Ecological Condition of Coastal Ocean Waters within Stellwagen Bank National Marine Sanctuary: 2008

NOAA Technical Memorandum NOS NCCOS 129

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Prepared By

W. Leonard Balthis[1], Jeffrey L. Hyland[1], Cynthia Cooksey[1], Michael H. Fulton[1], Edward F. Wirth[1], Donald Cobb[2], David N. Wiley[3]

Author Affiliations

[1] Center for Coastal Environmental Health and Biomolecular Research
National Oceanic and Atmospheric Administration
219 Fort Johnson Road
Charleston, SC 29412-9110

[2] U.S. Environmental Protection Agency
ORD/NHEERL Atlantic Ecology Division
27 Tarzwell Drive
Narragansett, RI 02882

[3] National Oceanic and Atmospheric Administration
Stellwagen Bank National Marine Sanctuary
175 Edward Foster Road
Scituate, MA 02066

Preface

This document presents the results of an assessment of ecological condition and potential stressor impacts in coastal-ocean waters of the Stellwagen Bank National Marine Sanctuary (SBNMS), based on sampling conducted in June 2008. The project was a collaborative effort by the U.S. Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA). It represents one of a series of studies, similar in protocol and design to EPA's Environmental Monitoring and Assessment Program (EMAP) and subsequent National Coastal Assessment (NCA), which extend these prior efforts in estuaries and inland waters out to the coastal shelf, from navigable depths along the shoreline seaward to the shelf break (approximate 100 m depth contour). Ecological assessments in National Marine Sanctuaries provide a basis for comparing conditions in these protected areas to surrounding non-sanctuary waters.

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Disclaimer

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List of Acronyms

ASE	Accelerated Solvent Extraction
CCMA	Center for Coastal Monitoring and Assessment
CDF	Cumulative Distribution Function
Chl *a*	Chlorophyll *a*
CRM	Certified Reference Material
CTD	Conductivity-Temperature-Depth
CV	Coefficient of Variation
CVAA	Cold Vapor Atomic Absorption
CWA	Clean Water Act
DDT	Dichlorodiphenyltrichloroethane
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphate
DO	Dissolved Oxygen
DQO	Data Quality Objectives
EAM	Ecosystem Approach to Management
EC50	Effective Concentration that reduces light output by 50% relative to controls
EI	Electron-impact Ionization
EMAP	Environmental Monitoring and Assessment Program
EPA	Environmental Protection Agency
ERL	Effects-Range Low
ERM	Effects-Range Median
ERM-Q	Effects-Range Median Quotient
GC/MS	Gas Chromatography/Mass Spectrometry
GFAA	Gas Flame Atomic Absorption
GMCC	Gulf of Maine Coastal Current
GRTS	Generalized Random Tessellation Stratified
ICP-MS	Inductively Coupled Plasma-Mass Spectrometry
LCM	Laboratory Control Materials
MAB	Mid-Atlantic Bight
MBDS	Massachusetts Bay Disposal Site
MDL	Method Detection Limit
MIT	Massachusetts Institute of Technology
MITIS	Marine Invader Tracking Information System
MWRA	Massachusetts Water Resources Authority
NAS	National Aquatic Species database
NCA	National Coastal Assessment
NCCOS	National Centers for Coastal Ocean Science
NCI	Negative Chemical Ionization
NEMESIS	National Exotic Marine and Estuarine Species Information System
NMDS	Non-metric Multidimensional Scaling
NMS	National Marine Sanctuaries
NMSP	National Marine Sanctuary Program
NOAA	National Oceanic and Atmospheric Administration
NS&T	National Status and Trends program

PAH	Polycyclic Aromatic Hydrocarbon
PBDE	Polybrominated Diphenyl Ether
PCB	Polychlorinated Biphenyl
RPD	Relative Percent Difference
SAB	South Atlantic Bight
SBE	Sea-Bird Electronics
SBNMS	Stellwagen Bank National Marine Sanctuary
SEC	Size Exclusion Chromatography
SQG	Sediment Quality Guideline
SRM	Standard Reference Material
TOC	Total Organic Carbon
TSS	Total Suspended Solids
UPGMA	Unweighted Pair Group Method using Arithmetic mean
USGS	U.S. Geological Survey

Executive Summary

In June 2008, the NOAA National Ocean Service (NOS), in conjunction with the EPA National Health and Environmental Effects Laboratory (NHEERL), conducted an assessment of the status of ecological condition of soft-bottom habitat and overlying waters within the boundaries of Stellwagen Bank National Marine Sanctuary (SBNMS). The sanctuary lies approximately 20 nautical miles east of Boston, MA in the southwest Gulf of Maine between Cape Ann and Cape Cod and encompassing 638 square nautical miles (2,181 km^2). A total of 30 stations were targeted for sampling using standard methods and indicators applied in prior NOAA coastal studies and EPA's Environmental Monitoring and Assessment Program (EMAP) and National Coastal Assessment (NCA). A key feature adopted from these studies was the incorporation of a random probabilistic sampling design. Such a design provides a basis for making unbiased statistical estimates of the spatial extent of ecological condition relative to various measured indicators and corresponding thresholds of concern. Indicators included multiple measures of water quality, sediment quality, and biological condition (benthic fauna, fish tissue contaminant levels).

Depths ranged from 31 – 137 m throughout the study area. About 76 % of the area had sediments composed of sands (< 20 % silt-clay), 17 % of the area was composed of intermediate muddy sands (20 – 80 % silt-clay), and 7 % of the sampled area consisted of mud (> 80 % silt-clay). About 70 % of the area (represented by 21 sites) had sediment total organic carbon (TOC) concentrations < 5 mg/g and all but one site (located in Stellwagen Basin) had levels of TOC < 20 mg/g, which is well below the range potentially harmful to benthic fauna (> 50 mg/g).

Surface salinities ranged from 30.6 – 31.5 psu, with the majority of the study region (approximately 80 % of the area) having surface salinities between 30.8 and 31.4 psu. Bottom salinities varied between 32.1 and 32.5 psu, with bottom salinities at all sites having values above the range of surface salinities. Surface-water temperatures varied between 12.1 and 16.8 ºC, while near-bottom waters ranged in temperature from 4.4 – 6.2 ºC. An index of density stratification ($\Delta\sigma_t$) indicated that the waters of SBNMS were stratified at the time of sampling. Values of $\Delta\sigma_t$ at 29 of the 30 sites sampled in this study (96.7 % of the study area) varied from 2.1 – 3.2, which is within the range considered to be indicative of strong vertical stratification ($\Delta\sigma_t > 2$) and typical of the western Gulf of Maine in summer.

Levels of dissolved oxygen (DO) were confined to a fairly narrow range in surface (8.8 – 10.4 mg/L) and bottom (8.5 – 9.6 mg/L) waters throughout the survey area. These levels are within the range considered indicative of good water quality (> 5 mg/L) with respect to DO. None of these waters had DO at low levels (< 2 mg/L) potentially harmful to benthic fauna and fish.

Total suspended solids (TSS) in surface waters ranged from 2.4 – 9.1 mg/L, with slightly higher values observed in bottom waters (3.4 – 15.1 mg/L). Most sites (90 % of the area sampled) had concentrations of bottom-water TSS $\leq$ 9.1 mg/L.

Dissolved inorganic nitrogen (DIN: nitrogen as nitrate + nitrite + ammonium) in surface waters of SBNMS ranged from 0.03 mg/L to 0.56 mg/L and averaged 0.09 mg/L. Ninety percent of the study area surface waters had DIN concentrations $\leq$ 0.07 mg/L. Bottom-water concentrations of

DIN tended to be higher than surface concentrations. For example, about 50% of bottom waters had DIN > 0.55 mg/L (near the maximum surface-water concentration of 0.56 mg/L) and the average concentration was 0.51 mg/L (range of 0.06 – 0.74 mg/L). Bottom-water DIN levels were higher at deeper sites in the sanctuary compared to shallower sites.

Concentrations of dissolved inorganic phosphorus (DIP) in surface waters ranged between 0.02 mg/L and 0.12 mg/L, averaging 0.03 mg/L. Ninety percent of the study area surface waters had DIP concentrations $\leq$ 0.04 mg/L. While the range of bottom-water concentrations of DIP (0.02 mg/L to 0.14 mg/L) were similar to those measured in surface waters, the mean (0.11 mg/L) and estimated percentiles were higher. Half of the study area had bottom-water DIP concentrations that were greater than the maximum surface DIN concentration (0.12 mg/L).

DIN:DIP ratios in surface waters ranged from 1.98 to 10.57 (mean of 3.73), which are strongly indicative of nitrogen limitation (DIN:DIP < 16).

Surface-water concentrations of chlorophyll *a*, an indicator of phytoplankton biomass and abundance, ranged from 0.31 µg/L to 1.65 µg/L and averaged 0.57 µg/L. Bottom-water concentrations of chlorophyll *a* were similar to concentrations in surface waters, ranging between 0.07 µg/L and 1.12 µg/L and averaging 0.36 µg/L.

Bottom sediments of SBNMS appeared to be relatively uncontaminated. No contaminants were found in excess of their corresponding Effects-Range Median (ERM) sediment quality guideline values. The entire survey region was rated in good condition (no chemicals above corresponding ERM values and < 5 chemicals above corresponding Effects-Range Low (ERL) values). Arsenic was one of only three chemicals that exceeded their corresponding ERL guidelines. The ERL exceedances for arsenic occurred at eleven sites, representing an estimated 36.7 % of the survey area. The concentration of arsenic at most sites (28 sites, 93% area) was within the range typical of uncontaminated near-shore marine sediments (5 – 15 µg/g dry weight total arsenic) and reflects its natural presence at low to moderate concentrations in crustal rocks of the region. Arsenic concentrations greater than 15 µg/g dry weight were found at two sites (stations 3 and 20) in the northern part of the sanctuary. Concentrations of lead and mercury in excess of the corresponding ERLs were observed at only one site (station 1) which was located in a deep, silty area of Stellwagen Basin approximately 4 nautical miles southeast of the Massachusetts Bay Disposal Site

Concentrations of a suite of metals, pesticides, and PCBs were measured in edible tissues (fillets) of 26 fish specimens (representing five distinct species) collected at 16 of the 30 stations and compared to risk-based EPA advisory guidelines for recreational fishers. Two of the 16 stations where fish were collected and retained for analysis had chemical contaminants in tissues above the corresponding upper human-health endpoints. The exceedances at these sites were for methylmercury (station 3, measured as total mercury and assumed to be all methylmercury) and total PCB (station 17). Stations 3 and 17 were located in a deep area adjacent to Gloucester Basin in the northern part of the sanctuary and in the southwest portion of the sanctuary in Stellwagen Basin, respectively. Lower human-health endpoints also were exceeded at one of the above sites and at an additional six sites, one of which had multiple exceedances. The exceedances of lower human-health guidelines were for methylmercury (measured as total mercury, as above) and inorganic arsenic. Thus, two of the 16 sites would be rated as "poor" with respect to contaminants in fish tissues according to EPA advisory guidelines, six would be rated as "fair", and the remaining eight sites would be rated as "good". The status with respect to fish tissue contamination of the remaining 14 sites where no fish were collected could not be determined.

Benthic taxonomic richness was relatively high in SBNMS assemblages, ranging from 10 – 45 per 0.04-m^2 grab and averaging 30 taxa/grab. Diversity (Shannon H′ (log_2)) averaged 3.6 overall, varying between 2.8 and 4.5 throughout the study area, and tended to be lowest among deeper, depositional sites in Stellwagen and Gloucester Basins. A total of 330 taxa were identified in the 60 grabs collected throughout the study area, of which 160 were identified to species level. Polychaetes, crustaceans, and molluscs were the dominant taxa both by percent abundance (69 %, 15 %, and 8 %, respectively) and percent of taxa (38 %, 33 %, and 20 %, respectively). Densities ranged from 612 – 15,500 ind/m^2 and averaged 6,723 ind/m^2.

The 10 dominant (most abundant) taxa, in decreasing order of abundance, included the syllid polychaete (Family Syllidae) *Exogone verugera*; maldanid polychaetes (Maldanidae); sabellid polychaetes (Sabellidae); the sabellid polychaete genus *Chone*; the polychaetes *Axiothella mucosa* (Maldanidae), *Prionospio steenstrupi* (Spionidae), and *Parapionosyllis longicirrata* (Syllidae); the gammarid amphipod genus *Unciola*; the polychaete *Exogone hebes*; and tubificid oligochaetes (Tubificidae). Shallow, sandy sites on Stellwagen Bank were dominated by maldanid and syllid polychaetes (mean densities of 2,129 ind/m^2 and 2,014 ind/m^2 for families Maldanidae and Syllidae, respectively). Densities and numbers of taxa were lowest in the deeper, depositional areas of Stellwagen and Gloucester Basins. Infaunal assemblages in the remainder of the sanctuary were characterized by high diversity and richness (number of taxa).

A small number of species collected as part of the 2008 SBNMS survey (i.e., *Harmothoe imbricata*) are considered to be cryptogenic (Ruiz et al. 2000). The only non-indigenous species identified in the present study was the gammarid amphipod *Microdeutopus gryllotalpa*, found at a single station (station 21). This species was listed in the SBNMS Final Management Plan and Environmental Assessment as a known invasive to the Gulf of Maine region, but had not yet been documented in SBNMS.

This study found no evidence of biological impacts linked to measured stressors. In fact, no indications of poor sediment or water quality relative to published evaluation thresholds were observed. These results suggest that waters and sediments of SBNMS are in good condition, with lower-end values of biological attributes representing parts of a normal reference range controlled by natural factors. Some influence of habitat type on infaunal density, diversity, and taxonomic richness was observed, with the shallower, sandy areas of Stellwagen Bank and the deeper, depositional regions of Stellwagen and Gloucester Basins emerging as distinct habitats, as described above.

It is possible that for some of these sites the lower values of benthic variables reflect symptoms of disturbance induced by other unmeasured stressors. In efforts to be consistent with the underlying concepts and protocols of earlier EMAP and NCA programs, the indicators in this study included measures of stressors, such as chemical contaminants and symptoms of eutrophication, which are often associated with adverse biological impacts in shallower estuarine and inland ecosystems. However, there may be other sources of human-induced stress in these offshore systems, particularly those causing physical disruption of the seafloor (e.g., commercial bottom trawling, cable placement, minerals extraction), that pose greater risks to living resources and which have not been captured adequately. Future monitoring efforts in these offshore areas should include indicators of such alternative sources of disturbance.

1.0 Introduction

The National Oceanic and Atmospheric Administration (NOAA) and the Environmental Protection Agency (EPA) each perform a broad range of research and monitoring activities designed to assess the status of coastal ecosystems and the potential effects of natural and human impacts. Authority to conduct such work is given by several legislative mandates including the Clean Water Act (CWA) of 1977 (33 U.S.C. §§ 1251 et seq.), National Coastal Monitoring Act of 1992 (Title V of the Marine Protection, Research, and Sanctuaries Act, 33 U.S.C. §§ 2801-2805), and the National Marine Sanctuary Act of 2000. To the extent possible, the two agencies have sought to coordinate related activities through partnerships with states and other institutions to prevent duplication of effort and to bring together complementary resources to fulfill common research and management goals. Accordingly, in June 2008, NOAA and EPA conducted a joint survey of ecological conditions in Stellwagen Bank National Marine Sanctuary (SBNMS). The sanctuary is located in the southwest part of the Gulf of Maine, located approximately 20 nautical miles east of Boston and encompassing 638 square nautical miles (2,181 km^2) of coastal ocean waters between Cape Ann and Cape Cod (Figure **1**).

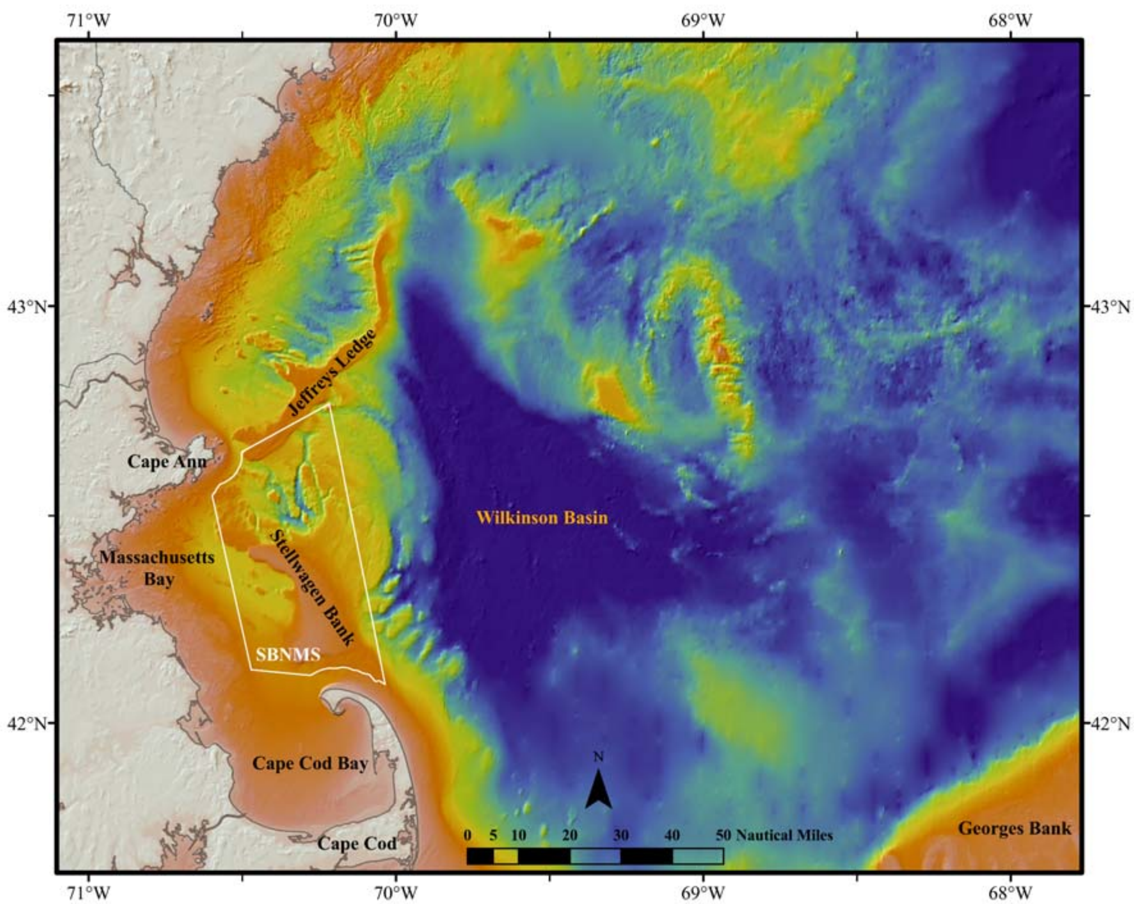

Figure 1. Map showing location of Stellwagen Bank National Marine Sanctuary (SBNMS) in the Gulf of Maine.

The present survey is part of a series of studies being conducted by NOAA and EPA to assess the condition of aquatic resources throughout coastal-ocean waters of the U.S. using multiple indicators of ecological condition. The protocols and design of these studies are similar to those used in EPA's Environmental Monitoring and Assessment Program (EMAP) and subsequent National Coastal Assessment (NCA), both of which have focused mainly on estuarine and inland waters. The offshore series extends these prior efforts onto the continental shelf, from approximately one nautical mile of the shoreline seaward to the shelf break (~100-m depth contour). Where applicable, sampling has included NOAA's National Marine Sanctuaries (NMS) to provide a basis for comparing conditions in these protected areas to surrounding non-sanctuary waters. To date such surveys have been conducted throughout the western U.S. continental shelf, from the Straits of Juan de Fuca, WA to the U.S./Mexican border (Nelson et al. 2008); shelf waters of the South Atlantic Bight (SAB) from Cape Hatteras, NC to West Palm Beach, FL (Cooksey et al. 2010); shelf waters of the mid-Atlantic Bight (MAB) from Cape Hatteras to Cape Cod, MA (Balthis et al. 2009); the continental shelf off southern Florida, from West Palm Beach in the Atlantic Ocean to Anclote Key in the Gulf of Mexico (see Cooksey and Hyland 2007 for cruise report); and the continental shelf along northeastern Gulf of Mexico (see Cooksey et al. 2010 for cruise report). Plans are underway to continue these surveys throughout the remaining portions of the Gulf of Mexico west of the Mississippi Delta and the New England coast north of Cape Cod.

The purpose of the present study was to assess the current status of ecological condition and stressor impacts in SBNMS and to provide this information as a framework for evaluating future changes due to natural or human-induced disturbances. To address this objective, the study incorporated standard methods and indicators applied in previous coastal EMAP/NCA projects (U.S. EPA 2001a, 2004, 2008) including multiple measures of water quality, sediment quality, and biological condition (benthic community health and fish tissue contamination). Synoptic sampling of the various indicators provided an integrative weight-of-evidence approach to assessing condition at each station and a basis for examining potential associations between the presence of stressors and biological responses. Another key feature was the incorporation of a probabilistic sampling design with stations (30 in total) positioned randomly throughout the study area. The probabilistic sampling design provided a basis for making unbiased statistical estimates of the spatial extent of condition relative to the various measured indicators and corresponding thresholds of concern. Other surveys in the current coastal-ocean series have applied stratified random sampling designs, with stations stratified by NMS vs. non-sanctuary status. However, since the present study was restricted to coastal ocean waters within the sanctuary boundaries, the assessment of condition relative to these various indicators did not include sanctuary vs. non-sanctuary comparisons.

Because the protocols and indicators are consistent with those used in previous EMAP/NCA estuarine surveys, comparisons can be made between conditions in offshore waters and those observed in neighboring estuarine habitats, thus providing a more holistic account of ecological conditions and processes throughout the inshore and offshore resources of the region. Such information should provide valuable input for future National Coastal Condition Reports, which historically have included limited coverage in offshore areas (e.g., U.S. EPA 2001a, 2004, 2008).

Results of this study should also provide valuable support to evolving interests within the U.S. and other parts of the world to move toward an ecosystem approach to management (EAM) of coastal resources (Murawski 2007; Marine Ecosystems and Management 2007). While the focus of the present study is on indicators of ecological condition, some human-dimension indicators have been included as well (e.g., fish contaminant levels relative to human-health guidelines, water clarity, marine debris, foul odors, oil slicks), which can be used to help address common public concerns such as "Are the fish safe to eat?" or "Is the water clean enough to swim in?" Humans are considered as both sources and receptors of ecosystem impacts in the EAM process.

This report attempts to describe the status of ecological condition in SBNMS with respect to the parameters measured in this study. A number of other publications are available which describe the sanctuary setting in general, its geology, oceanography, biological resources and habitat, and its commercial, recreational, and historical context. The Stellwagen Bank National Marine Sanctuary Final Management Plan and Environmental Assessment (U.S. Department of Commerce 2010) is one excellent source of information. In addition, an ecological characterization of SBNMS was conducted by the National Centers for Coastal Ocean Science (NCCOS), Center for Coastal Monitoring and Assessment (CCMA) in partnership with the National Marine Sanctuary Program (NMSP) in 2006, which describes physical, contaminant, and biological patterns of the SBNMS region (NCCOS 2006). These reports, together with other sources of information in the peer-reviewed literature (some of which are cited later in this report), provide a description of the processes influencing conditions in SBNMS and which place it in the larger context of the Gulf of Maine ecosystem.

2.0 Methods

2.1 Sampling Design and Field Collections

The sampling frame for this study was based on a generalized random-tessellation stratified (GRTS) design. The GRTS design represents a unified strategy for selecting spatially balanced probability samples of natural resources, in which sampling sites are more or less evenly dispersed over the extent of the resource (Stevens & Olsen 2004). Sampling was conducted from June 17 – 21, 2008 at 30 stations located within the boundaries of SBNMS (**Figure 2**, Appendix A).

Vertical water-column profiles of conductivity/salinity, temperature, depth, dissolved oxygen, and pH were conducted at each station using a Sea-Bird Electronics (SBE) Conductivity-Temperature-Depth (CTD) profiler, equipped with supplemental dissolved oxygen and pH sensors. The CTD was an SBE 9Plus with an 11Plus deck unit that provided real-time data recording of the vertical profile. The CTD was incorporated into a frame that included a rosette of 12 Nisken bottles used to collect water samples at discrete depths (near-surface, near-bottom). Water samples were analyzed for nutrients, total suspended solids (TSS), and chlorophyll *a*.

The CTD was lowered into the water until completely submerged and held just beneath the surface for three minutes while the water pump was allowed to purge any air from the system. The unit was then lowered to within one meter of the bottom at a rate of approximately 1 m s^{-1}.

Four Nisken bottles were fired at approximately 1 m below the surface and another four at near-bottom (approximately 1 m off the bottom).

Sediment samples were collected using a 0.04-m^2 Young-modified Van Veen grab sampler. Two replicate grab samples were retained for analysis of benthic infaunal composition, sieved onboard through a 0.5-mm screen, and preserved in 10% buffered formalin with rose bengal stain. The upper 2 – 3 cm of sediment from additional grabs (typically 1 or 2) was combined to yield a sediment composite, which was then homogenized and sub-sampled for analysis of metals, organic contaminants (pesticides, PCBs, PAHs, PBDEs), grain size (% silt-clay), and total organic carbon (TOC). Sediment samples (other than infauna) were kept frozen onboard the ship and later transferred to the respective analytical laboratories for analysis.

Hook-and-line fishing was attempted at all 30 stations. Targeted species included members of the orders Pleuronectiformes (flatfishes) and Gadiformes (cod, hake, haddock) , family Sparidae (porgies, scup), and the genera *Centropristis* (sea basses) and *Sebastes* (rockfishes). Specimens from three (Pleuronectiformes, Gadiformes, *Sebastes*) of the five groups listed above were collected from 18 of the 30 stations. Edible tissue (fillets) of 26 specimens from 16 of these stations was analyzed for metals, pesticides, PAHs, PCBs, and PBDEs.

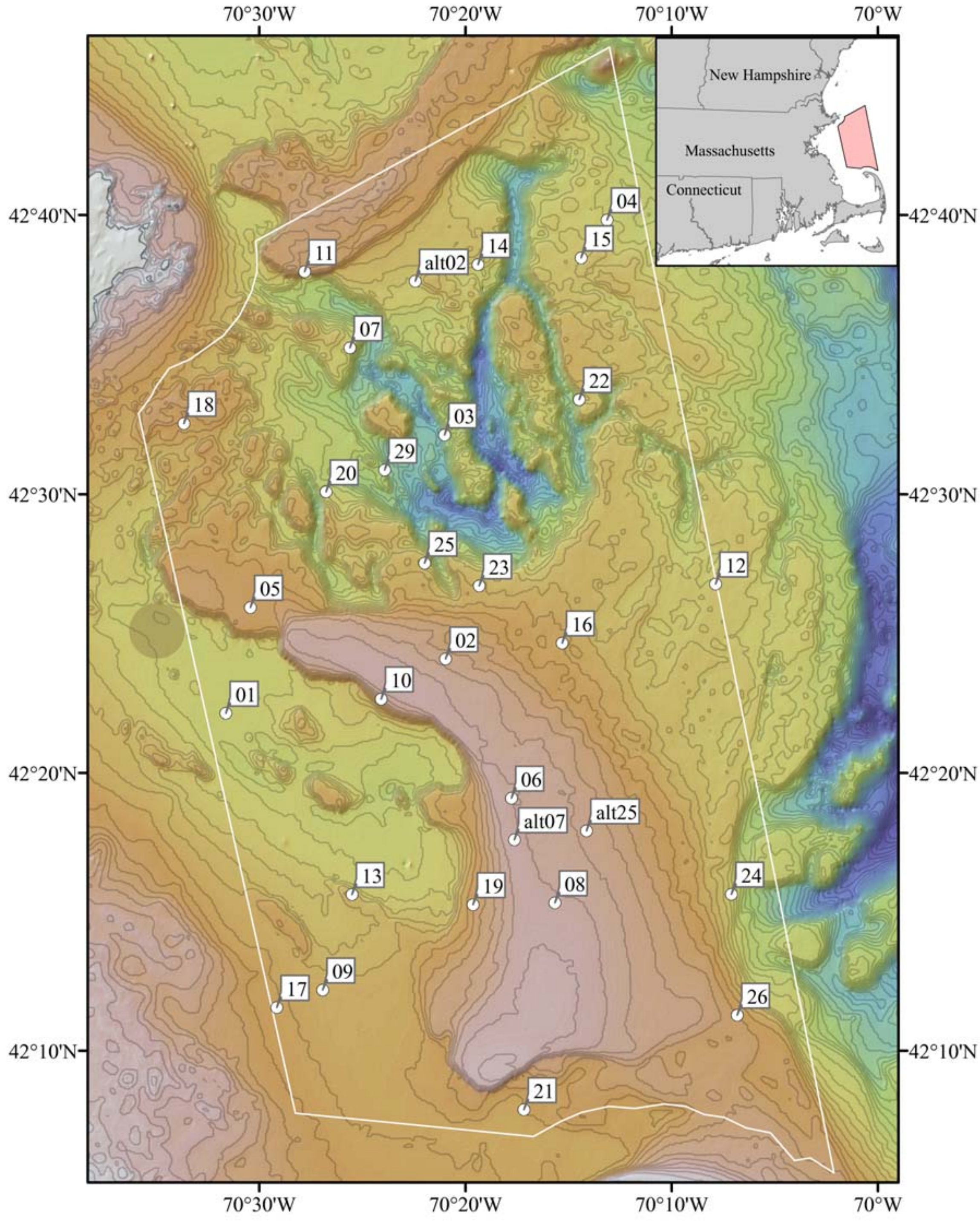

Figure 2. Map of SBNMS study area location and sampling sites.

2.2 Water Quality Analysis

Readings of temperature, conductivity/salinity, dissolved oxygen, depth, and pH were recorded directly from the CTD unit during its descent and ascent through the water column. An index of density stratification ($\Delta\sigma_t$) was calculated as the difference between the computed bottom and surface density (σ_t) values, where σ_t is the density of a parcel of water with a given salinity and temperature relative to atmospheric pressure (Fofonoff and Millard 1983). Dissolved inorganic nutrients, including nitrate (NO_3^-), nitrite (NO_2^-), orthophosphate (HPO_4^{2-}), silicate ($HSiO_3^-$), and ammonium (NH_4^+); chlorophyll *a*; and total suspended solids (TSS) were sampled at discrete water depths (near surface, mid-water, and near-bottom) and analyzed following standard methods (U.S. EPA 1997; U.S. EPA 1995). Only surface and bottom values for these various indicators are presented in this report. Data for all depths are included in the study database and are available on request to the authors.

2.3 Sediment TOC and Grain Size Analysis

Samples for grain size analysis were homogenized and diluted to a suspended slurry with the aid of a chemical dispersant and the suspension was passed through a 63µm sieve. The fine fraction passing through the sieve (< 63µm) and the coarse fraction retained on the sieve (> 63µm) were separately dried and weighed (see U.S. EPA 1995). Total organic carbon (TOC) was determined by combusting pre-acidified samples at high temperature and measuring the volume of carbon dioxide gas produced (U.S. EPA 1995).

2.4 Chemical Contaminant Analysis

2.4.1 Laboratory Sample Preparation

Sediment samples were kept frozen at approximately - 40 ºC prior to analysis. Samples were thawed in closed containers in a 4 ºC cooler for approximately 24 hours. Prior to extraction, samples were homogenized thoroughly by hand. Fish tissue samples were frozen upon receipt in the laboratory and stored at - 40 ºC until analysis. Fish were removed from the freezer and stored overnight at 4 ºC and allowed to thaw partially. The fish were filleted (skin-on) and homogenized well using a ProScientific homogenizer in 500 mL Teflon containers. The homogenized tissue sample was split into organic (pre-cleaned glass container) and inorganic (pre-cleaned polypropylene container) aliquots and stored at - 40 ºC until extraction or digestion. A percent dry-weight determination was made gravimetrically on an aliquot of the wet sediment and tissues.

2.4.2 Inorganic Sample Digestion and Analysis

Dried sediment was ground with a mortar and pestle and transferred to a 20 mL plastic screw-top container. A 0.25-g sub-sample of the ground material was transferred to a Teflon-lined digestion vessel and digested in 5 mL of concentrated nitric acid using microwave digestion. The sample was brought to a fixed volume of 50 mL in a volumetric flask with deionized water and stored in a 50-mL polypropylene centrifuge tube until instrumental analysis of Li, Be, Al, Fe, Mg, Ni, Cu, Zn, Cd, and Ag. A second 0.25-g sub-sample was transferred to a Teflon-lined digestion vessel and digested in 5 mL of concentrated nitric acid and 1 mL of concentrated hydrofluoric acid in a microwave digestion unit. The sample was then evaporated on a hot plate at 225 °C to near dryness and 1 mL of nitric acid was added. The sample was brought to a fixed volume of 50 mL in a volumetric flask with deionized water and stored in a 50 mL polypropylene centrifuge tube until instrumental analysis for V, Cr, Co, As, Sn, Sb, Ba, Tl, Pb, and U. Selenium was analyzed by hot plate digestion using a third 0.25-g sub-sample and 5 mL of concentrated nitric acid. Each sample was brought to a fixed volume of 50 mL in a volumetric flask with deionized water and stored in a 50 mL polypropylene centrifuge tube until instrumental analysis. Additionally, two to three grams wet tissue were microwave-digested in Teflon-lined digestion vessels using 10 mL of concentrated nitric acid along with 2 mL of hydrogen peroxide. Digested samples were brought to a fixed volume with deionized water in graduated polypropylene centrifuge tubes and stored until analysis. Finally, a separate inorganic aliquot was used for mercury analysis for both sediments and tissues. Approximately 0.5 g of wet sediment or tissue was analyzed on a Milestone DMA-80 Direct Mercury Analyzer.

All remaining elemental analyses were performed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) except for silver, which was determined using Graphite Furnace Atomic Absorption (GFAA) spectroscopy. Data quality was controlled by using a series of blanks, control solutions (Trace Metals in Drinking Water), and standard reference materials including NRC MESS-3 (Marine Sediments) and NIST 1566b (freeze-dried mussel tissue).

2.4.3 Organic Extraction and Analysis

An aliquot (10 g sediment or 5 g tissue wet weight) was extracted with anhydrous sodium sulfate using Accelerated Solvent Extraction (ASE) in either 1:1 methylene chloride:acetone (sediments) or 100% dichlormethane (tissues) (Schantz et al. 1997). Following extraction, samples were dried and cleaned using Gel Permeation Chromatography and Solid Phase Extraction to remove lipids and then solvent-exchanged into hexane for analysis. Samples were analyzed for PAHs, PBDEs, PCBs (by congener), and a suite of chlorinated pesticides using appropriate GC/MS technology. Data quality was assured by using a series of spiked blanks, reagent blanks, and appropriate standard reference materials including NIST 1944 (sediments) and NIST 1974b (mussel tissue).

2.5 Benthic Community Analysis

Identification and enumeration of benthic fauna was performed by Barry A. Vittor & Associates, Inc., Mobile, Alabama. Only skilled taxonomists conducted organism identification. A minimum of 10% of samples were rechecked by other qualified taxonomists for accuracy in identification and enumeration. Species lists from different labs were cross-checked, with external experts consulted for difficult identifications. Judged accuracy rates were well above standard levels for sorting and taxonomy (quality control reworks all $\geq$ 95 %).

Characteristics of benthic communities were assessed using standard measures of total faunal abundance (density/m^2), individual species abundances, species richness (number of taxa), and diversity (Shannon H′; Shannon 1948, Hayek and Buzas 1997). H′ was calculated using base-2 logarithms. Total faunal abundance was used to rank dominant taxa. Taxa were grouped according to higher taxonomic classifications to determine relative percentages (by abundance and number of taxa) of major groups of organisms (i.e., polychaetes, crustaceans, molluscs, echinoderms, other taxa). The full list of identified taxa was examined to evaluate the incidence of non-indigenous species vs. native species or ones with indeterminate status relative to invasiveness. Spatial patterns in benthic faunal distributions were also examined using a combination of hierarchical cluster analysis and non-metric multidimensional scaling (Clarke & Warwick 2001).

2.6 Sediment Toxicity Testing

Microtox® assays were conducted using the standardized solid-phase test protocols (Microbics Corporation 1992) and a Microtox Model 500 analyzer (Strategic Diagnostics Inc., Newark, DE). In this assay, sediment was homogenized and a 7.0 – 7.1 g sediment sample was used to make a series of sediment dilutions with 3.5% NaCl diluent, which were incubated for 10 minutes at 15 ºC. Luminescent bacteria (*Vibrio fisheri*) were then added to the test concentrations. The liquid phase was filtered from the sediment phase and bacterial post-exposure light output was measured using Microtox Omni Software. An EC50 value (the sediment concentration that reduces light output by 50% relative to the controls) was calculated for each sample. Triplicate samples were analyzed simultaneously. Sediment samples were classified as either toxic or nontoxic using criteria developed by Ringwood et al. (1997; Table 1 herein).

2.7 Data Analysis

The probabilistic sampling design used in this study allows calculation of estimates of the percent area of the resource that corresponds to specified values of a given parameter under consideration. Estimated cumulative distribution functions (CDFs), point estimates, and 95% confidence intervals were developed for water quality, sediment, and biological parameters measured in this study using formulas described in the EMAP statistical methods manual (Diaz-Ramos 1996). Calculation of CDFs was facilitated using algorithms (*spsurvey* package; Kincaid 2008) developed for R, a language and environment for statistical computing and graphics (R Development Core Team 2008).

Measured parameters were compared to established thresholds of concern, where available (Tables 1–3), and the corresponding percentiles of the estimated CDFs were reported. Where no such recommended levels of concern exist (e.g., benthic metrics), common distributional properties are reported (e.g., lower or upper percentiles).

Table 1. Thresholds used for classifying samples relative to various environmental indicators.

Indicator	Threshold	Reference
<u>Water Quality</u>		
Salinity (psu)	< 5 = Oligohaline 5 – 18 = Mesohaline >18 – 30 = Polyhaline > 30 = Euhaline	Carriker 1967
$\Delta\ \sigma_t$	> 2 = strong vertical stratification	Nelson et al. 2008
DO (mg/L)	< 2 = Low (Poor) 2 – 5 = Moderate (Fair) > 5 = High (Good)	USEPA 2008; Diaz and Rosenberg 1995
DIN/DIP	> 16 = phosphorus limited < 16 = nitrogen limited	Geider and La Roche 2002
<u>Sediment Quality</u>		
Silt-Clay Content (%)	> 80 = Mud 20 – 80 = Muddy Sand < 20 = Sand	USEPA 2008
TOC Content (mg/g)	> 50 = High (Poor) 20 – 50 = Moderate (Fair) < 20 = Low (Good)	USEPA 2008
	> 36 = High (Poor)	Hyland et al. 2005
Overall chemical contamination of sediments	≥ 1 ERM value exceeded = High (Poor); ≥ 5 ERL values exceeded = Moderate (Fair); No ERMs exceeded and < 5 ERLs exceeded = Low (Good)	USEPA 2008
Individual chemical contaminant concentrations in sediments	> ERM = High probability of bioeffects < ERL = Low probability of bioeffects	Long et al. 1995; Table 2 herein
Sediment toxicity using Microtox® assay	Silt-clay < 20 %: Toxic if EC50 < 0.5 % Silt-clay ≥ 20 %: Toxic if EC50 < 0.2 %	Ringwood et al. 1997

Table 1 (continued).

Indicator	Threshold	Reference
Biological Condition		
Reduced benthic taxonomic richness, diversity, or abundance	≤ lower 10^{th} percentile of all values for corresponding variable	Nelson et al. 2008
Chemical Contaminants in Fish Tissues	≥ 1 chemical exceeded Human Health upper limit = High (Poor) ≥ 1 chemical within Human Health risk range = Moderate (Fair) All chemicals below Human Health lower risk limit = Low (Good)	USEPA 2008
Individual chemical contaminants in fish tissues	Non-cancer (chronic systemic effects) endpoints based on consumption of four 8-ounce meals per month (general adult population). Cancer risk endpoints (1 in 100,000 risk level) based on consumption of four 8-ounce meals per month (general adult population).	USEPA 2000a; Table 3 herein

Table 2. ERM and ERL guideline values in sediments (Long et al. 1995).

Chemical	ERL	ERM
Metals (µg/g)		
Arsenic	8.2	70
Cadmium	1.2	9.6
Chromium	81	370
Copper	34	270
Lead	46.7	218
Mercury	0.15	0.71
Nickel	20.9	51.6
Silver	1	3.7
Zinc	150	410
Organics (ng/g)		
Acenaphthene	16	500
Acenaphthylene	44	640
Anthracene	85.3	1100
Fluorene	19	540
2-Methylnaphthalene	70	670
Naphthalene	160	2100
Phenanthrene	240	1500
Benzo[a]anthracene	261	1600
Benzo[a]pyrene	430	1600
Chrysene	384	2800
Dibenz[a,h]Anthracene	63.4	260
Fluoranthene	600	5100
Pyrene	665	2600
Low molecular weight PAHs	552	3160
High molecular weight PAHS	1700	9600
Total PAHs	4020	44800
4,4-DDE	2.2	27
Total DDT	1.58	46.1
Total PCBs	22.7	180

Table 3. Risk-based EPA advisory guidelines for recreational fishers (USEPA 2000a).

	EPA Advisory Guidelines Fish Tissue Concentration Range (wet weight) [a]	Health Endpoint
Metals (µg/g)		
Arsenic (inorganic)[b]	0.35 – 0.70	non-cancer
Cadmium	0.35 – 0.70	non-cancer
Mercury (methylmercury)[c]	0.12 – 0.23	non-cancer
Selenium	5.9 – 12.0	non-cancer
Organics (ng/g)		
Chlordane	590 – 1200	non-cancer
DDT (total)	59 – 120	non-cancer
Dieldrin	59 – 120	non-cancer
Endosulfan	7000 – 14000	non-cancer
Endrin	350 – 700	non-cancer
Heptachlor epoxide	15 – 31	non-cancer
Hexachlorobenzene	940 – 1900	non-cancer
Lindane	350 – 700	non-cancer
Mirex	230 – 470	non-cancer
Toxaphene	290 – 590	non-cancer
PAHs (benzo[a]pyrene)	1.6 – 3.2	cancer[d]
PCB (total)	23 – 47	non-cancer

[a] Range of concentrations associated with non-cancer and cancer health endpoint risk for consumption of four 8-oz meals per month.
[b] Inorganic arsenic, the form considered toxic, estimated as 2% of total arsenic.
[c] Because most mercury present in fish and shellfish tissue is present primarily as methylmercury and because of the relatively high cost of analyzing for methylmercury, the conservative assumption was made that all mercury is present as methylmercury (U.S. EPA, 2000a).
[d] A non-cancer concentration range for PAHs does not exist.

3.0 Results and Discussion

3.1 Depth and Water Quality

3.1.1 Depth

Bottom depths for the 30 stations sampled in coastal shelf waters of the SBNMS ranged from 31 m to 137 m (**Table 4**, **Figure 3**). The shallowest sites were located on top of Stellwagen Bank proper, while the deeper sites were in deep basins in the northern part of the sanctuary or in Stellwagen Basin. The mean depth of all sites sampled was 71 m.

3.1.2 General Water Characteristics: Temperature, Salinity, Water-Column Stratification, DO, pH, TSS

Temperatures of surface water (upper 2 m) ranged from 12.1 ºC to 16.8 ºC (**Table 4**). Fifty percent of the area sampled had surface temperatures ≤ 16 ºC, and only 10 % of the area had temperatures greater than 16.7 ºC (CDF 90^{th} percentile, **Table 4**). Bottom-water temperatures (lower 2 – 10 m of the water column, depending on station depth) were notably colder, ranging from 4.4 ºC to 6.2 ºC, with 50 % of the area ≤ 5.1 ºC and only 10 % exceeding 5.9 ºC.

Surface salinities varied within a narrow range between 30.6 psu and 31.5 psu. The mean and 50^{th} percentile (based on area) were 31.1 psu, with 10 % of the area having surface salinities between 30.6 psu and 30.8 psu. Bottom salinities varied between 32.1 and 32.5 psu, with a mean and median of 32.3 psu.

Some evidence of density stratification was observed among the stations sampled in this study. Computed values of $\Delta\sigma_t$ indicate that coastal shelf waters of the SBNMS at the time of this sampling were stratified, with 90 % of the survey area having values of $\Delta\sigma_t > 2.3$. Values of $\Delta\sigma_t$ at 29 of the 30 sites sampled in this study (96.7 % of the study area) ranged from 2.1 to 3.2, which is within the range considered to be indicative of strong vertical stratification ($\Delta\sigma_t > 2$; Nelson et al. 2008). These values are similar to summertime values reported for the western Gulf of Maine (Clark et al. 2006).

DO levels indicated that SBNMS waters were well-oxygenated. Measured DO concentrations occupied a fairly narrow range for both surface and bottom waters, with surface DO concentrations varying between 8.8 mg/L and 10.4 mg/L and bottom water concentrations between 8.5 mg/L and 9.6 mg/L. None of these waters had DO at low levels (< 2 mg/L) potentially harmful to benthic fauna and fish (**Table 4**, **Figure 3**). By comparison, other coastal and estuarine waters in the region had similar DO levels, although occupying a wider range of values. For example, reported ranges of bottom DO concentrations were 3.0 – 9.6 mg/L among 53 sites in Cape Cod Bay and 5.6 – 10.9 mg/L among 31 sites in Massachusetts Bay (including sites in Boston Inner Harbor) (NCA 2006).

The range of pH values was 7.9 – 8.0 for surface waters and 7.6 – 7.8 for bottom waters, which falls within the normal range for seawater of 7.5 – 8.5 (Pinet 2006).

Total suspended solids (TSS) ranged from 2.4 – 9.1mg/L in surface waters. Fifty percent of the area had TSS values $\leq$ 6.3 mg/L, and 90 % of the area had surface TSS values $\leq$ 8.7 mg/L. TSS concentrations in bottom waters were similar to those of surface waters. The area-weighted 50^{th} and 90^{th} percentiles were 6.5 mg/L and 9.1 mg/L, respectively. Concentrations of TSS in surface waters of Cape Cod Bay and Massachusetts Bay were slightly lower, varying from 0.02 – 4.60 mg/L and 0.50 to 8.70, respectively (NCA 2006).

The full range of values across all SBNMS stations, for the various water-quality variables discussed above, is displayed as CDF plots in **Figures Figure 3** and **Figure 4**. The mean values by station (average of multiple CTD measurements for near-surface and near-bottom waters for each station) appear in Appendices B and C.

Table 4. Summary of depth and water-column characteristics for near-bottom (lower 3 m) and near-surface (0.5 - 4 m) waters.

	Near-bottom water					Near-surface water				
	Mean	Range	CDF 10th pctl	CDF 50th pctl	CDF 90th pctl	Mean	Range	CDF 10th pctl	CDF 50th pctl	CDF 90th pctl
Depth (m)	71	31 - 137	34	65	93	—	—	—	—	—
Δσt	2.7	1.6 - 3.2	2.3	2.7	3	—	—	—	—	—
Temperature (ºC)	5.2	4.4 - 6.2	4.6	5.1	5.9	15.8	12.1 - 16.8	15.1	16	16.7
Salinity (psu)	32.3	32.1 - 32.5	32.2	32.3	32.5	31.1	30.6 - 31.5	30.8	31.1	31.4
DO (mg/L)	9.2	8.5 - 9.6	8.7	9.2	9.5	9.3	8.8 - 10.4	9	9.2	9.5
pH	7.7	7.6 - 7.8	7.6	7.7	7.8	8	7.9 - 8	7.9	8	8
DIN (mg/L)	0.51	0.06 - 0.74	0.32	0.55	0.68	0.09	0.04 - 0.56	0.05	0.05	0.07
DIP (mg/L)	0.11	0.02 - 0.14	0.09	0.12	0.13	0.03	0.02 - 0.12	0.02	0.03	0.04
DIN/DIP	8.16	5.81 - 9.57	6.30	8.35	9.15	3.73	1.98 - 10.57	2.29	3.08	4.93
Chl a (µg/L)	0.36	0.07 - 1.12	0.07	0.24	1	0.57	0.31 - 1.65	0.34	0.51	0.77
TSS (mg/L)	7	3.4 - 15.1	5	6.5	9.1	6.6	2.4 - 9.1	4.9	6.3	8.7

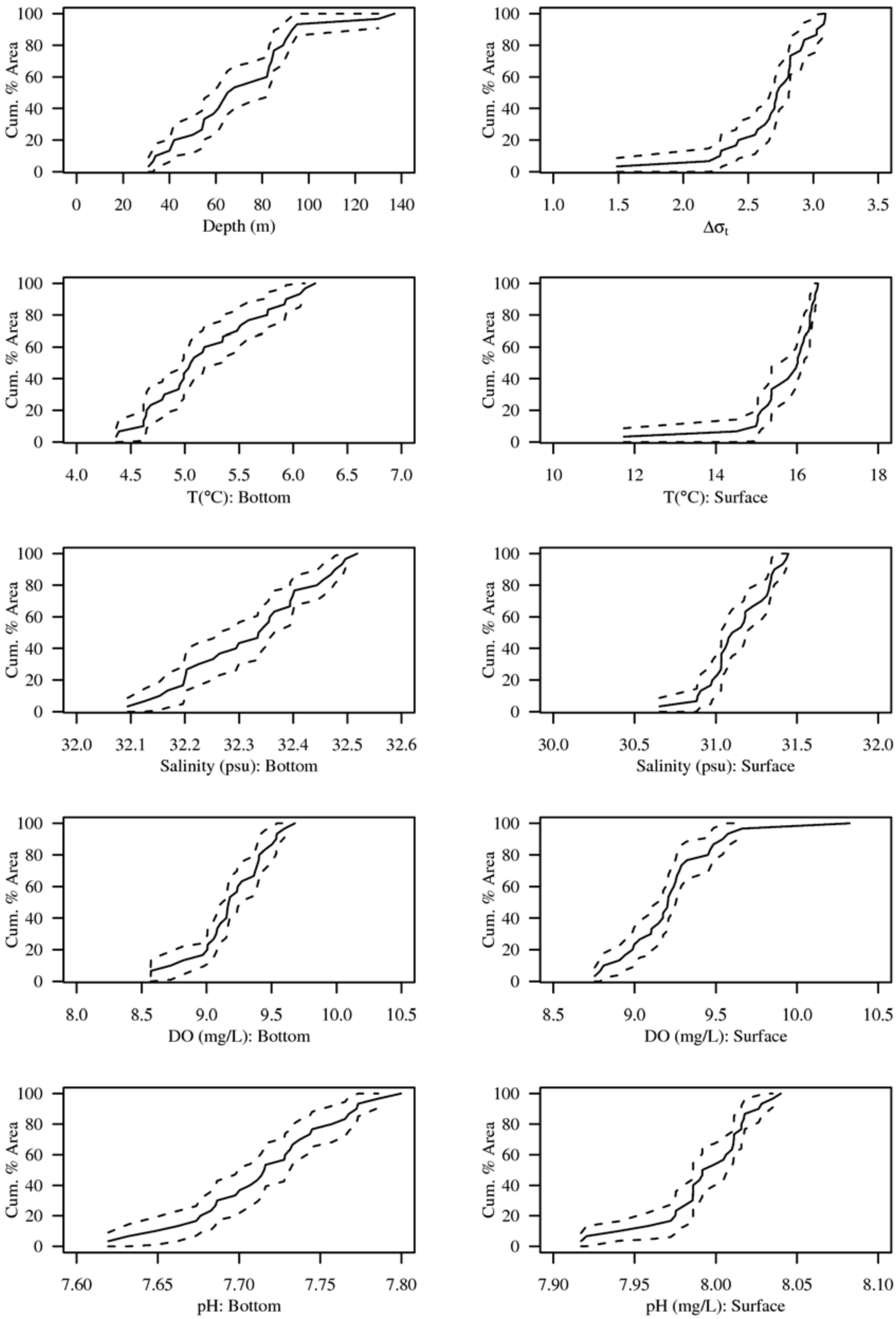

Figure 3. Percent area (and 95% confidence intervals) of SBNMS waters vs. selected water-quality characteristics.

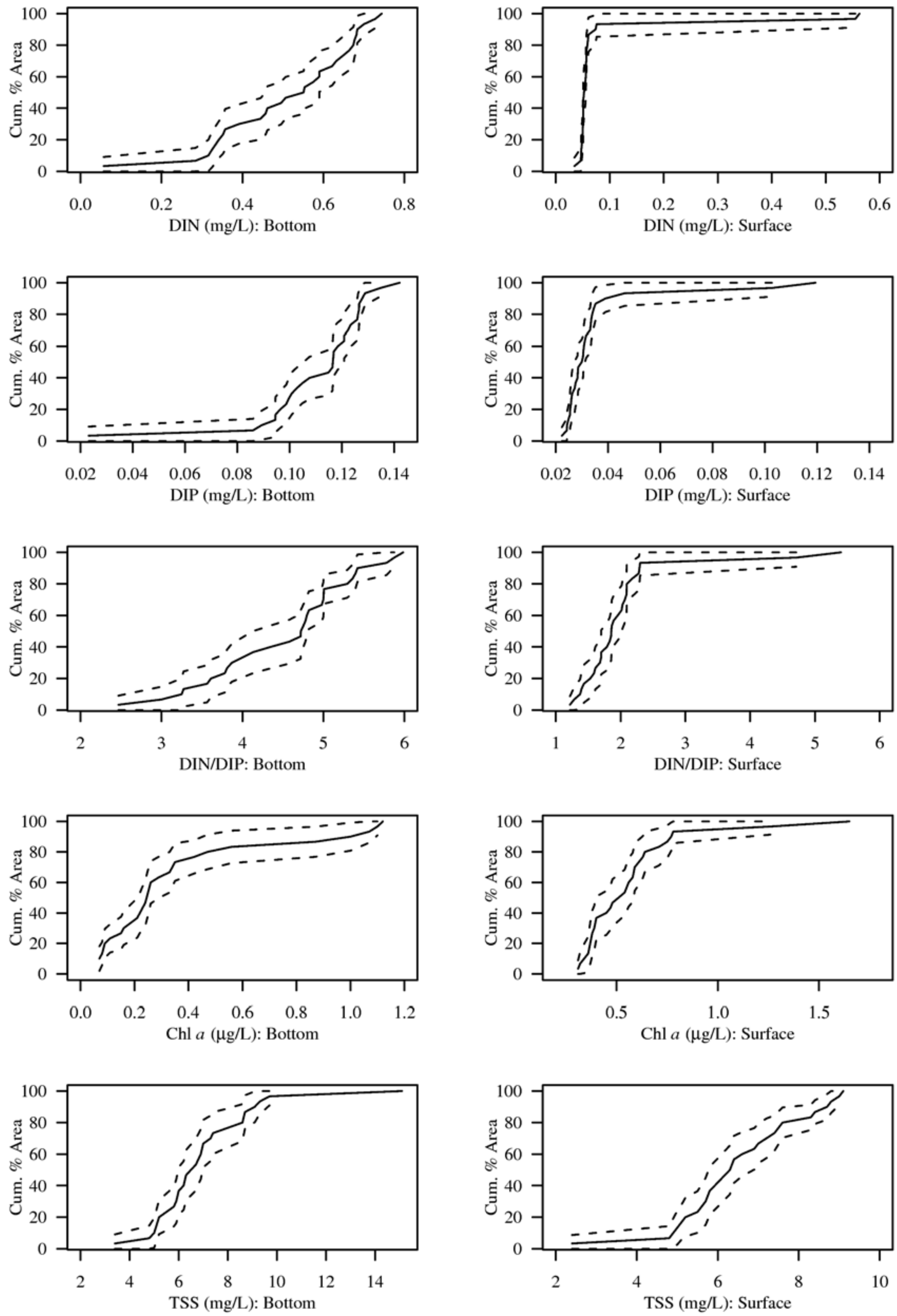

Figure 4. Percent area (and 95% confidence intervals) of SBNMS waters vs. nutrient, chlorophyll, and TSS concentrations.

3.1.3 Nutrients and Chlorophyll

The concentration of dissolved inorganic nitrogen (DIN: nitrogen as nitrate + nitrite + ammonium) in surface waters ranged from 0.03 mg/L to 0.56 mg/L and averaged 0.09 mg/L (**Table 4**, **Figure 4**). Ninety percent of the study area surface waters had DIN concentrations $\leq$ 0.07 mg/L. Bottom-water concentrations of DIN tended to be higher than surface concentrations. For example, about 50% of bottom waters had DIN > 0.55 mg/L (near the maximum surface-water concentration of 0.56 mg/L) and the average concentration was 0.51 mg/L (range of 0.06 – 0.74 mg/L). Reported surface-water concentrations of DIN in Cape Cod Bay and Massachusetts Bay (NCA 2006) range from 0 – 0.06 mg/L and 0 – 0.29 mg/L, respectively.

While there are no published water-quality guidelines for DIN in offshore waters, **Figure 5** shows the spatial distribution of DIN in bottom waters relative to evaluation cutpoints established for neighboring estuaries (USEPA 2008). The figure depicts a clear pattern of higher bottom-water DIN levels at deeper sites in comparison to shallower sites. Although for estuaries the criteria corresponding to high nutrient levels are used as an indication of eutrophication associated with terrestrial input of nitrogen, the concentrations observed here reflect the naturally nutrient-rich waters of the Gulf of Maine (and Stellwagen Bank). The principal source of nutrients that support the high offshore primary production is generally thought to be the influx into the Gulf of Maine of nutrient-rich deep Slope Water through the Northeast Channel (Townsend et al. 2006). In SBNMS, nutrient-rich bottom water upwells to the top of Stellwagen Bank and mixes with sunlight, causing suitable conditions for phytoplankton production (Clark et al. 2006) and contributing to the high productivity of sanctuary waters.

This association between bottom-water DIN and depth (as well as salinity) is also depicted in **Figure 6**. DIN was positively correlated with depth (R^2=0.4398, p<0.0001) and salinity (R^2=0.6416, p<0.0001). These observations are consistent with the patterns of seasonal stratification that occur in the western Gulf of Maine and Massachusetts Bay. The strong stratification of the water column in summer acts as a partial barrier to exchange between the surface waters and deeper bottom waters (Geyer et al. 1992). As the seasonal thermocline develops, surface layers are isolated from the deep-water nutrient source and nutrient exhaustion occurs in surface waters (Townsend et al. 2006).

Concentrations of dissolved inorganic phosphorus (DIP) in surface waters ranged between 0.02 mg/L and 0.12 mg/L, averaging 0.03 mg/L (**Table 4**). Ninety percent of the study area surface waters had DIP concentrations $\leq$ 0.04 mg/L. While the range of bottom-water concentrations of DIP (0.02 mg/L to 0.14 mg/L) were similar to those measured in surface waters, the mean (0.11 mg/L) and estimated percentiles were higher (**Table 4**). Half of the study area had bottom-water DIP concentrations that were greater than the maximum surface DIN concentration (0.12 mg/L). In comparison, reported surface-water DIP concentrations in Cape Cod Bay and Massachusetts Bay (NCA 2006) range from 0 – 0.02 mg/L and 0 – 0.09 mg/L, respectively.

The ratio of DIN to DIP was calculated as an index of nutrient limitation. A DIN:DIP ratio > 16 is considered to be indicative of phosphorus limitation, while values of DIN:DIP < 16 suggest that nitrogen is the limiting factor for primary production (Geider and La Roche 2002). DIN:DIP ratios (**Table 4**) ranged from 1.98 to 10.57 (mean of 3.73) in surface waters, and from 5.81 to 9.57 (mean of 8.16) in bottom waters, which are strongly indicative of nitrogen limitation.

Surface-water concentrations of chlorophyll *a*, an indicator of phytoplankton biomass and abundance, ranged from 0.31 µg/L to 1.65 µg/L and averaged 0.57 µg/L (**Table 4**). Bottom-water concentrations of chlorophyll *a* were similar to concentrations in surface waters, ranging between 0.07 µg/L and 1.12 µg/L and averaging 0.36 µg/L. In comparison, surface-water chlorophyll *a* concentrations in Cape Cod Bay and Massachusetts Bay (NCA 2006) ranged from 0.04 – 3.20 µg/L and 0.40 – 12.80 µg/L, respectively.

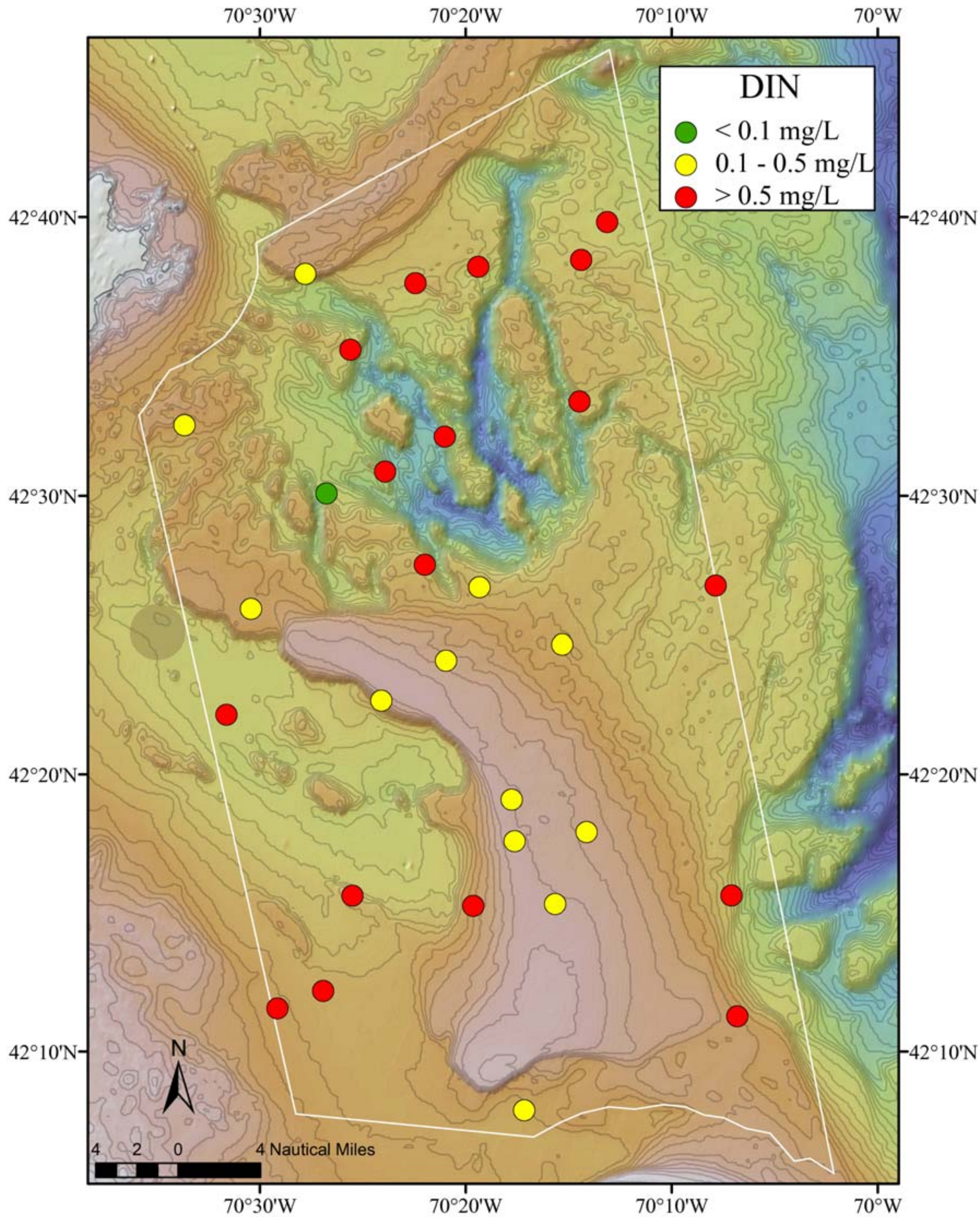

Figure 5. Bottom-water concentrations of dissolved inorganic nitrogen (DIN).

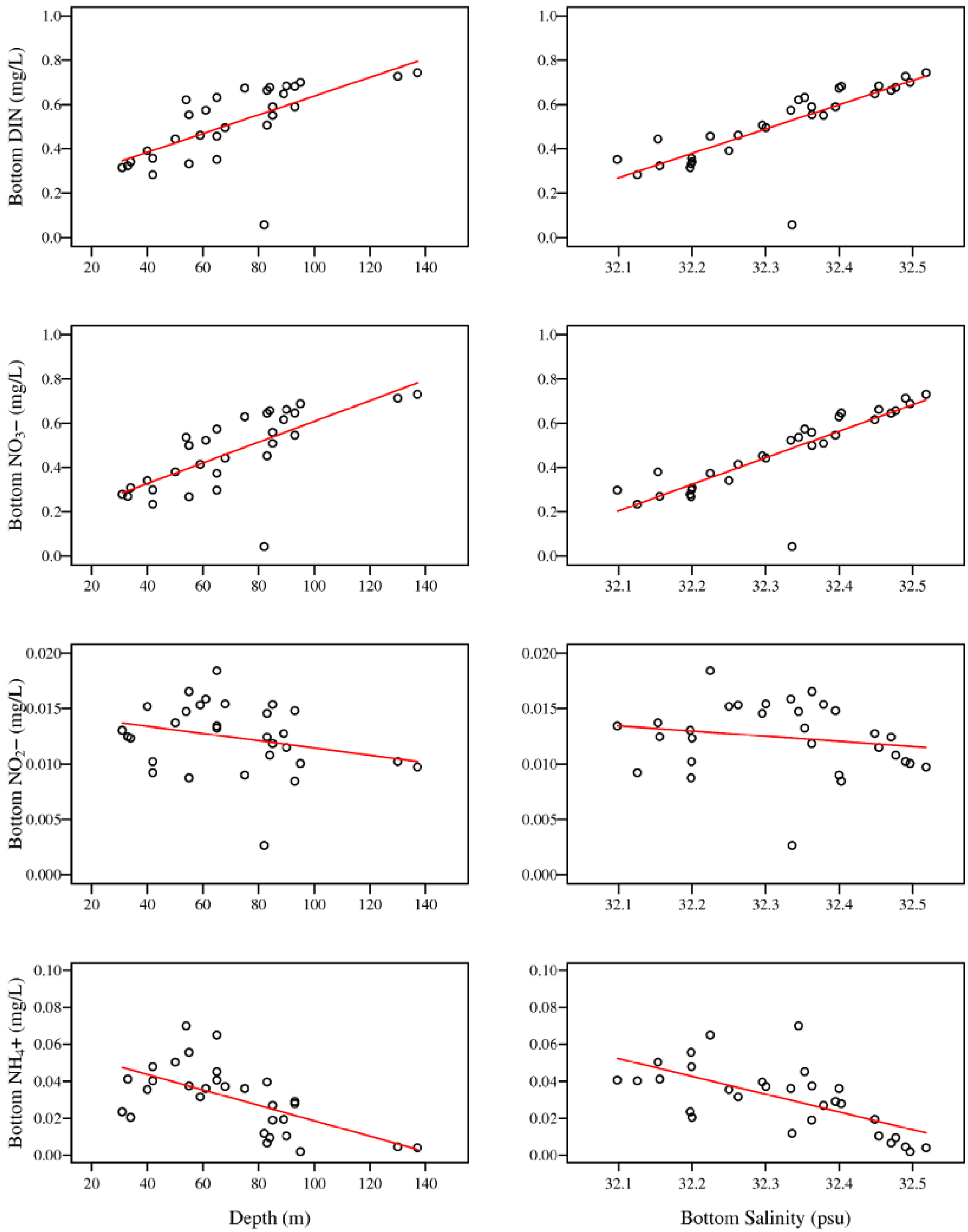

Figure 6. Relationship of bottom-water dissolved nitrogen (DIN and its constituent components) to depth and bottom salinity.

3.2 Sediment Quality

3.2.1 Grain Size and TOC

A large proportion of the survey area (76 % area) consisted of bottom sediments composed of sand and/or gravel (< 20 % silt-clay content). Five sites (17 % area) had sediments composed of intermediate muddy sands (20 – 80 % silt-clay), and two sites (7 % area) had sediments classified as muds (> 80 % silt-clay). These intermediate and muddy sites were located mainly in depositional areas, either in Stellwagen Basin or in the deeper parts of the sanctuary adjacent to Gloucester Basin (**Figure 8**). Results are summarized in **Table 5** and **Figure 7**, **Figure 8**, and **Figure 9**.

TOC content of sediments in general was low, ranging from 0.2 – 25.7 mg/g and averaging 4.8 mg/g throughout the sanctuary (**Table 5**). Nearly all of the study area (29 of 30 sites, 97 % area) had sediment TOC concentrations < 20 mg/g. Of those 29 sites, 21 (70 % area) had sediment TOC < 5 mg/g. Sediments at only one site (in Stellwagen Basin) had TOC concentration between 20 and 25 mg/g. All sites (100% of the area) had concentrations < 50 mg/g, below levels associated with a high incidence of effects on benthic fauna (**Figure 10**).

Sediments in other coastal and estuarine areas of the region showed similar distributions of percent fines (silt-clay) and TOC. For example, sediments in the deeper basin (i.e., depositional area) of Cape Cod Bay tended to be higher in percent silt-clay and TOC content. The proportion of silt-clay and TOC content of sediments also were higher in estuarine areas of Massachusetts Bay (Boston Inner Harbor, Broad Sound, Gloucester Harbor; NCA 2006).

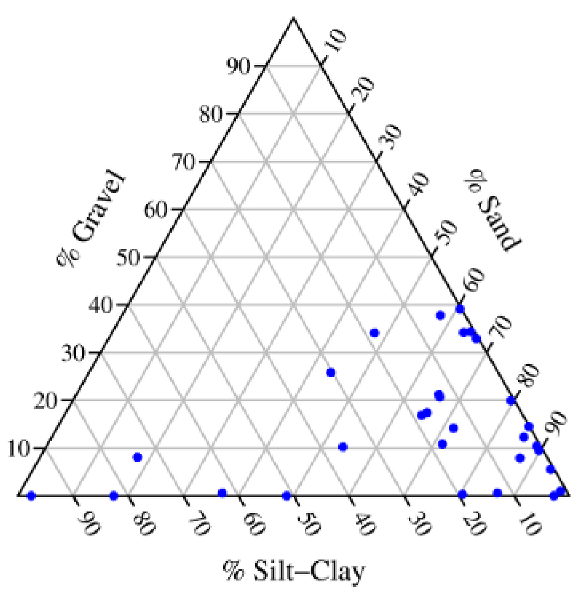

Figure 7. Distribution of percentages of gravel, sand, and silt-clay in surficial sediments.

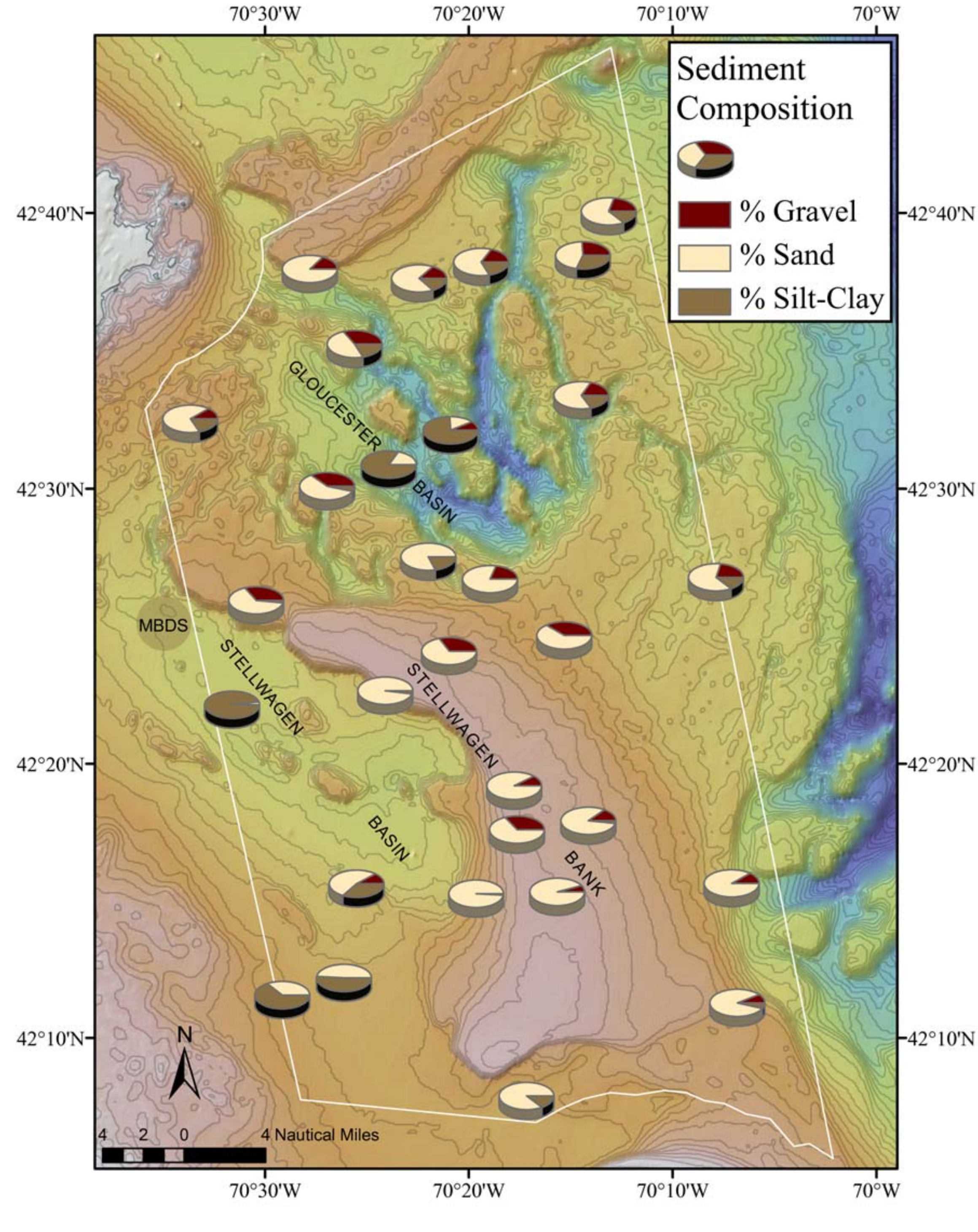

Figure 8. Percent gravel, sand, and silt-clay content of sediments.

Table 5. Summary of sediment characteristics.

Parameter	Mean	Range	CDF 10th pctl	CDF 50th pctl	CDF 90th pctl
TOC (mg/g)	4.8	0.2 – 25.7	0.3	2.8	10.2
% Silt-Clay	20	0.1 – 97.6	0.4	12.8	62.6
Mean ERM-Q	0.018	0.003 – 0.071	0.003	0.014	0.033

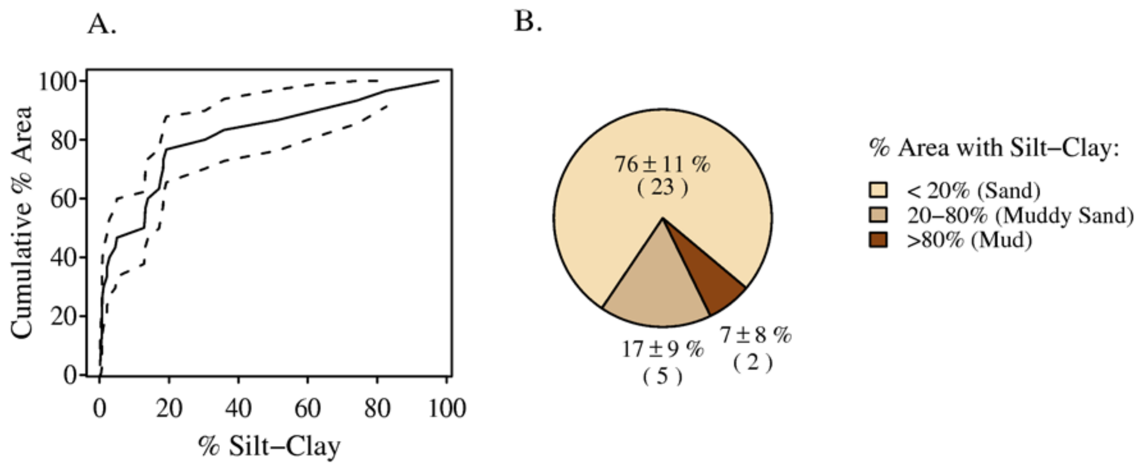

Figure 9. (A) Percent area (and 95% confidence intervals) represented by varying levels of silt-clay content of sediment (mg/g), and (B) percent area having TOC content within specified ranges.

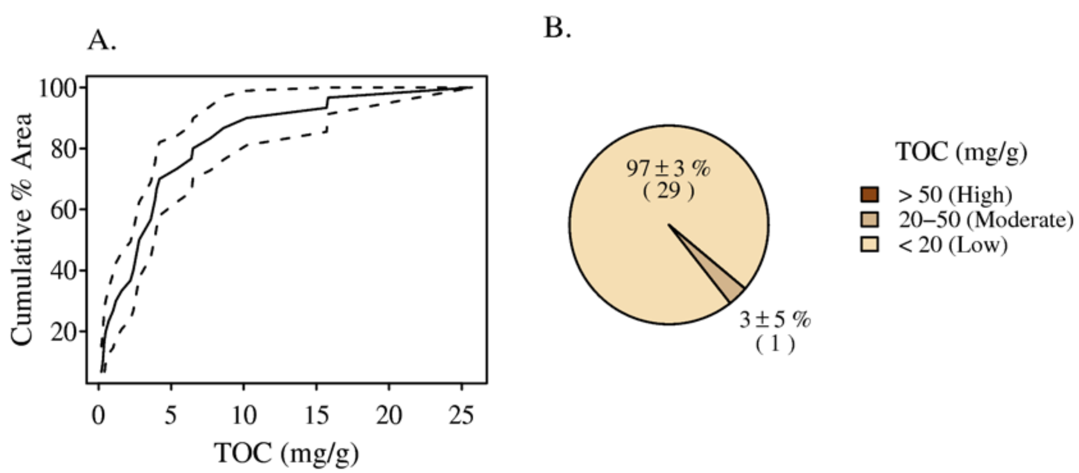

Figure 10. (A) Percent area (and 95% confidence intervals) represented by varying levels of TOC content of sediment (mg/g), and (B) percent area having TOC content within specified ranges.

3.2.2 Chemical Contaminants in Sediments

The biological significance of chemical contamination of sediments was evaluated by comparing measured contaminant concentrations to sediment quality guidelines (SQGs) developed by Long et al. (1995). Effects-Range Low (ERL) values represent lower bioeffect limits, below which adverse effects of contaminants on sediment-dwelling organisms are not likely to occur (the ERL corresponds to an expected incidence of toxicity of about 10%). Effects-Range Median (ERM) values are mid-range concentrations above which adverse biological effects are more likely to occur (the ERM is the concentration corresponding to an expected incidence of toxicity of about 50%). Any site having one or more chemicals in excess of their corresponding ERM values (see **Table 2**) was rated as having poor sediment quality; any site with five or more chemicals between the corresponding ERL and ERM values was rated as fair; any site with no ERMs exceeded and < 5 ERLs exceeded was rated as having good sediment quality (*sensu* U.S. EPA 2008). Overall sediment contamination from multiple chemicals also was expressed through the use of mean ERM quotients *(sensu* Long et al. 1998; Hyland et al. 1999, 2003). The mean ERM quotient (mean ERM-Q) is the mean of the ratios of individual chemical concentrations in a sample relative to corresponding published ERM values (using all chemicals in **Table 2** except nickel, low- and high-molecular-weight PAHs, and total PAHs). A useful feature of this method is that overall contamination in a sample from mixtures of multiple chemicals present at varying concentrations can be expressed as a single number that can be compared to values calculated the same way for other samples (either from other locations or sampling occasions).

The overall mean, range, and area-weighted percentiles of mean ERM-Qs are shown in **Table 5**. None of the stations had mean ERM-Qs high enough to suggest significant risks of adverse effects on benthic fauna. Hyland et al. (2003) reported the highest incidence of impaired benthic assemblages (85% of samples) in Virginian Province estuaries at mean ERM-Qs above a critical point of 0.473 and a low incidence of effects (9% of samples) at mean ERM-Qs ≤ 0.022. Although in the present study we are dealing with offshore benthic fauna, none of the stations had mean ERM-Qs in this upper bioeffect range (which are the most applicable guidelines known to us for comparison). Of the 30 sites sampled in this study, 22 (73.3% area) had mean ERM-Qs in the low (< 0.022) range reported by Hyland et al. (2003). The remaining 8 sites (26.7% area) had mean ERM-Qs in the moderate (0.022 – 0.098) range. Six of these eight sites corresponded to the mud/muddy-sand sites noted in the previous section and all eight were located either in Stellwagen Basin or adjacent to Gloucester Basin (**Figure 13**). No sites had mean ERM-Qs in either the high (0.098 – 0.473) or very high (> 0.473) range.

Compared to SBNMS, mean ERM quotients among 53 sites in Cape Cod Bay (NCA 2006) were similar, ranging from 0.001 – 0.104 (mean of 0.030). Mean ERM-Qs were higher in the deeper, depositional area of Cape Cod Bay, which also contained higher proportions of fine-grained sediments. In Massachusetts Bay, mean ERM-Qs were higher in some places and tended to be highest (> 0.100) in the more silty estuarine portions (Gloucester Harbor, Salem Sound, Broad Sound, Boston Harbor). The highest mean ERM-Qs occurred in Boston Inner Harbor, with values as high as 1.800 (NCA 2006).

Similar spatial patterns of contaminant levels were described by Hartwell et al. (2006), who found highest concentrations of metals and organic contaminants in and around Boston Harbor, intermediate concentrations in the middle and deeper areas of Massachusetts and Cape Cod Bays, and lowest on Stellwagen Bank.

In SBNMS, the more fine-grained, organically-enriched sediments were associated with higher levels of chemical contaminants (**Figure 11** and **Figure 12**). The regression fit of mean ERM quotient to sediment % silt-clay was significant, with $R^2 = 0.57$ ($p < 0.001$). The goodness-of-fit for sediment TOC was also significant, with $R^2 = 0.94$ ($p < 0.001$). Hence, with few exceptions, sediment TOC and silt-clay content appeared to be good predictors of overall sediment contaminant levels throughout the sanctuary.

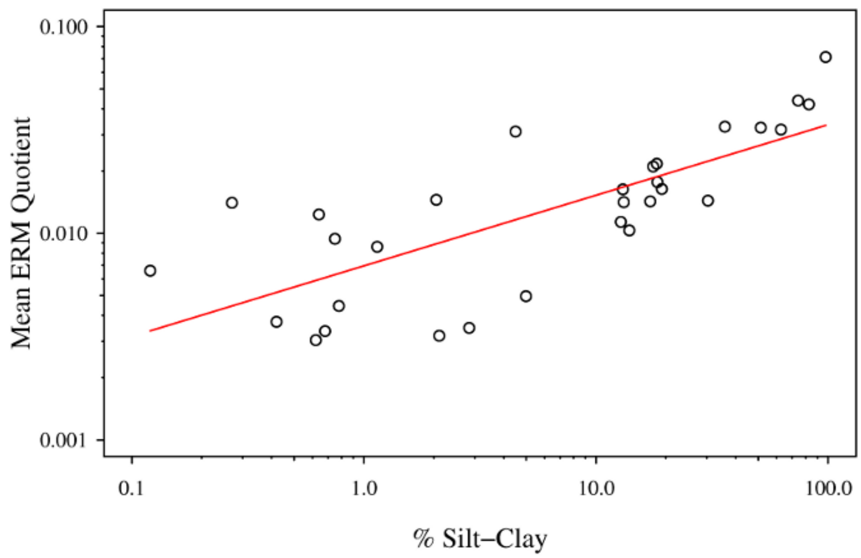

Figure 11. Plot of mean ERM quotient versus sediment % silt-clay.

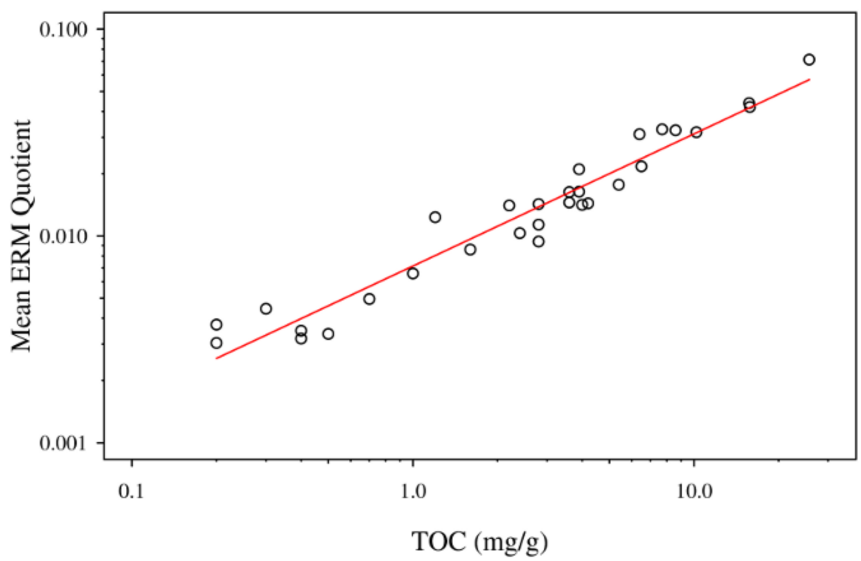

Figure 12. Plot of mean ERM quotient versus TOC content of sediment.

No contaminants were found in excess of their corresponding ERMs (**Table 6**). Only three chemicals, arsenic, lead, and mercury, exceeded their corresponding ERL guidelines. Thus, all stations (representing 100% of the survey area) would be ranked as having good sediment quality with respect to chemical contaminants based on the EPA's NCA guidelines (no ERM values exceeded and < 5 ERL values exceeded, USEPA 2008). The ERL exceedances for arsenic occurred at eleven sites, representing an estimated 36.7 % of the survey area. The concentration of arsenic at most sites (28 sites, 93% area) was within the range typical of uncontaminated near-shore marine sediments (5 – 15 µg/g dry weight total arsenic) reported by Neff (1997) and reflects its natural presence at low to moderate concentrations in crustal rocks of the region. Arsenic concentrations greater than 15 µg/g dry weight were found at two sites (stations 3 and 20) in the northern part of the sanctuary. Concentrations of lead and mercury in excess of the corresponding ERLs were observed at only one site (station 1) which was located in a deep, silty area of Stellwagen Basin approximately 4 nautical miles southeast of the Massachusetts Bay Disposal Site (MBDS, **Figure 13**).

Circulation in the Gulf of Maine is characterized by a cyclonic (counter-clockwise) gyre over the deep central basin (Ingham et al. 1992, Lynch et al. 1996, Lynch et al. 1997, Cook and Auster 2007). Within the context of this overall mean circulation pattern the western Gulf of Maine Coastal Current (GMCC) flows southwestward along the coast. This coastal current branches near Cape Ann, with the main branch continuing southward over Stellwagen Bank and east of Cape Cod and a weak branch proceeding southwestward into Massachusetts Bay (Lynch et al. 1996, Butman and Bothner 1997). The mean current through Massachusetts Bay flows southward through the bay, along the western shore, and easterly out of the bay north of Race Point. The deep basins of Massachusetts Bay are long-term sinks for fine-grained sediments, and contaminants discharged into Boston Harbor are sequestered in the sediments of Boston Harbor, Stellwagen Basin, and Cape Cod Bay (Butman and Bothner 1997). Tracer studies using osmium isotopes and silver have shown that sewage discharged into Boston Harbor has affected sediments in Cape Cod Bay, over 70km away (Ravizza and Bothner 1996). The distribution of sediment contaminant concentrations observed in the present study likely are the result of these overall patterns of circulation, transport, and deposition of fine-grained sediments in the deep basins of the sanctuary (i.e., Stellwagen Basin and Gloucester Basin).

Table 6. Summary of chemical contaminant concentrations in sediments ('N.D.' = not detected; '-' = no corresponding ERL or ERM available).

Analyte	Mean (Std. Dev.)	Range	Concentration ≥ ERL, < ERM		Concentration ≥ ERM	
			# Stations	% Area	# Stations	% Area
Metals (% dry)						
Aluminum	1.289 (1.080)	0.302 - 4.53	-	-	-	-
Iron	1.517 (1.375)	0.3 - 5.68	-	-	-	-
Trace Metals (µg/g dry mass)						
Antimony	0.155 (0.362)	0 - 1.12	-	-	-	-
Arsenic	7.210 (6.079)	1.54 - 29	11	36.7	0	0
Cadmium	0.046 (0.033)	0.009 - 0.146	0	0	0	0
Chromium	22.705 (13.857)	5.3 - 61.4	0	0	0	0
Copper	4.517 (4.172)	0.741 - 19.1	0	0	0	0
Lead	18.702 (9.969)	5.03 - 48.9	1	3.3	0	0
Manganese	417.703(287.002)	93.1 - 1330	-	-	-	-
Mercury	0.023 (0.033)	0.001 - 0.161	1	3.3	0	0
Nickel	8.252 (7.033)	1 - 28.5	-	-	-	-
Selenium	0.290 (0.289)	0 - 1.2	-	-	-	-
Silver	N.D. N.D.	N.D.	0	0	0	0
Tin	1.877 (1.582)	0.428 - 7.67	-	-	-	-
Zinc	26.272 (21.755)	4.4 - 94.1	0	0	0	0
PAHs (ng/g dry)						
Acenaphthene	0.369 (1.207)	0 - 5.5882	0	0	0	0
Acenaphthylene	4.667 (8.118)	0 - 36.645	0	0	0	0
Anthracene	6.920 (10.740)	0 - 48.914	0	0	0	0
Benz[a]anthracene	11.675 (17.889)	0 - 81.36	0	0	0	0
Benzo[a]pyrene	14.342 (20.401)	0 - 92.762	0	0	0	0
Benzo[b]fluoranthene	20.207 (27.319)	0 - 122.97	-	-	-	-
Benzo[g,h,i]perylene	12.215 (16.695)	0 - 76.363	-	-	-	-
Benzo[k]fluoranthene	7.240 (10.098)	0 - 45.911	-	-	-	-
Biphenyl	0.144 (0.789)	0 - 4.3212	-	-	-	-
Chrysene	14.284 (21.073)	0 - 98.486	0	0	0	0
Dibenz[a,h]anthracene	2.529 (4.038)	0 - 16.851	0	0	0	0
Dibenzothiophene	1.234 (2.500)	0 - 10.965	-	-	-	-
Fluoranthene	25.395 (36.230)	0 - 162.18	0	0	0	0
Fluorene	1.788 (3.283)	0 - 14.313	0	0	0	0
Indeno[1,2,3-c,d]pyrene	12.417 (18.010)	0 - 83.659	-	-	-	-
Naphthalene	6.096 (11.793)	0 - 51.544	0	0	0	0
1-Methylnaphthalene	1.388 (2.968)	0 - 12.215	-	-	-	-

Table 6 (continued).

Analyte	Mean	(Std. Dev.)	Range	Concentration ≥ ERL, < ERM # Stations	Concentration ≥ ERL, < ERM % Area	Concentration ≥ ERM # Stations	Concentration ≥ ERM % Area
2-Methylnaphthalene	2.669	(5.033)	0 - 20.283	0	0	0	0
2,6-Dimethylnaphthalene	1.491	(2.951)	0 - 10.165	-	-	-	-
2,3,5-Trimethylnaphthalene	0.145	(0.792)	0 - 4.3401	-	-	-	-
Phenanthrene	15.479	(21.679)	0 - 97.48	0	0	0	0
1-Methylphenanthrene	3.064	(4.601)	0 - 21.055	-	-	-	-
Pyrene	22.991	(33.973)	0 - 155.14	0	0	0	0
Low Molecular Weight PAHs	45.310	(73.540)	0 - 327.2532	0	0	0	0
High Molecular Weight PAHs	121.771	(173.971)	0 - 791.285	0	0	0	0
Total PAHs[a]	177.758	(261.897)	0 - 1186.7372	0	0	0	0
PCBs (ng/g dry)							
Total PCBs[b]	0.174	(0.291)	0 - 1.25	0	0	0	0
Pesticides (ng/g dry)							
2,4'-DDD (o,p'-DDD)	N.D.	N.D.	N.D.	-	-	-	-
2,4'-DDE (o,p'-DDE)	0.012	(0.047)	0 - 0.232	-	-	-	-
2,4'-DDT (o,p'-DDT)	N.D.	N.D.	N.D.	-	-	-	-
4,4'-DDD (p,p'-DDD)	0.015	(0.080)	0 - 0.438	-	-	-	-
4,4'-DDE (p,p'-DDE)	N.D.	N.D.	N.D.	0	0	0	0
4,4'-DDT (p,p'-DDT)	N.D.	N.D.	N.D.	-	-	-	-
Aldrin	N.D.	N.D.	N.D.	-	-	-	-
alpha-Chlordane	N.D.	N.D.	N.D.	-	-	-	-
Dieldrin	N.D.	N.D.	N.D.	-	-	-	-
Endosulfan I	N.D.	N.D.	N.D.	-	-	-	-
Endosulfan II (beta-Endosulfan)	N.D.	N.D.	N.D.	-	-	-	-
Endosulfan sulfate	N.D.	N.D.	N.D.	-	-	-	-
Endrin							
gamma-HCH (g-BHC, lindane)	0.006	(0.033)	0 - 0.183	-	-	-	-
Heptachlor	N.D.	N.D.	N.D.	-	-	-	-
Heptachlor epoxide	N.D.	N.D.	N.D.	-	-	-	-
Hexachlorobenzene (HCB)	N.D.	N.D.	N.D.	-	-	-	-
Mirex	N.D.	N.D.	N.D.	-	-	-	-
Total DDTs[c]	0.026	(0.091)	0 - 0.438	0	0	0	0
trans-Nonachlor	N.D.	N.D.	N.D.	-	-	-	-

[a] Sum of 23 measured PAHs.
[b] Sum of 21 measured PCB congeners.
[c] Sum of 2,4′-DDD, 4,4′-DDD, 2,4′-DDE, 4,4′-DDE, 2,4′-DDT, and 4,4′-DDT.

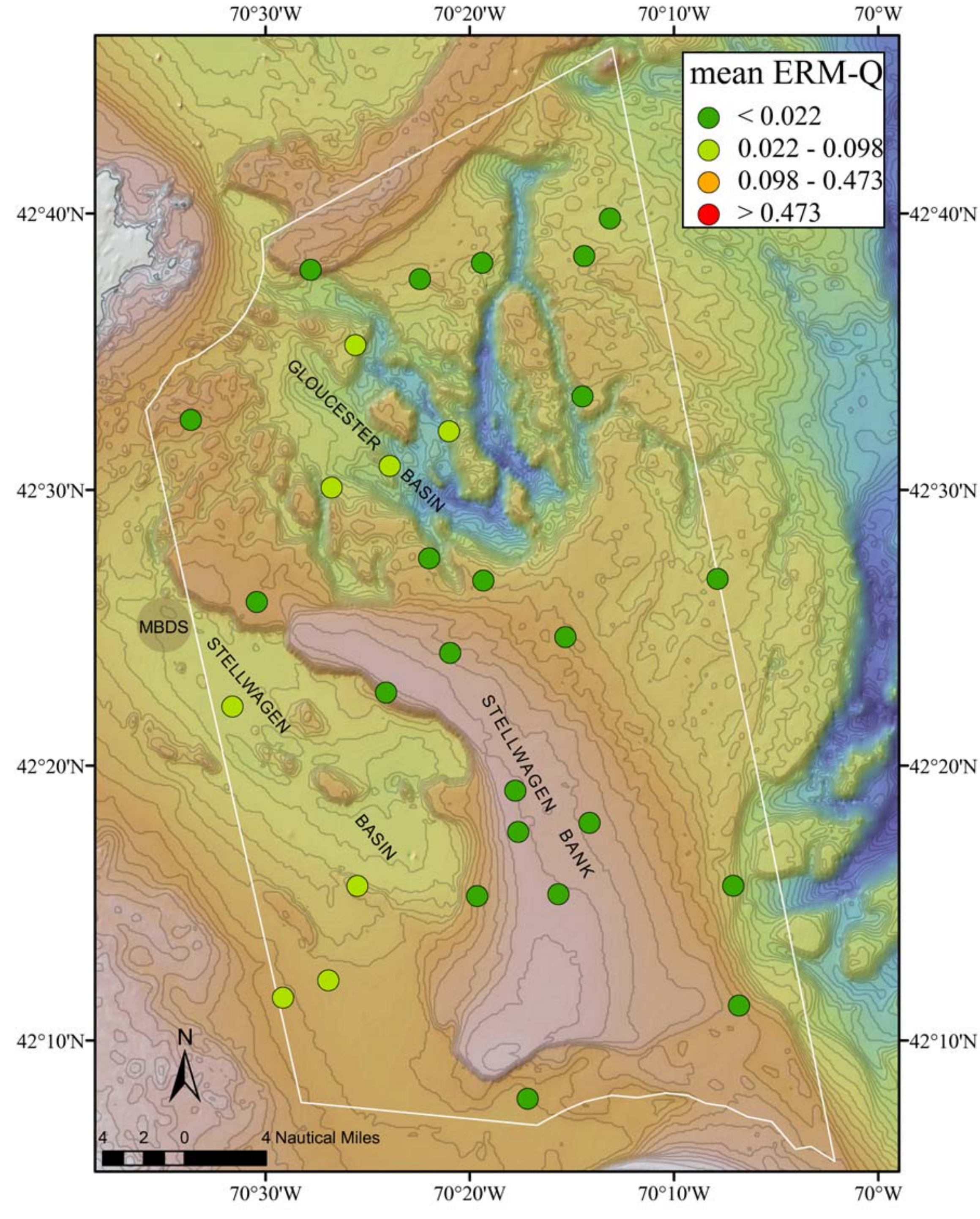

Figure 13. Mean ERM quotients (mean ERM-Q) calculated based on measured contaminant concentrations in sediments.

3.2.3 Sediment Toxicity

None of the 30 samples tested using the Microtox® assay were found to be toxic, based on the criteria listed in Table 1 (Ringwood et al. 1997). One site had an EC50 just above the toxicity threshold for sediments with silt-clay $\geq$ 20 % (station 29, EC50 = 0.2065 %, silt-clay = 82.64 %). This site was located in the northern part of the sanctuary (Gloucester Basin) at 130 m depth.

3.3 Chemical Contaminants in Fish Tissues

Collection of fish specimens by hook-and-line fishing was successful at 18 of the 30 stations sampled in this study. Of these specimens, 26 individuals representing five distinct species collected at 16 stations were used for tissue contaminant analysis. Species retained for analysis and the corresponding stations where they were collected are displayed in **Table 7**.

Table 7. Listing of fish specimens retained for tissue contaminant analysis and the stations where they were collected.

Station	Common Name	Scientific Name	Specimen No.
03	Haddock	*Melanogrammus aeglefinus*	1
	Acadian Redfish	*Sebastes fasciatus*	1
04	Atlantic Cod	*Gadus morhua*	1
	Haddock	*M. aeglefinus*	1
06	Red Hake	*Urophycis chuss*	1
			2
07	Red Hake	*U. chuss*	1
11	Silver Hake	*Merluccius bilinearis*	1
12	Haddock	*M. aeglefinus*	1
13	Red Hake	*U. chuss*[1]	1
			2
15	Atlantic Cod	*G. morhua*	1
	Haddock	*M. aeglefinus*	1
17	Silver Hake	*M. bilinearis*	1
	Red Hake	*U. chuss*	1
			2
20	Red Hake	*U. chuss*	1
21	Red Hake	*U. chuss*	1
22	Haddock	*M. aeglefinus*[2]	1
			2
24	Red Hake	*U. chuss*	1
25	Haddock	*M. aeglefinus*	1
	Red Hake	*U. chuss*[3]	1
			2
26	Red Hake	*U. chuss*	1
29	Acadian Redfish	*S. fasciatus*	1

[1] Two specimens were selected randomly from 6 available.
[2] Two specimens were selected randomly from 4 available.
[3] Two specimens were selected randomly from 3 available.

Concentrations of a suite of metals, pesticides, and PCBs were measured in edible tissues (fillets) of each of the fish specimens listed in **Table 7** and compared to risk-based EPA advisory guidelines for recreational fishers (**Table 3**). The guidelines selected for this analysis were endpoints associated with an average consumption rate of four 8-oz fish meals per month (from USEPA 2000a), which is consistent with the comparison basis used currently in the National Coastal Condition Report (USEPA 2008) and by States for setting fish advisories. A station was rated as "good" if all chemical contaminants listed in **Table 3** had concentrations below the corresponding lower endpoints, "fair" if at least one contaminant fell within the corresponding lower and upper endpoints, and "poor" if at least one contaminant occurred at a concentration above the upper endpoint (USEPA 2008).

Two of the 16 stations where fish were collected and retained for analysis had chemical contaminants in tissues above the corresponding upper human-health endpoints (**Table 8**). At station 03, the deepest site sampled in this study (137m) and located in the region of the sanctuary north of Stellwagen Bank adjacent to Gloucester Basin (Creed Basin), an Acadian redfish (*Sebastes fasciatus*) had methylmercury concentrations (measured as mercury and assumed to be all methylmercury, *sensu* U.S. EPA 2000a) of 0.371 µg/g wet weight, which is in excess of the upper human-health endpoint of 0.23 µg/g. Another specimen analyzed from this station (haddock, *Melanogrammus aeglefinus*) exceeded the lower methylmercury endpoint of 0.12 µg/g. The other upper human-health endpoint exceedance occurred at station 17, where a silver hake (*Merluccius bilinearis*) was found to contain 51.125 ng/g of total PCBs in edible tissue. Exceedances of lower guidelines (but not upper guidelines), besides the one noted above, occurred for methylmercury (stations 03, 04, 12, 22, and 25) and inorganic arsenic (stations 13, 20, and 25). Multiple lower-guideline exceedances were noted at station 25 (*M. aeglefinus*, methylmercury; *U. chuss*, inorganic arsenic and methylmercury). The foregoing results are summarized in **Table 8**. Overall mean fish tissue contaminant concentrations, ranges, and numbers of human-health advisory guideline exceedances, summarized by contaminant and irrespective of fish species, are listed in **Table 9**. With respect to risk-based EPA advisory guidelines, two sites would be classified as "poor", six sites as "fair", and the remaining eight sites (where fish were collected) would be classified as "good". The status of the 14 sites where no fish were collected is unknown.

Table 8. Listing of stations where concentrations of contaminants in fish tissues exceeded corresponding risk-based human-health guidelines.

Station	Fish species	Analyte	Concentration (wet weight)	Exceeded lower endpoint [1]	Exceeded upper endpoint [1]
03	*Melanogrammus aeglefinus*	Methylmercury [2]	0.151 µg/g	1	0
	Sebastes fasciatus	Methylmercury	0.371 µg/g	0	1
04	*Gadus morhua*	Methylmercury	0.145 µg/g	1	0
12	*M. aeglefinus*	Methylmercury	0.202 µg/g	1	0
13	*Urophycis chuss*	Inorganic Arsenic [3]	0.382 µg/g	1	0
17	*Merluccius bilinearis*	Total PCBs	51.125 ng/g	0	1
20	*U. chuss*	Inorganic Arsenic	0.368 µg/g	1	0
22	*M. aeglefinus*	Methylmercury	0.185 µg/g	1	0
25	*M. aeglefinus*	Methylmercury	0.188 µg/g	1	0
	U. chuss	Inorganic Arsenic	0.640 µg/g	1	0
		Methylmercury	0.122 µg/g	1	0

[1] Risk-based EPA advisory guidelines for recreational fishers (USEPA 2000a) listed in Table 3.
[2] Measured as total mercury and assumed to be all methylmercury.
[3] Estimated as 2% of total arsenic.

Table 9. Summary of contaminant concentrations (wet weight) measured in fish tissues. A total of 26 fish from 16 stations were analyzed. All measured contaminants are included. Concentrations are compared to human-health guidelines where available (from US EPA 2000a, also see Table 3 herein). ('N.D.' = Not detected; 'N.M.' = Not measured; '-' = no corresponding guideline available).

Analyte	Mean	Range	No. of fish exceeding health endpoints	
			≥ Lower & ≤ Upper	> Upper
Metals (µg/g wet weight)				
Aluminum	12.538	8.697 - 28.069	-	-
Arsenic	10.976	1.272 - 31.984	-	-
Arsenic (Inorganic)[a]	0.220	0.025 - 0.640	3	0
Barium	0.049	0.015 - 0.218	-	-
Beryllium	N.D.	0.000 - 0.000	-	-
Cadmium	0.001	0.000 - 0.005	0	0
Chromium	0.109	0.065 - 0.334	-	-
Cobalt	N.D.	0.000 - 0.000	-	-
Copper	0.319	0.209 - 1.060	-	-
Methylmercury (estimated)[b]	0.101	0.024 - 0.371	6	1
Iron	6.972	2.665 - 19.924	-	-
Lead	0.012	0.000 - 0.086	-	-
Lithium	0.011	0.000 - 0.026	-	-
Manganese	0.503	0.164 - 2.965	-	-
Nickel	0.064	0.000 - 1.181	-	-
Selenium	0.542	0.282 - 1.035	0	0
Silver	N.D.	0.000 - 0.000	-	-
Thallium	N.D.	0.000 - 0.000	-	-
Tin	0.001	0.000 - 0.033	-	-
Uranium	N.D.	0.000 - 0.000	-	-
Vanadium	0.214	0.058 - 0.671	-	-
Zinc	4.160	3.066 - 9.514	-	-
PAHs (ng/g wet weight)				
Acenaphthene	0.123	0.000 - 0.748	-	-
Acenaphthylene	0.003	0.000 - 0.055	-	-
Anthracene	0.011	0.000 - 0.162	-	-
Benz[a]anthracene	N.D.	0.000 - 0.000	-	-
Benzo[a]pyrene	N.D.	0.000 - 0.000	0	0
Benzo[b]fluoranthene	N.D.	0.000 - 0.000	-	-
Benzo[e]pyrene	N.D.	0.000 - 0.000	-	-
Benzo[g,h,i]perylene	N.D.	0.000 - 0.000	-	-
Benzo[j,k]fluoranthene	N.D.	0.000 - 0.000	-	-
Biphenyl	0.140	0.000 - 2.068	-	-
Chrysene+Triphenylene	N.D.	0.000 - 0.000	-	-
Dibenz[a,h]anthracene	N.D.	0.000 - 0.000	-	-
Dibenzothiophene	N.D.	0.000 - 0.000	-	-
Flouranthene	N.D.	0.000 - 0.000	-	-
Flourene	N.D.	0.000 - 0.000	-	-
Indeno[1,2,3-c,d]pyrene	N.D.	0.000 - 0.000	-	-
Napthalene	0.035	0.000 - 0.221	-	-
1-Methylnaphthalene	0.017	0.000 - 0.158	-	-
2-Methylnaphthalene	0.076	0.000 - 1.642	-	-
2,6-Dimethylnaphthalene	N.D.	0.000 - 0.000	-	-

Table 9 (continued).

Analyte	Mean	Range	No. of fish exceeding health endpoints	
			≥ Lower & ≤ Upper	> Upper
1,6,7-Trimethylnaphthalene	N.D.	0.000 - 0.000	-	-
Perylene	N.D.	0.000 - 0.000	-	-
Phenanthrene	0.059	0.000 - 1.535	-	-
1-Methylphenanthrene	0.017	0.000 - 0.158	-	-
Pyrene	N.D.	0.000 - 0.000	-	-
Total PAH	0.470	0.000 - 4.154	-	-
PBDEs (ng/g wet weight)				
PBDE 100	0.040	0.000 - 0.722	-	-
PBDE 138	N.D.	0.000 - 0.000	-	-
PBDE 153	N.D.	0.000 - 0.000	-	-
PBDE 154	N.D.	0.000 - 0.000	-	-
PBDE 17	N.D.	0.000 - 0.000	-	-
PBDE 183	N.D.	0.000 - 0.000	-	-
PBDE 190	N.D.	0.000 - 0.000	-	-
PBDE 28	N.D.	0.000 - 0.000	-	-
PBDE 47	0.239	0.000 - 2.657	-	-
PBDE 66	N.D.	0.000 - 0.000	-	-
PBDE 71	N.D.	0.000 - 0.000	-	-
PBDE 85	N.D.	0.000 - 0.000	-	-
PBDE 99	0.020	0.000 - 0.529	-	-
PCBs (ng/g wet weight)				
Total PCBs[c]	5.746	0.437 - 51.125	0	1
Pesticides (ng/g wet weight)				
2,4' - DDD (o,p' - DDD)	N.D.	0.000 - 0.000	-	-
2,4' - DDE (o,p' - DDE)	0.095	0.000 - 0.362	-	-
2,4' - DDT (o,p' - DDT)	0.028	0.000 - 0.735	-	-
4,4' - DDD (p,p' - DDD)	0.228	0.000 - 2.293	-	-
4,4' - DDE (p,p' - DDE)	0.849	0.000 - 8.292	-	-
4,4' - DDT (p,p' - DDT)	0.096	0.000 - 2.486	-	-
Aldrin	N.D.	0.000 - 0.000	-	-
Chlorpyrifos	N.D.	0.000 - 0.000	-	-
cis-Chlordane (alpha-Chlordane)	N.D.	0.000 - 0.000	-	-
Dieldrin	0.066	0.000 - 0.990	0	0
Endosulfan	N.M.	N.M.	0	0
Endosulfan I	N.D.	0.000 - 0.000	-	-
Endosulfan II	N.D.	0.000 - 0.000	-	-
Endosulfan sulfate	N.D.	0.000 - 0.000	-	-
Endrin	N.M.	N.M.	-	-
Heptachlor	N.D.	0.000 - 0.000	-	-
Heptachlor epoxide	N.D.	0.000 - 0.000	0	0
Hexachlorobenzene	0.037	0.000 - 0.495	0	0
Lindane	0.009	0.000 - 0.231	0	0
Mirex	N.D.	0.000 - 0.000	0	0
Total DDT	1.295	0.000 - 14.058	0	0
Total Chlordane	N.D.		0	0
Toxaphene	N.M.		-	-
trans-Nonachlor	N.D.	0.000 - 0.000	-	-

[a] Estimated as 2% of the measured total arsenic.
[b] Measured as total mercury and assumed to be all methylmercury.
[c] Sum of 79 measured PCB congeners.

3.4 Status of Benthic Communities

Macrobenthic infauna (those retained on a 0.5-mm sieve) were sampled at a total of 30 stations throughout the sanctuary. Two grabs (0.04 m^2 each) were collected at each station, resulting in a total of 60 grabs. Measures of taxonomic diversity and abundance were calculated separately for each of the 60 grabs and averaged by station where indicated in **Table 11** (e.g., *mean* # taxa/0.04 m^2, *mean* H′/0.04 m^2). The resulting data were used to assess the status of benthic community characteristics (taxonomic composition, diversity, abundance, and dominant taxa), the incidence of non-indigenous species, and potential linkages to ecosystem stressors throughout sanctuary waters.

3.4.1 Taxonomic Composition

A total of 330 taxa were identified throughout the study area, of which 160 were identified to the species level. Polychaetes were the dominant taxa (**Figure 14**, **Table 10**), both by percent of taxa (38 %) and percent abundance (69 %). Crustaceans and molluscs were the second and third dominant taxa, respectively, both by percent of taxa (33 % crustaceans, 20 % mollusks) and percent abundance (15 % crustaceans, 8 % mollusks). Collectively, these three groups represented 91 % of total taxa and 92 % of total faunal abundance. Crustaceans were represented primarily by amphipods (70 identifiable taxa, 21.2 % of the total number of taxa), followed by isopods (16 taxa, 4.8 % of total taxa), cumaceans (11 taxa, 3.3 % of total taxa), and tanaidaceans and ostracods (5 taxa each, 3 % of total taxa both groups combined; **Table 10**). Molluscs were represented mainly by bivalves (45 taxa, 13.6 % of total taxa), followed by gastropods (19 taxa, 5.8 % of total taxa).

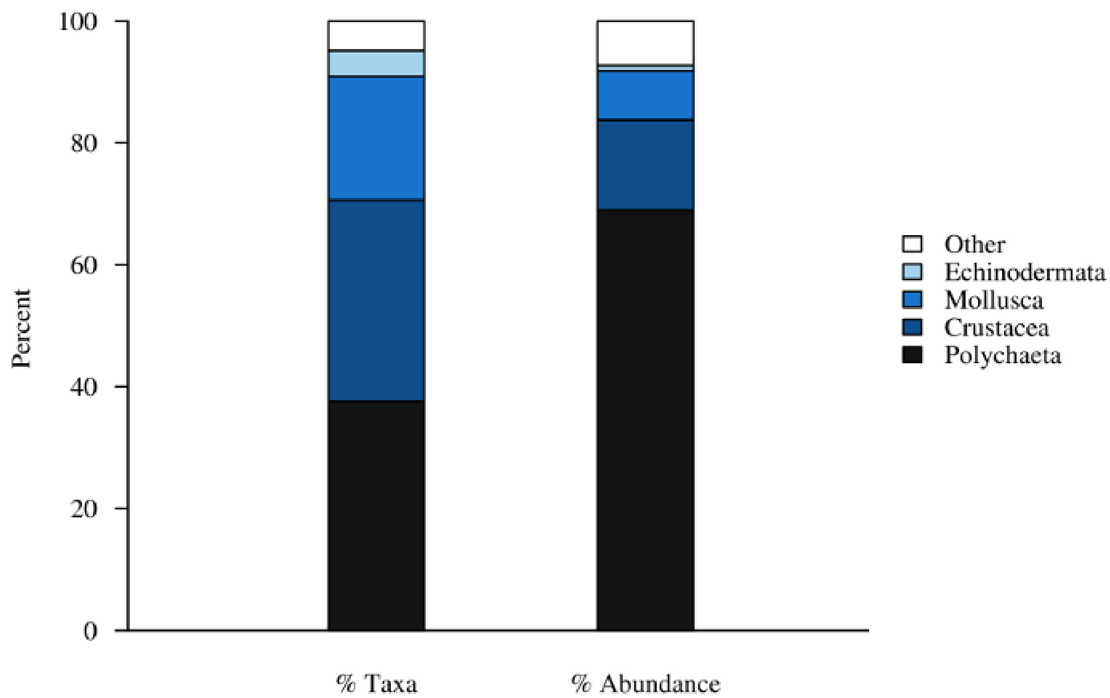

Figure 14. Relative percent composition of major taxonomic groups expressed as percent of total taxa and percent of abundance.

Table 10. Summary of major taxonomic groups of benthic infauna and corresponding numbers of identifiable taxa based on 60 0.04-m^2 grab samples.

Taxonomic Group	Number identifiable taxa	% Total identifiable taxa
Phylum Cnidaria		
Class Anthozoa*	1	0.3
Class Hydrozoa*	1	0.3
Phylum Platyhelminthes*	1	0.3
Phylum Nemertea*	2	0.6
Phylum Sipuncula*	2	0.6
Phylum Mollusca		
Class Aplacophora	1	0.3
Class Bivalvia	45	13.6
Class Gastropoda	19	5.8
Class Polyplacophora	1	0.3
Class Scaphopoda	1	0.3
Phylum Annelida		
Class Clitellata		
Subclass Oligochaeta*	2	0.6
Class Polychaeta	124	37.6
Phylum Arthropoda		
Subphylum Chelicerata*	1	0.3
Subphylum Crustacea		
Class Malacostraca		
Order Amphipoda	70	21.2
Order Cumacea	11	3.3
Order Decapoda	1	0.3
Order Isopoda	16	4.8
Order Mysida	1	0.3
Order Tanaidacea	5	1.5
Class Ostracoda	5	1.5
Phylum Phoronida*	1	0.3
Phylum Brachiopoda*	1	0.3
Phylum Echinodermata		
Class Asteroidea	3	0.9
Class Echinoidea	2	0.6
Class Holothuroidea	4	1.2
Class Ophiurida	5	1.5
Phylum Ectoprocta*	1	0.3
Phylum Chordata*	2	0.6
Phylum Porifera*	1	0.3
Total	*330*	*100*

* Taxonomic groups followed by an asterisk were assigned to the group ‘Other’ in Figure 11.

3.4.2 Abundance and Dominant Taxa

A total of 16,136 individuals were collected across the 30 stations (60, 0.04 m^2 grabs) sampled for benthos. Densities ranged from 612 – 15,500 ind/m^2 and averaged 6,723 ind/m^2 (**Table 11**, Appendix E). On an area-weighted basis, 50 % of the survey area had mean densities >5,650 ind/m and 10 % of the area (upper 10^{th} percentile) had mean densities > 12,688 ind/m^2 (**Table 9**, **Figure 15**).

The 50 most abundant taxa collected throughout SBNMS are listed in **Table 12**. The top 10 dominants, in decreasing order of abundance, included the syllid (Family Syllidae) polychaete *Exogone verugera*; maldanid polychaetes (Maldanidae); sabellid polychaetes (Sabellidae); the sabellid polychaete genus *Chone*; the polychaetes *Axiothella mucosa* (Maldanidae), *Prionospio steenstrupi* (Spionidae), and *Parapionosyllis longicirrata* (Syllidae); the gammarid amphipod genus *Unciola*; the polychaete *Exogone hebes*; and tubificid oligochaetes (Tubificidae).

3.4.3 Diversity

A total of 330 taxa were identified (160 to species) in 60 grabs collected throughout the study area. Taxonomic richness, expressed as the mean number of taxa present in replicate 0.04 m^2 grabs at a station, ranged from 10 to 45 taxa/grab, with an overall mean and median of 30 taxa/grab (**Table 11**). Area-weighted percentiles also are given in **Table 11**, and the full distribution of area-weighted estimates is illustrated in **Figure 15**.

Table 11. Mean, range, and selected distributional properties of key benthic variables. The benthic measures represent 60 0.04-m^2 grabs collected at 30 sites (2 replicate grabs at each station).

	Overall Mean	Overall Range	Area-based Percentiles[a]			Frequency-based percentiles[b]				
			CDF 10th pctl	CDF 50th pctl	CDF 90th pctl	10th	25th	50th	75th	90th
Mean # Taxa/0.04 m^2	30	10 - 45	18	30	40	19	23	30	36	43
Total # Taxa/0.08 m^2	46	15 - 72	27	48	63	28	35	48	56	66
Mean Density (#/m^2)	6,723	612 – 15,500	1,900	5,650	12,688	1,938	3,612	5,694	9,012	12,806
Mean H′/0.04 m^2	3.6	2.8 - 4.5	3.0	3.5	4.2	3.0	3.3	3.5	3.9	4.2

[a] Value of benthic variable corresponding to the designated cumulative % area of the estimated CDF.
[b] Corresponding lower 10th percentile, lower quartile, median, upper quartile, and upper 10th percentile of all values for each benthic variable.
Mean # taxa, mean density, and mean H′ represent the average of each of those measures calculated separately for the two grabs.
Total # taxa is the total number of taxa in both replicate grabs combined (0.08 m^2).

Table 12. Fifty most abundant benthic taxa. Mean density (#/m^2), and percent frequency of occurrence are based on 60 0.04-m^2 grabs. Classification: Native = native species; Crypto = cryptogenic species (of uncertain origin); Indeter = indeterminate taxon (not identified to a level that would allow determination of origin).

taxon	group	Classification	mean_density	pct_freq
Exogone verugera	Polychaeta	Native	311.3	47.4
Maldanidae	Polychaeta	Indeter	292.1	60.0
Sabellidae	Polychaeta	Indeter	266.8	32.6
Chone spp.	Polychaeta	Native	255.0	30.5
Axiothella mucosa	Polychaeta	Native	209.2	23.2
Prionospio steenstrupi	Polychaeta	Native	166.1	31.6
Parapionosyllis longicirrata	Polychaeta	Native	113.7	16.8
Unciola spp.	Crustacea	Native	103.7	23.2
Exogone hebes	Polychaeta	Native	103.4	31.6
Tubificidae	Other	Indeter	82.1	38.9
Ampharetidae	Polychaeta	Indeter	78.4	47.4
Unciola inermis	Crustacea	Native	69.2	12.6
Aricidea spp.	Polychaeta	Native	67.4	41.1
Anobothrus gracilis	Polychaeta	Native	66.8	38.9
Cirratulidae	Polychaeta	Indeter	66.1	51.6
Serpulidae	Polychaeta	Indeter	54.7	7.4
Polygordius spp.	Polychaeta	Native	54.7	18.9
Sphaerosyllis spp.	Polychaeta	Native	54.5	20.0
Enchytraeidae	Other	Indeter	54.5	11.6
Sipuncula	Other	Indeter	54.2	28.4
Eudorella hispida	Crustacea	Native	53.2	27.4
Cirrophorus spp.	Polychaeta	Native	51.6	25.3
Ericthonius fasciatus	Crustacea	Native	48.9	16.8
Leptochelia spp.	Crustacea	Native	43.2	16.8
Ascidiacea	Other	Indeter	41.1	27.4
Thyasira gouldii	Mollusca	Native	39.5	26.3
Ninoe nigripes	Polychaeta	Native	38.7	21.1
Spionidae	Polychaeta	Indeter	37.6	30.5
Levinsenia gracilis	Polychaeta	Native	35.3	23.2
Nephtyidae	Polychaeta	Indeter	34.2	37.9
Glyceridae	Polychaeta	Indeter	32.1	26.3
Portlandia frigida	Mollusca	Native	31.1	18.9
Hemipodus borealis	Polychaeta	Native	29.5	22.1
Aoridae	Crustacea	Indeter	27.9	13.7
Nucula delphinodonta	Mollusca	Native	26.3	26.3
Protodorvillea kefersteini	Polychaeta	Native	25.5	13.7
Astarte crenata subequilatera	Mollusca	Native	25.5	17.9
Terebellidae	Polychaeta	Indeter	25.3	29.5
Cerastoderma pinnulatum	Mollusca	Native	24.7	20.0
Spio spp.	Polychaeta	Indeter	23.9	25.3
Bivalvia	Mollusca	Indeter	23.4	30.5
Ampelisca spp.	Crustacea	Indeter	20.0	15.8
Galathowenia oculata	Polychaeta	Native	19.7	25.3
Actiniaria	Other	Indeter	19.2	11.6
Mediomastus californiensis	Polychaeta	Native	19.2	7.4
Astarte spp.	Mollusca	Native	18.7	15.8
Mediomastus spp.	Polychaeta	Native	18.4	18.9
Crenella decussata	Mollusca	Native	17.9	27.4
Aglaophamus circinata	Polychaeta	Native	17.4	27.4
Mayerella limicola	Crustacea	Native	17.4	16.8

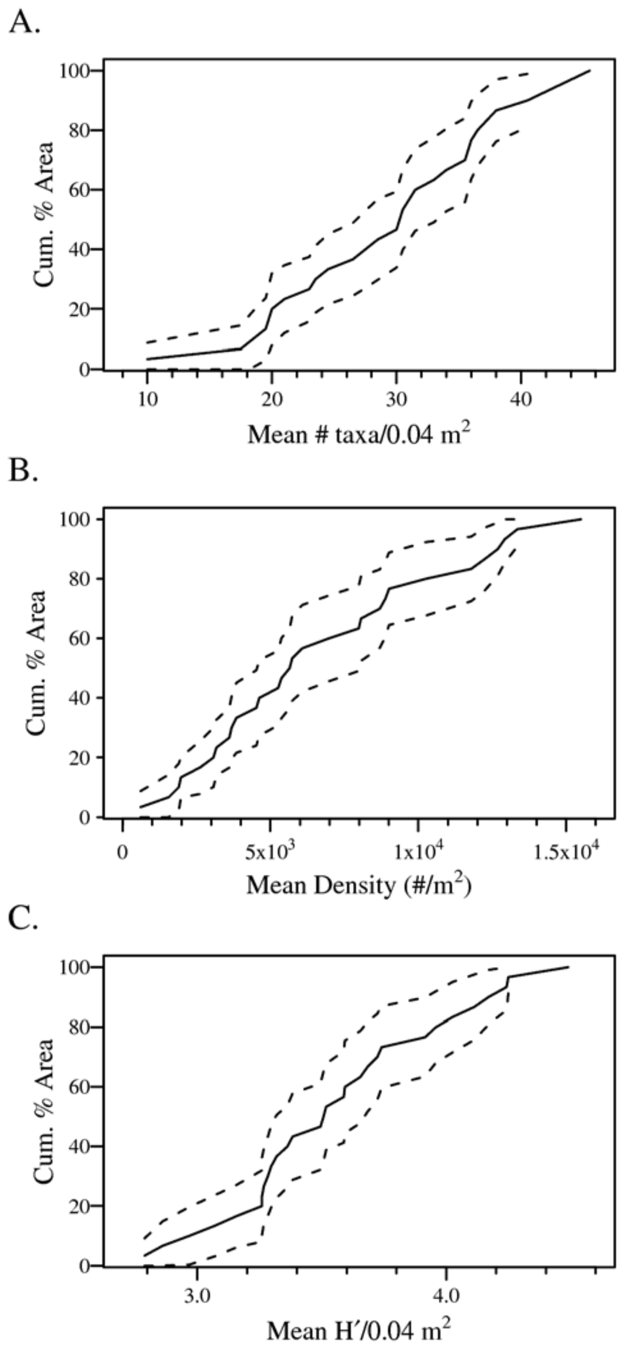

Figure 15. Percent area (and 95% confidence intervals) of SBNMS study area vs. benthic infaunal taxonomic richness (A), density (B), and H' diversity (C)

3.4.4 Patterns of biogeographic distribution

Benthic ecological community data were analyzed for patterns in faunal distributions using hierarchical cluster analysis of Bray-Curtis dissimilarities (unweighted pair-group method with arithmetic mean, or UPGMA) and non-metric multidimensional scaling (NMDS) in R (R Development Core Team 2008). Analyses were performed on double-square root-transformed abundances, with taxonomic classifications held at the Family level. Reasons for using family-level data were two-fold: first, analysis of families often reveals broad-scale patterns in benthic distributions (Clarke & Warwick 2001); second, many of the specimens collected (in particular, polychaete worms) were fragmented with no identifiable posterior end, which would be needed to identify beyond family. Consequently, many polychaetes (the dominant taxonomic group) were identified only to Family level.

From the cluster analysis, three main site groups emerge (**Figure 16**). Site Group A represents what may be termed a ‘top-of-bank’ assemblage, having shallow depths (31m – 55m, mean of 40m) and sandy sediments (65% - 97% sand, mean = 84%). Sediments at these sites also had very low silt-clay (0.4 – 5% silt-clay, mean = 1.8%) and TOC (0.2 – 0.7 mg/g, mean=0.4 mg/g) content. The seven stations comprising this site group were characterized by relatively high densities (overall mean density = 8,330 ind/m^2) and dominated by maldanid and syllid polychaetes (mean densities of 2,129 ind/m^2 and 2,014 ind/m^2 for families Maldanidae and Syllidae, respectively). These two polychaete families represent 50% cumulative density of all taxa found at Site Group A stations. Other taxa in this site group, in decreasing order of abundance, were gammarid amphipod crustaceans (Family Aoridae), tubificid oligochaetes (Family Tubificidae), and other polychaete worms (Families Paraonidae, Polygordiidae, Glyceridae, and Serpulidae). Taken together, the taxa listed above made up nearly 80% cumulative density of taxa found in Site Group A.

The next site group (Site Group B, **Figure 16**) appears to represent sites in depositional environments of Stellwagen Basin and Gloucester Basin. These sites tended to be of intermediate or deep depths (61m – 130m, mean of 85m), with relatively high sediment silt-clay (36% - 98% silt-clay, mean = 66%) and TOC (7.7 – 25.7 mg/g) content. Densities of benthic infauna were relatively low at these sites (overall mean density = 1,735 ind/m^2). The top dominants included a number of polychaete families (i.e., Lumbrineridae, Spionidae, Ampharetidae, Paraonidae), bivalve molluscs (Thyasiridae), and other polychaete worms (Maldanidae, Cirratulidae, Trichobranchidae, Cossuridae, and Orbiinidae). Along with other bivalve molluscs (Periplomatidae) and gammarid amphipod crustaceans (Phoxocephalidae), these taxa made up 80% cumulative density of taxa in Site Group B.

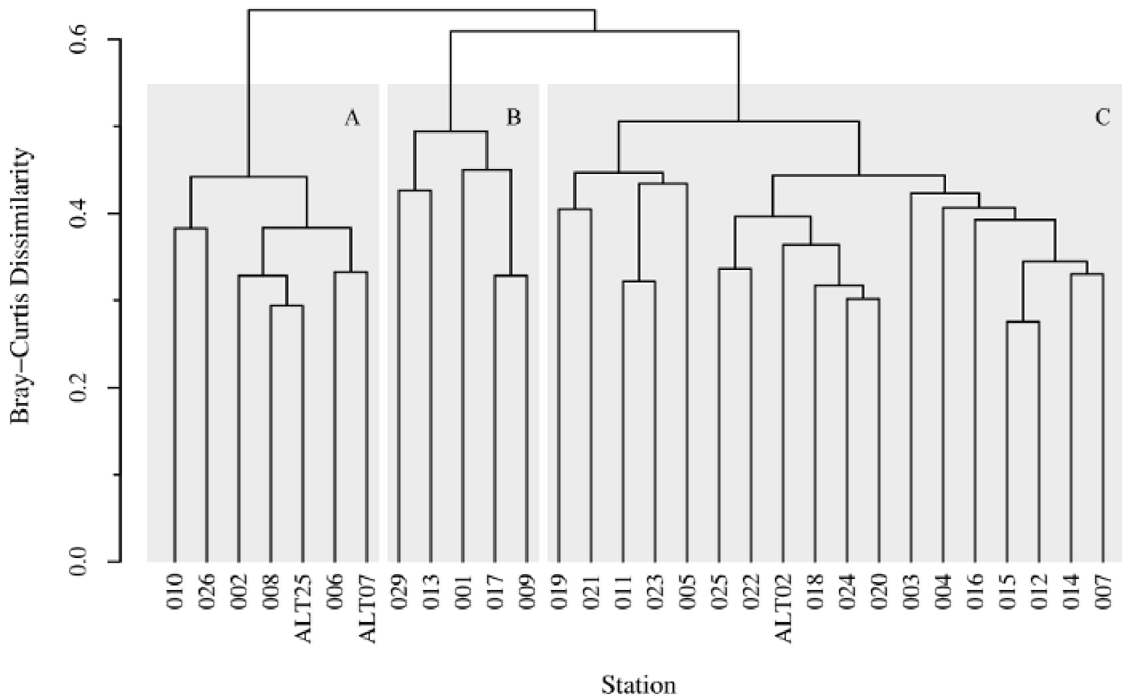

Figure 16. Dendrogram resulting from hierarchical cluster analysis.

The number of taxa among stations in Site Group A (mean of 24.7 taxa/grab) was greater than that of Site Group B (mean of 17.4 taxa/grab), though mean Shannon diversity (H′) was slightly lower (3.27 *vs*. 3.44, respectively). This likely is due to a less even distribution of taxonomic abundance in Site Group A compared to Site Group B (mean Pielou's evenness, J′ = 0.70 and 0.83, respectively), where the infaunal assemblages of Site Group A are dominated by a few taxa as described above.

The same site groups emerge from NMDS analysis of the same community dataset (**Figure 17**). Adding vectors of abiotic variables such as depth and % silt-clay to the plot helps to illustrate the influence of these factors on the distributions of benthic taxa as discussed above. While Site Groups A and B are described in the previous two paragraphs, the stations labeled as Site Group C in **Figure 16** appear to be representative of habitats that are intermediate along the gradients of sediment type and depth. Most sites were of intermediate depth (mean depth = 79 m), with sediment silt-clay content $\leq$ 30 %, and TOC from 2 – 7 mg/g. Mean infaunal density among these sites (7,484/m^2) was intermediate between that of Site Groups A and B, though only slightly less than Site Group A. Because of the range of habitat types represented by stations in Site Group C, mean taxonomic diversity (3.71) and richness (35.4 taxa/grab) were higher than either Site Group A or B. Taxa were slightly more equitably distributed (mean J′ = 0.72) than Site Group A, but considerably less so than Site Group B.

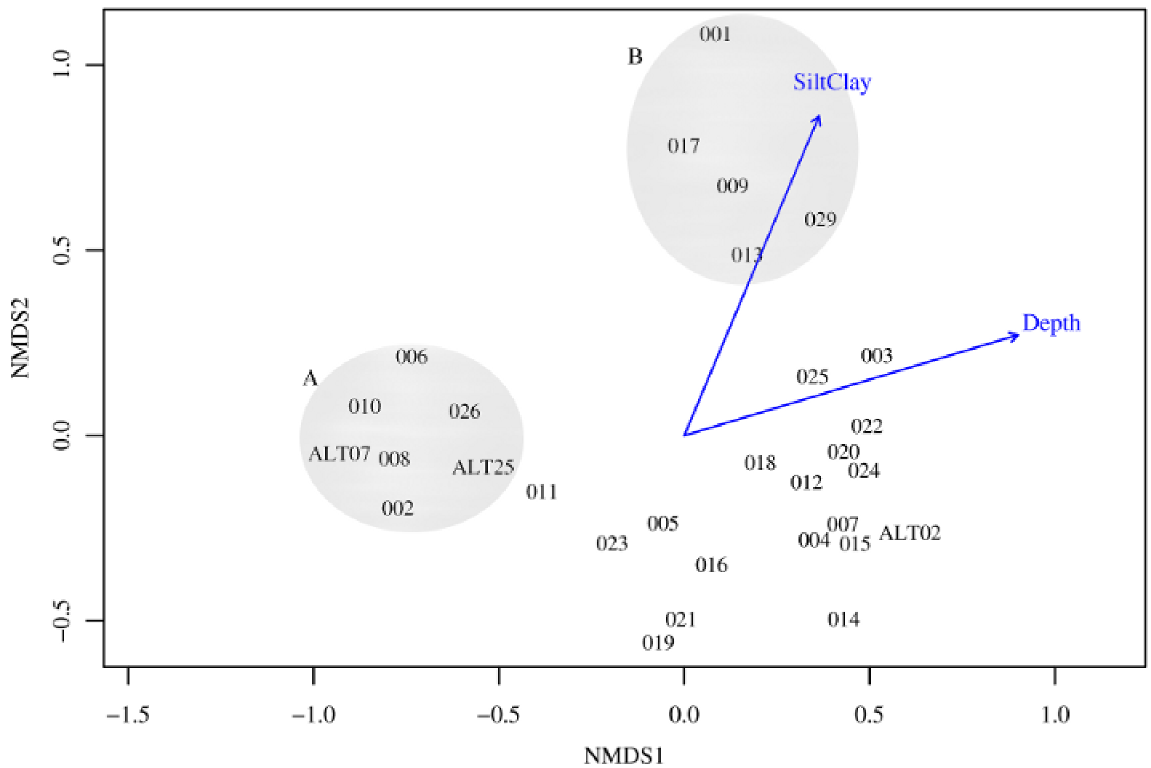

Figure 17. Ordination plot derived from non-metric multidimensional scaling (NMDS).

In their assessment of the benthic community of Boston Harbor, Massachusetts/Cape Cod Bay, and Stellwagen Bank, Hartwell et al. (2006) described three major habitat zones: Boston Harbor (muddy, shallow, low salinity); Stellwagen Bank (coarse sand, low TOC); and the deeper, open-water areas of Massachusetts Bay, Cape Cod Bay, and Stellwagen Basin (fine sand, deep, higher TOC). Our analysis appears to resolve further the latter habitat zone into the deep, silty, high TOC areas (Site Group B) and Site Group C (intermediate silt-clay, TOC, and depth). As noted in their assessment (Hartwell et al. 2006), the Massachusetts Water Resources Authority (MWRA) concluded in their benthic community analysis (Maciolek 2005) that the largest differences among community groups was related primarily to grain size.

In the present study, overall mean infaunal densities tended to be lower at sites with higher percent silt-clay content (**Figure 18**; $R^2 = 0.19$, $p = 0.017$). These sites also had lower numbers of taxa and higher concentrations of TOC (Figure **19**; $R^2 = 0.21$, $p < 0.011$).

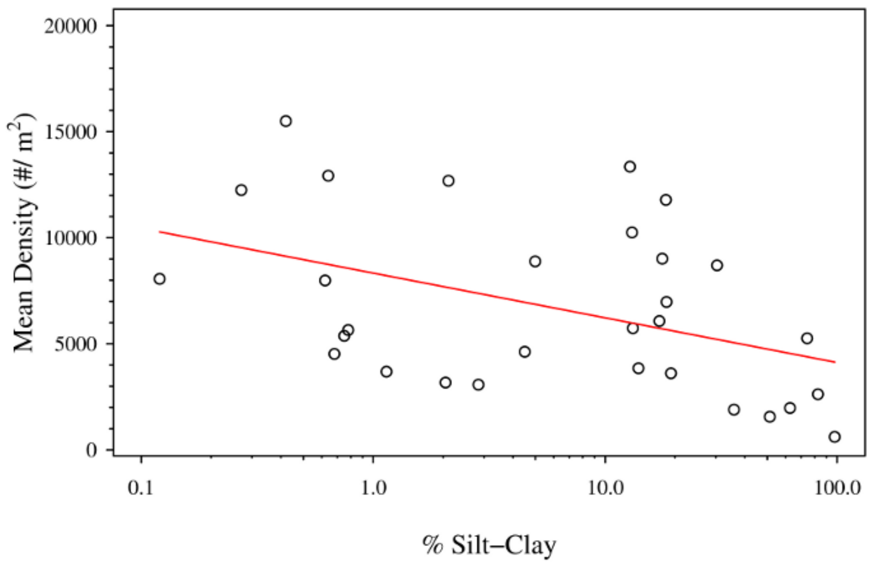

Figure 18. Plot of mean density (#/m^2) versus sediment % silt-clay.

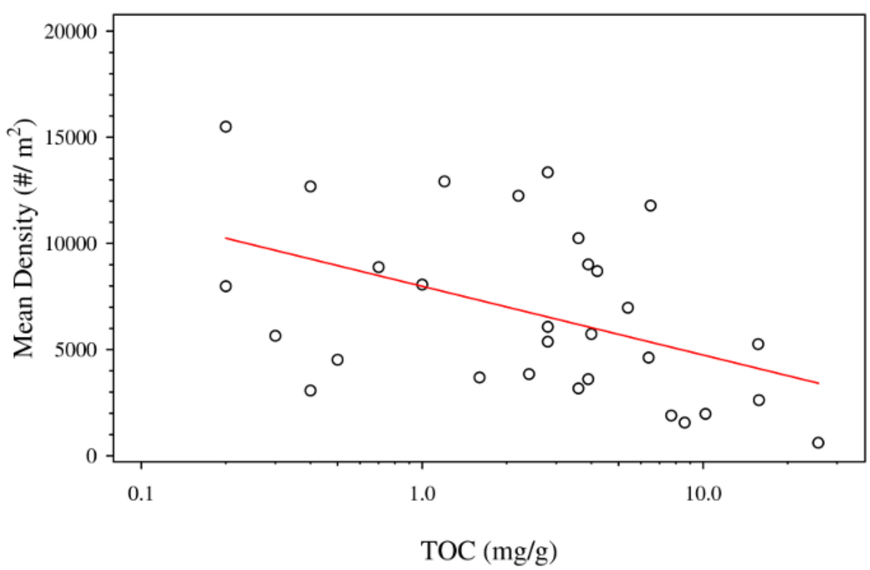

Figure 19. Plot of mean density (#/m^2) versus TOC content of sediment.

Though numbers of taxa were lower at sites having very high % silt-clay and high TOC sediment content, there also were fewer taxa present at sites where organic carbon was scarce (and, perhaps, limiting). The observed pattern of species richness (**Figure 20**) appears to reflect general conceptual models of benthic response to organic enrichment (Pearson and Rosenberg 1978, Hyland et al. 2005), with low numbers of taxa at stations with sediments low in organic carbon, higher numbers of taxa with increasing TOC, and then declining numbers of taxa at highly organically-enriched sites.

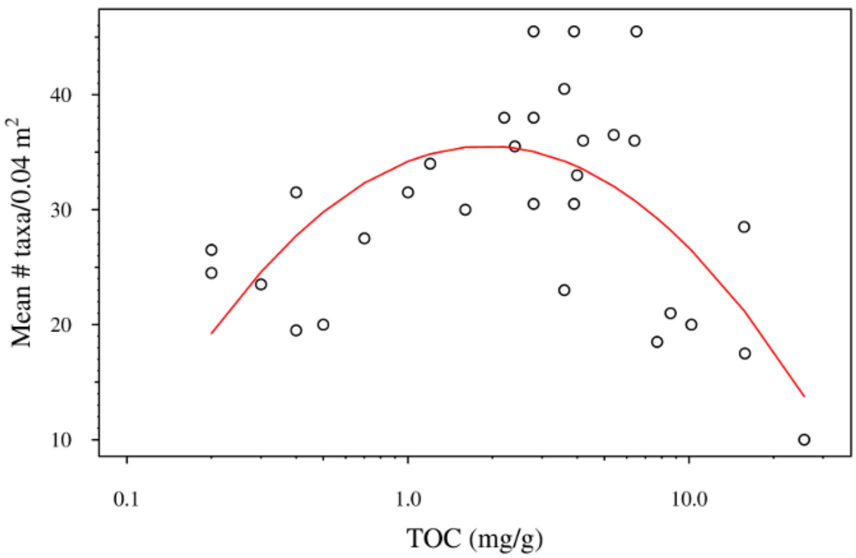

Figure 20. Plot of mean # of taxa (per 0.04 m^2) versus TOC content of sediment.

3.4.5 Non-indigenous Species

The list of taxa collected in SBNMS was examined for the occurrence of non-native and exotic species by searching NISbase, a distributed database on non-indigenous species that queries a number of different information systems. Databases that are part of NISbase include the U.S. Geological Survey (USGS) National Aquatic Species Database (NAS, U.S. Geological Survey 2004), the Smithsonian National Exotic Marine and Estuarine Species Information System (NEMESIS, Fofonoff et al. 2003), the Massachusetts Institute of Technology Sea Grant Program Marine Invader Tracking Information System (MITIS, MIT 2008), and the NOAA National Benthic Inventory (NBI 2004), among others. A small number of species collected as part of the 2008 SBNMS survey (i.e., *Harmothoe imbricata*) are considered to be cryptogenic (Ruiz et al. 2000). The only non-indigenous species identified in the present study was the gammarid amphipod *Microdeutopus gryllotalpa*, found at a single station (station 21). This species was listed in the SBNMS Final Management Plan and Environmental Assessment (U.S. Department of Commerce 2010, Table 4) as a known invasive to the Gulf of Maine region, but had not been documented yet in SBNMS. A number of specimens collected in this study were only identified to higher taxonomic level (e.g., Phylum Bryozoa (=Ectoprocta), Porifera; Order Actiniaria; Class Ascidiacea, Hydrozoa; Family Mysidae; Genus *Caprella*, *Molgula*). Hence, it was not possible to determine definitively whether additional known invasives from these groups were present in samples from SBNMS.

3.5 Potential Linkage of Biological Condition to Stressor Impacts

Multi-metric benthic indices are commonly used to summarize and classify benthic habitat conditions along the continuum from non-degraded to degraded (see review by Diaz et al. 2004) and have been developed for a variety of estuarine applications (Engle et al. 1994, Weisberg et al. 1997, Van Dolah et al. 1999, Llansó et al. 2002a, 2002b, Hale and Heltshe 2008). A desired characteristic of these indices is the ability to discriminate between impaired *versus* unimpaired benthic condition, based on key biological attributes (e.g., numbers of species, diversity, abundance, biomass, relative proportion of pollution-sensitive or pollution-tolerant species), while taking into account natural controlling factors. Such indices have been developed for estuaries of the mid-Atlantic states and Chesapeake Bay (Weisberg et al. 1997, Llansó et al. 2002a, 2002b) and nearshore Gulf of Maine (Hale and Heltshe 2008). An index is being developed for near-coastal NJ (to 3 km; Strobel et al. 2008), but no such index exists that would be directly applicable to the offshore waters of SBNMS.

In the absence of a benthic index, we attempted to assess potential stressor impacts in the present study by evaluating linkages between reduced values of biological attributes (numbers of taxa, diversity, and abundance) and synoptically measured indicators of poor sediment or water quality. Using the lower 10^{th} percentile as a basis for defining 'low' values, we looked for co-occurrences of low values of biological attributes with indications of poor sediment or water quality defined as follows (*sensu* U.S. EPA 2000b for dissolved oxygen, U.S. EPA 2004 for other indicators): ≥ 1 chemical in excess of ERMs (from Long et al. 1995), TOC > 50 mg/g, and DO in near-bottom water < 2.0 mg/L.

We found no association of low values of biological attributes (as defined above) with indicators of poor sediment or water quality. In fact, no indications of poor sediment or water quality were observed based on these criteria. The highest observed TOC concentration was 25.7 mg/g (Appendix A), well below 50 mg/g as well as the more conservative bioeffect threshold of 35 mg/g TOC published in Hyland et al. (2005). DO concentrations in bottom waters were at least 8.5 mg/L (Appendix B) and no ERM exceedances were observed (Appendix D). These results suggest that sediments and overlying waters of SBNMS are in good condition, with lower-end values of biological attributes (Appendix E) representing parts of a normal reference range controlled by natural factors.

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5.0 Appendices

Appendix A. Locations (latitude, longitude), depth, and sediment characteristics of sampling stations.

Station	Latitude	Longitude	Depth (m)	Gravel (%)	Sand (%)	Silt-Clay (%)	TOC (mg/g)
01	42.36902	-70.52692	93	0.0	2.4	97.6	25.7
02	42.40162	-70.34907	42	32.9	66.7	0.4	0.2
03	42.53540	-70.35034	137	8.1	17.6	74.3	15.7
04	42.66465	-70.21794	90	20.7	66.1	13.2	4.0
05	42.43304	-70.50733	55	34.2	63.7	2.1	3.6
06	42.31778	-70.29494	34	9.5	89.7	0.8	0.3
07	42.58792	-70.42620	85	34.1	47.6	18.3	6.5
08	42.25497	-70.26070	33	5.5	93.9	0.6	0.2
09	42.20325	-70.44878	65	0.0	48.7	51.3	8.6
10	42.37727	-70.40142	42	0.0	97.2	2.8	0.4
11	42.63309	-70.46301	50	14.5	85.4	0.1	1.0
12	42.44634	-70.13119	84	21.2	65.7	13.1	3.6
13	42.26046	-70.42533	75	10.3	53.8	35.9	7.7
14	42.63698	-70.32280	89	16.9	64.8	18.4	5.4
15	42.64134	-70.24021	83	25.8	43.8	30.4	4.2
16	42.41108	-70.25529	59	39.1	60.6	0.3	2.2
17	42.19279	-70.48567	61	0.6	36.8	62.6	10.2
18	42.54229	-70.56082	65	10.8	71.6	17.6	3.9
19	42.25418	-70.32759	54	1.0	97.9	1.1	1.6
20	42.50134	-70.44600	82	37.8	57.7	4.5	6.4
21	42.13129	-70.28621	65	0.6	86.6	12.8	2.8
22	42.55612	-70.24165	95	17.4	65.5	17.1	2.8
23	42.44507	-70.32237	68	19.9	79.4	0.6	1.2
24	42.26105	-70.11768	93	10.4	88.8	0.8	2.8
25	42.45865	-70.36629	83	0.3	80.5	19.2	3.9
26	42.18791	-70.11456	55	7.9	87.1	5.0	0.7
29	42.51436	-70.39874	130	0.0	17.4	82.6	15.8
ALT02	42.62745	-70.37403	85	14.2	71.9	13.9	2.4
ALT07	42.29310	-70.29426	31	34.4	65.0	0.7	0.5
ALT25	42.29822	-70.23617	40	12.3	85.6	2.1	0.4

Appendix B. Near-bottom water characteristics by station.

Station	Temp. (ºC)	Salinity (psu)	DO (mg/L)	pH	DIP (mg/L)	DIN (mg/L)	Nitrate+ Nitrite (µg/L)	Ammonium (µg/L)	N/P	Silicate (µg/L)	Chlorophyll a (µg/L)	TSS (mg/L)
01	4.4	32.4	8.5	7.6	0.142	0.682	653.9	27.8	8.19	953.6	0.21	6.9
02	5.6	32.2	9.4	7.7	0.089	0.357	309.4	47.9	8.27	577.8	0.56	15.1
03	4.6	32.5	9.1	7.7	0.127	0.744	739.8	4.1	9.26	794.9	0.09	5.8
04	4.9	32.5	9.0	7.7	0.127	0.683	673.1	10.4	8.71	773.1	0.08	8.7
05	5.5	32.2	9.3	7.7	0.086	0.333	277.0	55.7	8.49	388.5	1.10	6.2
06	6.1	32.2	9.6	7.8	0.095	0.341	320.9	20.5	6.48	295.8	1.07	8.7
07	5.1	32.4	9.2	7.7	0.123	0.590	570.7	19.1	8.03	766.0	0.26	5.2
08	5.9	32.2	9.5	7.8	0.100	0.324	282.6	41.2	6.65	367.2	0.87	7.0
09	4.7	32.4	8.8	7.7	0.126	0.632	586.7	45.2	9.15	689.9	0.23	6.3
10	6.1	32.1	9.5	7.8	0.095	0.284	243.4	40.3	6.30	357.8	1.12	5.9
11	5.8	32.2	9.5	7.8	0.108	0.445	394.2	50.4	8.22	415.0	0.42	5.2
12	4.8	32.5	9.2	7.7	0.128	0.677	667.3	9.4	8.52	658.1	0.07	6.0
13	4.4	32.4	8.5	7.6	0.135	0.674	637.7	36.1	8.78	892.3	0.25	7.4
14	5.0	32.4	9.1	7.7	0.121	0.648	628.6	19.5	8.96	883.7	0.11	5.2
15	5.0	32.5	9.1	7.7	0.122	0.664	657.0	6.6	8.65	687.7	0.07	9.1
16	5.5	32.3	9.5	7.7	0.101	0.461	429.9	31.6	8.35	502.5	0.29	8.6
17	4.8	32.3	9.0	7.7	0.115	0.575	538.7	36.1	9.01	824.5	0.26	6.7
18	5.9	32.1	9.4	7.8	0.099	0.352	311.2	40.6	7.14	610.8	0.35	8.0
19	4.6	32.3	8.7	7.7	0.129	0.621	551.3	70.0	9.57	701.2	0.24	7.3
20	5.1	32.3	9.1	7.7	0.023	0.057	45.3	11.8	5.81	106.6	0.25	6.0
21	5.0	32.2	9.1	7.6	0.121	0.457	392.3	65.0	7.96	600.6	0.33	5.0
22	4.7	32.5	9.1	7.7	0.117	0.700	698.0	2.0	9.38	696.3	0.07	9.3
23	5.3	32.3	9.4	7.7	0.105	0.495	458.2	37.2	8.73	491.1	0.21	6.7
24	5.0	32.4	9.2	7.7	0.118	0.590	561.0	29.0	8.70	559.5	0.15	5.8
25	5.3	32.3	9.3	7.7	0.117	0.507	467.0	39.6	8.08	601.3	0.34	7.0
26	5.1	32.4	9.2	7.7	0.116	0.553	515.8	37.6	8.65	517.9	0.22	6.3
29	4.6	32.5	9.0	7.7	0.126	0.728	723.3	4.5	9.13	733.2	0.09	9.7
ALT02	5.2	32.4	9.1	7.7	0.117	0.551	524.0	26.9	8.24	711.8	0.16	4.8
ALT07	6.2	32.2	9.5	7.8	0.096	0.316	292.2	23.5	6.06	317.7	1.00	3.4
ALT25	5.8	32.3	9.4	7.8	0.103	0.391	355.8	35.6	7.29	328.9	0.47	6.9

Appendix C. Near-surface water characteristics by station.

Station	Temp. (ºC)	Salinity (psu)	DO (mg/L)	pH	DIP (mg/L)	DIN (mg/L)	Nitrate+ Nitrite (µg/L)	Ammonium (µg/L)	N/P	Silicate (µg/L)	Chlorophyll a (µg/L)	TSS (mg/L)
01	15.4	31.2	9.5	8.0	0.028	0.035	34.0	0.6	1.98	162.3	0.77	6.6
02	16.8	30.9	9.0	8.0	0.028	0.056	50.5	5.0	3.84	394.4	0.56	5.5
03	16.0	31.2	9.2	8.0	0.031	0.051	51.2	0.2	2.67	68.9	0.54	7.2
04	15.8	31.4	9.0	8.0	0.034	0.055	53.1	1.6	2.70	218.0	0.63	8.7
05	16.8	31.0	9.2	8.0	0.030	0.056	46.7	9.1	4.08	205.0	0.54	6.4
06	16.0	31.0	9.2	8.0	0.029	0.049	47.0	1.5	2.86	68.1	0.58	7.4
07	16.7	30.8	9.3	8.0	0.026	0.060	57.6	2.8	4.02	179.0	0.38	6.3
08	15.3	31.4	9.3	8.0	0.039	0.074	59.4	14.3	4.34	37.4	0.56	6.3
09	16.1	31.1	9.2	8.0	0.030	0.056	56.3	0.2	2.93	15.0	0.31	5.7
10	16.8	31.3	9.0	8.0	0.025	0.055	50.5	5.0	4.14	222.7	0.37	5.8
11	16.6	30.8	9.2	8.0	0.032	0.058	57.5	0.9	3.02	279.9	0.40	5.1
12	15.8	31.4	9.0	8.0	0.035	0.050	49.9	0.5	2.30	40.7	0.37	8.8
13	16.2	31.0	9.0	8.0	0.025	0.057	48.0	8.9	4.93	66.9	0.47	6.3
14	16.0	31.4	9.2	8.0	0.033	0.076	53.0	22.5	6.14	301.1	0.34	5.0
15	16.5	31.3	8.8	8.0	0.031	0.049	49.1	0.3	2.55	4.4	0.38	9.1
16	15.9	31.1	9.1	8.0	0.025	0.053	47.4	5.8	4.14	46.3	0.59	8.4
17	16.2	30.9	9.3	8.0	0.022	0.047	44.1	2.7	3.76	192.4	0.71	5.8
18	12.1	31.3	10.4	8.0	0.046	0.059	59.4	0.1	2.03	270.5	1.65	8.3
19	16.4	31.0	9.2	8.0	0.024	0.051	49.0	1.6	3.54	1.2	0.32	6.4
20	16.1	31.1	9.3	8.0	0.103	0.555	496.7	58.2	10.57	663.3	0.45	6.3
21	15.5	30.6	9.7	7.9	0.024	0.050	50.0	0.2	3.28	77.6	1.26	2.4
22	15.4	31.4	9.3	8.0	0.026	0.052	46.8	5.5	3.99	14.1	0.39	9.0
23	16.4	31.0	8.9	8.0	0.028	0.051	50.6	0.0	2.82	91.7	0.75	7.6
24	14.6	31.4	9.5	7.9	0.034	0.048	47.3	0.8	2.29	40.6	0.48	5.7
25	15.4	31.2	9.5	7.9	0.027	0.050	47.0	2.8	3.26	193.0	0.61	5.0
26	15.5	31.1	9.3	7.9	0.033	0.057	54.5	2.2	2.92	18.1	0.64	6.9
29	16.4	31.0	9.0	8.0	0.026	0.051	50.7	0.1	3.08	38.0	0.36	7.6
ALT02	16.5	31.3	9.2	8.0	0.119	0.563	535.4	27.2	8.22	719.9	0.40	4.8
ALT07	15.1	31.2	9.3	8.0	0.034	0.046	40.5	5.7	2.80	64.0	0.78	5.2
ALT25	15.1	31.2	9.3	8.0	0.031	0.047	44.9	2.2	2.68	31.9	0.59	7.0

Appendix D. Summary by station of mean ERM quotients and the number of contaminants that exceeded corresponding ERL or ERM values (from Long et al. 1995).

Station	# of ERLs Exceeded	# of ERMs Exceeded	Mean ERM-Q
01	3	0	0.071
02	0	0	0.004
03	1	0	0.044
04	0	0	0.014
05	0	0	0.015
06	0	0	0.004
07	1	0	0.022
08	0	0	0.003
09	0	0	0.032
10	0	0	0.003
11	0	0	0.007
12	1	0	0.016
13	1	0	0.033
14	1	0	0.018
15	0	0	0.014
16	1	0	0.014
17	0	0	0.032
18	0	0	0.021
19	0	0	0.009
20	1	0	0.031
21	0	0	0.011
22	1	0	0.014
23	1	0	0.012
24	0	0	0.009
25	0	0	0.016
26	0	0	0.005
29	1	0	0.042
ALT02	0	0	0.010
ALT07	0	0	0.003
ALT25	0	0	0.003

Appendix E. Summary by station of benthic macroinfaunal (>0.5mm) characteristics. Two replicate benthic grabs ($0.04m^2$ each) were processed from each station. H′ derived using base 2 logarithms. (*Values within lower 25th percentile of all values of a specific benthic variable; **values within lower 10th percentile.)

Station	Mean # Taxa per Grab	Total # Taxa	Mean Density (# / m^2)	Mean H′ per Grab
01	10**	15**	613**	3.0**
02	27	39	15,500	2.9**
03	29	45	5,263	3.7
04	33	53	5,738	3.7
05	23*	40	3,175*	3.3*
06	24	32*	5,650	3.5
07	46	70	11,788	4.0
08	25	37	7,988	3.3*
09	21*	36	1,563**	3.7
10	20*	29*	3,075*	3.2*
11	32	52	8,063	3.6
12	41	63	10,250	3.1*
13	19**	29*	1,900**	3.5
14	37	56	6,975	3.9
15	36	54	8,700	3.3*
16	38	58	12,250	4.0
17	20*	33*	1,975*	3.6
18	46	72	9,013	4.2
19	30	49	3,688	4.2
20	36	59	4,625	4.1
21	38	63	13,350	3.3*
22	31	48	6,075	2.8**
23	34	51	12,925	3.4
24	46	71	5,375	4.5
25	31	48	3,613	3.7
26	28	35*	8,888	3.3*
29	18**	24**	2,625*	3.4
ALT02	36	56	3,850	4.2
ALT07	20*	27**	4,525	3.3*
ALT25	32	47	12,688	3.5

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Gary F. Locke
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David Kennedy
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