Estuaries Vol. 25, No. 6A, p. 1219–1230 December 2002

An Estuarine Benthic Index of Biotic Integrity for the Mid-Atlantic Region of the United States. I. Classification of Assemblages and Habitat Definition

ROBERTO J. LLANSÓ[1,*], LISA C. SCOTT[1], DANIEL M. DAUER[2], JEFFREY L. HYLAND[3], and DAVID E. RUSSELL[4]

[1] *Versar, Inc., 9200 Rumsey Road, Columbia, Maryland 21045-1934*
[2] *Department of Biological Sciences, Old Dominion University, Norfolk, Virginia 23529*
[3] *National Oceanic and Atmospheric Administration, National Ocean Service, 219 Fort Johnson Road, Charleston, South Carolina 29412-9110*
[4] *U.S. Environmental Protection Agency, Region III, Environmental Science Center, 701 Mapes Road, Ft. Meade, Maryland 20755-5350*

ABSTRACT: An objective of the Mid-Atlantic Integrated Assessment Program (MAIA) of the U.S. Environmental Protection Agency is to develop an index for assessing benthic community condition in estuaries of the mid-Atlantic region of the United States (Delaware Bay through Pamlico Sound). To develop such an index, natural unimpaired communities must first be identified and variability related to natural factors accounted for. This study focused on these two objectives; Llansó et al. (2002) describe the index. Using existing data sets from multiple years, classification analyses of species abundance and discriminant analysis were employed to identify major habitat types in the MAIA region and evaluate the physical characteristics that structure benthic infaunal assemblages. Sampling was restricted to soft bottoms and to the index development period, July through early October. The analyses revealed salinity and sediment composition as major factors structuring infaunal assemblages in mid-Atlantic estuaries. Geographical location was a secondary factor. Nine habitat classes were distinguished as a combination of 6 salinity classes, 2 sediment types, and the separation of North Carolina and Delaware-Chesapeake Bay polyhaline sites. The effect of sediment types on faunal assemblages was restricted to polyhaline sites, which were separated into two sediment groups above and below 90% sand content. Assemblages corresponding to each of these 9 habitats were identified in the context of widely recognized patterns of dominant taxa. Differences between North Carolina and Delaware-Chesapeake Bay polyhaline assemblages were attributed to the relative contributions of species and not to differences in species composition. No zoogeographic discontinuities could be identified. Our results reinforce the findings of recent studies which suggest that, with respect to estuarine benthic assemblages, the boundary between the Virginian and the Carolinian Provinces be moved to a new location south of Pamlico Sound.

Introduction

Over the past decade there has been an effort to characterize environmental conditions and gradients of coastal regions. Many assessments of environmental condition have focused on benthic assemblages because the benthos respond predictably to natural and anthropogenic stress (Pearson and Rosenberg 1978; Dauer 1993; Wilson and Jeffrey 1994). Several efforts have been aimed at developing indices of benthic condition for estuaries and coastal regions (e.g., Weisberg et al. 1997; Engle and Summers 1999a; Van Dolah et al. 1999; Paul et al. 2001; Smith et al. 2001). Although some of these indices are applicable to large coastal regions, the emphasis has been on the characterization of single estuaries and local conditions, especially in the mid-Atlantic region of the United States (Weisberg et al. 1997; Adams et al. 1998). Regional assessments, however, are critical for effective management of coastal ecosystems, and this requires a comprehensive strategy that integrates key, region-wide, environmental problems. One such regional assessment is the Mid-Atlantic Integrated Assessment (MAIA) Program of the U.S. Environmental Protection Agency.

MAIA is a cooperative effort of federal and state agencies for the evaluation of ecosystem health. MAIA was established in 1995 to assess the condition of the natural resources of the mid-Atlantic region of the U.S. (Bradley and Landy 2000). The MAIA region encompasses the watersheds of the Delaware Bay, Chesapeake Bay, the coastal bays of the Delmarva peninsula, and the Albemarle-Pamlico estuarine system (Fig. 1). One of the objectives

---

[*] Corresponding author; tele: 410/964-9200; e-mail: llansorob@versar.com.

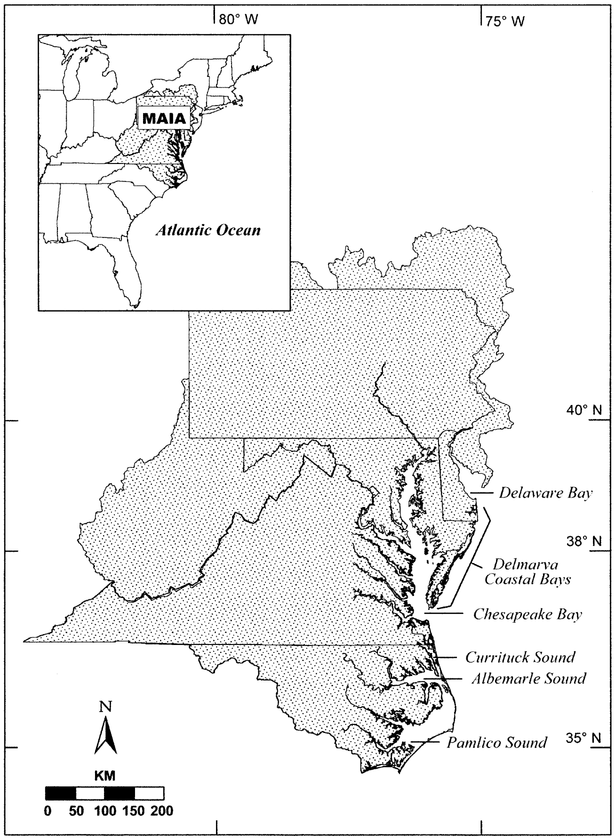

Fig. 1. Mid-Atlantic Integrated Assessment (MAIA) region.

of MAIA is to characterize the condition of mid-Atlantic estuaries using a common set of measurements applied over the entire region. To achieve this objective, we developed an index of benthic community condition for application throughout the MAIA region. The index is described in a separate manuscript (Llansó et al. 2002). We chose an index based on a scoring system approach similar to that of the benthic index of biotic integrity (B-IBI) developed for Chesapeake Bay (Weisberg et al. 1997) because of its simplicity, ease of interpretation, and previous successful application for assessing benthic community condition in Chesapeake Bay (Dauer and Llansó in press; Llansó et al. in press) and throughout estuaries of the southeastern U.S. (Van Dolah et al. 1999).

The development of an index of benthic community condition for the MAIA region requires the identification of reference conditions in key community attributes to which attributes from putatively degraded sites can be compared. In addition, habitat factors that control unimpaired assemblage structure need to be identified to ensure that natural differences in benthic assemblages related to habitat type do not confound index interpretation. Other index development efforts applicable to portions of the MAIA region have identified sediment type, salinity, and latitude as factors structuring estuarine benthic assemblages, and have partitioned the data into habitat classes defined by these factors (e.g., Weisberg et al. 1997; Van Dolah et al. 1999). Although numerous studies have focused on the identification of factors that control benthic infaunal assemblages in estuaries of the mid-Atlantic region (e.g., Mountford et al. 1977; Maurer et al. 1978; Chester et al. 1983; Tourtellotte and Dauer 1983; Holland et al. 1987), most are system-specific and have not described habitat types and associated assemblages on a region-wide basis.

The objective of the present study is to identify major habitat types in the MAIA region based on benthic infaunal classification analysis and the evaluation of the physical characteristics that structure these assemblages. The resulting habitat classification will be the basis for the partition of data and the formulation of an index of benthic community condition that accounts for variability due to habitat type. We also describe the benthic assemblages and discuss these results in terms of differences between zoogeographic provinces.

Methods

Data from seven sampling programs were assembled for this study (Table 1). One sampling program was specifically established in 1997 for the MAIA project, while the remaining were part of long-term monitoring programs that have sampled estuaries in the region from as early as 1984. Only sites that included benthic information and were sampled during the summer, defined as July 1 through October 7, were used in this study. Summer is the time of the year when benthic assemblages and associated ecological processes show the greatest response to both natural and anthropogenic stress. For this reason, our analysis used only data collected during the summer season. The resulting database contained 1,999 sites, 19 of which were sampled in multiple years yielding a total of 2,083 sampling events. Data for sites sampled more than once during the summer were averaged. All sampling programs used a 440-cm^2 Young grab (one to three grabs per site), sieved samples through a 0.5-mm mesh screen, and identified organisms to the lowest possible taxonomic level. Details on specific sampling protocols and measurements taken in each of the programs can be found in the references provided in Table 1.

Data sets used to describe community structure were first standardized to ensure common species nomenclature. Incidental and epifaunal organisms were eliminated from the data, and taxa such as

TABLE 1. Data sources used in this study.

Program	Time Period	Sampling Location	References
Mid-Atlantic Integrated Assessment	1997–1998	Chesapeake and Delaware estuaries	Strobel 1998
Environmental Monitoring and Assessment, Carolinian Province	1997–1998	Chowan and Neuse Rivers	Hyland et al. 1998, 2000
Environmental Monitoring and Assessment, Carolinian Province	1994–1997	Pamlico-Albemarle Sounds and tributaries	Hyland et al. 1998, 2000
National Oceanic and Atmospheric Administration, National Status and Trends	1997–1998	Delaware estuary, Chesapeake Bay	Hartwell et al. 2001
Maryland Long-Term Benthic Monitoring	1984–1998	Maryland portion of Chesapeake Bay	Ranasinghe et al. 1999
Virginia Benthic Monitoring	1985–1998	Virginia portion of Chesapeake Bay	Dauer et al. 1998
Environmental Monitoring and Assessment, Virginian Province	1990–1993	Virginian Province	Paul et al. 1999
Coastal Bays Joint Assessment	1993	Delaware and Maryland coastal bays	Chaillou et al. 1996

the Anthozoa and Nemertina for which there was variable taxonomic effort between collection programs, were combined at the phylum or class levels (a complete list is available from the author). We excluded epifauna from all the analyses of the index development effort, including those leading to the characterization of assemblages and habitat factors in this study, because these organisms are not fully exposed to chemical contaminants in sediments and were not expected to be sensitive indicators of sediment quality.

Reference (non-degraded) sites were then selected according to dissolved oxygen, sediment contaminant, and sediment toxicity criteria. These criteria were similar to those used to define reference sites in previous studies (Weisberg et al. 1997; Van Dolah et al. 1999). We excluded degraded sites from the present study so that natural gradients in community composition could be identified without the confounding influence of anthropogenic effects. Only sites for which all sampling events had associated dissolved oxygen and chemistry data were considered. Sites were defined as reference if, for all sampling events, dissolved oxygen concentrations were greater than 3.0 ppm, no chemical contaminant concentration exceeded Long et al.'s (1995) effects range-median concentrations, no more than two chemical contaminants exceeded Long et al.'s (1995) effects range-low concentrations, and sediments were not toxic in *Ampelisca abdita* or Microtox bioassays. Amphipod bioassays followed guidelines provided in American Society for Testing Materials (1993) protocols, and were considered to indicate toxicity when mean test survival was significantly different from and less than 80% of control survival. Microtox bioassays were considered to indicate toxicity when the EC_{50} of test sediments (sediment concentration that reduces bacterial light production by 50% relative to water controls) was ≤ 0.2 for sediments with silt-clay content $\geq 20\%$, the EC_{50} was ≤ 0.5 for sediments with silt-clay content $< 20\%$, or the EC_{50} of test sediments was significantly different from controls (Ringwood et al. 1997). A dissolved oxygen criterion of 3.0 ppm for point-in-time measurements is consistent with other benthic index approaches and with the general literature which suggests that concentrations below 3.0 ppm adversely affect benthos (Diaz and Rosenberg 1995).

Benthic infaunal assemblages and habitat groups were identified using classification (cluster) analysis (Boesch 1977a). Four hundred sixty reference sites were used in the analysis to identify affinities between sites based on mean species abundance. Also, inverse (by species) classifications were produced to identify the species responsible for site segregation. All analyses were conducted using the computer program COMPAH (Eugene Gallagher, Environmental Science Program, University of Massachusetts, Boston, Massachusetts). The Bray-Curtis similarity coefficient and the flexible sorting method (with β coefficient $= -0.25$, see Boesch 1977a) were used. Abundance data were standardized to values per square meter and transformed to log $(x+1)$ to lessen the sensitivity of the similarity measure to large abundances. In addition, nodal analysis (Williams and Lambert 1961; Boesch 1977a) was used to relate the groups derived from normal and inverse classifications. Dominant species were identified using the Biological Index Value (McCloskey 1970). The index is a reflection of the frequency with which a species is present in the assemblage, and it was computed by assigning 10 points to the first numerically dominant species at each site, nine points to the second, etc. A score of 0 was assigned to species ranking below the tenth position. Tied species received the average of their individual scores. Ranking scores for the 10 most abundant species were then summed over all sites for each of the groups derived from the classification of sites.

Prior to cluster analysis, taxonomic designations with more than one level of identification were treated by removing the higher level (e.g., genus) and keeping the lower level (e.g., species) of identification. Taxa occurring in no more than 10 sampling events across data sets were also eliminated from the analysis. This last procedure eliminated 59% of the taxa while keeping 96% of the cumulative total abundance in the analysis. The elimination of species occurring in low frequencies usually helps clarify the distribution patterns of the more common species (Boesch 1977a). Habitat classes were delineated by examining salinity, substrate, depth, and station location information of sites grouped in cluster analysis, and by multiple discriminant analysis to correlate site group separation with environmental variables (Green and Vascotto 1978; Hyland et al. 1991). Variables used in discriminant analysis were salinity, percent silt-clay (transformed to arcsine $\sqrt{p}$ to approximate normality, where p is a proportion), percent total organic carbon (TOC), depth, and latitude. Total structure coefficients, which are the correlations between the original variables and the discriminant functions, served as a measure of the relative contribution of each variable to group separation.

Results

Habitat Characterization

Site classifications showed patterns of spatial variation that could be explained primarily on the basis of differences in salinity and secondarily on the basis of differences in sediment composition (Fig. 2). Some sites were separated by geographical location. Water depth and sampling year did not appear to be factors in the grouping of sites.

Thirteen major groups of sites defined by the benthic assemblages could be distinguished in the dendrogram. Ten of these groups corresponded closely to one of six salinity classes defined according to a modified Venice System: tidal freshwater (0.0–0.5‰), oligohaline (0.5–5‰), low mesohaline (5–12‰), high mesohaline (12–18‰), polyhaline (18–27‰), and euhaline (> 27‰). Two additional groups indicated conditions that were transitional between adjacent salinity classes (Fig. 3), and one group consisted of outliers of mixed salinity. Although the ten salinity groups were distinct in the dendrogram, some sites with salinity measurements corresponding to different salinity classes were grouped together. Adding the rare species (see methods) or decreasing the number of taxa available for classification did not result in improved site segregation.

A relationship between sediment characteristics and site segregation was discernible within the polyhaline and euhaline salinity groups (Fig. 4). Two groups of sites within each of these salinity classes were distinct in the dendrogram at broad levels of

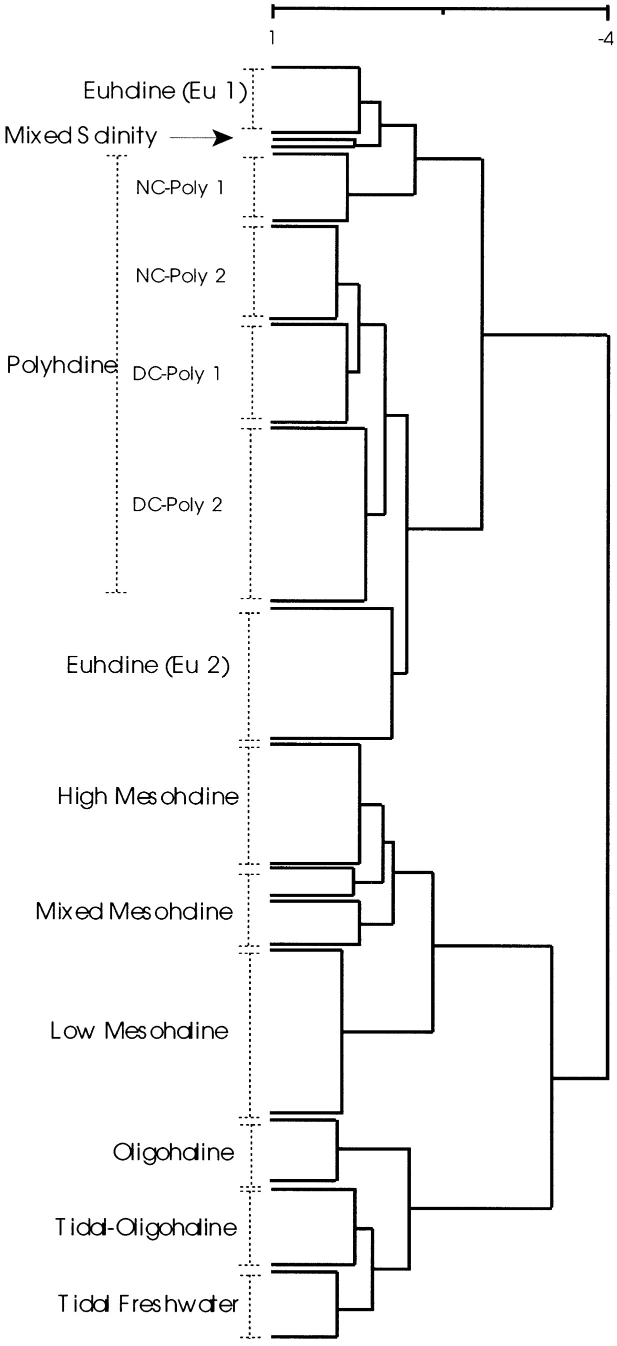

Fig. 2. Cluster analysis of 460 reference (non-degraded) sites in the Mid-Atlantic Integrated Assessment (MAIA) region. Sites were separated according to salinity. Polyhaline and euhaline sites were further separated according to sediment type and geographical location. Individual sites and small groupings within major cluster groups have been omitted for clarity. Eu 1 = high-energy euhaline; Eu 2 = Delaware-Chesapeake Bay euhaline; NC-Poly 1 = North Carolina polyhaline silt and clay; NC-Poly 2 = North Carolina polyhaline sand; DC-Poly 1 = Delaware-Chesapeake Bay polyhaline sand; DC-Poly 2 = Delaware-Chesapeake Bay polyhaline silt and clay.

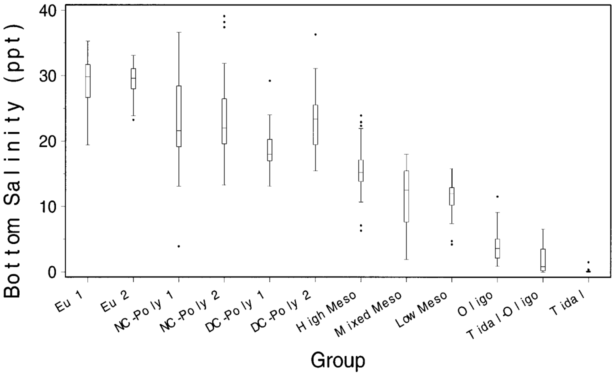

Fig. 3. Salinity ranges for 12 groups of sites identified by cluster analysis. Boxes are interquartile ranges (25 and 75 percentiles); range bars (1.5 interquartile range) show maximum and minimum of non-outliers; small horizontal lines within boxes are medians; dots are outliers. Eu 1 = high-energy euhaline; Eu 2 = Delaware-Chesapeake Bay euhaline; NC-Poly 1 = North Carolina polyhaline silt and clay; NC-Poly 2 = North Carolina polyhaline sand; DC-Poly 1 = Delaware-Chesapeake Bay polyhaline sand; DC-Poly 2 = Delaware-Chesapeake Bay polyhaline silt and clay; High Meso = high mesohaline; Mixed Meso = transitional group between high and low mesohaline; Low Meso = low mesohaline; Oligo = oligohaline; Tidal-Oligo = transitional group between tidal freshwater and oligohaline; Tidal = tidal freshwater.

mud and sand. Polyhaline sites with high sand content were generally separated from polyhaline sites with varying amounts of silt and clay above 10%. A group of euhaline sites with high sand content was distinct in the dendrogram. The effect of sediment type was not entirely clear as there was overlap between sand and silt-clay groups. In particular, the separation between euhaline site groups appeared to be related to the energy of the habitat rather than to percent silt and clay. The euhaline site group with high sand content consisted of shallow coastal sites or sites near barrier-island inlets exposed to wave action. The overriding factor structuring assemblages at these locations is likely to be sediment mobility. Notwithstanding the overlap in sediment types, a distinction between sand and silt-clay groups based on silt-clay interquartile (25–75%) range distributions could be made for the polyhaline sites (Fig. 4).

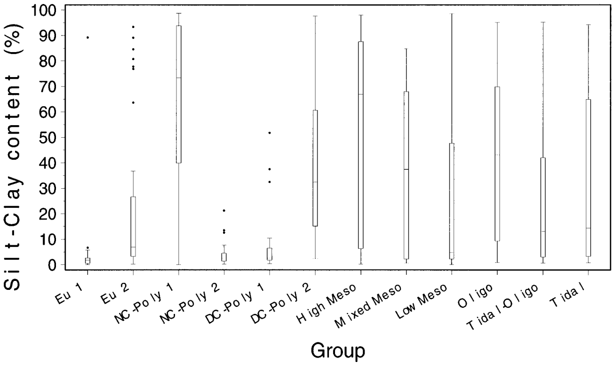

Fig. 4. Silt-clay ranges for 12 groups of sites identified by cluster analysis. Boxes are interquartile ranges (25 and 75 percentiles); range bars (1.5 interquartile range) show maximum and minimum of non-outliers; small horizontal lines within boxes are medians; dots are outliers. Eu 1 = high-energy euhaline; Eu 2 = Delaware-Chesapeake Bay euhaline; NC-Poly 1 = North Carolina polyhaline silt and clay; NC-Poly 2 = North Carolina polyhaline sand; DC-Poly 1 = Delaware-Chesapeake Bay polyhaline sand; DC-Poly 2 = Delaware-Chesapeake Bay polyhaline silt and clay; High Meso = high mesohaline; Mixed Meso = transitional group between high and low mesohaline; Low Meso = low mesohaline; Oligo = oligohaline; Tidal-Oligo = transitional group between tidal freshwater and oligohaline; Tidal = tidal freshwater.

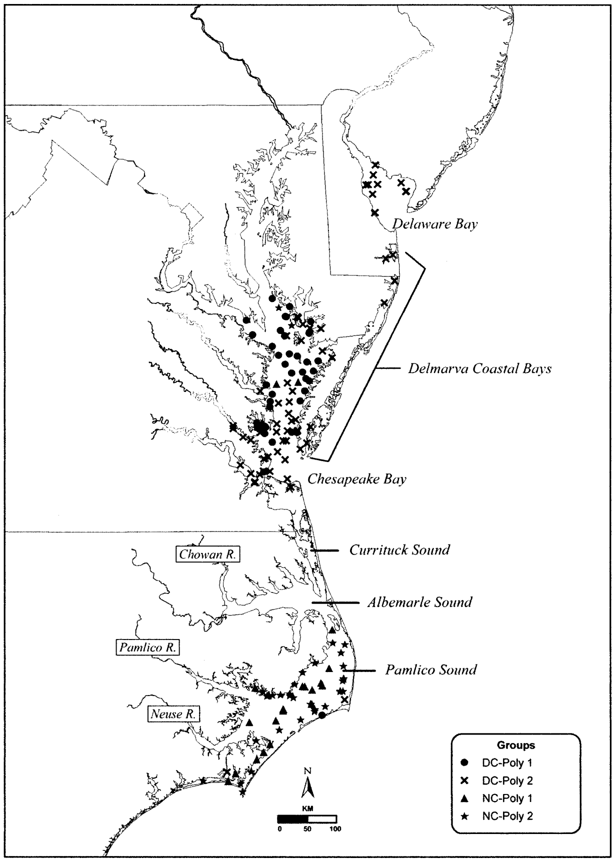

Fig. 5. Geographical distribution of 4 of 12 habitat groups identified by cluster analysis. DC-Poly 1 = Delaware-Chesapeake Bay polyhaline sand; DC-Poly 2 = Delaware-Chesapeake Bay polyhaline silt and clay; NC-Poly 1 = North Carolina polyhaline silt and clay; NC-Poly 2 = North Carolina polyhaline sand.

In addition to salinity and sediment groups, polyhaline and euhaline sites in the Pamlico-Albemarle Sound region were generally separated from all others (Fig. 5). No separation based on geographical location was discernible for the lower salinity groups. High salinity groups in the Pamlico-Albemarle Sound region exhibited a substantial

TABLE 2. Total structure coefficients of abiotic environmental variables on the first 3 discriminant functions (DF), which accounted for 98% of the cumulative variance. These are the correlations between the discriminating variables and the discriminant functions. Correlations considered important on each function are underlined. TOC = total organic carbon.

Variable	DF I	DF II	DF III
Salinity (‰)	0.994	0.070	−0.007
Silt-Clay (arcsine $\sqrt{p}$)	−0.156	0.936	0.259
Depth (m)	0.194	0.327	0.072
Latitude (decimal degrees)	−0.069	−0.276	0.882
TOC (%)	−0.245	0.776	−0.043

TABLE 3. Habitats defined in the Mid-Atlantic Integrated Assessment (MAIA) region. na = not applicable.

Habitat	Bottom Salinity (‰)	Silt-Clay (< 62 μ) Content by Weight (%)
Tidal freshwater	0–0.5	na
Oligohaline	≥0.5–5	na
Low mesohaline	≥5–12	na
High mesohaline	≥12–18	na
Delaware-Chesapeake Bay polyhaline sand	≥18–27	0–10
Delaware-Chesapeake Bay polyhaline silt and clay	≥18–27	>10
North Carolina polyhaline sand	≥18	0–10
North Carolina polyhaline silt and clay	≥18	>10
Delaware-Chesapeake Bay euhaline	≥27	na

amount of overlap, with many euhaline and polyhaline sites clustering together.

Multiple discriminant analysis of physical parameters indicated highly significant separation of groups ($p < 0.0001$) as defined by the numerical classification. Three discriminant functions accounted for 98% of the cumulative variance. The first function accounted for 83% of the among-group variance and was related to salinity (Table 2). The second discriminant function accounted for 12% of the among-group variance and revealed the influence of silt and clay in the high salinity habitats. The second function was also related to TOC content of the sediment, though the influence of TOC is probably a reflection of the strong correlation between TOC and percent silt-clay. The third discriminant function accounted for 3% of the variance and was related to latitude. The variance accounted for by additional functions was considered negligible and added little to the interpretation.

Based on the above results, sites were classified into six habitat classes according to salinity: tidal freshwater, oligohaline, low mesohaline, high mesohaline, polyhaline, and euhaline. The polyhaline habitat can further be divided into sand and silt-clay strata segregated according to latitude into two groups: North Carolina estuaries and Delaware-Chesapeake Bay (inclusive of coastal bays). A distinction could not be made between polyhaline and euhaline habitats in the North Carolina estuaries. Nine habitat classes based on macroinfaunal species composition and abundance were defined for the MAIA region (Table 3). The high-energy euhaline habitat was not included in this classification because sediment properties (e.g., median grain size, sorting coefficient) that may aid in the classification of sites into this habitat were not measured by the sampling programs used in this study. We include this habitat in the characterization of species assemblages below.

SPECIES ASSEMBLAGES

Using 143 taxa, twenty-three species groups were distinguished in the inverse classification analysis. This distinction was based on the separation of species groups from other groups in the analysis, rather than on a predetermined level of similarity. The dendrogram is not shown here but a list of species by group is presented in Table 4. Nodal analysis revealed most species groups as having clear affinities with some of the site groups, providing an explanation for the observed site classification. Some species, particularly those in group 17 (Table 4), had no particular affinity with any one site group but presented a moderate to high frequency of occurrence among sites in the mesohaline to euhaline salinity range. Species exhibiting a moderate to high frequency of occurrence across sites were euryhaline species of broad distribution in the higher salinity habitats and in most sediment types. These species were often numerically dominant.

Species groups 1, 4, and 6 (Table 4) characterized high-energy euhaline sites in terms of frequency of occurrence. These sites exhibited a lower number of species than euhaline sites elsewhere. Numerically dominant species at these sites were the bivalves *Tellina agilis* and *Spisula solidissima,* nemerteans, the polychaete *Leitoscoloplos* sp., and the amphipods *Parahaustorius longimerus, Rhepoxynius hudsoni,* and *Acanthohaustorius millsi* (Table 5). Species groups 9 and 17 characterized low-energy euhaline sites from Delaware to Chesapeake Bay. Species in groups 5, 7, 15, and 16 had high affinity for these sites, occurring in low frequency but seldom occurring elsewhere. Numerically dominant species of the Delaware-Chesapeake Bay euhaline site group were the polychaete *Mediomastus ambiseta* and the bivalve *T. agilis.*

North Carolina polyhaline sites (≥ 18‰) were characterized by species groups 3 and 17. Species in group 3 occurred in low frequency, but were mostly restricted to these sites. Silt and clays differed from sands in having lower number of species and in dominance patterns. Numerically-dom-

TABLE 4. Species groups identified by inverse classification analysis of 460 sites used in this study.

- Group 1
  - *Acanthohaustorius millsi*
  - *Paraonis fulgens*
  - *Parahaustorius longimerus*
  - *Spio pettiboneae*
- Group 2
  - *Ogyrides alphaerostris*
  - *Parahesione luteola*
- Group 3
  - *Aglaophamus verrilli*
  - *Apoprionospio pygmaea*
  - Sipuncula
  - *Magelona* spp.
  - *Pseudeurythoe ambigua*
- Group 4
  - *Americhelidium americanum*
  - *Nephtys picta*
  - *Rhepoxynius hudsoni*
- Group 5
  - *Brania wellfleetensis*
  - *Caulleriella* sp. B (Blake)
  - *Neanthes arenaceodentata*
  - *Cirrophorus* spp.
- Group 6
  - *Ancinus depressus*
  - *Spisula solidissima*
- Group 7
  - *Amastigos caperatus*
  - *Spio setosa*
  - *Aricidea catherinae*
  - *Euceramus praelongus*
  - *Polygordius* spp.
- Group 8
  - *Asabellides oculata*
  - *Nephtys incisa*
  - *Nucula proxima*
  - *Upogebia affinis*
- Group 9
  - *Ampelisca verrilli*
  - *Tellina agilis*
  - *Tharyx* sp. A Morris
  - *Oxyurostylis smithi*
  - *Ensis directus*
  - *Owenia fusiformis*
  - *Phyllodoce arenae*
  - *Mercenaria mercenaria*
- Group 10
  - *Ancistrosyllis hartmanae*
  - *Branchiostoma caribaeum*
  - *Loimia medusa*
  - *Spiophanes bombyx*
  - *Parvilucina multilineata*
  - *Podarkeopsis levifuscina*
  - *Pseudeurythoe paucibranchiata*
- Group 11
  - *Drilonereis longa*
  - *Nassarius vibex*
  - *Glycera dibranchiata*
  - *Lyonsia hyalina*
  - *Scoloplos rubra*
  - *Gemma gemma*
  - *Haminoea solitaria*
  - *Leptosynapta tenuis*
  - *Scolelepis texana*
- Group 12
  - *Aligena elevata*
  - *Chaetopterus variopedatus*
  - *Bhawania heteroseta*
  - *Prionospio perkinsi*
  - *Nephtys cryptomma*
  - *Scolelepis bousfieldi*
- Group 13
  - *Clymenella torquata*
  - *Listriella clymenellae*
  - *Macoma tenta*
  - *Saccoglossus kowalevskii*
  - *Sigambra tentaculata*
- Group 14
  - *Cabira incerta*
  - *Monticellina baptisteae-dorsobrachialis* complex
  - *Microphiopholis atra*
- Group 15
  - *Anadara transversa*
  - *Podarke obscura*
  - *Capitella capitata* complex
  - *Mysella planulata*
  - *Parapionosyllis longicirrata*
  - *Prionospio heterobranchia*
  - *Dipolydora socialis*
  - *Polycirrus* spp.
  - *Uniciola serrata*
- Group 16
  - *Arabella iricolor-multidentata* complex
  - *Demonax microphthalmus*
  - *Tagelus divisus*
  - *Ceratonereis irritabilis*
  - *Carazziella hobsonae*
  - *Cyathura burbancki*
  - *Diopatra cuprea*
  - *Scoletoma tenuis*
  - *Exogone dispar*
  - *Glycera americana*
  - *Macroclymene zonalis*
  - *Melinna maculata*
  - *Notomastus* sp. A Ewing
  - *Sabaco elongatus*
- Group 17
  - *Acteocina canaliculata*
  - *Mediomastus ambiseta*
  - *Glycinde solitaria*
  - *Paraprionospio pinnata*
  - *Phoronis* spp.
  - *Heteromastus filiformis*
  - *Streblospio benedicti*
  - *Neanthes succinea*
  - Nemertina
  - Oligochaeta
  - *Mulinia lateralis*
- Group 18
  - *Ampelisca abdita-vadorum* complex
  - *Leucon americanus*
  - *Pectinaria gouldii*
  - *Rictaxis punctostriatus*
  - *Leitoscoloplos robustus*
  - *Leitoscoloplos* sp.
  - Anthozoa
  - *Listriella barnardi*
  - *Spiochaetopterus costarum*
  - *Polydora cornuta*
- Group 19
  - *Ameroculodes* species complex
  - *Lepidactylus dytiscus*
  - *Laeonereis culveri*
  - *Cyclaspis varians*
  - *Eteone foliosa*
- Group 20
  - *Chiridotea almyra*
  - *Rangia cuneata*
  - *Tubificoides* spp.
- Group 21
  - *Cyathura polita*
  - *Marenzelleria viridis*
  - *Macoma mitchelli*
  - *Leptocheirus plumulosus*
  - *Eteone heteropoda*
  - *Macoma balthica*
- Group 22
  - *Hargeria rapax*
  - *Hobsonia florida*
- Group 23
  - *Aulodrilus pigueti*
  - *Tanytarsus* spp.
  - *Dicrotendipes* spp.
  - Chironomidae
  - *Corbicula fluminea*
  - *Polypedilum* spp.
  - *Chironomus* spp.
  - *Coelotanypus* spp.
  - *Limnodrilus hoffmeisteri*
  - Tubificidae immature without capilliform chaetae
  - *Cryptochironomus* spp.
  - *Procladius* spp.
  - Tubificidae immature with capilliform chaetae
  - Ceratopogonidae
  - *Isochaetides freyi*
  - *Cladotanytarsus* spp.

TABLE 5. Mean abundance m^{-2} (± SD) and Biological Index Value (BIV) of numerically-dominant macroinfauna in each of nine habitat classes, plus the high-energy euhaline, defined by classification of sites in the Mid-Atlantic Integrated Assessment (MAIA) region. Only sites where the species was present (n) were used in the calculation of means. N = total number of sites in a habitat class. BIVs were obtained by assigning rank scores to numerically dominant species for each site, and summing scores for the 10 most abundant species over all sites in each habitat class. Species are listed by BIV, from highest to lowest. Eu 1 = high-energy euhaline; Eu 2 = Delaware-Chesapeake Bay euhaline; NC-Poly 1 = North Carolina polyhaline silt and clay; NC-Poly 2 = North Carolina polyhaline sand; DC-Poly 1 = Delaware-Chesapeake Bay polyhaline sand; DC-Poly 2 = Delaware-Chesapeake Bay polyhaline silt and clay; High Meso = high mesohaline; Low Meso = low mesohaline; Oligo = oligohaline; Tidal = tidal freshwater.

Habitat	Species	Mean Abundance (SD)	BIV	n
Eu 1	*Tellina agilis*	129.7 (216.1)	118.5	17
(N = 26)	Nemertina	175.0 (513.3)	103.5	16
	Leitoscoloplos sp.	117.2 (140.2)	97.5	14
	Parahaustorius longimerus	365.3 (457.8)	82.0	9
	Rhepoxynius hudsoni	167.0 (213.2)	66.0	10
	Spisula solidissima	193.7 (280.4)	56.0	7
	Acanthohaustorius millsi	1904.7 (1580.0)	50.8	6
	Ampelisca abdita-vadorum complex	26.5 (42.8)	41.0	6
	Nephtys picta	36.7 (38.6)	40.8	10
	Paraonis fulgens	151.5 (139.6)	39.0	5
Eu 2	*Mediomastus ambiseta*	1011.1 (1352.6)	347.5	48
(N = 50)	*Tellina agilis*	1059.1 (2623.7)	221.9	41
	Oligochaeta	273.8 (365.2)	199.3	47
	Tharyx sp. A Morris	124.1 (138.3)	107.0	36
	Ampelisca verrilli	170.6 (272.2)	101.0	38
	Mulinia lateralis	180.6 (257.4)	99.0	37
	Exogone dispar	378.2 (615.8)	97.5	24
	Acteocina canaliculata	127.3 (129.4)	91.0	39
	Ampelisca abdita-vadorum complex	325.2 (713.9)	87.5	33
	Streblospio benedicti	132.0 (175.4)	87.0	31
NC-Poly 1	Nemertina	94.5 (101.9)	180.6	22
(N = 25)	*Paraprionospio pinnata*	83.8 (85.2)	148.0	20
	Aceteocina canaliculata	159.8 (146.8)	132.0	16
	Sigambra tentaculata	52.8 (47.2)	101.2	17
	Phoronis spp.	44.7 (49.5)	71.8	15
	Mediomastus ambiseta	108.6 (223.4)	67.1	12
	Magelona spp.	39.0 (33.1)	49.5	10
	Pseudeurythoe ambigua	62.9 (52.7)	44.0	9
	Streblospio benedicti	65.9 (67.4)	35.0	5
	Macoma tenta	33.5 (37.5)	34.1	7
NC-Poly 2	*Acteocina canaliculata*	306.4 (316.1)	241.5	36
(N = 36)	*Parvilucina multilineata*	332.2 (301.2)	229.4	33
	Mediomastus ambiseta	378.8 (565.1)	192.5	27
	Phoronis spp.	364.5 (1018.7)	180.5	30
	Nemertina	76.0 (59.8)	132.4	35
	Paraprionospio pinnata	69.9 (54.6)	102.7	27
	Tellina agilis	80.6 (75.8)	80.3	22
	Mulinia lateralis	93.3 (143.0)	79.0	24
	Glycinde solitaria	53.3 (51.4)	64.4	26
	Ampelisca verrilli	81.6 (85.5)	46.5	17
DC-Poly 1	*Acteocina canaliculata*	468.1 (543.8)	249.0	37
(N = 38)	*Phoronis* spp.	405.2 (544.2)	230.6	36
	Glycinde solitaria	190.1 (134.2)	188.1	38
	Mediomastus ambiseta	622.6 (1461.5)	153.5	27
	Oligochaeta	323.5 (443.5)	135.0	30
	Rictaxis punctostriatus	124.0 (116.3)	97.3	29
	Heteromastus filiformis	111.9 (198.5)	80.0	31
	Paraprionospio pinnata	112.6 (150.9)	60.1	26
	Branchiostoma caribaeum	302.0 (605.6)	55.5	15
	Gemma gemma	4402.6 (16050.5)	53.0	14
DC-Poly 2	*Mediomastus ambiseta*	1553.3 (2613.2)	532.7	64
(N = 66)	*Paraprionospio pinnata*	303.0 (306.2)	339.5	63
	Acteocina canaliculata	353.1 (443.2)	301.5	58
	Glycinde solitaria	165.9 (134.3)	272.9	65
	Oligochaeta	250.1 (490.1)	146.4	42
	Leucon americanus	132.3 (254.6)	130.9	47

TABLE 5. Continued.

Habitat	Species	Mean Abundance (SD)	BIV	n
	Streblospio benedicti	340.8 (677.8)	118.0	32
	Neanthes succinea	141.6 (347.9)	99.8	44
	Ampelisca abdita-vadorum complex	113.9 (141.6)	99.3	41
	Nemertina	89.0 (92.1)	96.1	58
High Meso (N = 46)	*Streblospio benedicti*	330.2 (412.6)	297.0	42
	Mulinia lateralis	220.3 (407.5)	214.5	31
	Heteromastus filiformis	134.8 (384.5)	166.5	33
	Mediomastus ambiseta	565.1 (1110.2)	156.8	25
	Glycinde solitaria	71.7 (83.8)	143.3	33
	Macoma mitchelli	166.0 (220.4)	137.0	22
	Paraprionospio pinnata	168.6 (222.1)	128.3	22
	Oligochaeta	275.6 (703.2)	120.8	21
	Nemertina	47.6 (54.5)	113.5	32
	Neanthes succinea	77.1 (81.6)	97.0	20
Low Meso (N = 60)	*Macoma michelli*	656.8 (568.0)	443.0	58
	Heteromastus filiformis	544.4 (587.4)	428.2	60
	Streblospio benedicti	230.7 (284.0)	282.2	56
	Marenzelleria viridis	281.3 (320.8)	275.0	56
	Cyathura polita	138.6 (116.9)	232.5	55
	Neanthes succinea	215.0 (273.7)	224.8	54
	Oligochaeta	832.0 (1623.7)	212.0	45
	Leptocheirus plumulosus	418.0 (493.7)	205.5	34
	Nemertina	83.4 (83.9)	150.5	58
	Laeonereis culveri	165.2 (170.5)	123.5	28
Oligo (N = 23)	*Tubificoides* spp.	444.7 (600.4)	176.5	23
	Marenzelleria viridis	301.6 (476.8)	145.0	19
	Cyathura polita	194.7 (291.8)	129.5	20
	Rangia cuneata	108.5 (137.0)	109.0	17
	Leptocheirus plumulosus	698.1 (837.3)	92.0	13
	Coelotanypus spp.	294.7 (327.9)	66.5	10
	Limnodrilus hoffmeisteri	556.2 (585.3)	47.5	6
	Tubificidae imm. without capilliform chaetae	62.7 (99.4)	43.5	9
	Hobsonia florida	176.4 (215.3)	42.0	7
	Nemertina	38.7 (49.6)	42.0	9
Tidal (N = 25)	Tubificidae imm. without capilliform chaetae	1710.1 (2047.3)	211.0	23
	Limnodrilus hoffmeisteri	312.0 (349.6)	165.0	24
	Corbicula fluminea	415.8 (412.3)	136.8	18
	Coelotanypus spp.	127.5 (122.3)	118.5	21
	Polypedilum spp.	268.7 (399.5)	99.5	15
	Tubificidae imm. with capilliform chaetae	195.5 (260.2)	93.0	15
	Cyathura polita	110.1 (102.2)	88.0	15
	Procladius spp.	64.8 (86.4)	74.0	20
	Chironomus spp.	456.4 (1332.9)	66.8	14
	Cryptochironomus spp.	38.7 (34.5)	62.8	18

inant species of North Carolina polyhaline silt and clay sites were nemerteans, the polychaete *Paraprionospio pinnata,* and the gastropod *Acteocina canaliculata* (Table 5). Dominant species of North Carolina polyhaline sand sites were the gastropod *A. canaliculata* and the bivalve *Parvilucina multilineata.*

Delaware-Chesapeake Bay polyhaline sites (18–27‰) were characterized by species groups 17 and 18, and by other species with a lower frequency of occurrence among these sites. Low frequency species groups 8 and 10–14 differentiated many of these sites from other site groups. Species groups 8 and 12–14 had a higher affinity for silt and clays, while species groups 10 and 11 had a higher affinity for sands. Numerically dominant species of Delaware-Chesapeake Bay silt and clay sites were the polychaetes *M. ambiseta* and *P. pinnata,* and the gastropod *A. canaliculata* (Table 5). Sand sites were dominated by *A. canaliculata,* the phoronid *Phoronis* spp., and the polychaete *Glycinde solitaria.*

Species group 17 (Table 4) characterized both high and low mesohaline sites. In addition, low mesohaline sites included many species in groups 19 and 21. Numerically dominant species of high mesohaline sites were the polychaete *Streblospio benedicti* and the bivalve *Mulinia lateralis* (Table 5). Low mesohaline sites were dominated by the bivalve *Macoma mitchelli* and the polychaete *Heteromastus fil-*

iformis. Species groups 20 and 22 characterized oligohaline sites with dominance of *Tubificoides* spp. and the polychaete *Marenzelleria viridis* (Table 5). Species group 23 characterized the tidal freshwater with dominance of mature and immature (most tubificids without capilliform chaetae) *Limnodrilus hoffmeisteri.*

Discussion

The classification analysis of estuarine sites in the mid-Atlantic region of the U.S. revealed assemblages of organisms that were mainly associated with salinity gradients and sediment type, reinforcing results from previous studies. Weisberg et al. (1997), for example, distinguished five salinity habitats in the Chesapeake Bay that correspond closely to the salinity habitats described in this study and to the Venice System for the classification of estuarine waters. The salinity habitats defined in this study were the tidal freshwater, oligohaline, low mesohaline, high mesohaline, polyhaline, and euhaline. Weisberg et al.'s study (1997) did not distinguish euhaline sites within the Chesapeake Bay. In the present study we found that the separation of euhaline sites was closer to the 27‰ breakpoint than to the generally accepted 30‰. Weisberg et al. (1997) also classified assemblages according to sediment type at the cut-off level of 60% sand. Our classification analysis could only separate sites with a percentage of sand content above 90% in the polyhaline region. In our study dominant species in the mesohaline to euhaline salinity range were not restricted to one substrate, but were broadly distributed in different types of sediment with peaks of abundance in either sand or mud. There was also considerable overlap in the distribution of species across adjacent salinity types. These results suggest that infaunal assemblages in the estuaries of the mid-Atlantic region represent a continuum along the environmental gradient. This pattern has been widely reported for the Hudson River estuary (Ristich et al. 1977), Delaware Bay (Maurer et al. 1978), Chesapeake Bay (Boesch 1977b; Holland et al. 1987; Diaz and Schaffner 1990), South Carolina estuaries (Calder et al. 1977), and Georgia's Ogeechee River estuary (Dörjes and Howard 1975).

Our analysis of benthic community composition was restricted to macroinfaunal assemblages, to the summer index period, and to non-degraded sites in the mid-Atlantic region of the U.S. Using these types of data, our characterization of dominant species across salinity and sediment types in the MAIA region agrees well with characterizations from previous investigations. A consistent pattern of dominant taxa along the estuarine gradient of U.S. east coast temperate estuaries emerges from this and previous studies (Tenore 1972; Calder et al. 1977; Ristich et al. 1977; Maurer et al. 1978; Holland et al. 1987). Tidal freshwater habitats are dominated by oligochaete and insect larvae, particularly limnodrilid oligochaetes (*Limnodrilus* spp.) and chironomid insect larvae, and the bivalve *Corbicula fluminea* can also be abundant. Oligohaline habitats are dominated by the polychaete *M. viridis,* the amphipod *Leptocheirus plumulosus,* and the isopod *Cyathura polita,* although each of these species can be common in low mesohaline regions. Additional taxa that can dominate oligohaline habitats are the polychaete *Hobsonia florida,* tubificid oligochaetes (particularly *Tubificoides* spp.), the bivalve *Rangia cuneata,* and the amphipod *Lepidactylus dytiscus.* Throughout the mesohaline and polyhaline regions euryhaline polychaetes can be dominants, including *Neanthes succinea, P. pinnata, S. benedicti, G. solitaria,* and *H. filiformis.* Additional taxa that can dominate in mesohaline habitats are the bivalves *M. mitchelli, Macoma balthica,* and *M. lateralis,* and the cumacean *Leucon americanus.* In polyhaline regions, in addition to the previously listed euryhaline polychaetes species, dominant species may include the polychaetes *Clymenella torquata* and *Glycera dibranchiata.* In both polyhaline and euhaline regions dominants include the capitellid polychaete *M. ambiseta,* the gastropod *A. canaliculata,* the bivalve *T. agilis,* ampeliscid amphipods, phoronids, and nemerteans. In these regions, the bivalve *Gemma gemma* is usually concentrated in high densities in a small number of sites. In polyhaline and euhaline regions with coarse sediments (usually indicative of a high energy habitat), additional dominants are phoxocephalid and haustoriid amphipods, the bivalve *S. solidissima,* and a variety of polychaetes such as nepthyds, paraonids, and syllids.

In the above studies, as well as in the present study, both sediment type and salinity were major determinants in species distributional patterns. Sediment type was a minor factor compared to salinity. Some species were clearly restricted to groups of sites with sediments containing a high percentage of sand (Tourtellotte and Dauer 1983; this study), but the dominant species of other site groups were widespread across sediment types.

In addition to salinity and sediment type, our classification analysis separated sites by geographical location. Most polyhaline and euhaline sites in North Carolina estuaries (Albemarle and Pamlico Sounds) were separated from all others (see Fig. 5). These results are consistent with those of Van Dolah et al. (1999), who found that stations in the Environmental Monitoring and Assessment Carolinian Province (inclusive of North Carolina estuaries) separated by latitude in polyhaline-euhaline habitats and were less distinguishable geographically at lower salinities. The differences observed in the present study between the higher salinity North Carolina sites and those of similar salinity to the north could have been attributed to biotic discontinuities between the Carolinian and Virginian zoogeographic provinces. We were unable to identify any group of species unique to North Carolina estuaries. Differences in assemblages between North Carolina and Delaware-Chesapeake estuaries were related to the relative abundance contributions of species and not to differences in species composition resulting in geographic discontinuities. The North Carolina species assemblages identified in this study appear to be typical of estuarine habitats of other mid-Atlantic estuaries. Suggestions of a zoogeographic barrier associated with a thermal gradient may exist for coastal shelf waters off North Carolina (Cutler 1975), but our results do not provide evidence for a barrier within the estuary. Engle and Summers (1999b), who observed evidence of latitudinal gradients in the estuarine benthos along the U.S. Atlantic coast (Cape Cod to Biscayne Bay), also found that the benthic fauna of Albemarle-Pamlico Sound were more similar to the Virginian Province fauna than to the fauna of the more southern portions of the Carolinian Province. The Albemarle-Pamlico Sound is usually considered part of the Carolinian Province. Engle and Summers (1999b) suggested that the boundary between the Virginian and Carolinian Provinces, with respect to estuarine benthic assemblages, be moved to a new location south of Albemarle-Pamlico Sound.

In this study, benthic samples from non-degraded reference sites throughout the MAIA region have been classified into habitat categories of similar biological composition. Results provide a basis for understanding how benthic assemblages of the region are distributed in relation to natural environmental factors and for beginning to define reference-range conditions in key benthic attributes by habitat type. This understanding is an essential step in the process of developing a benthic index that can be used region-wide to assess effects of pollution reliably and that takes into account variability related to natural habitat factors.

ACKNOWLEDGMENTS

This work was funded and managed by the U.S. Environmental Protection Agency (EPA), through its Office of Research and Development, under Contract No. 68-D-98-002 to Technology Planning and Management Corporation via a subcontract with Versar, Inc. Many fruitful discussions among the participants of a benthic workshop significantly contributed to the preparation of this manuscript. We especially thank Ray Alden (University of Nevada, Las Vegas), Richard Batiuk (Chesapeake Bay Program), Richard Eskin (Maryland Department of the Environment), Edythe Humphries (Delaware Department of Natural Resources), and Rick Kutz (EPA's Mid-Atlantic Integrated Assessment Team) for providing comments to an earlier draft of this manuscript. Ananda Ranasinghe (Southern California Coastal Water Research Program) initially directed the project and provided many valuable suggestions. Thuzar Myint managed the database and conducted statistical analyses. We are also grateful to Jawed Hameedi (National Oceanic and Atmospheric Administration) and John Paul (EPA Region II) for access to the National Status and Trends and Environmental Monitoring and Assessment data, respectively, used in this study. Virginia Engle (EPA Gulf Ecology Division) and an anonymous reviewer provided valuable peer-review comments. This manuscript has been subjected to the EPA's review and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation by EPA for use.

LITERATURE CITED

ADAMS, D. A., J. S. O'CONNOR, AND S. B. WEISBERG. 1998. Sediment quality of the NY/NJ Harbor system. Final report. An investigation under the Regional Environmental Monitoring and Assessment Program (REMAP), EPA/902/R-98/001. U.S. Environmental Protection Agency—Region 2, Division of Environmental Science and Assessment, Edison, New Jersey.

AMERICAN SOCIETY FOR TESTING MATERIALS. 1993. Guide for conducting 10-day static sediment toxicity tests with marine and estuarine infaunal amphipods. ASTM E-1367-92. American Society for Testing Materials, Philadelphia, Pennsylvania.

BOESCH, D. F. 1977a. Application of numerical classification in ecological investigations of water pollution. Virginia Institute of Marine Science Special Scientific Report No. 77. Virginia Institute of Marine Science, Gloucester Point, Virginia.

BOESCH, D. F. 1977b. A new look at the zonation of benthos along the estuarine gradient, p. 245–266. *In* B. C. Coull (ed.). Ecology of Marine Benthos. University of South Carolina Press, Columbia, South Carolina.

BRADLEY, M. P. AND R. B. LANDY. 2000. The mid-Atlantic Integrated Assessment (MAIA). *Environmental Monitoring and Assessment* 63:1–13.

CALDER, D. R., B. B. BOOTHE, JR., AND M. S. MACLIN. 1977. A preliminary report on the estuarine macrobenthos of the Edisto and Santee River Systems, South Carolina. South Carolina Marine Resources Center Technical Report No. 22. South Carolina Wildlife and Marine Resources Department, Charleston, South Carolina.

CHAILLOU, J. C., S. B. WEISBERG, F. W. KUTZ, T. E. DEMOSS, L. MANGIARACINA, R. MAGNIEN, R. ESKIN, J. MAXTED, K. PRICE, AND J. K. SUMMERS. 1996. Assessment of the ecological condition of the Delaware and Maryland coastal bays. EPA/620/R-96/004. U.S. Environmental Protection Agency, Office of Research and Development, Washington, D.C.

CHESTER, A. J., R. L. FERGUSON, AND G. W. THAYER. 1983. Environmental gradients and benthic macroinvertebrate distributions in a shallow North Carolina estuary. *Bulletin of Marine Science* 33:282–295.

CUTLER, E. B. 1975. Zoogeographical barrier on the continental slope off Cape Lookout, North Carolina. *Deep-Sea Research* 22: 893–901.

DAUER, D. M. 1993. Biological criteria, environmental health and estuarine macrobenthic community structure. *Marine Pollution Bulletin* 26:249–257.

DAUER, D. M., M. F. LANE, H. G. MARSHALL, AND K. E. CARPENTER. 1998. Status and trends in water quality and living resources in the Virginia Chesapeake Bay: 1985–1997. Prepared for the Virginia Department of Environmental Quality, Richmond, Virginia. Old Dominion University, Norfolk, Virginia.

DAUER, D. M. AND R. J. LLANSÓ. In press. Spatial scales and probability based sampling in determining levels of benthic community degradation in the Chesapeake Bay. *Environmental Monitoring and Assessment.*

Diaz, R. J. and R. Rosenberg. 1995. Marine benthic hypoxia: A review of its ecological effects and the behavioural responses of benthic macrofauna. *Oceanography and Marine Biology Annual Review* 33:245–303.

Diaz, R. J. and L. C. Schaffner. 1990. The functional role of estuarine benthos, p. 25–56. *In* M. Haire and E. C. Krome (eds.). Perspectives on the Chesapeake Bay, 1990, Advances in Estuarine Sciences. Chesapeake Bay Program Report No. CBP/TRS41/90. Chesapeake Research Consortium, Gloucester Point, Virginia.

Dörjes, J. and J. D. Howard. 1975. Estuaries of the Georgia Coast, U.S.A.: Sedimentology and biology. IV. Fluvial-marine transition indicators in an estuarine environment, Ogeechee River-Ossabaw Sound. *Senckenbergiana Maritima* 7:137–179.

Engle, V. D. and J. K. Summers. 1999a. Refinement, validation, and application of a benthic condition index for Northern Gulf of Mexico estuaries. *Estuaries* 22:624–635.

Engle, V. D. and J. K. Summers. 1999b. Latitudinal gradients in benthic community structure in western Atlantic estuaries. *Journal of Biogeography* 26:1007–1023.

Green, R. H. and G. L. Vascotto. 1978. A method for analysis of environmental factors controlling patterns of species composition in aquatic communities. *Water Research* 12:583–590.

Hartwell, S. I., J. Hameedi, and M. Harmon. 2001. Magnitude and extent of contaminated sediment and toxicity in Delaware Bay. NOAA Technical Memorandum NOS NCCOS CCMA 148. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, Maryland.

Holland, A. F., A. T. Shaughnessy, and M. H. Hiegel. 1987. Long-term variation in mesohaline Chesapeake Bay macrobenthos: Spatial and temporal patterns. *Estuaries* 10:227–245.

Hyland, J. L., L. Balthis, C. T. Hackney, G. McRae, A. H. Ringwood, T. R. Snoots, R. F. Van Dolah, and T. L. Wade. 1998. Environmental quality of estuaries of the Carolinian Province: 1995. Annual statistical summary for the 1995 EMAP-Estuaries Demonstration Project in the Carolinian Province. NOAA Technical Memorandum NOS ORCA 123. National Oceanic and Atmospheric Administration, National Ocean Service, Office of Ocean Resources Conservation and Assessment, Silver Spring, Maryland.

Hyland, J. L., W. L. Balthis, C. T. Hackney, and M. Posey. 2000. Sediment quality of North Carolina estuaries: An integrative assessment of sediment contamination, toxicity, and condition of benthic fauna. *Journal of Aquatic Ecosystem Stress and Recovery* 8:107–124.

Hyland, J. L., E. Baptiste, J. Campbell, J. Kennedy, R. Kropp, and S. Williams. 1991. Macroinfaunal communities of the Santa Maria Basin on the California outer continental shelf and slope. *Marine Ecology Progress Series* 70:147–161.

Llansó, R. J., D. M. Dauer, J. H. Vølstad, and L. C. Scott. In press. Application of the benthic index of biotic integrity to environmental monitoring in Chesapeake Bay. *Environmental Monitoring and Assessment.*

Llansó, R. J., L. C. Scott, J. L. Hyland, D. M. Dauer, D. E. Russell, and F. W. Kutz. 2002. An estuarine benthic index of biotic integrity for the mid-Atlantic region of the United States. II. Index development. *Estuaries* 25:1231–1242.

Long, E. R., D. D. Macdonald, S. L. Smith, and F. D. Calder. 1995. Incidence of adverse environmental effects within ranges of chemical concentrations in marine and estuarine sediments. *Environmental Management* 19:81–97.

Maurer, D., L. Watling, P. Kinner, W. Leathem, and C. Wethe. 1978. Benthic invertebrate assemblages of Delaware Bay. *Marine Biology* 45:65–78.

McCloskey, L. R. 1970. The dynamics of the community associated with a marine scleractinean coral. *Internationale Revue der Gesamten Hydrobiologie* 55:13–81.

Mountford, N. K., A. F. Holland, and J. A. Mihursky. 1977. Identification and description of macrobenthic communities in the Calvert Cliffs region of the Chesapeake Bay. *Chesapeake Science* 18:360–369.

Paul, J. F., J. H. Gentile, K. J. Scott, S. C. Schimmel, D. E. Campbell, and R. W. Latimer. 1999. EMAP-Virginian Province four-year assessment report (1990–93). EPA 600/R-99/004. U.S. Environmental Protection Agency, Atlantic Ecology Division, Narragansett, Rhode Island.

Paul, J. F., K. J. Scott, D. E. Campbell, J. H. Gentile, C. S. Strobel, R. M. Valente, S. B. Weisberg, A. F. Holland, and J. A. Ranasinghe. 2001. Developing and applying a benthic index of estuarine condition for the Virginian Biogeographic Province. *Ecological Indicators* 1:83–99.

Pearson, T. H. and R. Rosenberg. 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanography and Marine Biology Annual Review* 16:229–311.

Ranasinghe, J. A., L. C. Scott, and F. S. Kelley. 1999. Chesapeake Bay water quality monitoring program, long-term benthic monitoring and assessment component. Level 1 Comprehensive report, July 1984–December 1998. Prepared for Maryland Department of Natural Resources, Tidewater Ecosystem Assessments. Versar, Inc., Columbia, Maryland.

Ringwood, A. H., M. E. DeLorenzo, P. E. Ross, and A. F. Holland. 1997. Interpretation of Microtox solid-phase toxicity tests: The effects of sediment composition. *Environmental Toxicology and Chemistry* 16:1135–1140.

Ristich, S. S., M. Crandall, and J. Fortier. 1977. Benthic and epibenthic macroinvertebrates of the Hudson River. I. Distribution, natural history and community structure. *Estuarine and Coastal Science* 5:255–266.

Smith, R. W., M. Bergen, S. B. Weisberg, D. Cadien, A. Dalkey, D. Montagne, J. K. Stull, and R. G. Velarde. 2001. Benthic response index for assessing infaunal communities on the Southern California mainland shelf. *Ecological Applications* 11: 1073–1987.

Strobel, C. J. 1998. Environmental Monitoring and Assessment Program, Mid-Atlantic Integrated Assessment, Estuaries Component. Field Operations and Safety Manual. U.S. Environmental Protection Agency, Atlantic Ecology Division, Narragansett, Rhode Island.

Tenore, K. R. 1972. Macrobenthos of the Pamlico River estuary, North Carolina. *Ecological Monographs* 42:51–69.

Tourtellotte, G. H. and D. M. Dauer. 1983. Macrobenthic communities of the lower Chesapeake Bay. II. Lynnhaven Roads, Lynnhaven Bay, Broad Bay, and Linkhorn Bay. *Internationale Revue der Gesamten Hydrobiologie* 68:59–72.

Van Dolah, R. F., J. L. Hyland, A. F. Holland, J. S. Rosen, and T. R. Snoots. 1999. A benthic index of biological integrity for assessing habitat quality in estuaries of the southeastern USA. *Marine Environmental Research* 48:269–283.

Weisberg, S. B., J. A. Ranasinghe, D. M. Dauer, L. C. Schaffner, R. J. Diaz, and J. B. Frithsen. 1997. An estuarine benthic index of biotic integrity (B-IBI) for the Chesapeake Bay. *Estuaries* 20:149–158.

Williams, W. T. and J. M. Lambert. 1961. Nodal analysis of associated populations. *Nature* 191:202.

Wilson, J. G. and D. W. Jeffrey. 1994. Benthic biological pollution indices in estuaries, p. 311–327. *In* J. M. Krammer (ed.). Biomonitoring of Coastal Waters and Estuaries. CRC Press, Boca Raton, Florida.

Received for consideration, September 26, 2001
Accepted for publication, May 17, 2002