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# Detrimental effects of sedimentation on marine benthos: what can be learned from natural processes and rates?

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**Abstract**

Benthic organisms are adapted to the natural processes of sediment movement, erosion and deposition. Laboratory studies have cataloged the range of responses to flow and sediment movement that allow benthos to survive, and even to thrive, under intense, storm-driven sediment movement. Extreme sedimentation events also result from man's modifications of the nearshore marine environment, and the scale and magnitude of these alterations can often greatly exceed that of natural occurrences. Unfortunately, there is little of the quantitative information necessary for predicting how materials placement, sediment deposition and erosion will affect the ecology of these environments. We are using both field and laboratory approaches in Delaware Bay to address two questions. First, what rates and frequencies of sediment movement characterize natural events, and second, what rates and frequencies are detrimental to representative benthic species and functional groups. We present these results as case studies that address ecological impacts of dredge materials placement, site selection and benthic community responses. Quantifying natural sedimentation rates and the susceptibility of macrofauna by functional groups are both critical to reliably predicting environmental impacts. If biological effects are parameterized appropriately (i.e. in terms of natural processes), it may be possible to employ the existing knowledge-base of benthic ecology to predict effects of disturbances and to design projects that will minimize these impacts. Materials placement that is analogous to natural events should allow community responses to follow natural seasonal and successional trends and to exhibit minimal anthropogenic impacts. When sedimentation exceeds natural thresholds, then impacts may involve total loss of the community and subsequent colonization by pioneer species. In this latter case, an entirely different suite of ecological processes will drive impacts and recovery, potentially leading to dramatically altered benthic communities. Understanding organisms' sublethal responses and drawing on experimental ecological studies will lead to improved prediction of benthic community responses and more reliable assessment of project impacts. © 2002 Elsevier Science B.V. All rights reserved.

*Keywords:* Detrimental effects; Sedimentation; Marine benthos; Delaware Bay; Worm reefs; Tubeworm nodules

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## 1. Introduction

Current approaches to the effects of high rates of sedimentation on benthic organisms are limited in scope and ineffective. New approaches are

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necessary to properly understand the effects of erosion and deposition extremes on marine benthic organisms. Using examples from ongoing work in the field and in our laboratory, we will illustrate some ways in which these limitations may be overcome, yielding results of direct relevance to dredge project design and benthic resource management. By applying these new concepts and drawing upon the ecological processes literature, we believe that it will be possible to better predict direct impacts, to determine appropriate options for site remediation, and to assess the potential for beneficial uses of dredge material.

## 2. Basic assertions

Even the casual visitor to the seashore will appreciate that sediment movement is a natural phenomenon. Waves and tides move sand, and the rates of movement are greatly modulated by the wind and weather (Miller and Sternberg, 1988; Hall, 1994; Sherwood et al., 1994). The most severe agents of sediment movement on the Mid-Atlantic coast are winter nor'easters and summer hurricanes. Seasonally, the ocean shoreline erodes during the winter and accretes in the summer. Sandbars shoal and shift, and if not charted frequently pose a hazard to navigation in shallow waters. Ripples on the sandflat at low tide attest to the power of water to erode and transport sand grains even in relatively sheltered environments. From the intertidal zone to the subtidal, sands, silts and clays are continually subject to the action of waves and tidal currents to transport them along and across the shoreline.

These sediments are inhabited by a variety of marine benthic organisms, which display a range of adaptations to deposition and erosion of the sea bottom. Benthic fauna survive intense storm events that control and shape the coastlines (Bock and Miller, 1995). Many are surprisingly resilient to 'sand-blasting' by sediment transport (Miller et al., 1992; Hall, 1994). Infauna can burrow up and down in the sediment to maintain contact with the sediment-water interface, and this implies that certain species or functional groups, even certain community assemblages, are adapted to frequent, natural sediment movement, burial and erosion. In fact, it is likely that susceptibility to sediment movement and burial will vary considerably among taxa (Jumars and Nowell, 1984; Snelgrove and Butman, 1994; Hall, 1994). For example, large and deep dwelling deposit feeders may be tolerant to deposition and erosion because of their size and burrowing ability (Tuck et al., 2000). Since our most frequent storms are nor'easters, winter populations may be more tolerant to sedimentation events than summer populations (Tettelbach et al., 1998). The association of benthic community with bottom type (for example, sand, silt or clay) has been recognized for almost 100 years (Gray, 1981; Levinton, 1995; Snelgrove and Butman, 1994; Raffaelli and Hawkins, 1996). This correlation is apparently driven by the dynamics of sediment movement rather than static, easily measurable variables like sediment grain size (Nowell and Jumars, 1984; Peterson, 1991; Snelgrove and Butman, 1994; Hall, 1994).

Natural processes like winds and tides are not the only agents of sediment movement. In an attempt to counteract natural forces, we rebuild beaches, deepen channels for navigation, and restore habitat with dredge materials placement (National Research Council, 1995). These efforts alter otherwise natural patterns of deposition and erosion by protecting the shore from wave action and interrupting longshore transport. To be effective, dredging projects typically must move sediment at rates that far exceed those typical in nature. Large amounts of sediment must be moved over the lifetime of a funded project in order to counter the more gradual but persistent, longer-term transport driven by natural forces. Dredging, dredge material disposal and beach nourishment have all become commonplace management practices. The engineering scale and heightened public visibility of beach nourishment projects make them newsworthy and politically significant. It is clear that such projects will continue to be employed to foster economic development (Kester et al., 1983; National Research Council, 1995; Clark, 1996).

## 3. Critical issues

While beach projects have many positive societal benefits, they also cause the disruption of coastal benthic habitats and living resources (National Research Council, 1995). The traditional mainstays of benthic resource assessment are coring and grab sampling of the seafloor, preservation of organisms in formalin, and faunal enumeration in the laboratory. These techniques are aptly known as 'kill'em and count'em' methodologies. At a tentatively chosen disposal site, benthic sampling and analysis ensues as part of the impact assessment process. Based on a comparison of the target and control sites in terms of community composition and unique species (if any), an assessment of potential impacts is made. Special interest groups often challenge the claim of no significant (or adverse) impact, and project approval is based less on objective scientific analysis than public opinion, regulatory rulings and legal judgements. While grounded in standardized methods of benthic macrofaunal sampling and analysis, we believe that the benthic community approach to defining environmental impacts is far too simplistic, and we will offer alternatives below.

Macrofaunal biomass, diversity indicators and other derived variables can be calculated from the faunal data and used to assess community structure. Criteria such as species richness, diversity indices, or biomass-depth indicators are not universally applicable or accepted metrics capable of relating numerical data to environmental health and habitat value. Even those methods shown to work (e.g. Weisberg et al., 1997) are not routinely applied when appropriate. The value of a habitat is far more than its species list, yet it is difficult to place a value on organisms that are unfamiliar or have no commercial use. Economic importance is often reflected in a distinguishing biological or unique habitat characteristics rather than an overall derived index of health or resiliency. Derived indices do not weight highly visible species, specialized ecological niches nor key trophic positions. Trophic links and community structure are often unresolved or must be inferred from the literature despite the potential for effects to propagate up food webs. Effective sampling design and adequate statistical power are prerequisites that are unfortunately often lacking or are only considered ad hoc (National Research Council, 1995). Experimental design principles show that before-after comparisons are far more reliable for detecting impacts than those with only control or reference sites (Stewart-Oaten and Bence, 2001). Finally, it is implicitly assumed that dredging or disposal will invariably kill all organisms and that the entire benthic community will be lost. Certain benthic species are known, however, to colonize disturbed and/or organically enriched sites. It is a changed community for better or worse–not a lifeless seafloor–that reemerges (Hall, 1994; Newell et al., 1998; Zajac and Whitlatch, 2001).

The difficulties discussed above have not been fully appreciated in project designs that are based solely on engineering and economic considerations (National Research Council, 1995). Not surprisingly, the net result of such feeble analysis is the dissatisfaction of all parties involved. We suggest new approaches in which we parameterize biological effects on recognized ecological groups in light of field-measurable and project-design parameters. We believe that the result will be a superior means by which to predict impacts and to make value judgements between management options.

### *3.1. When do rates fall outside natural norms?*

Sediment transport itself is not detrimental to most benthic organisms. Erosion does not necessarily result in defaunation of the bottom, just as deposition does not always result in burial and smothering of the benthic community. Thus it is a matter of degree whether erosion and deposition will have negative consequences. Unfortunately, a direct comparison of natural rates relevant to the organisms as compared with rates measured and designed into projects is problematic for several reasons.

Natural sedimentation processes have characteristic length and time scales related to their forcing functions, principally via wind, waves and tides (Komar, 1998). Along most coastlines, the tides rise and fall twice a day, and strong winds and high waves are associated with the passage of storm fronts. While most weather systems cause little variation in sediment movement above background levels, occasional or seasonal events like hurricanes and nor 'easters may drive many years' worth of normal sediment movement. The impacts of such episodic, often catastrophic, events are often widespread, extending to 10s or 100s of kilometers along the coastline. Despite their geological importance, big events such as these are the most technologically challenging to quantify and the least well characterized as a result.

As conventionally measured, sediment transport is movement of material in a horizontal direction along the seafloor (Komar, 1998). Typically, this is quantified in terms of an advective mass flux per second moving per unit width of the bed, usually as grams per second per centimeter cross-stream. Sediment transport models are designed to predict thresholds of sediment motion and horizontal fluxes of sediment from near-bottom flow parameters such as flow speed, hydraulic bottom roughness or shear stress. Changes in sediment height, erosion or deposition occur as a result of gradients (or in three-dimensions, divergences) in horizontal fluxes, yet a vertical dimension is rarely included in quantitative analyses. Herein lies the fundamental disparity between what sediment transport models and engineering principles can provide and what is ecologically relevant to the organisms.

For benthic infauna, horizontal sediment movement itself is largely irrelevant, and it is the up and down movement of the bed, erosion and deposition that is critical (Miller and Sternberg, 1988). Most benthic organisms live in the top 10 cm of the seabed and must maintain some connection to the sediment water interface for ventilation and feeding. Excessive deposition can lead to burial, smothering or crushing of benthic organisms. Conversely, erosion removes sediment and organisms, thus defaunating erosive sites in a process termed 'washout' by Hall (1994) (see also Thistle et al., 1995). Both deposition and erosion can result in a change of bottom sediment level and possibly sediment grain size. In the water column, high levels of resuspended fine materials may be detrimental to benthic suspension feeders (Bock and Miller, 1994). When diffusion of oxygen through sediments or irrigation of the sediments by tube builders is prevented, hypoxia and anoxia result and typically lead to significant changes in the benthic community (Diaz and Rosenberg, 1995). Although benthic animals themselves move sediment as part of feeding, defecation, burrowing and tube-building activities, these are at rates much smaller than those driven by near-bottom flows (Grant, 1983; Miller and Sternberg, 1988).

Finally, we are largely ignorant of the magnitudes of erosion and deposition that are detrimental. In fact, it is well recognized that deposition of detritus can be beneficial to deposit feeders, and some species shift feeding upon surface sediment to particles in near-bed transport under certain flow conditions (Turner and Miller, 1991; Miller et al., 1992). In order to evaluate deleterious rates, each species could be brought in to the laboratory, and subjected to an array of deposition and erosion trials ranging from low to high values as determined from field measurements. Potential effects could include tube building or cutting, withdrawal or burrowing into the sediment, maintaining contact with the sediment surface for ventilation and respiration, actively mixing sediment layers (bioturbation) and migration to more favorable areas (including post-larval transport). Since each species could respond somewhat differently, each member of the benthic community must be examined, necessitating an exhaustive analysis. How these members may respond in a community or exhibit co-adaptations to erosion and deposition could not be revealed by this species-focused procedure. Alternatively, sedimentation experiments could be conducted in the field with responses measured at the community level, though not without considerable expense and multidisciplinary effort (Thrush et al., 1997). This type of community-based approach relies heavily on numerical or faunal abundance responses and therefore may register only to lethal effects.

### 3.2. *Defining the adaptive envelope*

Benthic organisms are clearly adapted to some level of sediment movement. However, critical, quantitative data gaps make it impossible to hypothesize how different rates of sediment movement will affect certain species or functional groups. We suggest that a graphical concept of an adaptive envelope would be valuable in considering an organism's tolerance and accommodation to its environment. For any given environmental parameter, a species exhibits adaptations and tolerances to changes in that parameter. If this tolerance is broad, the envelope is wide in a certain dimension. Narrow tolerances define an envelope of only limited extent in that dimension. Taken in sum, the tolerances to salinity, temperature, depth of burial, sulfide content of the sediment, et cetera, define a multifactor region or volume for each species. This region will have many dimensions and a complicated shape. A region potentially varies over the annual cycle as well as throughout an organism's life cycle. Most benthic organisms have a distinct larval phase and undergo a metamorphosis. A complete reconstruction or elaboration of their adaptive envelope would accompany this change in lifestyle.

Organisms forming a given benthic community live together in a single habitat, and should have adaptive envelopes that are similar in some dimensions but complementary in others. For tolerance to abiotic stressors (for example, temperature and salinity), we would expect adaptive envelopes to overlap considerably. In other dimensions, especially those relating to biological interactions like competition, the boundaries may be sharply defined and complementary. Functionally similar organisms, those with like roles in the community, for example, habitat utilization or trophic position, would have similar adaptive envelopes. When environmental conditions or biotic interactions fall outside an envelope, we anticipate a response, the magnitude of which should be related to the degree to which the envelope is exceeded. Also, adaptive dimensions may not be independent, and stresses need not act in one direction only. Thus the interaction of stressors may lead to potential consequences that would not be anticipated from a less comprehensive analysis. We expect sediment movement, erosion and deposition, to be represented in one or more dimensions of this adaptive envelope.

Benthic ecologists usually study biogenic sediment movement within the framework of bioturbation. These effects on benthic organisms and communities are well studied (Brenchley, 1981; Grant, 1983; Miller and Jumars, 1986; Posey, 1986; Suchanek and Colin, 1986; Tamaki, 1987; Tamaki and Ingole, 1993; Krager and Woodin, 1993; summarized in Hall, 1994; Rasmussen et al., 1998; Wildish et al., 1998; Woodin et al., 1998; Modig and Olafsson, 2001). Biological sediment movement is variable in mechanism and form, and turnover rates are relatively low with some seasonal variation. In contrast, dredge materials disposal represents the virtually instantaneous deposition of a meter or more of sediment, and frequently 100% mortality of the buried community. There are few data to gauge the impacts of insults between small- (biogenic) and large-scale (anthropogenic) events despite their importance and common occurrence (VanBlaricom, 1982; Newell et al., 1998).

Boundaries of adaptive envelopes, especially as relating to sedimentation, remain poorly defined. This is chiefly because biologists experiment with low rates of sediment movement (studies cited above), while geologists study and model large-magnitude, often catastrophic events (Sherwood et al., 1994; Newell et al., 1998; Komar, 1998). Between these extremes are situations about which we know little because they are rarely investigated by either discipline. This is precisely the information applicable to engineering-scale projects designed with short-term rates far in excess of natural ones. With the exception of storm events, natural rates of sediment movement, disturbance, et cetera, are clearly minimal bounds on the adaptive envelope for the organism. The key question is how far outside those natural boundaries organisms exhibit only sublethal responses. This adaptive envelope is a conceptual device, and it would defeat our purposes to overanalyze its implications. Its utility lies in allowing us to see that not all environmental variations or anthropogenic impacts are necessarily detrimental, recognizing that there is a range of responses to be expected from each species. Groups of species within and among communities will respond similarly, and this may be predictable from their envelopes. We are now focused on how to determine the magnitude of perturbations exceeding the adaptive envelope and leading to negative consequences.

### 3.3. *Relative rates as a first approach towards defining adaptive limits*

A scaling analysis approach, borrowed from the physical sciences and engineering, may provide relevant understanding and insight to the impacts of sedimentation on benthic organisms (Miller et al., 1984; Jumars, 1993). The characteristic scales or rates of any potentially important processes are formed into ratios, and their relative magnitudes suggest which processes must be considered and which may be ignored. As an example, we can compare sediment erosion rate and burrowing ability, or sediment deposition rate and tube building. If the rates of erosion or deposition are low in comparison with burrowing or tube building, then sediment movement will have little impact. If the maximum concentration of resuspended fine material is low compared with the natural near-bottom seston concentration, then resuspension will have little or no impact. Length scale can likewise be subject to scaling analysis: if organisms move or larvae can disperse much more broadly than the horizontal dimensions of the engineering project, then the population as a whole may suffer little consequence assuming that the surrounding bottom is comparable habitat. Similarly, finfish spawning and migration, or invertebrate reproduction and dispersal are typically phased seasonally, and this timing can be compared directly with the project scheduling. These approaches are routinely implemented with respect to emplacement practices (thin layer or capping with preferred bottom type), management of turbidity and silt loads, buffer zones, and operational windows (National Research Council, 1995).

### 3.4. *When is the adaptive envelope exceeded?*

Engineering projects that intend to redress natural changes by design move larger amounts of sediment in a shorter time than occurs naturally under normal conditions, a reality dictated by logistics, economics and contractual deadlines. Nonetheless, if impact tolerances can be measured, even if for selected species, this information may prove useful in dredge material disposal project design. Benthic adaptations and responses take a wide variety of forms, reflecting the multidimensional shape of the adaptive envelope. Consequently it requires an intimate knowledge of benthic lifestyles and habits to scale them appropriately against natural or man-made processes. Fortunately, it may not be necessary to test every species or to extrapolate blindly from one species to another if a functional group analysis (Fauchald and Jumars, 1979) is undertaken. Such an approach should allow managers to build-in effective mitigation strategies and to implement adaptive management projects based on rapid monitoring of site properties such as layer thickness and depth to anoxia.

## 4. Case studies in Delaware Bay

In Delaware Bay (Fig. 1), we are using field and lab studies to determine what rates and frequencies of sediment movement occur naturally, and further, what rates and frequencies are detrimental to representative benthic species and functional groups. As a preliminary step, we completed a white paper literature study (Miller, 1999a) to build upon previous efforts and to identify data gaps. Subsequently, we have used field studies and laboratory experiments to investigate sedimentation effects on nearshore benthic communities. Our studies are designed specifically to address concerns raised over the impact of sand stockpiling in the lower Delaware Bay as part of the US Army Corps of Engineers' Delaware River Main Channel Deepening Project (USACE, 1997). At present, the status of the Army Corps of Engineers' project remains open. In response to heightened public concern in 1998, sand stockpile locations near unusual hard-bottom benthic communities (e.g. tubeworm nodules, described below) were relocated to avoid potential fishery and habitat-related impacts. At this writing, the Corps proposes to use the dredge material to restore

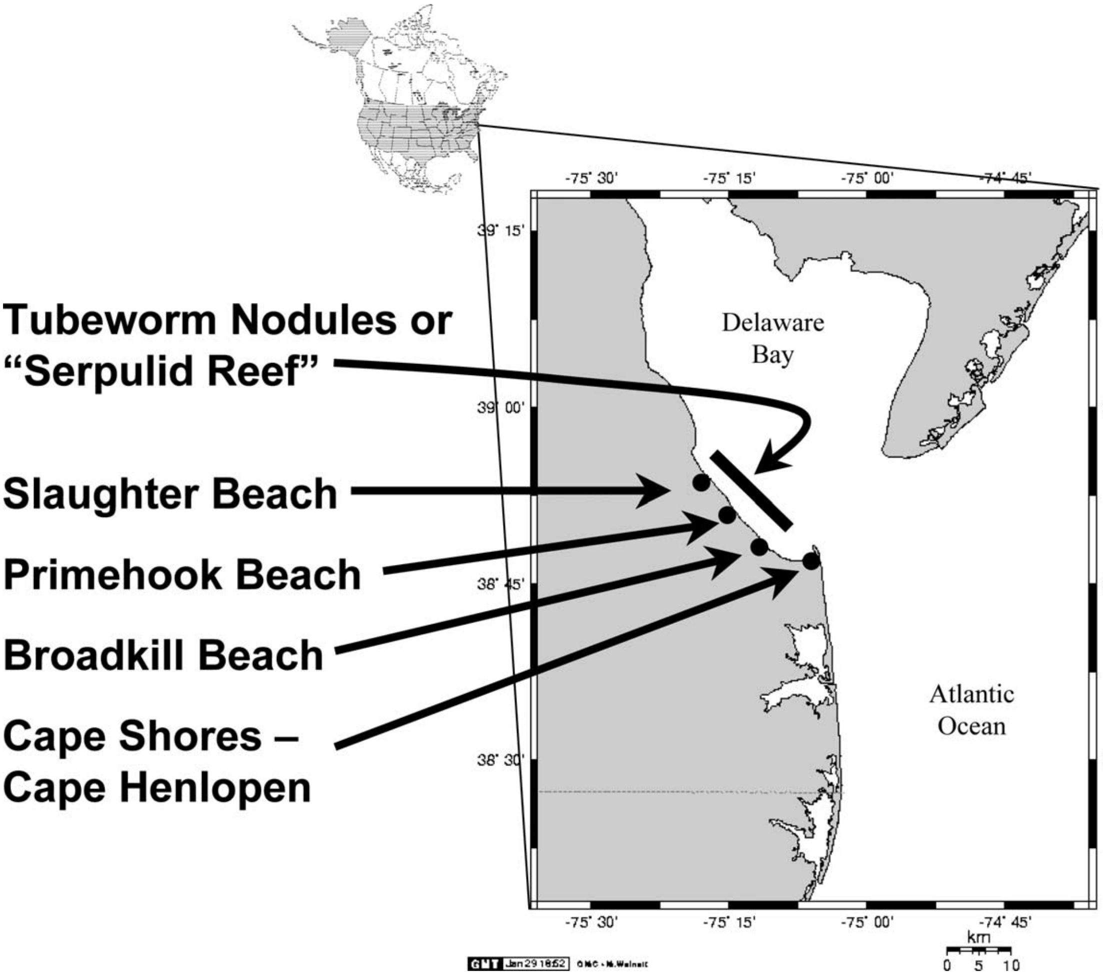

Fig. 1. Map showing location of Delaware Bay and beaches where intertidal transects were deployed and where sandbuilder worms reefs have been found. Also indicated is the approximate location of the subtidal tubeworm nodule reefs in the lower Delaware Bay.

beaches along the Delaware shoreline, and this will impact directly yet another benthic community (sandbuilder worm reefs, also described below). In the absence of a firm scientific basis for impact assessment, public pressure in large part has driven decisions to date. This ongoing debate serves to re-emphasize the need to be able to predict impacts and understand consequences.

Maurer and colleagues undertook the last comprehensive, published study of Delaware Bay benthic communities over 25 years ago. This work represents a critical snapshot of the Delaware Bay, with the most accessible publications being Maurer et al. (1978b, 1979a,b). Related publications include those by Maurer and Watling (1973b), Watling and Maurer (1973), Maurer (1974a,b), Maurer et al. (1974), Watling and Maurer (1976), Maurer and Aprill (1979). Unfortunately, the lack of community-level studies since that time coupled with increased development, land use changes, beach erosion, habitat alteration and other natural and anthropogenic modifications in the marine environment make it difficult to know with any certainty the status of the benthic communities at present. For some benthic groups, taxonomic revisions make it difficult to even compile reliable species lists. In many cases, the only intervening information is highly summarized (Billheimer et al., 1997), unpublished (Chaillou and Weisberg, 1995) or anecdotal. In any case, it is virtually impossible to gauge status and trends from such spatially and temporally spotty information. Recent work on Delaware Bay benthos has shifted focus from the whole community to selected species or trophic processes (Maurer et al., 1981a, 1992; Brown, 1982; Bianchi, 1988; Bianchi and Rice, 1988; Miller et al., 1992; Bock and Miller, 1994, 1995, 1996, 1997, 1999; Karrh and Miller, 1994, 1996).

We now overview the results of our field and laboratory studies as of November 2001, which are continuing as part of two Masters thesis projects. The presentation here is only in summary form and does not represent a formal publication of the results, which will appear in refereed journal articles elsewhere. Specifically, we present results from field studies designed to first measure temporally and spatially relevant sediment movement, secondly laboratory deposition experiments based on the field data, and lastly a consideration of two hard-bottom communities in Delaware Bay likely to be impacted by planned dredging and beach restoration projects. We present these results to demonstrate how the approaches outlined above, especially the measurements of erosion and deposition relevant to infauna and the concept of an adaptive envelope, can be realized.

### 4.1. Sediment deposition and erosion in the intertidal zone

To measure natural rates of sediment erosion and deposition on the Delaware shoreline, we established intertidal transects at three locations along a 23-km stretch of coastline in the lower Delaware Bay (Fig. 1): Cape Henlopen-Breakwater Harbor, Primehook Beach and Slaughter Beach. On each sandflat, we deployed two transects of PVC posts, which acted as permanent sediment markers, running bay ward across 40 m of the lower intertidal zone (Fig. 2). Monthly measurements of post heights above the sediment shows erosion or deposition by apparent increases or decreases in post height over the sampling interval. Ancillary measurements of temperature, salinity, sediment grain size and macrofaunal infauna and epifauna abundance have also been taken. We have monitored these sedimentation transects in this manner for over 18 months, and at selected times have conducted more frequent biweekly and daily sampling.

At each of the sites, transects included three sections on the sandflat: a low tide terrace (or sandflat), a trough, and a shore parallel sandbar. We have analyzed these data by computing averages and standard deviations of sediment height changes for each post, for sandflat sections, and for seasonal periods. We used 3D ribbon charts to visualize changes in the sediment and to track elevation trends. We also employed scatterplots including sediment parameters and wind and wave data from an offshore weather buoy to relate changes to environmental forcing. Digital photographs taken each month have aided in interpreting the lateral movement of sandbar crests and troughs across transects and parallel to shore.

In these data, there is surprisingly little net change in sediment height when averaging these changes over a year or the entire data set. Overall, there is little net erosion or deposition, and annual mean changes are less than 2 cm. Seasonally, the most erosion occurred during the spring, the most deposition in the winter, and the summer consistently showed the least changes in sediment elevation. Maximum monthly change at the sites ranged from 17 cm of deposition to 22 cm of erosion. However, within these generalities, the three sites responded differently: Primehook sediment elevation was the most variable, and there was no correlation of monthly sediment changes at one site with the other two. In addition, the maximum observed deposition occurred at Primehook Beach, one of the two exposed sites, while the maximum erosion occurred at Cape Henlopen, the most protected of the sites. Spatially within each transect, sediment elevation changes were larger on the sandflat and the sand bar and least in the trough, although the position of these features remained largely unchanged over the study period.

The nor'easter of 25 January 2000 represents a natural experiment that we monitored with our transects. This storm blanketed the entire Atlantic coast from South Carolina to Maine, and was the deepest snowfall in Sussex County in 4 years. The

Fig. 2. Photograph of sedimentation transects at Cape Henlopen, Delaware taken 20 November 1999 near the time of low tide.

tide gauge at Breakwater Harbor, Lewes (inside Cape Henlopen) recorded maximum water levels of 7.6 feet above MLLW, the 16th highest extreme recorded for that station. At Cape Henlopen, almost 17 cm of sediment were deposited on the sandflat, while 4 cm were deposited on the bar. In contrast, changes on the Primehook and Slaughter Beaches amounted to less than 3-cm net change at any location. These three sites responded differently in terms of sediment erosion and deposition in response to this large storm event, thus reinforcing the differences among sites seen in monthly sediment movement data.

In January 2001, we monitored Breakwater Harbor transects on a daily basis within two, consecutive spring tide windows. Daily changes during these non-storm periods were about 1 cm, relatively small and near the precision of our measurements. When compared with the large monthly values, the daily data suggests that monthly measurements capture much of the variability found on these sandflats. Monthly changes, even in the absence of notable, weather-driven sedimentation events exceed the depth to which most macrofauna are found. Over the year, however, sediment eroded is deposited and vice versa, and recognizable features of sandflat topography remain in constant positions with respect to the shoreline.

Our data measure erosion and deposition in the vertical dimension. In contrast, much if not all of the past studies on sediment erosion and deposition in Delaware Bay have been related to horizontal movement of the shoreline, at or above the high tide mark. While these investigations have been conducted both in our study area (e.g. Maurmeyer, 1974, 1978; Weil, 1977; Hoyt, 1981) and on the New Jersey side of Delaware Bay (Phillips, 1986; Nordstrom and Jackson, 1992; Jackson, 1995, 1999), it is difficult to relate shoreline retreat to impacts on benthic communities just off shore. Shoreline changes, even substantial retreat or accretion, may result in little impact if communities can shift landward or seaward in response to any gradual changes in sediment elevation relative to the tides.

### 4.2. Laboratory deposition and erosion experiments

Our transect erosion and deposition field measurements have been invaluable in the design of laboratory experiments with realistic sedimentation rates. To date, we have conducted deposition experiments with three benthic species from lower Delaware Bay, the infaunal red-gilled mud worm, *Marenzelleria viridis*, and the epifaunal, motile mud snail, *Ilyanassa obsoleta*, and the sessile, reef-forming sandbuilder worm, *Sabellaria vulgaris*.

The red-gilled mud worm is a dominant member of the nearshore benthic community at the Cape Henlopen-Breakwater Harbor sandflat. *M. viridis* are concentrated in dense patches of up to several thousand per square meter on the low tide terrace sandflat adjacent to the beach (Ray, 1989; Bock and Miller, 1995). They are obligate deposit feeders and deep burrowers, with large individuals' tubes extending up to 30 cm into the sediment (Miller et al., 1992; Bock and Miller, 1996, 1997). This species is widespread along the US East Coast and has recently invaded northern Europe (Dauer et al., 1980; Röhner et al., 1996; Sardá et al., 1998). *M. viridis* is generally considered an estuarine oligohaline endemic species (Dauer et al., 1980) although its distribution in the high salinity areas of the lower Bay appears to be strictly controlled by and limited to sites of submarine groundwater discharge and locally reduced salinity (Miller and Blank, 1996; Miller and Candelaria, 1997; Miller, 1999b). We have conducted both deposition and erosion experiments with this species in laboratory seawater tables. Worms collected from Cape Henlopen were established in plastic containers in the laboratory and allowed to rebuild tubes, acclimate and resume deposit feeding. For our experiments, layers of sand from the collection site were applied in a predetermined thickness, and the containers were monitored periodically for resumption of normal activities over the next 48 h. Changes in the sediment surface, gain or loss of 5 cm, have little effect on tube building and feeding. *M. viridis*'s initial response to deposition is to re-establish contact with the surface via paired burrow openings, unlike the one surface opening per tube in established individuals. Within 24 h of deposition or erosion, most individuals resume deposit feeding as evidenced by the accumulation of string-like fecal pellets at the burrow opening.

Mud snails, *I. obsoleta*, are also prominent on the Breakwater Harbor sandflat. Mud snails are obligate omnivores widely distributed along the US East Coast (Curtis and Hurd, 1981; Levinton et al., 1995; Curtis, 1995; Curtis et al., 2000). On our sandflat, these epifauna are found in large aggregations crawling on and burrowing just below the surface ($<2$ cm, Miller et al., 1992). Because of the burrowing ability and lateral motility exhibited by this species, our experimental treatments have been more rigorous, involving deposition of 10–30 cm of sediment. Snails collected at the Cape Henlopen sandflat were transported to the laboratory, and subsequently transferred to large plastic buckets for deposition experiments. Following deposition of a layer of sandflat sand of known thickness, the buckets were monitored periodically for the emergence of snails above the added sediment layer. Most snails exhibited the ability to burrow up through 10 cm of sediment to the surface within 4–8 h, re-emerge on the surface and resume active surface crawling. Snails took longer to re-emerge from deeper layers of sediment, but within 24 h, over half of the snails were seen crawling above a 15-cm deposited layer. Experiments using increments of thinner layers of sediment (for example, four 5-cm layers at 2-h intervals) in comparison with a layer of the same total thickness deposited at one time showed that snails emerge from the thin layers quickly enough to better tolerate incremental deposition. Thus total layer thickness in addition to the frequency of deposition has a role in the snail's tolerance to sedimentation.

We have also conducted experiments with a sessile, suspension-feeding and reef-building polychaete, *S. vulgaris*, the sandbuilder worm. As with the other species, this worm is common along the lower shores of Delaware Bay. There, colonies of tubes built from sand grains form reef-like structures on artificial rock substratum and even sand beaches at the lowtide line (Wells, 1970; Curtis, 1973, 1975, 1978; Pembroke, 1976; Woodard, 1978; see additional detail, below). Small, fist-sized colonies were collected from Slaughter Beach along with their attached basal material of gravel or cobble and these colonies were established in plastic containers in a seawater table prior to experiments. Medium sand and fine gravel was deposited on the colonies in layers of known thickness. Within 2 h of deposition of 0.5 cm, some worms had emerged, and consistently more individuals emerged sooner from the sand than gravel. While similar results were obtained with deposition of a 1-cm layer, a 2-cm deposition of either sediment prevented worms' contact with the surface for all but a very few individuals. Colonies became anoxic after 7 days, indicating a lethal effect of the 2-cm layer. Thus, while the colonies have a certain ability to withstand sediment deposition, even an additional centimeter of sediment can have lethal consequences.

These initial results demonstrate that these dominant intertidal species are adapted to a degree to sediment erosion and deposition regularly observed in their environment. These species were chosen in part because of their abundance, accessibility and our previous experience with them in the laboratory. More importantly, they are representatives of contrasting motility, burrowing and trophic groups. Such an approach is a priori based on the adaptations or roles of the organisms in their environment and thus is superior to a purely taxonomic analysis. We designed our experiments to determine what amount of deposition a given species can tolerate and subsequently return to apparently normal feeding, burrowing or crawling activity. Progressively harsher treatments will eventually define the limits of their sublethal response. Subsequent experiments will deposit sediment layers in increments to gauge if treatments applied over time have moderated detrimental effects. Our experiments pertain to the limits of a functional response (and conceptually their adaptive envelope), rather than assessing solely defaunation or mortality under a set of conditions chosen to represent conventional practices.

### 4.3. Previous studies

Defaunation and mortality due to dredge material disposal was addressed by Maurer and his coworkers in laboratory deposition experiments on Delaware Bay benthos (Maurer et al., 1978a). These results were published in three parts by taxonomic group: molluscs (Maurer et al., 1981b), crustaceans (Maurer et al., 1981c) and polychaete worms (Maurer et al., 1982). These authors conclude that because a fraction of buried animals do return alive to (or near) the surface, some upward degree of motility and recolonization of dredge material is expected. When considering all results together, the authors conclude that it is necessary to expand on their studies by increasing the number of taxa (species, genera and higher taxa) and testing species in combinations (Maurer et al., 1985, 1986). Maurer's studies are often cited even today as they represent one of only a few such projects to document the burrowing abilities of benthic fauna through sand overburden (National Research Council, 1995)

Maurer and Aprill (1979) conducted a companion field study of the benthic community and invertebrate biomass on a sandflat at Cape Henlopen, roughly a kilometer from our Breakwater Harbor site. In comparison, their site was more exposed to wave and tidal currents and composed of coarser sand material. From their analysis, they concluded that the benthic fauna was stable and resilient across a gradient of considerable sediment mobility. A highly simplified community of specialized organisms, much like that found on open ocean sand beaches (Gorzelany and Nelson, 1987; Peterson et al., 2000) inhabits this sedimentologically extreme environment. Nearby protected areas (including our sedimentation transect site) harbor many more infaunal species. Thus sediment movement, even at rates judged extreme by natural standards, potentially results in an altered benthic community rather than total loss of benthic macrofauna.

Our preliminary results concur with Maurer et al.'s overall conclusions, yet there are some important differences. In our view, species chosen for study should be selected for their numeric dominance, representation of a group of functionally similar species or otherwise noteworthy characteristics, rather than for experimental convenience or taxonomic coverage. Sublethal responses can be studied, but parameters to be measured will have to be separately chosen for each species. Experimental treatments can be based on realistic magnitudes of sediment movement actually measured in the animal's habitat, rather than for the convenience of the experimenter.

### 4.4. Hard-bottom communities in Delaware Bay: serpulid reefs, 'coral beds,' tubeworm nodules and sampling issues

The above described field studies and experiments focus on the soft-sediment benthic communities in Delaware Bay. Hard-bottoms, much of which are biological in origin, are also an important habitat in the Bay, and these communities are known for their biological productivity and diversity. The most widely recognized hard bottoms are the oyster reefs in the mid- and upper Bay found especially on the New Jersey side. Due to the economic potential and management interest, oyster beds have been extensively studied (Maurer and Watling, 1973a,b; Bryant and Pennock, 1988). However, it is important to note that distinct hard and soft-bottom communities appear throughout the rest of the Bay in a fragmented, mosaic pattern related to sediment type (Watling et al., 1976; Kinner and Maurer, 1978; Maurer et al., 1978b; Chaillou and Weisberg, 1995; Billheimer et al., 1997). Unfortunately, these benthic communities have received little attention from scientists and resource managers.

A 'serpulid reef,' consisting of calcareous tubes built by a polychaete worm *Hydroides dianthus*, was identified and studied by Maurer and colleagues (Leathem et al., 1976; Kinner and Watling, 1976; Haines, 1978; Haines and Maurer, 1980a,b). The results of our preliminary sampling in 1998–1999 in the same area (off Broadkill Beach, roughly 6 km offshore and 7 m in depth) (Fig. 1) generally concur with those early studies cited above. We found that the reef exists on the bottom as clumps of rounded, fist-sized nodules (Fig. 3). A shell or pebble core is surrounded with polychaete worm tubes of either one of two types, white and calcareous (*H. dianthus* tubes) or alternatively built of darker sand grains (*S. vulgaris* tubes, same species described above). Other species, such as the single-horned bryozoan, *Schizoporella unicornis*, may be present in abundance and contribute to the nodules overall physical structure. These observations provide scientific justification for the alternative term 'tube worm nodules' because 'serpulid reef' does not reflect the unusual consortium of species found there.

Another misnomer, 'coral beds' is sometimes applied to these hard-bottom reefs, but this label is also problematic. The coral beds are not coral nor are they coral reefs, although confusingly one species of coral (star coral, *Astrangia danae*) is associated with the beds. The two polychaetes and the bryozoan comprise the major structural components of the nodule matrix, and it is the layer of the bryozoan that often lends a pink or orange color to the nodules (Fig. 3). In addition, other species find a niche in the beds, including: *Polydora ligni* (mud worm), *Polycirrus eximius* (terebellid worm), *Mediomastus ambiseta* (capitellid worm), *Corophium simile* (slender tube amphipod), *Uniciola serrata* (amphipod), mud crabs (*Panopeus herbstii* and *Dyspanopeus sayi*), and hermit crabs (*Pagurus pollicaris*), among others (see Haines, 1978). None of these species is rare in the Bay, and all can be found elsewhere singly and in abundance. However, we believe that it is the co-occurrence of *H. dianthus* and *S. vulgaris* that gives rise to the unique nodules and unusual physical structure of the reef. For simplicity, we will hereafter use the terms tubeworm nodules or tubeworm nodule reef. These terms are simultaneously taxonomically accurate and morphologically descriptive of the defining characteristics of this benthic community.

The conventional benthic sampling device, a benthic grab, samples a single point on the bottom, but only if the sediment is soft enough to permit penetration. Hard objects can lodge in the jaws and allow the sample to wash away upon retrieval to the deck. A dredge samples a line hundreds of meters to kilometers long, though probably with highly uneven and unknown efficiency (Kingsford and Battershill, 1998). In hard-bottom communities using either of these methods, sample return is inconsistent and spatial resolution is essentially nill. Gear bias results from a grab preferentially returning samples and infauna from muddy sediments, while a clam

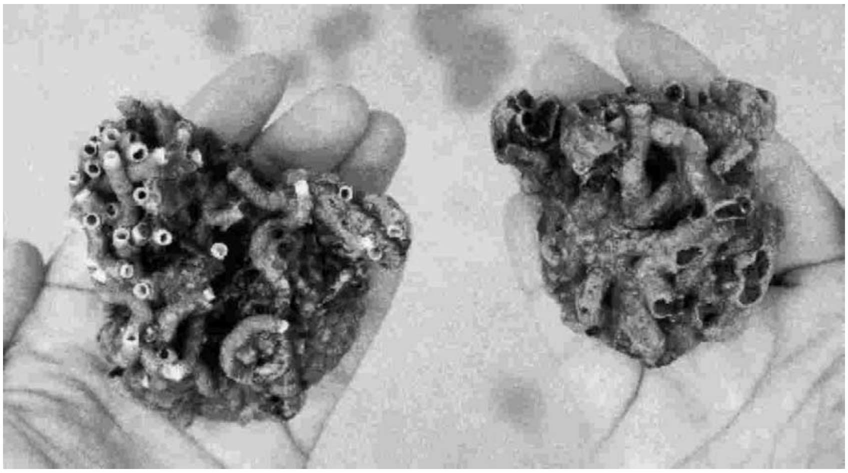

Fig. 3. Photograph of tubeworm nodules from offshore of Broadkill Beach, Delaware Bay, showing nodules dominated by tubes of *Hydroides dianthus* (left, with white tube ends) or *Sabellaria vulgaris* (right, darker tubes).

dredge retains only large pieces of hard substratum and tough epifauna. As with all benthic 'kill'em and count'em' studies, sample sorting, species identification and enumeration represent a considerable workload and create a sample-processing bottleneck. This analytical constraint severely limits the number of samples that can be sorted, hence the area that can be surveyed, and thus the total amount of information that can result from a project with limited funding. For Delaware Bay's reef communities, Haines and Maurer showed that grab and dredge sampling revealed very different pictures of the same benthic community (Haines, 1978; Haines and Maurer, 1980a,b).

Acoustic and other remote sensing methods hold much promise when bottom type varies and large areas must be surveyed (e.g. Cutter and Diaz, 1998; Kingsford and Battershill, 1998; Mayer et al., 1998; Morrisey et al., 1998; Service, 1998; Smith and Greenhawk, 1998; Hamilton et al., 1999). These non-invasive, non-destructive methods provide superior spatial resolution and coverage. In particular, side-scan sonar is a proven means of rapidly mapping a heterogeneous mosaic of bottom types (e.g. Wright et al., 1987; Wildish et al., 1998). Our preliminary work has shown that the hard bottoms created by tubeworm nodules and mussel clumps appear as scattered strong reflectors that are quite distinct from the surrounding muddy and sandy sediments in the Bay. These results can be used to design subsequent bottom sampling or experimentation at relevant ecological scales (Bell et al., 1997; Thrush et al., 1996, 1997; Guichard et al., 2000; Bianchi and Morri, 2001).

In July 1999, in conjunction with Marine Search & Survey, Incorporated and aboard the M/V Grizzly charter boat, we tested the ability of side-scan sonar to map the tubeworm nodules. We were able to repeat and extend our survey in September 2000 and January 2001 (Hauser and Miller, 2001). In addition to side-scan sonar, we used a bottom classification system known as RoxAnn$^{TM}$ (e.g. Greenstreet et al., 1997; Caddell, 1998; Pinn and Robertson, 1998; MacDougall and Black, 1999) to survey a 5 km$^2$ area to further map the hard bottoms and to compare bottom-classification and side scan methodologies. Hard bottoms were readily apparent on both systems in real time. Subsequent georeferencing using GIS software showed a perfect match in hard-bottom detection between the side-scan and bottom classification results. Grab sampling for ground truthing demonstrated that the hard grounds were tubeworm nodules or mussel clumps and in some cases a mixture of the two. While side-scan sonar yielded an image that showed the meter-scale and larger structure of the beds, RoxAnn™ was more effective at differentiating among biogenic hard grounds and gravel bottoms.

### *4.5. Hard-bottom communities in Delaware Bay: worm rocks and intertidal shoreline reefs*

Another hard-bottom benthic community, known as worm rocks, was observed at Cape Shores (adjacent to Cape Henlopen-Breakwater Harbor) and at Slaughter Beach (Fig. 1) in the Fall of 1999 (Fig. 4). These are intertidal, monospecific reefs of the sandbuilder worm, *S. vulgaris*, and are a phenomenon apparently characteristic of Delaware Bay populations (Wells, 1970). These reefs are formed along the shoreline low in the intertidal zone on the low-tide terrace and are composed of sand-grain tubes. While the worm rocks were widespread and documented in the literature in the 1970s (Wells, 1970; Curtis, 1973, 1975; Pembroke, 1976; Curtis, 1978; Woodard, 1978), all subsequent information that we have been able to uncover is anecdotal. The reasons for this 1999 reef-set are likewise unknown. Since their establishment, we have noted the worm rocks presence and condition monthly and photodocumented the reefs. We have observed the growth and decay of the reef at both locations, and identified additional reef development on rocks at Broadkill Beach. Judging by the length and diameter of the sand tubes, we inferred that there was a set of new individuals in the late summer of 2000. When excavated, reef fragments are always attached to cobbles or other large pieces of the substratum. We conclude that stable, clear hard substratum is necessary for reef initiation, although sufficient wave action seems likewise necessary to suspend sand-grain material for tubes. Tubes in these reefs, unlike those in the tubeworm nodules, grow vertically in spaghetti-like clumps. Burrowing by crabs and over settlement by blue mussels and a tube-dwelling ampharetid polychaete appear to weaken and smother the sandbuilder worms. While located low in the intertidal zone, these reefs would be essentially buried by beach nourishment and destroyed by beach bulldozing. Such projects have been carried out at one of the worm rocks study sites (Cape Shores) and are proposed for the other locations in the lower Bay at Broadkill Beach and Slaughter Beach.

Fig. 4. Photograph of intertidal worm rocks or sandbuilder worm (*Sabellaria vulgaris*) reef at Slaughter Beach taken on 26 October 1999.

Despite tremendous development of the coastal region of Delaware and the growing awareness of the fishery productivity of this habitat, there has been no scientific assessment of the hard grounds generally, and tubeworm nodules or sandbuilder reefs in particular, in the past 30 years. The lower Bay is subject to extensive container shipping and oil lightering, a cross-bay vehicle ferry, as well as commercial and recreational fishing and crabbing. Along the shoreline, extensive residential development has occurred at Broadkill, Primehook and Slaughter Beaches. This beachfront is now routinely maintained by dredging and beach nourishment projects. Anecdotes from local residents, charter boat captains, and even scientific and professional colleagues suggest that the '(tubeworm nodules) are not what they used to be', but there is precious little quantitative data on which to gauge trends in habitat quality. Recent, though now abandoned plans by the US Army Corps of Engineers (USACE, 1997) to use a site amongst or near the tubeworm nodules for sand storage of dredge materials (Kropp, 1994; Ruddy, 1994, 1995) raised concern among a number of public groups. Recreational sport fishermen and charter boats heavily fish the tubeworm nodules areas, but again there is little scientific information on the use of the habitat by commercial fish species, especially striped bass and tautog. Currently, the Army Corps of Engineers proposes to use dredge material for beach restoration, and the potential impact on benthic communities has now shifted from subtidal to intertidal worm reef communities. While these benthic communities likely offer reef-like habitat, diverse invertebrate prey and possible protection from predators (Gregory and Anderson, 1997; Burrows et al., 1999; Able et al., 1999; Wood, 1999), the extent to which this contributes to, rather than simply concentrates, the overall productivity of the area's fisheries is unknown.

## 5. Predicting impacts from new data and the ecological literature

We recognize that the treatment levels employed in our experiments described above are less severe than would be expected in a dredging project. Deposition treatments on the order of 10 cm per day were chosen intentionally to fall between biological rates and the typical dredging project. Lower rates typical of bioturbation are known to affect benthos and are relatively well studied in the field and lab (Krager and Woodin, 1993). There is little doubt that deposition of one meter of sand will exterminate the buried benthic community, and behavioral experiments with dead animals will not yield interesting data. We expect little or no mortality under low and modest rates of sediment erosion and deposition characteristic of natural processes (Miller et al., 1992), and many studies have cataloged behavioral and physiological responses (cited in Hall, 1994). For ease of measurement and the ability to control other factors, such responses are best studied in the laboratory (e.g. Hall, 1994; Krager and Woodin, 1993; Woodin et al., 1998).

Excessive sediment movement can result in total defaunation of the seafloor and be followed by the recolonization of specialized benthic fauna (Zajac and Whitlatch, 2001). It is precisely these responses that are well suited to study by conventional benthic community analysis. Unfortunately, the limits of the adaptive envelope for any given species are likely to fall between the limits of normal, natural variation commonly studied in the lab and extreme events difficult or impossible to simulate in the laboratory or in field experiments (Thrush et al., 1997). This presents a challenge to the experimenter, but one that can yield handsome rewards. Our ongoing experiments are designed to address the questions of tolerance: What magnitude of burial is detrimental, and how frequently can such an insult be survived? Answers to these questions may allow the design of projects having less impact on the benthic communities, or to at least better predict those impacts likely to occur.

Laboratory measurements, in conjunction with functional grouping analysis, should allow prediction of impacts by species. This level of detail permits designers to weigh susceptibility by unique or characteristic species, life stages or recruitment windows. Alteration of project design in terms of real-time monitoring of dredge materials depth, project scheduling and seasonality is possible. Ten, 10-cm layers over some period, may be feasible and far less injurious to benthic fauna than one, 1-m layer. Sublethal responses likely include changes in feeding and growth, burrowing and tube building, larval settlement and post-larval immigration. If thick material layers are necessary, it may be possible to deposit the material in hummocks, mimicking the natural ridge and swale topography of shallow, exposed offshore regions (Schaffner and Boesch, 1982). Interspersing deposition sites and natural communities in buffer zones may allow gradual, non-lethal dispersal of the material and simultaneously facilitate recolonization of the site.

Results from the proposed experiments will also lead to a better understanding of responses to natural events and other important ecological processes. While having direct reference to the laboratory experiments, the field measurements of erosion and deposition bear on recruitment, disturbance and competitive interactions. The significance of sediment dynamics (and not just near-bed flow) has long been considered in recruitment and population studies (Eckman, 1983; Tamaki, 1987; Emerson and Grant, 1991; Snelgrove et al., 1993; Tamaki and Ingole, 1993). Hydro- and sediment-dynamic effects will propagate to generally more visible and valued species (e.g. crabs, fish and birds) via the food web, and the evaluation of impacts must be made with this in mind. Natural events range continuously from inconsequential to catastrophic, and there is no sharp break in the frequency and magnitude of weather-driven sediment transport events. Likewise, there is a gradient of man-made insults, from beach combing, clamming and bait-digging, to trawling, organic enrichment at sewage outfalls, sea bed drilling and dredge material disposal. Storms and other large-scale and magnitude events garner the most notice and research despite their relative infrequence. A critical and timely ecological question is to what extent small-scale processes scale-up to large natural events (Thrush et al., 1997; Estes and Peterson, 2000) and where do man-made disturbances fall on this continuum. A comprehensive analysis of disturbances at various scales will lead to a better understanding and prediction of responses.

Our advocated approach is not a replacement for the conventional analysis: the key is recognizing and predicting when and where defaunation versus sublethal effects are likely. When conventional project design cannot be altered, the standard assumption is the worst-case scenario: the extermination of the benthic community. Defaunation triggers an alternative ecological response, recolonization, involving a different suite of biological processes (e.g. Newell et al., 1998). This response to disturbances is a far better studied phenomenon (Zajac and Whitlatch, 1982; Raffaelli and Hawkins, 1996; Newell et al., 1998). There are exciting, new methodologies (Whitlatch and Osman, 1998) that can be brought to bear on this issue. This top-down approach, in both literal and figurative terms, will drive management and scientific investigation in certain directions. It should be possible, however, to determine beforehand if project design can accommodate benthic fauna and assess mitigation strategies, and not just presuppose a total loss of the benthic community.

## 6. Conclusions

In this paper, we have argued for a new approach to real-life coastline management situations, one that goes well beyond conventional impact monitoring and assessment. Standard macrofaunal sampling and whole community analysis have been mainstays of benthic ecology and continue to develop novel tools for more probing analyses. Inferences derived from whole-community assessments must be based on a firm empirical and theoretical basis, preferably through rigorous experimentation and not just correlation among field sites or extrapolation from spatial patterns to temporal responses.

In answer to the question posed in this paper's title (‘What can be learned from natural processes and rates?’), we believe that there is much to be gained by supplementing the conventional approach and viewing sedimentation impacts in light of natural phenomena and rates. Unfortunately, parameters that are relevant to the organisms (for example, change in sediment height or depth to anoxia) are rarely those of interest to nearshore geologists and shoreline engineers. Textbook and literature studies can be used to guide research, but often the key, relevant variables such as deposition rates on ecologically relevant scales have never before been measured directly. In some cases, simple technology is adequate, as we have demonstrated with our erosion posts at field transects. In other cases, new techniques must be developed and used to sample adequately and provide reliable data. Examples include acoustic remote sensing methods such as side scan sonar and sea bed classification techniques.

Laboratory studies can define the adaptive envelope of species and functional groups. Field rates should be used to guide laboratory experiments and ensure that the results will be applicable. Since benthic organisms exhibit a variety of adaptive and response envelopes, experimental treatments and measured response variables will have to be deliberately chosen for each species. While daunting to consider having to conduct bioassays on each species in an impact study, this exercise does have two benefits. It focuses one's attention on the most important species. This organism may be a numerical dominant, possesses a key ecological role, have commercial value or otherwise be notable or threatened. Categorizing the species in ecologically appropriate functional groups may save considerable effort here. This perspective allows one to draw upon the extensive marine-benthic, ecological process-oriented literature. Overall, we feel this approach has many advantages over conventional methodologies that measure effects in terms of numerical community responses.

Whether or not this new approach is applied, it is incumbent to sample the benthos adequately. Despite their value as fish habitat, hard bottoms have received less attention than deserved despite the likelihood that their sessile organisms are those most susceptible to the effect of sediment disturbance. Core and grab samplers work poorly or not at all when hard substratum is present. The result is at best an incomplete, and at worst misleading, picture of the benthic communities present at a site. In certain cases, gear biases can be overcome by using bottom imaging and acoustic remote sensing techniques. Based on a determination of the most significant fauna or functional groups, a full benthic community analysis may be unnecessary.

Our arguments are intended to address the ecological aspects of dredge materials placement, site selection and impacts. Quantifying natural sedimentation rates and the susceptibility of macrofauna by functional groups is one key towards understanding environmental impacts. If materials placement is or can be made to be analogous to natural events, then community responses will follow natural seasonal and successional trends and exhibit minimal anthropogenic impacts. If sedimentation exceeds natural thresholds, then impacts will likely involve total loss of the community and subsequent colonization by pioneer species and be driven by an entirely different suite of ecological processes. This case may lead to dramatically altered benthic communities. A rigorous, ecologically grounded approach will surely lead to a more reliable and comprehensive prediction of which of these two situations will present itself in response sedimentation in marine benthic communities.

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