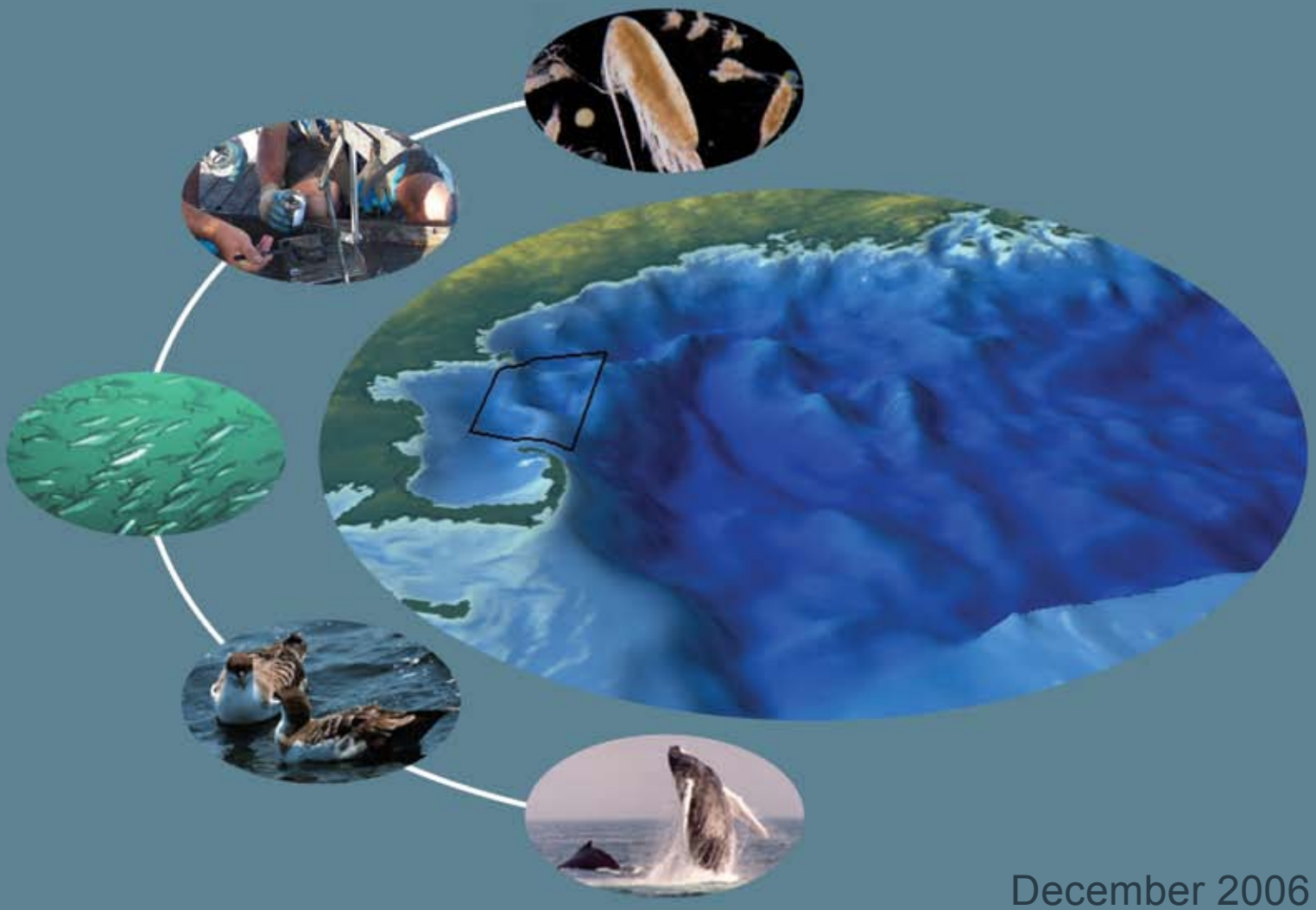
An Ecological Characterization of the Stellwagen Bank National Marine Sanctuary Region

Oceanographic, Biogeographic, and Contaminants Assessment



December 2006

Prepared for the National Marine Sanctuary Program
and Stellwagen Bank National Marine Sanctuary

NOAA Technical Memorandum NCCOS 45

Editors
Tim Battista (NCCOS)
Randy Clark (NCCOS)
Simon Pittman (NCCOS)



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Center for Coastal Monitoring and Assessment (CCMA)
NOAA/NOS/NCCOS
1305 East West Highway (SSMC-IV, N/SCI-1)
Silver Spring, MD 20910

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United States Department of Commerce	National Oceanic and Atmospheric Administration	National Ocean Service
Carlos M. Gutierrez Secretary	Conrad C. Lautenbacher, Jr. Administrator	John H. Dunnigan Assistant Administrator

ABOUT THIS DOCUMENT

This ecological characterization represents the continuation of an ongoing partnership between the National Marine Sanctuary Program (NMSP) and the National Centers for Coastal Ocean Science (NCCOS), Center for Coastal Monitoring and Assessment (CCMA). The purpose of this collaboration is to apply a biogeographical approach to the management of marine resources within the National Marine Sanctuaries. This particular work, conducted in collaboration with the Stellwagen Bank National Marine Sanctuary (SBNMS) and scientists conducting research within the Gulf of Maine region, builds on and advances biogeographic techniques developed by CCMA's Biogeography Team for other National Marine Sanctuaries including Channel Islands, Cordell Bank, Gulf of Farallones, Monterey Bay, and Gray's Reef. At the onset of the project, CCMA, SBNMS, and NMSP staff identified a set of targeted research topics to fill existing gaps in baseline environmental data, and enhance the understanding of key ecological patterns and processes to support the Management Plan Review process. Four objectives were addressed in the ecological characterization of SBNMS: 1) conduct analysis of geospatial distributions of selected fishes, seabirds, marine mammals, and contaminants within the Sanctuary and Gulf of Maine region, 2) identify biological and physical datasets that can be used to augment existing Sanctuary data for a comprehensive biogeographic assessment in a GIS environment, 3) identify ecologically important areas within the Sanctuary and surrounding region, and 4) model the physical and biological dependencies that may explain the temporal and spatial dynamics of the ecosystem represented within the Sanctuary and Gulf of Maine region.

The ecological characterization consists of three complementary components: a text report; a suite of quantitative spatial and statistical analyses that characterize physical, contaminant, and biological patterns of the Stellwagen Bank NMS region; and an extensive geodatabase of all spatial, temporal, derived, and primary datasets acquired, assimilated, and analyzed to conduct the characterization. The ecological characterization report provides essential information on the distribution of modeled and observed species needed to support the development of monitoring and scientific studies, the development of educational material, and support of other spatially-explicit management decisions. The results of this ecological characterization are available via hard copy and website. For more information on this effort please visit the NCCOS Biogeography Team webpage dedicated to this project at http://ccma.nos.noaa.gov/ecosystems/sanctuaries/stellwagen_nms.html or direct questions and comments to:

Mark E. Monaco, Ph.D.
Biogeography Team Lead
National Oceanic and Atmospheric Administration
1305 East West Highway
SSMC 4, N/SCI-1
Silver Spring, MD 20910
Phone: (301) 713-3028 x 160
Email: Mark.Monaco@noaa.gov

Or

Craig D. MacDonald, Ph.D.
Stellwagen Bank National Marine Sanctuary Superintendent
National Oceanic and Atmospheric Administration
175 Edward Foster Road
Scituate, MA 02066
Phone: (781) 545-8026
Email: Craig.MacDonald@noaa.gov

PROJECT TEAM

Dennis Apeti – NOAA National Centers for Coastal Ocean Science
Peter Auster – NOAA National Undersea Research Center, University of Connecticut
Tim Battista – NOAA National Centers for Coastal Ocean Science
Randy Clark – NOAA National Centers for Coastal Ocean Science
Bryan Costa – NOAA National Centers for Coastal Ocean Science
Arthur Desch – NOAA National Centers for Coastal Ocean Science
Ian Hartwell – NOAA National Centers for Coastal Ocean Science
Ben Haskell – NOAA Stellwagen Bank National Marine Sanctuary
Jamie Higgins – NOAA National Centers for Coastal Ocean Science
Sarah Davidison Hile – NOAA National Centers for Coastal Ocean Science
Falk Huetmann – University of Alaska, Fairbanks
Robert Kenney – University of Rhode Island
Craig MacDonald – Stellwagen Bank National Marine Sanctuary
Jim Manning – NOAA Northeast Fisheries Science Center
Andrew Mason – NOAA National Centers for Coastal Ocean Science
Kevin McMahon – NOAA National Centers for Coastal Ocean Science
Mark Meyers – NOAA Northwest Fisheries Science Center
Mark Monaco – NOAA National Centers for Coastal Ocean Science
Connie Moy – NOAA National Centers for Coastal Ocean Science
Simon Pittman – NOAA National Centers for Coastal Ocean Science
Rachael Reed – Calvin College
Dave Wiley – NOAA Stellwagen Bank National Marine Sanctuary

EXECUTIVE SUMMARY

The mission of NOAA's National Marine Sanctuary Program (NMSP) is to serve as the trustee for a system of marine protected areas, to conserve, protect, and enhance their biodiversity, ecological integrity, and cultural legacy while facilitating compatible uses. Since 1972, thirteen National Marine Sanctuaries, representing a wide variety of ocean environments, have been established, each with management goals tuned to their unique diversity. Extending from Cape Ann to Cape Cod across the mouth of Massachusetts Bay, Stellwagen Bank National Marine Sanctuary (NMS) encompasses 2,181 km^2 of highly productive, diverse, and culturally unique Federal waters (Figure 1). As a result of its varied seafloor topography, oceanographic conditions, and high primary productivity, Stellwagen Bank NMS is utilized by diverse assemblages of seabirds, marine mammals, invertebrates, and fish species, as well as containing a number of maritime heritage resources. Furthermore, it is a region of cultural significance, highlighted by the recent discovery of several historic shipwrecks. Officially designated in 1992, Stellwagen Bank became the Nation's twelfth National Marine Sanctuary in order to protect these and other unique biological, geological, oceanographic, and cultural features of the region.

The Stellwagen Bank NMS is in the midst of its first management plan review since designation. The management plan review process, required by law, is designed to evaluate, enhance, and guide the development of future research efforts, education and outreach, and the management approaches used by Sanctuaries. Given the ecological and physical complexity of Stellwagen Bank NMS, burgeoning anthropogenic impacts to the region, and competing human and biological uses, the review process was challenged to assimilate and analyze the wealth of existing scientific knowledge in a framework which could enhance management decision-making. Unquestionably, the Gulf of Maine, Massachusetts Bay, and Stellwagen Bank-proper are extremely well studied systems, and in many regards, the scientific information available greatly exceeds that which is available for other Sanctuaries. However, the propensity of scientific information reinforces the need to utilize a comprehensive analytical approach to synthesize and explore linkages between disparate information on physical, biological, and chemical processes, while identifying topics needing further study. Given this requirement, a partnership was established between NOAA's National Marine Sanctuary Program (NMSP) and the National Centers for Coastal Ocean Science (NCCOS) so as to leverage existing NOAA technical expertise to assist the Sanctuary in developing additional ecological assessment products which would benefit the management plan review process.

CCMA's Biogeography Team, recognized leaders in the field of ecological assessments, had the capability to provide the necessary analytical tools and skills to support the Stellwagen Bank NMS requirements. At the initiation of the project, CCMA met repeatedly with Sanctuary staff to discuss Sanctuary scientific needs and define a collaborative project commensurate with the scope, duration, and support of the partnership effort. As prescribed in the NMSP/NCCOS partnership agreement, CCMA staff worked closely with Sanctuary staff to plan the analytical approach, conduct the ecological characterization, interpret the results, and compile the findings into a report (Kendall and Monaco, 2003).

The Purpose

> *"Most reserve locations and boundaries were drawn by a political process that focused on economics, logistics, or public acceptance, while largely overlooking or ignoring how the complex ecology and biology of an area might be affected by reserve protection."* (Halpern and Warner, 2003).

Ensuring that National Marine Sanctuaries are an effective tool for conservation and management requires that the Sanctuary location and size adequately incorporates relevant marine ecology, oceanographic conditions, and anthropogenic impacts (Browman and Stergiou, 2004). NCCOS and the NMSP have committed to evaluating Sanctuary marine resources using biologically-based regional distribution patterns as part of the Sanctuary management plan review process. In the case of several existing Sanctuaries, this includes evaluating boundary modification as part of the management plan review.

The two fundamental principles implemented as part of the Biogeography Team's commitment to conducting an ecological characterization of Stellwagen Bank NMS included: 1) evaluating marine resource distribution patterns and trends based on an integrated biogeographic approach and 2) conducting the biogeographic assessment at a regional spatial scale relevant to the conditions being characterized.

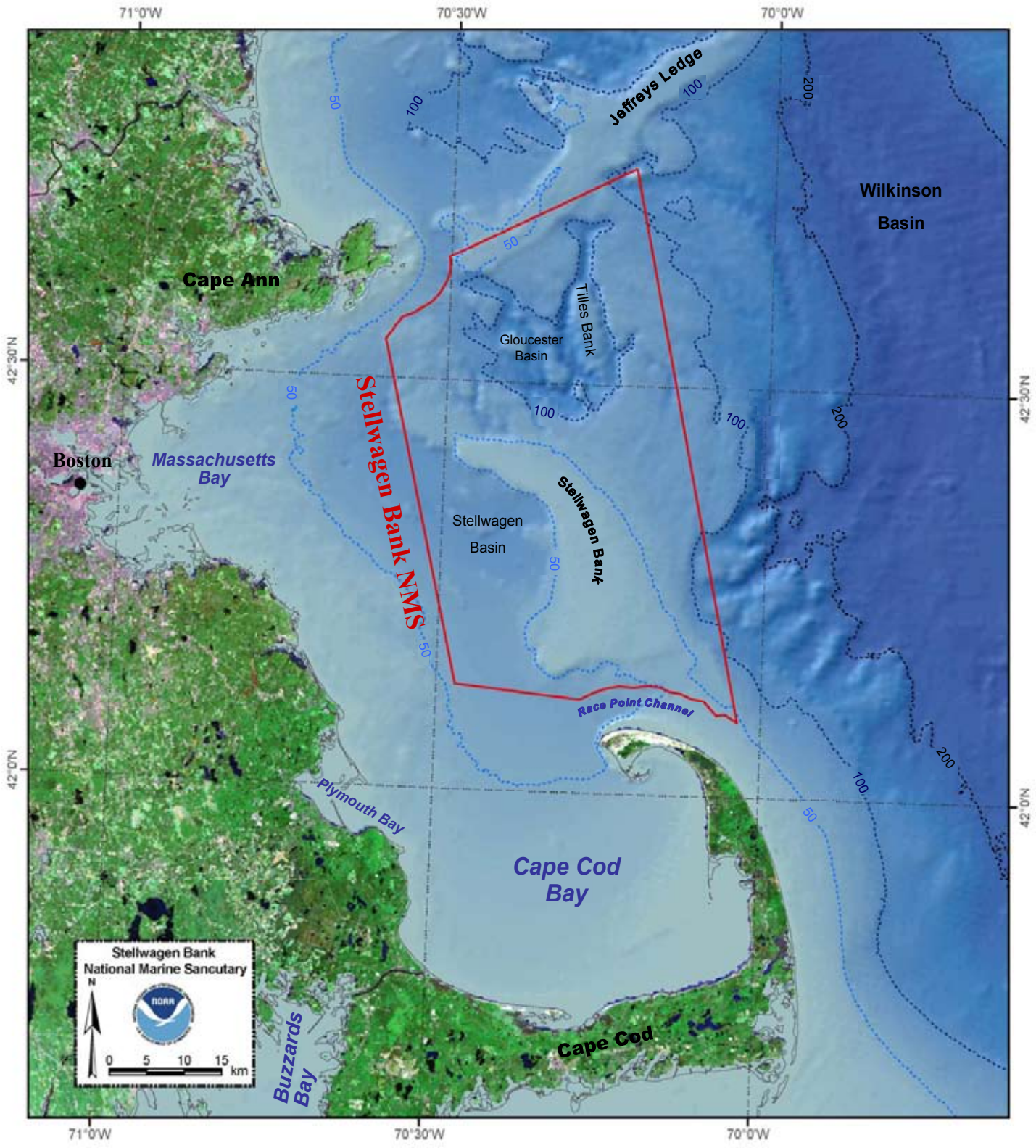


Figure 1. Boundary of Stellwagen Bank National Marine Sanctuary.

Biogeographic Analysis

Biogeographic analysis is an ideal tool for scientists and Sanctuary managers to evaluate biodiversity conservation and ecosystem integrity across the continuum of spatial and temporal scales. Completing a biogeographic assessment of the distribution of such resources within, across, and beyond the Sanctuary boundary is critical for understanding the Sanctuary within the wider ecological context and understanding how the ecosystem composition changes through time. Using the biogeographic approach, managers can explore potential changes in resource distribution that result from alternative management practices. For example, in Stellwagen Bank NMS this includes considering a relocation of the Boston Harbor shipping channel to reduce marine mammal vessel strikes, expansion of the Sanctuary boundary to encompass additional biological hotspots, and the refinement of monitoring efforts to overcome existing gaps in understanding and data coverage.

The biogeographic process is organized around the development of geospatial data layers, integrated analyses, and specific quantitative products to aid in resource management (Figure 2). Biogeographic data assembled and compiled for this product were derived from a wide range of sources including academia, Federal/State government, and data housed within the Stellwagen Bank NMS and Biogeography Program. Many of the data utilized for this project were compiled to explicitly address previous data gaps in understanding and coverage. For instance, remote sensing and GIS technologies were utilized to provide a comprehensive data set on oceanographic conditions (i.e. internal waves, water stratification, thermal fronts, and circulation patterns). Additionally, analyses on the distribution of several marine resources (i.e. seabirds, cetaceans, zooplankton and icthyoplankton) were made possible through extensive efforts to compile, integrate, effort-correct, and spatially enable previously disparate datasets gathered by various universities, NGOs, and Federal/State agencies.

The biogeographic data utilized for this project encompass, as completely as possible, the distribution of ecologically and economically important species and physical, biological, and chemical habitat variables influencing their distribution. All of these data were integrated into a GIS geodatabase using a common spatial framework at biologically-relevant spatial scales. The GIS geodatabase enables visualization of species' and community spatial and temporal patterns, and facilitates statistical manipulation and combination of information to produce relevant geospatial products. The production of spatially-explicit biogeographic analyses such as "hotspot" identification, mapping of community metrics, and development of spatial predictive species models are made possible only through the integration of statistics and GIS.

Regional Context

Due to the high mobility, temporal fluctuation, and dynamic nature of many of the biological and physical conditions within the Stellwagen Bank NMS, analysis of distribution patterns and ecological linkages must be conducted at a spatial scale which extends beyond the Sanctuary boundary. Ecologically meaningful patterns within Stellwagen Bank NMS are a subset of patterns that are largely determined by and extend throughout the Gulf of Maine. For example, research has shown that individuals of several protected species found within the Stellwagen Bank move extensively throughout the Gulf of Maine (Baumgartner and Mate, 2005). Therefore, evaluating the efficacy and effectiveness of management strategies and the relative importance of ecological hotspots within the Sanctuary is predicated on understanding the condition of resources and the broader spatial and temporal movements of animals throughout the region as a whole. This report considers the physical and biological phenomena at a scale including, but extending beyond the Sanctuary boundary, and then evaluates the results so as to explain conditions occurring within the Sanctuary.

When embracing ecosystem management practices, it is incumbent that management jurisdictions and regulatory policy must fully consider, encompass, and represent the ecosystem characteristics of the biogeographic region. The Gulf of Maine, a 93,239 km^2 semi-enclosed sea in the Northwest Atlantic Ocean, is a distinct biogeographical region (Figure 3) from surrounding Scotian Shelf, Georges Bank, and Southern New England regions based on oceanographic and ecological characteristics (e.g. water masses, patterns of primary production, geographic patterns of species assemblages) (Cook and Auster, 2006). There are four hydrographically distinct sub-regions in the Gulf of Maine each having unique physical, hydrographic, and oceanographic conditions: estuarine areas, coastal regions, the central Gulf, and shallow offshore Banks. Stellwagen Bank NMS is centrally located within the generally well-mixed coastal Gulf of Maine biogeographic region, but species abundance,

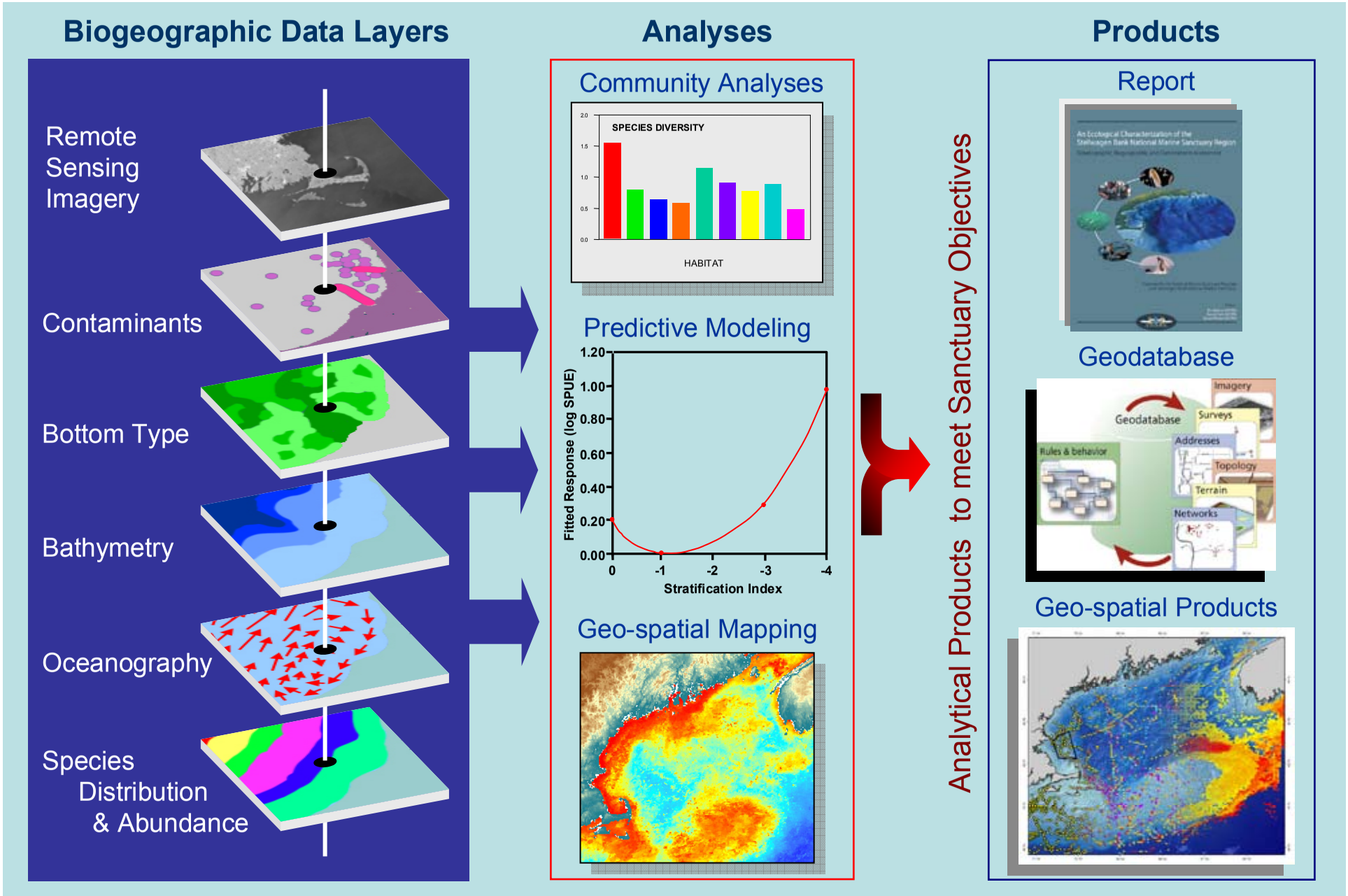


Figure 2. Generalized biogeographic approach used to study Stellwagen Bank National Marine Sanctuary.

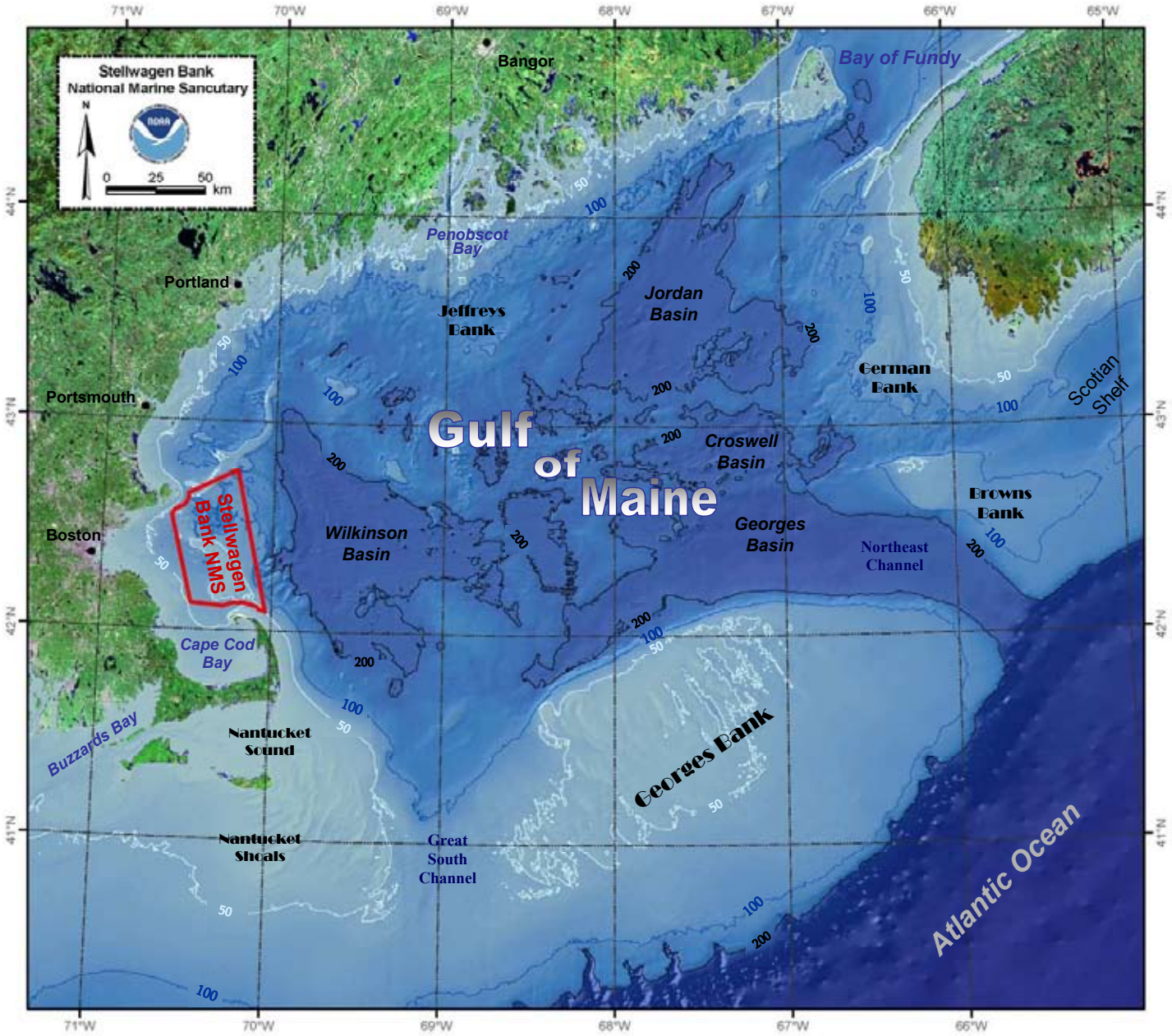


Figure 3. Gulf of Maine study region.

distribution, and population dynamics are strongly influenced by large spatial and temporal variability of physical conditions of the three other regions (Greene et al., 2004).

The success of exploring species spatial and temporal distribution, population shifts, and understanding physical oceanographic phenomena is largely determined by the quality of data being analyzed. Limitations of data within Stellwagen Bank NMS therefore needed to capture dynamics throughout the entire Gulf of Maine to develop environmental linkages which could then be used to explain the broad-scale patterns Gulf of Maine-wide and trends occurring with the Sanctuary proper. For instance, traditionally, cetacean and seabird sightings data have been represented as digital and non-digital distribution maps (atlases) using spatially aggregated observations, mean monthly density in large spatial grids, or summarized data represented as contours of relative abundance. While the “atlas” approach has made a valuable contribution to the understanding of broad-scale spatial patterns of seabirds, few studies have attempted to link the spatial and temporal patterns of seabirds and cetaceans to the surrounding environment at each location. Furthermore, the spatial resolution of these types of maps is coarse, and predictions are usually discontinuous due to limited sampling effort.

Natural and anthropogenically induced variability in environmental condition is an important component in determining the resilience and productivity of marine ecosystems. Long-term re-structuring of species assemblages are controlled by broad scale trends in environmental condition occurring at decadal or greater temporal scales (e.g. water stratification, North Atlantic Oscillation), whereas high amplitude shorter frequency variations (e.g. food availability, recruitment) induce local instabilities or distribution shifts of biological components (Sissenwine and Murawski, 2004). Understanding how well Stellwagen Bank NMS represent the diversity of species present within and among the Gulf of Maine biogeographic region is critical for assessing the conservation value of marine resources and identifying gaps in the protection of biological diversity (Auster and Shackell, 2000). Through the development of sophisticated modeling techniques, it is now possible to link the distribution and abundance of biota quantitatively and temporally with the multi-dimensional environment at specific locations. This approach has the additional desired benefit of being able to analyze natural and anthropogenic changes occurring outside Stellwagen Bank NMS which will ultimately affect distributions found within the Sanctuary.

This Document

The scientific team for this project represents an unparalleled depth and breadth of expertise. CCMA's collaboration with Stellwagen Bank NMS and academic experts offered a previously uncapitalized opportunity to integrate a wide range of expertise both within the Center, as well as outside experts. The project provided an opportunity to integrate the capabilities of CCMA's Biogeography an Coastal and Oceanographic Assessment Status and Trends teams into a unified, interdisciplinary product. The extent of the teaming approach is reflected in the diversity of topics, size, and scope of the products. The report, map products, and geodatabase provide managers and scientists with a suite of analyses and information that, when coupled with pre-existing Sanctuary geospatial information, enables improved research, monitoring, and analysis activities within the Stellwagen Bank NMS region.

This report provides a series of science-based ecological studies that together offer a regional characterization of the Gulf of Maine based on the coupling of physical-chemical-biological processes. The modeling of ecological linkages implemented for this project has been demonstrated to be a valuable tool in advancing our knowledge and identifying the gaps in understanding of the many complex processes that dictate the overall ecosystem dynamics of the Gulf of Maine. This product would not have been possible without the critical step of peer review and contributions from a number of experts.

The following is an abbreviated executive summary of each of the five detailed chapters contained in the Ecological Characterization of Stellwagen Bank National Marine Sanctuary region:

Physical and Oceanographic Setting

Stellwagen Bank is a partial boundary between Massachusetts Bay and the Gulf of Maine. As such it affects the conditions within Massachusetts Bay, and to a lesser extent, conditions in adjacent waters in the Gulf of Maine. The water properties in the vicinity of Stellwagen Bank are determined in part by the large scale counter-clockwise circulation pattern and seasonal density layers within the Gulf of Maine. Oceanographic features on the Bank itself are primarily related to the strong tidal currents driven by an approximately three meter tidal range. These tidal currents interact directly with the sediments on the Bank, limiting accumulation of fine sediments. Tidal flows over the shallow Bank generate relatively large currents and during stratified periods internal waves (both stationary lee waves and propagating waves) result from these currents. All of these physical phenomena have the potential to enhance the flux of nutrients into the upper layer during periods of stratification, and thereby contribute to the high levels of productivity found in the region of the Bank. Additional nutrients may be supplied to the surface layers in the vicinity of the Bank by the tidal flow of water up the slopes of the Bank. In conjunction with the shallow depth, these currents may generate sufficient turbulence to mix nutrient rich water into the surface layer. The water column is generally stratified during the period from late spring through early fall, when light is maximum. Seasonal stratification suppresses water column mixing, contributing to the depletion of nutrients in the upper layer of the water column. Energetic tidal currents at the Bank overcome stratification, and thus lead to enhanced productivity. Strong primary productivity during the spring and fall promote rich secondary production which in turn fuels the ecologically diverse pelagic and benthic ecosystems. From a management and ecological perspective, it is necessary to understand the large-scale oceanographic patterns and how they influence the smaller-scale management unit of the Sanctuary. The Physical and Oceanographic Setting chapter contained

within this report synthesizes and summarizes the wealth of scientific information for the large-scale ecosystem and its implications to the oceanographic patterns observed within the Sanctuary.

Characterization of Chemical Contaminants

The status and trends of trace elements and organic contaminants in Massachusetts Bay as whole were assessed with the objective of investigating export of contaminants to the system. The foregoing assessment was conducted using contaminant concentrations in both sediment and tissue (mussels and fish). The current status of chemical contaminants in the shallow portions of Stellwagen Bank is significantly lower than those of the other region of Massachusetts Bay including Cape Cod Bay. Boston Harbor is the most polluted zone of the Massachusetts Bay/Cape Cod system. Sediments in the deep areas in Stellwagen Basin are accumulating contaminants from a variety of sources. The temporal assessment revealed no statistically significant trends for trace metals and PAHs, while banned, but persistent organic contaminants (DDTs and chlordanes) show very slow decreasing trends over the monitoring years. The persistence of some organic compounds at relatively high concentrations in Boston Harbor, implies that the Harbor may be a continuing source of contaminants to other areas of Massachusetts Bay. However, data in the current study indicates that pollution impacts in the Stellwagen Bank National Marine Sanctuary appear minimal. There is no indication that relocation of the Publicly Owned Treatment Works (POTW) effluent has had short term consequences on the magnitude of export of contaminants from Boston to Stellwagen Bank NMS. That is not to say that contaminant export from Boston is not occurring, only that it does not appear to have accelerated. Discharge reductions from improved sewage treatment efficiencies implemented by the Massachusetts Water Resources Authority have definitely aided in this regard.

Marine Fishes

The Gulf of Maine has 652 documented species. The large diversity of marine fishes is attributed to the proximity of the region situated between the Acadian and Virginian biogeographic regions. Seasonal shifts in temperature and productivity facilitate the mixing of northern and southern migrants, as well as on-shelf movements of slope and deep sea species. Stellwagen Bank NMS (and the Gulf of Maine) is dominated by resident species and species composition is seasonally affected. Additionally, a wide diversity of habitats and oceanographic conditions promote a diverse assemblage of species within the Sanctuary. Species diversity metrics were highly variable throughout the region and show that areas of ecological significance are not consistent spatially and/or temporally and are indicative of dynamic continental shelf fish communities. The Sanctuary's high productivity is depicted as an area of high larval fish abundance, which is directly influenced by the oceanography of the region which facilitates high primary productivity. The wide diversity of habitats supports many species within a variety of trophic guilds of commercial or recreational relevance, such as cod and haddock. Several species within the Sanctuary are listed as a species of concern under the Endangered Species Act. Lastly, several species are abundant within the Sanctuary, but have limited distribution within the Gulf of Maine, (i.e. alligatorfish and snake blenny). The Sanctuary is also an important spawning ground for sand lance, an important prey item for many bird and mammals species.

Seabirds Distribution and Diversity

Seabirds form an important ecological component of the Gulf of Maine ecosystem and their broad-ranging movements, longevity and sensitive dependence on fish prey make them useful bioindicators of ecosystem condition and change. The Gulf of Maine region including Stellwagen Bank has been recognized locally and internationally as an important area for seabirds, some of which have traveled many thousands of kilometers to utilize the rich food resources of the region. Areas with a high abundance and richness of seabirds are often considered of special interest in marine resource management strategies and in the design of marine protected areas (MPAs) or networks of MPAs. Determining which areas of the open ocean are most important to seabirds requires quantitative information on the spatial and temporal distribution of seabird species. This report describes the summer and winter distributions of several seabird species across the Gulf of Maine, with special emphasis on Stellwagen Bank. Novel regression tree techniques were applied to develop predictive spatial models and to quantitatively link the presence of seabirds with their environment, including data on sea surface conditions and bathymetry. We produced both effort-corrected presence maps and predictive maps of species occurrence for selected seabird species. Of the birds included in this study, sightings data indicated that non-breeding summer migrants (Greater Shearwater and Wilson's Storm-petrel) were most prevalent within Sanctuary waters. At the scale of the Gulf of Maine, bathymetric features such as the coastline, the nearshore slopes along the northern sections of the Gulf of Maine, as well as bathymetric features such as Georges Bank, the Great South Channel, the Northeast Channel, and the waters offshore from the southern tip of Nova Scotia appear to represent distinct

features supporting a high diversity and abundance of seabirds. Overall, depth and sea surface temperature were the most important predictors. This information can be used to identify potential ecological hotspots and coldspots of occurrence both inside and outside the Sanctuary for both summer months and winter months.

Cetacean Distribution and Diversity

The southern Gulf of Maine provides essential resources for approximately 13 species of whale and dolphin, several of which are endangered species. Stellwagen Bank represents a high-use area for many of the endangered large whales, yet relatively few studies have attempted to explain quantitatively the spatial and temporal distribution patterns for these populations over such a broad geographical area. For this report we first quantified and described seasonal spatial patterns of relative abundance for individual species of cetaceans, and for all large whales combined and all dolphins/porpoises combined. We then developed a spatially-explicit modeling approach for exploring cetacean-environment linkages using a wide range of environmental data with varying spatio-temporal resolutions. We incorporated both relatively static features, such as derivatives of bathymetric structure and relatively dynamic variables, such as prey abundance, sea surface conditions and water column structure (stratification).

Patterns of abundance revealed that some geographic areas consistently exhibited high abundance of multiple cetacean species, but that individual species exhibited distinctive spatio-temporal patterns across seasons. Our methods allowed us to rank the importance of individual environmental variables and in general, we found that static features, most notably the 100 m isobath, were better predictors of cetacean distribution patterns than were dynamic features, such as sea surface temperature and chlorophyll a concentration. The shoals and slope waters adjacent to the 100 m isobath including Stellwagen Bank and Jeffreys Ledge were identified as key high-use areas for all abundant cetacean species in the southern Gulf of Maine. Information on the specific environmental characteristics of high-use areas combined with maps of relative abundance provide useful ecological insights and essential baseline information to support individual species management and ecosystem-based management.

REFERENCES

Auster, P. and N. Shackell. 2000. Marine protected areas for the temperate and boreal North Atlantic: the potential for sustainable fisheries and conservation of biodiversity. Northeastern Naturalist. 7:419-434.

Baumgartner, M.F. and B.R. Mate. 2005. Summer and fall habitat of North Atlantic right whales (*Eubalaena glacialis*) inferred from satellite telemetry. Canadian Journal of Fisheries and Aquatic Sciences 62:527-543.

Browman, H. and K. Stergiou. 2004. Marine protected areas as a central element of ecosystem-based management: defining their location, size, and number. Marine Ecology Progress Series. 274:271-272.

Cook, R. and P. Auster. 2006. A bioregional classification for the continental shelf of the northeastern North America for conservation analysis and planning based on representation. Marine Sanctuaries Conservation Series NMSP-06-09. National Oceanic and Atmospheric Administration, National Marine Sanctuary Program. Silver Spring, MD. 12 pp.

Greene, C., A. Pershing, B. Monger, M. Benfield, E. Durbin, and M. Casas. 2004. Supply-sided responses of climate-driven changes in North Atlantic Ocean. Oceanography. 17:60-71

Halpern, B. and R. Warner. 2003. Matching marine reserve design to reserve objectives. Proceedings of the Royal Society of London. Series B, Biological Science. 270:1871-1878.

Kendall, M. and M. Monaco. 2003. Biogeography of the National Marine Sanctuaries. NCCOS Technical Report. National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science. Silver Spring, MD. 15 pp.

Sissenwine, M. and S. Murawski. 2004. Moving beyond 'intelligent tinkering': advancing an Ecosystem Approach to Fisheries. Marine Ecological Progress Series. 274:291-295.

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