1.4	NS	80.3	0.8	NS	15.7	0.4	NS
Time × side	2	264.7	10.5	**	288.9	3.0	NS	108.5	2.8	NS
Before *vs* after × side	1	526.1	158.6	*	568.6	61.5	NS	202.4	14.0	NS
Among before × side	1	3.3			9.2			14.5		
Time × station (side)	8	25.3	7.1	***	95.9	10.2	***	39.0	14.6	***
Residual	36	3.6			9.4			2.7		
Cochran's test			$C = 0.49$**			$C = 0.23$ NS			$C = 0.36$*	

individual sediment fractions tested whether temporal (before *vs.* after) patterns of change differed between stations at the medium depth directly receiving sediments and the medium-depth station on transect D1, approximately 1 km outside the area of disposal. Sedimentological data, which were expressed as proportions, were arcsine transformed prior to analysis. For the macroinvertebrates, nMDS plots were used to identify depths at which assemblages differed between control and putatively disturbed transects. For the only depth (medium) at which such a pattern was exhibited, Similarity Percentages analysis (SIMPER; PRIMER-E Ltd., Plymouth, UK; Clarke, 1993) identified the taxa contributing most to dissimilarity among stations and for which subsequent ANOVAs were done. Densities were transformed using $\ln(x + 1)$ to reduce heterogeneity in variances. Cochran's (1951) *C*-test indicated in several tests on sediments that variances remained heterogeneous at $\alpha = 0.05$ following transformation. These data were still analyzed because analysis of variance is relatively robust to heterogeneous variances (Box, 1953; Underwood, 1997).

RESULTS

Changes in Bathymetry

Large differences in bathymetry existed between east and west sides of Beaufort Inlet before and after sediment deposition. The extent of the delta was smaller on the east side, and the depth gradient accordingly steeper. Topographic surveys by USACE done at the medium depth, where the captain's log indicated that sediments were deposited, did not show a detectable change in bottom topography between August 1994, 6 months before the first disposal, and February 1996, 1 year after this first, minor disposal (Figure 2a,b). Surveys done in May 1996, immediately after the second disposal, indicated an increase in elevation at stations at medium depth on transect D3 and, to a much smaller extent, D2 (Figure 2c). Consistent with the captain's log, D1 appeared to be outside the area of disposal. Increased elevations at D2 and D3 were still evident in February 1996, almost a year after the deposition (Figure 2d). Only slight transport and spread of sediments from the sites of initial deposition was apparent from the bathymetry.

Patterns in Sediment Particle Sizes

Differences in sediment-size distributions were evident between the eastern (filled symbols) and western (unfilled symbols) sides of the inlet in nMDS ordinations done separately for each depth (Figure 3). An initial ordination for the medium depth, including only data from times before-1 and before-2, indicated that change in sediment-size composition between times before and after the smaller 1995 deposition did not differ between transects on the western, disturbed side of the inlet (unfilled symbols) and transects on the eastern, control side (filled symbols; Figure 3a). This analysis was conducted for the medium depth only because that is where deposition occurred and thus where any sedimentological responses would be most evident. Absence of any detectable impact of the first minor deposition even at medium depth allowed us to measure (conservatively) the impact of the second, major disturbance relative to background change exhibited between the first two sampling dates. In subsequent, more inclusive nMDS ordinations that incorporated all three sampling dates, the east-west difference at shallow (Figure 3b) and deep (Figure 3d) depths was of similar magnitude at each time of sampling. At the medium depth (Figure 3c), a difference also existed, but the difference increased following (triangles) the major (March–April 1996) deposition of dredged material on the western side of the inlet. Eight months after this major deposition, the two medium-depth stations at which sediment was deposited (on transects D2 and D3) had sediments most different from those on the eastern, undisturbed side of the inlet. Although the medium-depth station on transect D1 did not receive direct deposition of sediment (Figure 2c), this station nonetheless also exhibited a greater difference in grain size composition from the eastern transects in December 1996 following the major deposition than at either of the two before times.

Isolating the results of the medium-depth nMDS so as to more clearly portray the trajectories of change over time demonstrated how the relative magnitudes and directions of

Table 3. *Results of asymmetrical analyses of variance comparing the proportion (by weight) of sediment fractions in samples between times before (before-1, before-2) and after the major depostion of dredged spoil, among stations on the western (disturbed) side of the inlet. Data were arcsine transformed prior to analysis. Medium depth = 7.9 m; shallow depth = 5.8 m.* n *= 3.*

		Granules/Pebbles ($\Phi < -1$)			Very Coarse Sand ($-1 < \Phi < 0$)			Coarse Sand ($0 < \Phi < 1$)			Medium Sand ($1 < \Phi < 2$)			Fine Sand ($2 < \Phi < 3$)		
Source	DF	MS	F	Sig.	MS	F	Sig.	MS	F	Sig.	MS	F	Sig.	MS	F	Sig.
Time	2	18.1	2.2	NS	99.8	19.8	***	297.7	30.8	***	1050.9	194.0	***	237.5	9.7	**
Station	2	41.6	5.2	*	22.3	4.4	*	33.2	3.4	NS	81.2	15.0	***	11.2	0.5	NS
Time × station	4	57.1	7.1	**	24.1	4.8	**	32.8	3.4	NS	10.6	2.0	NS	60.7	2.5	NS
Before *vs* after	2	113.4	162.5	**	48.2	2459.6	***	65.4	335.4	**	20.4	29.3	*	15.9	0.2	NS
Among before	2	0.7			0.0			0.2			0.7			105.5		
Residual	18	8.1			5.1			9.7			5.4			24.4		
Cochran's test		$C = 0.63$*			$C = 0.84$**			$C = 0.75$**			$C = 0.65$**			$C = 0.72$**		

NS = $p > 0.05$.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.01$.

changes between time periods varied with perturbation (Figure 3c[i–iii]). At each station on the three control transects (C1, C2, C3), change between times before-1 (circles) and before-2 (squares) was of a similar magnitude to change between times before-2 (squares) and after (triangles; Figure 3c[i]; Table 1). There was no consistent direction to the changes exhibited during the second period of time at these control stations. On transects directly receiving dredged material, changes were smaller between the two times before the major (March–April 1996) deposition (before-1: circles; before-2: squares) than between before-2 (squares) and after (triangles; Figure 3c[iii]), although this difference between time periods was statistically significant only at D2 (Table 1). After the major deposition of sediment, both of these stations exhibited large movements towards the upper left in ordination space. The medium-depth station on transect D1, which did not receive direct deposition of sediment, did not display a significantly larger change in the time period after major deposition (Figure 3c[ii]; Table 1), but the direction of movement in ordination space was similar to that of D2 and D3 and unlike that of any of the controls (Figure 3c[i]).

As in results of our multivariate analyses of sedimentological patterns, contrasts of individual size fractions revealed differences between the eastern and western sides of Beaufort Inlet (Figure 4). Sediments on the eastern side of the inlet (white bars) generally had greater proportions of fine sand and silt/clay and smaller proportions of coarse and medium sand than those on the western side (black bars; Figure 4). At shallow and medium depths, this difference became accentuated after the major deposition of dredge spoil on the western side of the inlet in early 1996. Large increases in the proportion by weight of (i) very coarse sand at the shallow and medium depths, (ii) coarse sand at the shallow depth, and (iii) coarse granules/pebbles and medium sand at the medium depth (Figure 4) were observed on the western, disturbed side of the inlet (black bars) but not on the eastern, undisturbed side (white bars) 8 months after the major deposition. The postdeposition increases in very coarse and coarse sands at the shallow depth were evident only at one station, that on transect D2 (data not shown). Relative to simultaneous changes on the eastern side of the inlet, proportions of very fine sands, silts, and clays at medium depth decreased in sediments on the western side between times before (before-1 and before-2) and after the disturbance (Figure 4). At the medium depth, only the increases in very coarse sand and medium sand on the disturbed side were statistically significant at $\alpha = 0.05$ (ANOVA: significant Before *vs.* After × Side interaction; Table 2).

On the western side of the inlet, changes at medium depth in the proportions of sediment fractions between times before and after the major deposition of sediment (Figure 5) showed significant interactions with station for four of the nine size fractions analyzed (Table 3). In separate plots for pebbles/granules, very coarse sands, and coarse sands (Figure 5), these interactions appeared to be driven by large changes at the station on transect D2 (gray bar), which had received direct sediment deposition (Figure 2). The proportions by weight of granules/pebbles and both very coarse and coarse sand categories increased substantially at D2 following the major disposal, whereas postdeposition increases in very coarse and coarse sand were smaller at the other two stations (Figure 5a,b,c). In contrast, the proportion by weight of the medium sand category (Figure 5d) increased more at the station on D3 (black bar), which had received the greatest amount of sediment deposition (Figure 2), than at the station on transect D1 (white bar; outside the area of deposition) or D2 (gray bar; receiving direct but lesser deposition). Stations on D1 and D2 displayed similar, but smaller, increases in medium sand following the major disposal.

Patterns in the Composition of Invertebrate Assemblages

Differences in composition of macrobenthic assemblages were generally evident between the eastern (filled symbols) and western (unfilled symbols) sides of the inlet in nMDS ordinations done separately for each depth (Figure 6). An initial ordination for the medium depth, including only times before-1 and before-2, showed that the magnitude of change in assemblages between times before and after the first minor deposition at stations on the western, disturbed side of the inlet (unfilled symbols) was within the range found for sta-

Table 3. *Extended.*

		Very Fine Sand ($3 < \Phi < 3.5$)			Coarse Silt ($3.5 < \Phi < 4$)			Medium-Fine Silt ($4 < \Phi < 8$)			Very Fine Silt/Clay ($\Phi > 8$)		
Source	DF	MS	F	Sig.	MS	F	Sig.	MS	F	Sig.	MS	F	Sig.
Time	2	900.9	88.6	**	428.2	466.2	***	466.7	177.7	***	3.3	0.3	NS
Station	2	331.7	32.7	**	35.3	38.5	***	21.2	8.1	**	5.4	0.4	NS
Time × station	4	36.6	3.6	*	3.3	3.6	*	34.6	13.2	***	4.4	0.4	NS
Before *vs* after	2	20.8	0.4	NS	4.1	0.9	NS	17.7	0.3	NS	5.9	2.0	NS
Among before	2	52.4			4.5			51.6			2.9		
Residual	18	10.1			0.9			2.6			12.5		
Cochran's test		$C = 0.42$ NS			$C = 0.34$ NS			$C = 0.29$ NS			$C = 0.49$ NS		

tions on the eastern, control side (filled symbols; Figure 6a). This analysis was conducted for the medium depth only because that is where deposition occurred and where statistically significant sedimentological responses were detected. In subsequent, more inclusive nMDS ordinations including all three sampling dates, assemblages of benthic macroinvertebrates at the shallow depth exhibited similar differences between the eastern (filled symbols) and western (unfilled symbols) sides of the inlet on each date (Figure 6b). At the deep depth, differences in composition of benthic assemblages between eastern and western sides of the inlet were less distinct than at shallow and medium depths, and decreased through time (Figure 6d). At the medium depth, the east-west difference in benthic assemblage composition was much greater following the major disposal of sediment (triangles) than at either of the before times (circles and squares: Figure 6c).

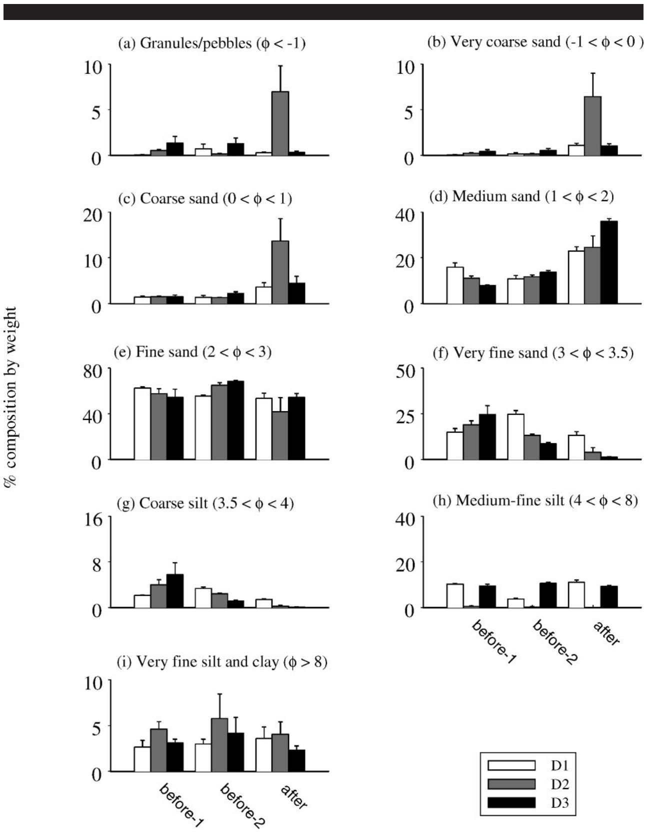


Figure 5. Mean (+SE) proportion, in each size class, of sediments by weight, collected from medium-depth stations on the disturbed side of the inlet that were outside (light gray: D1) or inside (dark gray: D2, D3) the area directly receiving sediments, on two dates before (before-1, December 1994; before-2. February, 1996) and one date after (December, 1996) the major deposition of dredged materials in March–April 1996. $n = 3$.

Isolating the results of the medium-depth nMDS so as to more clearly portray the trajectories of temporal change demonstrated how the relative magnitudes and directions of changes between time periods varied among stations (Figure 6c[i–iii]). At the control stations, C1 and C2, change between times before-1 and before-2 was of similar magnitude to change between before-2 and after (Figure 6c[i], Table 4). At C3, change was greater between before-1 and before-2 than between before-2 and after (Figure 6c[i], Table 4). Assemblages at the three stations on the western (disturbed) side of the inlet, in contrast, changed more between before-2 and after than between before-1 and before-2 (Figure 6c[ii and iii], Table 4). The direction of change of assemblage composition in ordination space during the final time period that included the major sediment deposition differed between the control stations (C1, C2, and C3) on the eastern side of the inlet, which moved towards the lower right in Figure 6, and the stations on the western, disturbed side (D1, D2, and D3), which moved towards the left. During this final time period after major deposition, the larger magnitude and differential direction of change in assemblage composition of the two stations (D2 and D3) that received direct deposition separated them further than D1 from the cluster of other stations (Figure 6c).

SIMPER analyses identified the taxa Spionidae, Haustoriidae, Veneridae, Oweniidae, Tellinidae, Phoxocephalidae, and Lucinidae as most important in contributing to differences among medium-depth stations across the three dates of sampling (Table 5). ANOVAs done on the abundances of each taxon identified as an important contributor to dissimilarity patterns revealed only two cases of significance. The abundance of tellinids was greater on the eastern than the western side of the inlet at all times (Figure 7; Table 6). Only the abundance of spionid polychaetes followed temporal and spatial patterns that were consistent with impacts of distur-

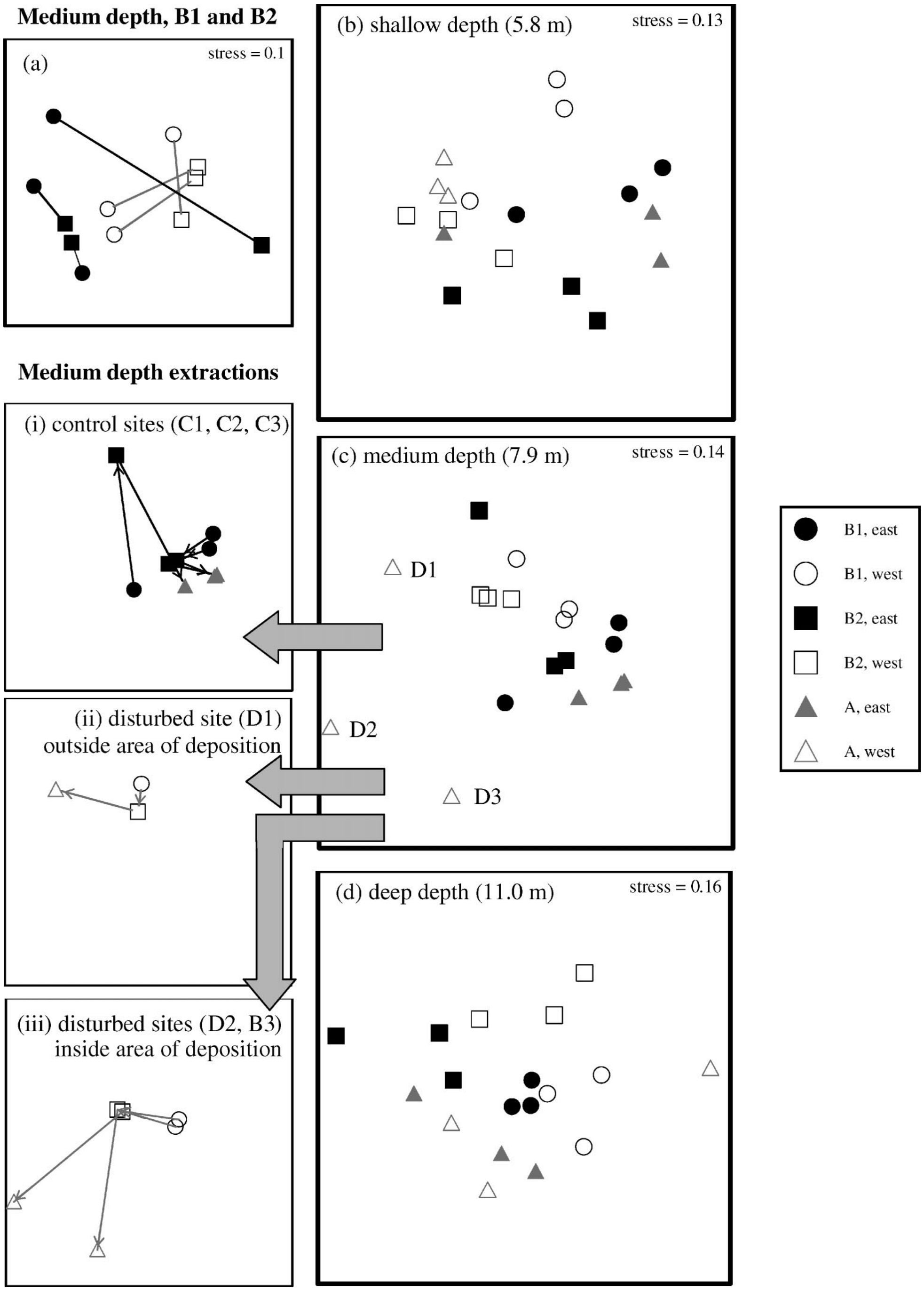


Figure 6. nMDS ordinations of assemblages of infauna at control (filled symbols) and disturbed (unfilled symbols) transects at (a) medium depth before (before-1, circles) and after (before-2, squares) the minor deposition in February–March 1995 and at (b) shallow, (c) medium, and (d) deep depths on two dates before (before-1, before-2; black symbols) and one date after (gray symbols) the major deposition of sediment on the western ebb-tidal delta of Beaufort Inlet in March–April 1996. D1, D2 and D3 denote points corresponding to disturbed sites at the after time. (i–iii) are extractions of the plot for the medium depth (c), more clearly depicting temporal trajectories of change for each of the sampling stations by including arrows. Points represent centroids of untransformed data ($n = 5$). Bray-Curtis measures of dissimilarity were used.

Table 4. *Results of analyses of variance comparing magnitudes of Bray-Curtis measures of dissimilarity in assemblages of benthic macroinvertebrates calculated between the two times (before-1, before-2) prior to the major deposition of sediment on the western delta of the Beaufort Inlet with those calculated between times before (before-2) and after deposition, among the six stations sampled at a medium depth. Ti = time comparison (2 levels: before 1 to before-2 [B1B2]; before 2 to after [B2A]), St = station (6 levels: control 1 [C1], control 2 [C2], control 3 [C3], disturbed 1 [D1], disturbed 2 [D2], disturbed 3 [D3]).* n = 25 *possible pairwise comparisons of cores.*

	DF	MS	F	Sig.
Ti	1	198	1.7	NS
St	5	3041	27.1	***
Ti × St	5	699	6.2	***
Residual	288	112		
Cochran's Test			$C = 0.20$**	
SNK			C1: B1B2 = B2A	
Ti × St			C2: B1B2 = B2A	
			C3: B1B2 > B2A	
			D1; B1B2 < B2A	
			D2: B1B2 < B2A	
			D3: B1B2 < B2A	

NS = $p > 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

bance (Figure 8; Table 6). Large, though nonsignificant (Table 6), decreases in the abundance of this taxon were seen at medium-depth stations on each of the western transects following the disturbance. None of the taxa increased in abundance following the coarsening of sediments on the western side of the inlet.

DISCUSSION

Physical disturbance is important in determining the composition of assemblages of benthic invertebrates in soft sediments (HALL, 1994; PROBERT, 1984; THRUSH *et al.,* 1996). Disturbance can occur routinely on estuarine and sea floors because, unlike bedrock, a sediment surface can be readily eroded by currents and waves (e.g., ONG and KRISHNAN, 1995) and because deposition of sediments can occur naturally after storm events (e.g., DOBBS and VOZARIK, 1983) or during disposal of dredged materials (e.g., RHOADS, MCCALL, and YINGST, 1978).

The response of benthic macroinvertebrates to sediment deposition potentially has two components, pulse and press (BENDER, CASE, and GILPIN, 1984). The pulse response encompasses the immediate short-term mortality arising from burial and suffocation, a process that may be largely independent of the character of the sediments. The press response is created by transformation of biologically important characteristics of the deposited sediments (e.g., grain size distribution, organic content, and perhaps mineralogy), factors that continue to affect benthic communities for an indefinite period of time lasting until initial sediment character returns. Our study demonstrated sizeable sedimentological transformations towards pebbles/gravels and coarse and very coarse sands, lasting in excess of eight months, at locations where the major deposition of dredged materials occurred (medium depth on transects D2 and D3: Figure 3). Although the associated biological responses that we documented (Figure 6) may combine impacts of both the pulse and the press components of disturbance, the passage of eight months since the pulse disturbance is likely to have permitted substantial recruitment of the small infaunal invertebrates that dominated the assemblage sampled by our cores (FLEMER *et al.*, 1997; ROSENBERG, 1977). Consequently, we suspect that these biological responses mainly reflect consequences of the press component of disturbance.

Despite deposition of 114,690 m^3 of dredged material in January–March 1995, comparison of the bathymetric surveys done by USACE in August 1994 and February 1996 failed to show any topographic changes at medium depth, at which the sediment was disposed (Figure 2). The absence of detectable topographic changes after that first minor deposition may be explained by the relatively small quantity of sediments relative to the area over which they were distributed. Neither the size-frequency distribution of sediments (Figure 3a) nor the composition of the faunal assemblage (Figure 6a) revealed an impact of this minor deposition.

In contrast to the first deposition, the second deposition in March–April 1996 of six times as much dredged material produced substantially elevated mounds on the sea floor, clearly evident in bathymetry of May 1996 and little changed by February 1997 (Figure 2). The bathymetric mapping depicted deposition only at medium depth and only at the stations on transects D2 and, more intensely, D3. Correspondingly, sedimentological changes were greatest at those two stations (Figure 3), with large increases in coarser size fractions (Figure 5), and changes in benthic infaunal assemblages were greatest at those locations as well (Figure 6).

Sedimentological and benthic biological sampling both indicate that the deposited materials were spread by physical transport after deposition to influence a wider area than that which, according to the captain's log, directly received sediments. Transport of deposited sediments occurred in an easterly or northeasterly direction toward the inlet (to D1) and toward shallower depths, consistent with the net direction of physical forcing (USACE, 2001). Thus, no evidence of the coarse sediment signal appeared and no detectable change in benthic assemblages occurred after the major sedimentation at any of the deep stations. Were the slope much steeper, turbidity flows could conceivably have been induced towards deeper water through slope instability (BURD, MACDONALD, and BOYD, 2000). Among stations outside the zone of direct deposition, the one that exhibited the strongest sediment signal (Figure 3c[ii]) and the only biological response (Figure 6c[ii]) was the medium-depth station on transect D1, about 1 km east of the closest site of sediment deposition. Although the biological impact of transport of coarse sediments to this station was detectable, multivariate analysis of assemblage composition showed that, unlike direct deposition, this perturbation did not displace the benthic assemblage far from the cluster of control points (Figure 6c). The only other station exhibiting receipt of transported sediments from the deposition sites was the shallow station on transect D2, where coarse fractions were enhanced eight months after the major deposition. This shallow-depth station on transect D2 was located about 500 m inshore of the medium-depth station on

Table 5. *Taxa contributing most (and their percent contribution) to Bray-Curtis measures of dissimilarity between sites at the medium depth, across the three times of sampling, as calculated using SIMPER. C1, C2, C3 = eastern, control stations. D1, D2, D3 = western, disturbed stations. Av. Dissim. = average Bray-Curtis measure of dissimilarity between pairs of samples for each combination of sites.*

Between control stations					
C1 & C2		C1 & C3		C2 & C3	
Taxon	% Contrib.	Taxon	% Contrib.	Taxon	% Contrib.
Spionidae	17	Haustoriidae	17	Haustoriidae	19
Veneridae	6	Spionidae	14	Spionidae	12
Oweniidae	6	Tellinidae	5	Phoxocephalidae	6
Capitellidae	5	Capitellidae	4	Tellinidae	5
Magelonidae	4	Cirratulidae	4	Veneridae	5
Av. Dissim.	76	Av. Dissim.	84	Av. Dissim.	87
Between disturbed stations					
D1 & D2		D1 & D3		D2 & D3	
Taxon	% Contrib.	Taxon	% Contrib.	Taxon	% Contrib.
Haustoriidae	19	Haustoriidae	20	Haustoriidae	11
Phoxocephalidae	11	Phoxocephalidae	13	Spionidae	10
Spionidae	8	Spionidae	10	Lucinidae	7
Tellinidae	6	Tellinidae	7	Phoxocephalidae	7
Lucinidae	6	Cirratulidae	6	Tellinidae	6
Av. Dissim.	82	Av. Dissim.	88	Av. Dissim.	86
Control *vs.* disturbed					
C1 & D1		C1 & D2		C1 & D3	
Taxon	% Contrib.	Taxon	% Contrib.	Taxon	% Contrib.
Haustoriidae	16	Spionidae	15	Spionidae	16
Spionidae	14	Haustoriidae	6	Haustoriidae	6
Phoxocephalidae	9	Lucinidae	6	Veneridae	5
Tellinidae	5	Veneridae	5	Tellinidae	5
Veneridae	5	Capitellidae	4	Lucinidae	5
Av. Dissim.	89	Av. Dissim.	87	Av. Dissim.	86
Control *vs.* disturbed					
C2 & D1		C2 & D2		C2 & D3	
Taxon	% Contrib.	Taxon	% Contrib.	Taxon	% Contrib.
Haustoriidae	17	Spionidae	14	Spionidae	15
Spionidae	13	Haustoriidae	6	Haustoriidae	6
Phoxocephalidae	9	Lucinidae	6	Oweniidae	6
Tellinidae	5	Oweniidae	5	Tellinidae	5
Oweniidae	4	Magelonidae	4	Lucinidae	4
Av. Dissim.	91	Av. Dissim.	88	Av. Dissim.	87
Control *vs.* disturbed					
C3 & D1		C3 & D2		C3 & D3	
Taxon	% Contrib.	Taxon	% Contrib.	Taxon	% Contrib.
Haustoriidae	24	Haustoriidae	19	Haustoriidae	19
Spionidae	12	Spionidae	12	Spionidae	13
Phoxocephalidae	9	Tellinidae	6	Tellinidae	6
Tellinidae	6	Phoxocephalidae	5	Phoxocephalidae	5
Cirratulidae	6	Lucinidae	5	Cirratulidae	4
Av. Dissim.	83	Av. Dissim.	87	Av. Dissim.	86

that same transect, but the direction of sediment transport seems more likely to have been to the northeast, given the positioning of the majority of the deposited materials closer to transect D3 (Figure 2). The sedimentological signal was apparently too small to elicit any detectable response in the composition of the benthic infaunal assemblage.

The detection of an impact of deposition following the large but not the small disposal suggests that the magnitude of sediment deposition at a site will determine the degree of sedimentological and biological impacts. Large quantities of sediment take longer periods to erode and disperse than do smaller quantities of sediment, resulting in longer-lasting biological impacts. Thus, multiple depositions of small quantities of sediment, sufficiently separated in time to allow complete dispersal of sediments between depositions, may disturb the benthos less than a single, large deposition. If the frequency with which sediment is deposited exceeds the period of time required for its dispersal, persistent changes to

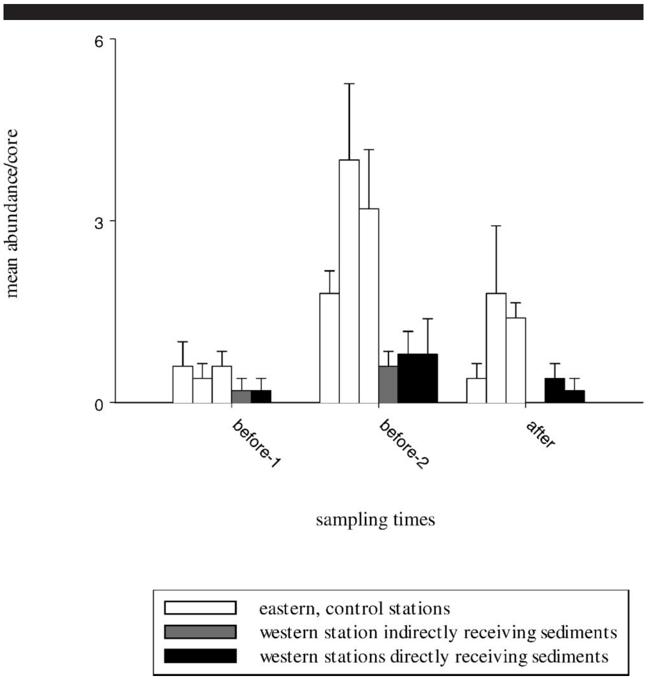


Figure 7. Mean (+SE) numbers of tellinids per core collected from medium depth on control transects (white bars; C1, C2, C3) and transects on the disturbed side of the inlet that indirectly (light gray; D1) or directly (dark gray; D2, D3) received sediments, on two dates before (before-1, December 1994; before-2, February 1996) and one date after (December 1996) the major deposition of dredged materials in March–April 1996. $n = 5$.

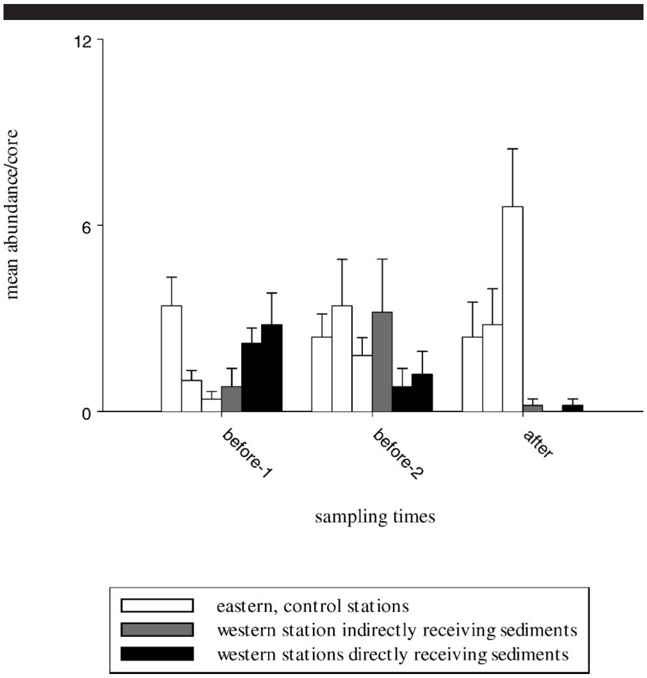


Figure 8. Mean (+SE) numbers of spionids per core collected from medium depth on control transects (white bars; C1, C2, C3) and transects on the disturbed side of the inlet that indirectly (light gray; D1) or directly (dark gray; D2, D3) received sediments, on two dates before (before-1, December 1994; before-2, February 1996) and one date after (December 1996) the major deposition of dredged materials in March–April 1996. $n = 5$.

its sedimentology and benthic biota at the site of deposition may, however, be induced.

Our study was not designed properly to test whether nourishing beaches through transport of sediments deposited on ebb-tidal deltas and other shallow subtidal shoals would have less serious ecological impacts than direct deposition on the intertidal beach. In our study, sediments were deposited at a 7.9-m depth, which lies beyond the depth of closure that defines the outer limit of the beach sand-sharing system. Furthermore, sampling was not done sequentially after deposition in a design that would allow description of the transport process and its impacts. Nevertheless, the results contribute

Table 6. *Results of asymmetrical analyses of variance comparing the abundances of macrofaunal taxa at medium depth between times before (before-1 [B1], before-2 [B2]) and after (A) the major deposition of dredge spoil on the west side of the ebb-tidal delta. Data were ln(*x *+ 1) transformed prior to analysis. C = eastern, control side; D = western, disturbed side; Sig. = significance level.* n *= 5.*

		(i) Spionidae			(ii) Tellinidae		
Source	DF	MS	*F*-ratio	Sig.	MS	*F*-ratio	Sig.
Time	2	0.31	0.29	NS	3.18	34.42	***
Side	1	5.49	NO TEST		5.85	NO TEST	
Station (side)	4	0.09	0.09	NS	0.25	2.68	NS
Time × side	2	3.31	3.10	NS	0.57	6.19	*
Before *vs* after × side	1	5.56	5.22	NS	0.02	0.02	NS
Among before × side	1	1.07				1.12	
Time × station (side)	8	1.07	2.72	*	0.09	0.45	NS
Before *vs* after × station	4	1.17	1.21	NS	0.09	0.99	NS
Among before × station	4	0.97				0.09	
Residual	72	0.39				0.21	
Cochran's test			$C = 0.15$ NS			$C = 0.24$ NS	
Student-Neuman-Keuls contrast						B1: C > D	
Time × side						B2: C > D	
						A: C > D	

NS = $p > 0.05$.
* $p < 0.05$.

some insights into the benthic biological impacts of transport of deposited sediments. There were large impacts on sedimentology and on composition of the benthic assemblage at the deposition site, whereas both sediments and benthic assemblages changed much less at the site affected by sediment transport. This alone may imply reduced biological impacts from transported sediments. To the degree that the impacts on benthic assemblages in this study were driven by the press disturbance of persistence of mismatched sediments, a beach nourishment project that deposits compatible (very similar) sediments onto subtidal shoals may induce even less biological impact in locations receiving transported sediment than what was documented here. Studies investigating the ecological impacts of beach nourishment have concluded that the degree to which properties of introduced sediments match those of the native sediments is the most important determinant of impact and rate of recovery of intertidal beach benthos (NELSON, 1993; PETERSON, HICKERSON, and GRISSOM JOHNSON, 2000). The spread of granulometrically and mineralogically compatible sediments from deposition sites on subtidal shoals along shore and onto intertidal beaches for the purpose of beach nourishment may not greatly expand the area of impact of disturbance on benthic biota beyond the deposition site itself. During the course of our study, extreme weather conditions, which likely influenced the dispersal of sediments, occurred on two occasions. In June 1996, Bertha, a class 2 hurricane, crossed the North Carolina coast about 80 km southwest of Beaufort Inlet, between Wrightsville Beach and Topsail Island, bringing high waves and winds of up to 80 mph to Beaufort Inlet. Strong winds and high waves were also experienced in autumn from a second 1996 hurricane, Fran, which made landfall near Bald Head Island (160 km southwest). These storm events may have been responsible for much of the sediment transport that occurred after the second, major deposition.

Spionid polychaetes were the only infaunal taxon to show clear impact of the deposition of sediment. This taxon, which typically inhabits muddy sediments (e.g., GALLAGHER and KEAY, 1998; SNELGROVE, 1994), was relatively abundant in sediments on both sides of the inlet prior to the major deposition. Eight months after deposition of coarser sediments, few spionids were found at the stations on the western, disturbed side of the inlet (Figure 8). RHOADS, MCCALL, and YINGST (1978) similarly observed lower abundances of spionid polychaetes in disturbed than in undisturbed sediments of Long Island Sound 8 months after the addition of coarse sediments to the fine-grained bottom. In contrast to these responses to deposition of coarse sediments, the deposition of mining tailings, dominated by fine-grained sediments, into a British Columbia fjord resulted in increased abundances of spionids several months later (BURD, MACDONALD, and BOYD, 2000). The differing response of spionids to the addition of coarse sediments and fine sediments suggests that this taxon is responding to the press disturbance of sediment modification, not a pulse disturbance associated with smothering (see also LENIHAN *et al.*, 2003).

Most experimental tests of sediment disturbance on benthic assemblages have been logistically constrained to small spatial scales (<1 m^2) (e.g., PETERSON, 1985; ZAJAC and WHITLATCH, 1982a, 1982b). Studies of deposition of dredged materials like this one and that of RHOADS, MCCALL, and YINGST (1978) reveal that this form of disturbance also operates to modify benthic assemblages on the scale of hundreds of meters. The general ability to scale upward from experiments to predict recovery rates for marine benthic assemblages may depend upon the degree to which key organisms disperse more readily over short distances than over kilometers. For example, species whose reproduction involves direct development may be poorer colonizers over longer distances than species that disperse via planktonic larvae.

Even before the deposition of sediment, the sedimentology and ecology of the eastern and western sides of Beaufort Inlet differed markedly at shallow and medium depths. Sediments on the eastern side of the inlet were generally muddier than those on the western side and supported greater abundances of tellinids (Figure 7). Depth contours revealed that the extent of the delta was greater on the western side, such that its slope in the offshore direction graded more slowly than that on the eastern side. The asymmetry of the inlet extends also to separation of water masses on the two sides (HENCH and LUETTICH, 2003). Cross-stream dynamics generate a “wall” down the center of the inlet during the stronger phases of the tide and tend to keep water masses on the two sides separate. Had the dredge spoil been deposited on the eastern rather than the western side of the inlet, the biological impact of the disturbance is likely to have been much greater because of the poorer granulometric match between preexisting sediments and the dredged materials. Despite this persistent difference between the two sides of the inlet, we were able to test for an impact of the disturbance by using a beyond-BACI design and testing for a significant time by disturbance interaction (UNDERWOOD, 1992). This statistical approach and the use of the very powerful nMDS, which may detect patterns in assemblages in the absence of statistically significant univariate trends (CLARKE, 1993), were critical to our ability to derive insight into the nature of benthic biological responses to the disturbance of sediment deposition. Results provide promising indications that dredged materials now treated as spoils might be deposited on subtidal shoals for nourishment of beaches without wide-scale impacts on the benthos. An explicit test of this suggestion is now in order.

CONCLUSIONS

(1) Major depositions of dredged materials that have granulometry substantially coarser than native sediments can result in sizeable sedimentological and topographic transformations to ebb-tidal shoals at depths of 7.9 m, lasting in excess of 8 months.

(2) As long as large modifications in sedimentology persist, this press-type of physical disturbance will maintain assemblages of benthic macroinvertebrates that differ in composition from those found in native sediments.

(3) At Beaufort Inlet, sedimentological and biological changes were greatest where sediments were directly dumped. Smaller changes to both the sediment size distribution of sediments and the assemblage composition of benthic in-

vertebrates were evident at down-drift sites up to 500 m away.

(4) Smaller biological impacts to the benthos, 8 months after the deposition, at sites receiving transported sediments than at the sites where direct deposition occurred suggest that using subtidal instead of intertidal deposition to nourish eroding beaches may better preserve benthic invertebrate resources on the productive beach habitat.

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