Office of National Marine Sanctuaries
National Oceanic and Atmospheric Administration
NATIONAL MARINE SANCTUARIES CONSERVATION SCIENCE SERIES

Relevance of the Northeast Integrated Ecosystem Assessment for the Stellwagen Bank National Marine Sanctuary Condition Report (2007-2017)

November 2019 | sanctuaries.noaa.gov | National Marine Sanctuaries Conservation Science Series ONMS-19-08

Suggested Citation:
Pittman, S.J. 2019. Relevance of the Northeast Integrated Ecosystem Assessment for the Stellwagen Bank National Marine Sanctuary Condition Report (2007-2017). Marine Sanctuaries Conservation Science Series ONMS-19-08. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 44 pp.

Cover image: Stellwagen Bank National Marine Sanctuary is home to a variety of ecologically and economically important species. Image: Simon J. Pittman

U.S. Department of Commerce
Wilbur Ross, Secretary

National Oceanic andAtmospheric Administration
Neil A. Jacobs, Ph.D.
Assistant Secretary of Commerce for Environmental Observation and Prediction

National Ocean Service
Nicole LeBoeuf, Assistant Administrator (Acting)

Office of National Marine Sanctuaries
John Armor, Director

Report Authors:

Simon J. Pittman[1,2]

[1]Biogeography Branch, Marine Spatial Ecology Division, National Centers for Coastal Ocean Science, National Oceanic and Atmospheric Administration, Silver Spring, Maryland 20910, USA

[2]Seascape Analytics Ltd., Plymouth PL2 1RP, United Kingdom

About the National Marine Sanctuaries Conservation Series

The Office of National Marine Sanctuaries, part of the National Oceanic and Atmospheric Administration, serves as the trustee for a system of underwater parks encompassing more than 600,000 square miles of ocean and Great Lakes waters. The 14 national marine sanctuaries and two marine national monuments within the National Marine Sanctuary System represent areas of America's ocean and Great Lakes environment that are of special national significance. Within their waters, giant humpback whales breed and calve their young, coral colonies flourish, and shipwrecks tell stories of our nation's maritime history. Habitats include beautiful coral reefs, lush kelp forests, whale migration corridors, spectacular deep-sea canyons, and underwater archaeological sites. These special places also provide homes to thousands of unique or endangered species and are important to America's cultural heritage. Sites range in size from less than one square mile to almost 583,000 square miles. They serve as natural classrooms and cherished recreational spots, and are home to valuable commercial industries.

Because of considerable differences in settings, resources, and threats, each marine sanctuary has a tailored management plan. Conservation, education, research, monitoring, and enforcement programs vary accordingly. The integration of these programs is fundamental to marine protected area management. The Marine Sanctuaries Conservation Series reflects and supports this integration by providing a forum for publication and discussion of the complex issues currently facing the sanctuary system. Topics of published reports vary substantially and may include descriptions of educational programs, discussions on resource management issues, and results of scientific research and monitoring projects. The series facilitates integration of natural sciences, socioeconomic and cultural sciences, education, and policy development to accomplish the diverse needs of NOAA's resource protection mandate. All publications are available on the Office of National Marine Sanctuaries website (http://www.sanctuaries.noaa.gov).

Disclaimer

Report content does not necessarily reflect the views and policies of the Office of National Marine Sanctuaries or the National Oceanic and Atmospheric Administration, nor does the mention of trade names or commercial products constitute endorsement or recommendation for use.

Report availability

Electronic copies of this report may be downloaded from the Office of National Marine Sanctuaries website at http://sanctuaries.noaa.gov.

Contact

Simon J. Pittman
Director
Seascape Analytics Ltd.
13 Haddington Road
Plymouth PL2 1RP, United Kingdom

sjpittman@gmail.com

Table of contents

Abstract

The Office of National Marine Sanctuaries recognize the strategic importance of assessing the conditions and trends within sanctuary waters relative to the conditions and trends observed at broader geographical scales. This report provides a synthesis of existing data from a wide variety of sources on the condition and trends for the Gulf of Maine region within which Stellwagen Bank National Marine Sanctuary is located. Data compiled for the Northeast Integrated Ecosystem Assessment form a major contributor to the information in this report. The report was commissioned to support the latest condition report for Stellwagen Bank National Marine Sanctuary with a focus on changes in ecological conditions in the water quality, habitat quality, and living resources that have occurred in the Gulf of Maine since the last condition report in 2006.

Key words

ecosystem-based management, indicators, environmental change, seascape context, marine protected areas, Gulf of Maine, habitat quality

Chapter 1

BACKGROUND

NOAA is conducting a multi-line office data synthesis initiative (FY16-18) called the Integrated Ecosystem Assessment (IEA) Program for the Northeast U.S. Continental Shelf (Cape Hatteras to the northern Gulf of Maine. The program has assembled an extensive body of physical, ecological, and socioeconomic indicators and a wide range of ecosystem models for this region with the purpose of enabling regional ecosystem-based management. The IEA process is an iterative and flexible stepwise approach involving the following steps: defining ecosystem goals, assessing the status of ecosystem indicators and attributes, analyzing risk, and evaluating the likely outcomes and trade-offs among alternative management strategies (Fig. 1). The IEA framework was designed to provide a more holistic approach to assimilate scientific knowledge in a format suitable for providing advice to inform marine ecosystem-based management (Harvey et al. 2017). One of the key strengths of the IEA process in practice is its role in assimilating, standardizing, and maximizing the value of the vast amount of available information about a marine ecosystem (Levin et al. 2009).

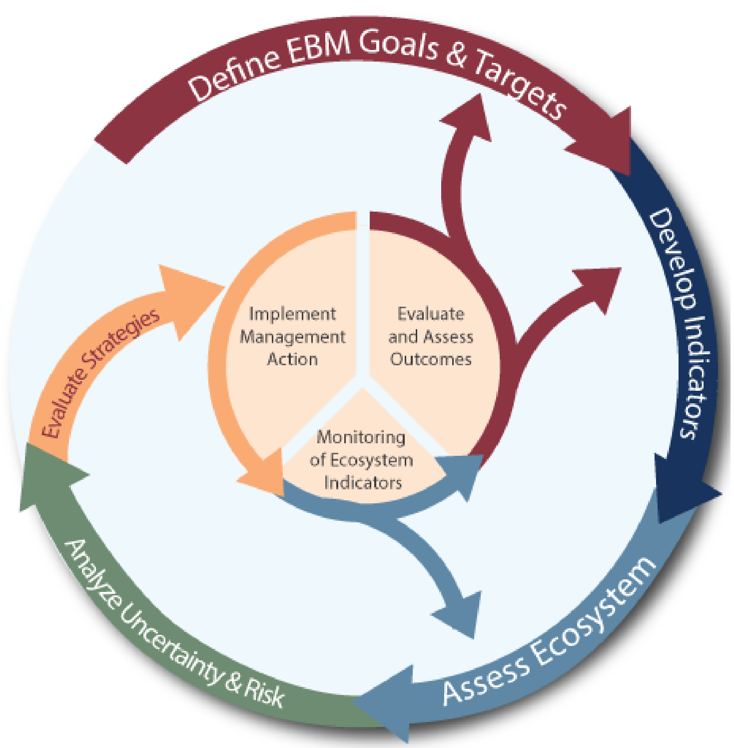

Figure 1. Conceptual model for the IEA process. Image: Samhouri et al. 2014

The data analysed through the Northeast IEA process are of interest to Stellwagen Bank National Marine Sanctuary because the sanctuary is located within the Gulf of Maine subregion of the Northeast IEA focus area (Fig. 2). It is becoming increasingly clear that strong linkages exist between water conditions, nutrient cycling, and biological population dynamics across the Gulf of Maine region. This suggests that the entire Gulf varies as a cohesive interconnected ecological unit within which Stellwagen Bank National Marine Sanctuary is a significant management area. The sanctuary recognizes the strategic importance of assessing the conditions and trends within sanctuary waters relative to the conditions and trends observed at broader geographical scales (i.e., the surrounding Gulf of Maine region). This information need was specifically recognized (Goal 1, Objective 5) in the Northeast IEA proposal with the aim of providing IEA data and products to support development of quantitative metrics for the Stellwagen Bank National Marine Sanctuary condition report. The condition report poses questions related primarily to water quality, habitat quality, and living resources, followed by identification of human activities that influence condition (Table 1).

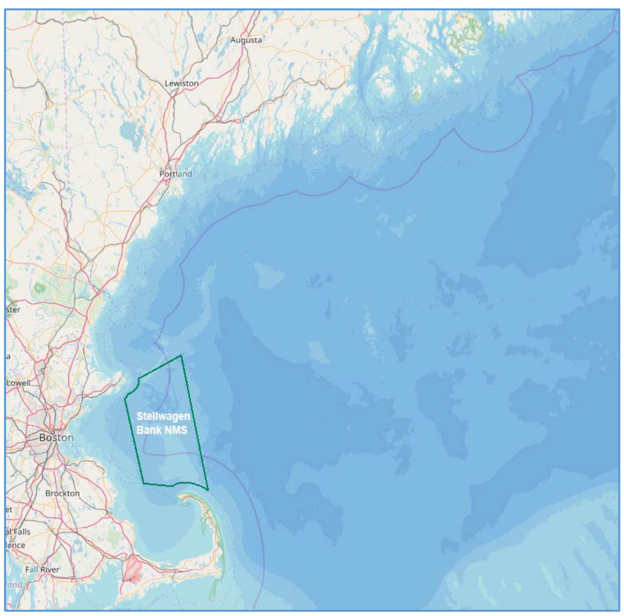

Figure 2. Stellwagen Bank National Marine Sanctuary is located within the Gulf of Maine sub-region of the Northeast Integrated Ecosystem Assessment focus area. Image: Seascape Analytics

In April 2017, NOAA's Northeast Fisheries Science Center released the first major synthesis emerging from the Northeast IEA process in the report "State of the Ecosystem-Gulf of Maine and Georges Bank." The purpose of the report was to provide ecosystem-scale information for fishery managers through tracking of trends and reporting of interconnections in a diverse set of indicators.

On August 10, 2017, scientists from NOAA's National Centers for Coastal Ocean Science (NCCOS) Biogeography Branch and NOAA's Office of National Marine Sanctuaries met to discuss the data needs for the next Stellwagen Bank National Marine Sanctuary condition report. The following tasks emerged from the discussion.

Tasks of the initial report:

Task 1: Identify and document IEA data relevant to each question of the condition report, focusing primarily on changes to water quality, habitat, and living resources since the last condition report (2006).
Task 2: Identify any regional trends in biophysical conditions detected or forecast.
Task 3: Identify and document any relevant knowledge gaps and potential caveats in the IEA data.

Table 1. Questions addressed by the condition report. In placing the sanctuary within a broader regional context, this report replaces the word sanctuary with *regional* in the following questions. Note: Maritime archaeological resources were not adequately addressed by IEA data.

Section	2017 question
Water quality	Q1 – What is the eutrophic condition of regional waters and how is it changing? Q2 – Do regional waters pose risks to human health and how are they changing? Q3 – Have recent changes in climate altered water conditions and how are they changing? Q4 – Are other stressors, individually or in combination, affecting water quality, and how are they changing? Q13 – What are the levels of human activities that may adversely influence water quality and how are they changing?
Habitat quality	Q5 – What is the integrity of major habitat types and how is it changing? Q6 – What are contaminant concentrations in regional habitats and how are they changing? Q14 – What are the levels of human activities that may adversely influence habitats and how are they changing?
Living resources	Q7 – What is the status of keystone and foundation species and how is it changing? Q8 – What is the status of other focal species and how is it changing? Q9 – What is the status of non-indigenous species and how is it changing? Q10 – What is the status of biodiversity and how is it changing? Q15 – What are the levels of human activities that may adversely influence living resource quality and how are they changing?

Chapter 2

WATER QUALITY

Q1: What is the eutrophic condition of regional waters and how is it changing?

Eutrophication is an ecosystem response to increases in nutrient inputs such as nitrogen and phosphorus, typically from human sources. Nearshore coastal waters of the Gulf of Maine receive nutrients from land-based sources, aquaculture, atmospheric deposition, and oceanic upwelling and circulation. Nutrients influence the growth of benthic plants, phytoplankton, and other bloom forming organisms such as dinoflagellates and bacteria, with consequences through the food chain. Upwelled waters mix with Scotian Shelf waters and with runoff and riverine plumes to form the Maine Coastal Current, which make the region highly productive (GOMC 2010). Fluxes of offshore water masses and their nutrient loads are the major source of nutrients for phytoplankton production in the region, including annual blooms of the toxic dinoflagellate *Alexandrium fundyense*. Since the 1970s, the Gulf of Maine has been experiencing a changing nutrient regime thought to be influenced by increasing colder and fresher water from the Arctic with lower nitrate (NO_3) but higher silicate ($Si(OH)_4$) concentrations (Townsend et al. 2010) affecting the magnitude of blooms (Townsend et al. 2014). Therefore, through water circulation and nutrient recycling the conditions at the scale of the Gulf of Maine will influence the water nutrient and productivity patterns observed within Stellwagen Bank National Marine Sanctuary.

Using methods described by Hak & Comer (2017), coastal landscape condition was evaluated and mapped by NatureServe for the Gulf of Maine revealing an area of relatively low condition index value for coastal watersheds in the southwest Gulf of Maine. The index reflects the extensive level of human-altered landscape and source of pollution in the terrestrial coastal areas closest to Stellwagen Bank National Marine Sanctuary. In Liebman et al. (2012), however, water quality sampling conducted in nearshore waters indicated that the southern Gulf of Maine waters (using National Coastal Assessment methods) are classified as good-fair quality for dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorous (DIP), and chlorophyll *a* concentration. When frequency of occurrence and spatial coverage are also integrated with concentration as an indicator of eutrophication then Casco Bay, Maine; Plum Island Sound, Massachusetts; Massachusetts Bay; and Cape Cod Bay are considered to have a high level of chlorophyll *a* that has increased since 1999. Cape Cod Bay has also experienced an increase in macroalgae since 1999 (Liebman et al. 2012). In Great Bay, macroalgae have replaced 6% of seagrass meadows between 1996 and 2007, specifically in areas of high nitrogen concentrations (NHDES 2009). The summary of combined information from the NOAA and Environmental Protection Agency (EPA) assessments for hypoxic conditions between 2000 and 2006 show no to low occurrence of low dissolved oxygen in the bays and estuaries of the southwest Gulf of Maine.

Q2: Do regional waters pose risks to human health and how are they changing?

Harmful algal blooms

Several harmful algal bloom (HAB) species occurring within the Gulf of Maine system are known to produce neurotoxins that have the potential to threaten human and ecosystem health (Li et al. 2011). Much progress has been made in forecasting and monitoring HABs in the Gulf of Maine. Annual forecasts (weekly in spring & summer) are issued based on the distribution of cysts of nuisance toxic dinoflagellate species, *Alexandrium fundyense*, a primary cause of paralytic shellfish poisoning in the Gulf of Maine (Thomas et al. 2010). In 2008, the first seasonal forecast for paralytic shellfish poisoning in the Gulf of Maine was issued and correctly predicted a large toxic bloom, resulting in closures for shellfish harvesting in the western Gulf of Maine as far south as Cape Cod. Compiled maps of historical shellfish harvesting closures and duration of closures are also a valuable source of data to understand the spatial and temporal trends in toxic bloom events (Kleindinst et al. 2014).

Between 1978 and 2011, records for the entire Gulf of Maine indicate a combined total of closure days amounting to over 13 years duration. Closure records for the western Gulf of Maine during the five years prior (2001-2005) to the publication of the Stellwagen Bank National Marine Sanctuary condition report (2006) indicate that an estimated 872 km of coastline was closed to shellfish harvesting with a total summed closure duration of 585 days. In the following five years (2007-2011), an estimated 1260 km of coastline was closed with a total duration of 493 days (Kleindinst et al. 2014).

Surveys of *A. fundyense* cysts in surface sediments ("seedbeds") reveal that a major expansion of the mid-coast Maine seedbed occurred in 2009 following an intense red tide bloom (Anderson et al. 2014) that impacted the southwestern Gulf of Maine as far south as Stellwagen Bank National Marine Sanctuary (Figs. 3A, B). Changes in regional-scale water conditions, however, suppressed the magnitude of the bloom in 2010 (Fig. 3C). Near-surface waters were warmer, fresher, and more stratified with lower nutrients than expected and a weaker-than-normal coastal current lessened *A. fundyense* transport into the western Gulf of Maine and Massachusetts Bay (McGillicuddy et al. 2011). This highlights the importance of considering changes to Gulf-of-Maine-wide oceanographic processes in understanding the conditions within Stellwagen Bank National Marine Sanctuary.

Blooms of the toxic marine diatom *Pseudo-nitzschia* spp. have also increased in the Gulf of Maine, including in the region of Stellwagen Bank and Cape Cod (Fig. 4). More than 14 *Pseudo-nitzschia* species have been identified in the Gulf of Maine, of which seven are known to produce the neurotoxin domoic acid. Domoic acid which accumulates in filter-feeding bivalves and fish and can cause amnesic shellfish poisoning in humans or domoic acid poisoning in marine mammals, seabirds, and some fish (Fernandes et al. 2014).

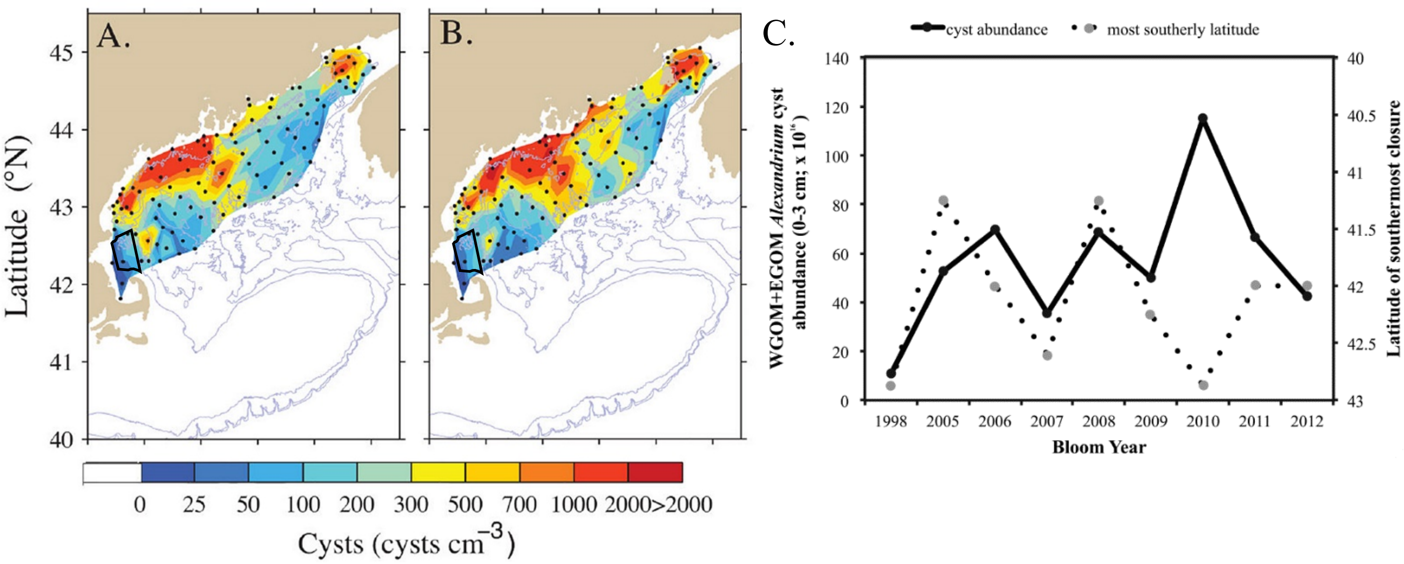

Figure 3. Multi-year (2004-2011) mean cyst abundance (*A. fundyense*) in: (A) surface (0-1 cm) sediment layer, and (B) 1-3 cm sediment layer. (C) Time-series of cyst abundance (cysts × 10^{16}) in the western Gulf of Maine (WGOM) and the latitude of southernmost closure the following year (note axis reversal). Images: Anderson et al. 2014

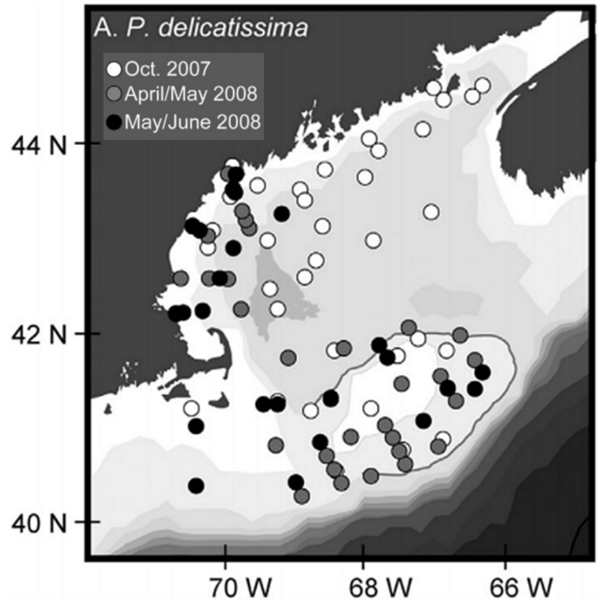

Figure 4. Samples collected (2007-2008) with presence of toxic diatom *Pseudo-nitzschia delicatissima.* Image*:* Fernandes et al. 2014

Q3: Have recent changes in climate altered water conditions and how are they changing?

Water temperature

The 2017 summary of conditions for the Northeast Continental Shelf provided by NOAA's Northeast Fisheries Science Center (NEFSC) concludes that sea surface temperatures continue to be above average, with 2016 the second warmest year on record after 2012 (Fig. 5A). A trend of increasing area of warm (16-27°C) water habitat in recent years has been estimated, and decreasing area of cool (5-15°C) water has occurred since 1980 (Figs. 5B, C). A 33-year (1982-2014) time series of sea surface temperature data indicates an increased trend of warming (>0.4°C decade–1) waters in the Gulf of Maine with significant trends towards earlier summer starts, later summer ends, and longer summer duration over the entire study region (Thomas et al. 2017).

Temperature strongly influences both the physical conditions in the region (driving ocean circulation) and biological distributions through the influence of temperature on biological rates. In response to warming, many fish and invertebrate species have moved to cooler northern waters and cooler deeper waters (see "living resources" section). High-resolution climate models predict further substantial changes to the distribution of suitable thermal habitat for many marine species.

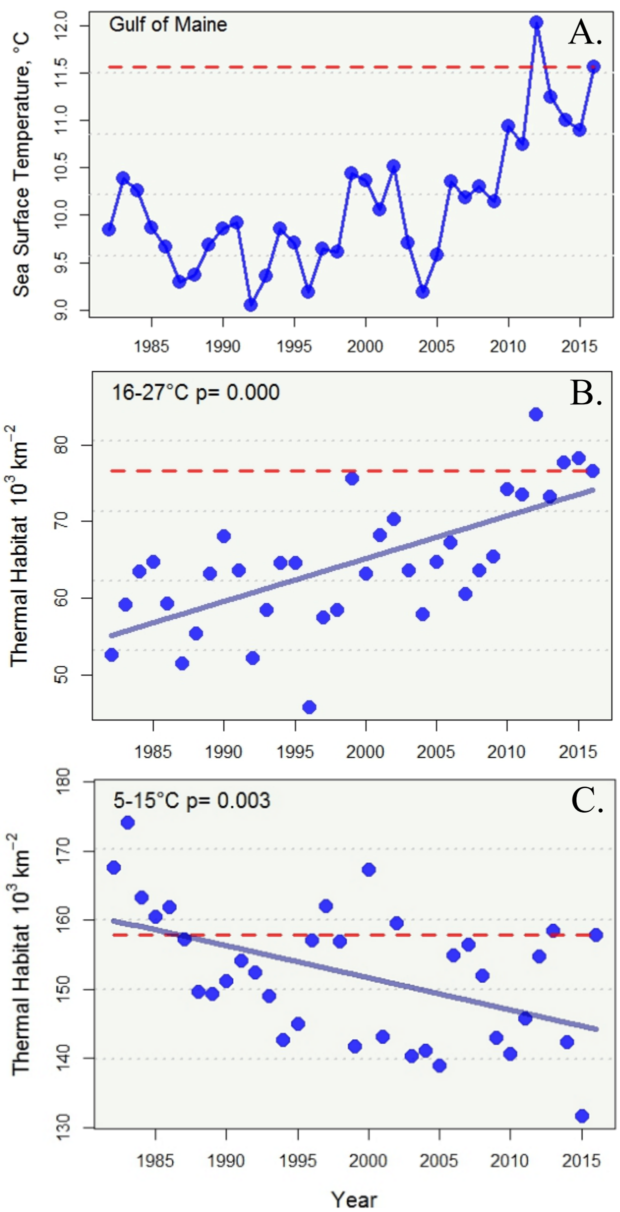

Figure 5. (A) Thermal change in the waters of the Gulf of Maine region (1980 – 2016); (B) increase in area of warm waters; (C) decrease in area of cool waters. Image: State of the Ecosystem report, NOAA NEFSC

At broader temporal scales, the effect of North Atlantic Oscillation on surface waters appears to exhibit a four-year time lag, whereas a two-year time lag has been observed for deeper waters entering the Gulf of Maine (Xu et al. 2015). Furthermore, although decadal fluctuations are well-documented, the late 1980s experienced an abrupt warming resulting in the reported climate regime shift (Lo & Hsu 2010), representing a major change in the Earth's biophysical systems from the upper atmosphere to the depths of the ocean (Reid et al. 2016).

The strength of temperature fronts has increased in the Gulf of Maine since 2009 (Fig. 6).

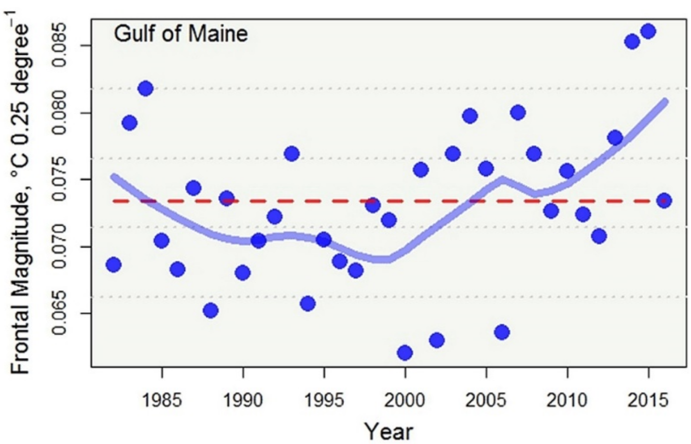

Figure 6. Frontal magnitude in the Gulf of Maine. Blue line is a smoothed time series fitted trend. Red dashed lined indicates the 2016 data. Image: State of the Ecosystem report, NOAA NEFSC

Stratification

Stratification refers to the vertical stacking of layers of water of different densities at different depths within the water column. Variations in the timing and magnitude of stratification play a role in driving changes in the seasonal cycles of nutrients, plankton, and higher-trophic-level consumers (Greene et al. 2012). Hydrographic measurements made by NEFSC represent the most comprehensive ongoing shelf-wide record of hydrographic measurements on the Northeast U.S. continental shelf.

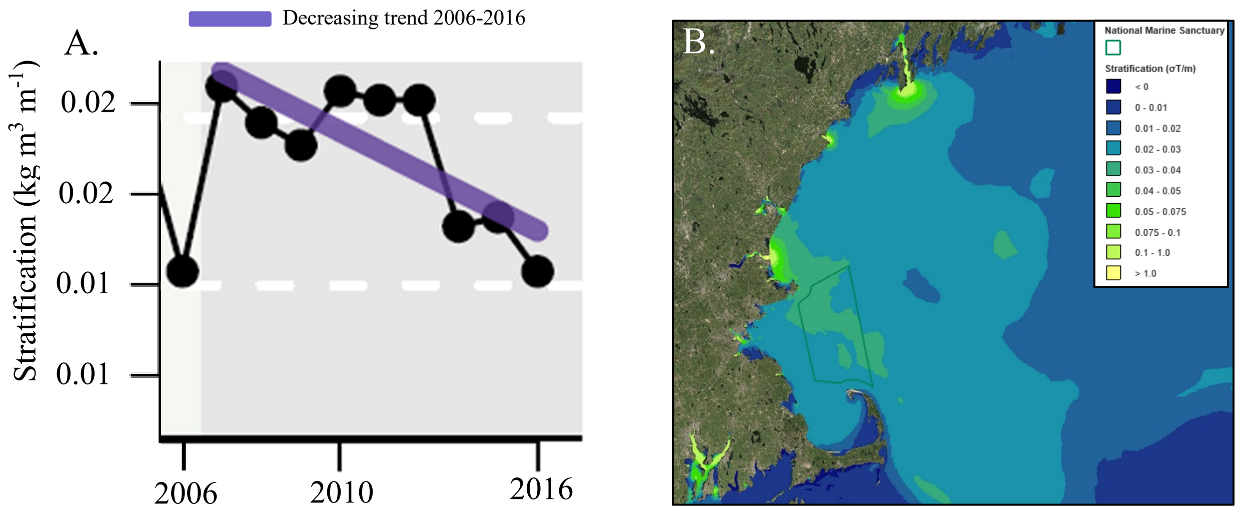

Figure 7. (A) Annual mean density stratification in the Gulf of Maine from 2006 to 2016 calculated between the surface and 50 meters depth. Image: State of the Ecosystem report, NOAA NEFSC; (B) Modelled long-term (1978-2013) annual mean stratification calculated between the surface and 20 meters and divided by the difference in depth between the two observations. Image: Northeast Ocean Data Portal

These measurements show that stratification of the water column in the Gulf of Maine has fluctuated around the long-term mean since the late 1980s, with no significant trend until 2007, after which stratification weakened significantly (2007-2015) (Fig. 7). This may be caused by warming and decreased influence of freshwater (Li et al. 2017). Decreased stratification can potentially affect system productivity by increasing the nutrient supply from bottom waters to the phytoplankton in the surface layers, which can result in extensive blooms. Stratification has been identified as a driver of zooplankton community composition and is linked to ecosystem regime shifts in the Gulf of Maine (Morse et al. 2017).

Ocean acidification

Chemical changes in seawater as a result of the uptake of carbon dioxide (CO_2) include increasing concentrations of dissolved inorganic carbon (DIC), the production of carbonic acid (lowering of pH), an increase in the partial pressure of seawater CO_2 ($pCO_{2,sw}$), and a decrease in the availability of carbonate ion (Gledhill et al. 2015). Nutrients from land-based sources also affect the local carbonate chemistry. The Gulf of Maine is especially vulnerable to ocean acidification due to naturally low pH and aragonite saturation states (Ω_{AR}). Aragonite saturation state in the U.S. Northeast coastal waters on average is close to a borderline value of 1, below which seawater chemical conditions would favor dissolution of aragonite shell (Wang et al. 2017).

In laboratory experiments, negative impacts of declining pH and aragonite saturation

(Ω_{AR}) have been demonstrated for American lobster, soft shell clam, hard clam, eastern oyster, bay scallop, longfin squid, and summer flounder (reviewed by Gledhill et al. 2015). These impacts are further predicted to impact food webs and ecosystem structure (Fay et al. 2017). The pCO_2 and aragonite concentrations show decadal cycles; however, the natural variability of the carbonate system in the Gulf of Maine has not yet been adequately characterized to understand the drivers of the temporal trends. Comparison of the change in DIC and total alkalinity between samples from the southern Gulf of Maine in summer of 2007, 2012, and 2014/2015 revealed higher DIC, but with a strong linear relationship with salinity and highly variable with depth (Wang et al. 2017) (Fig. 8). Between 2013 and 2015, annual mean Ω_{AR} was 1.86 in water less than 60 m, 1.43 between 60-160 m, and 1.34 in water deeper than 160 m over Wilkinson Basin. It has been predicted that mean Ω_{AR} of the subsurface and bottom water in Wilkinson Basin will approach under-saturation in 30 to 40 years (Wang et al. 2017).

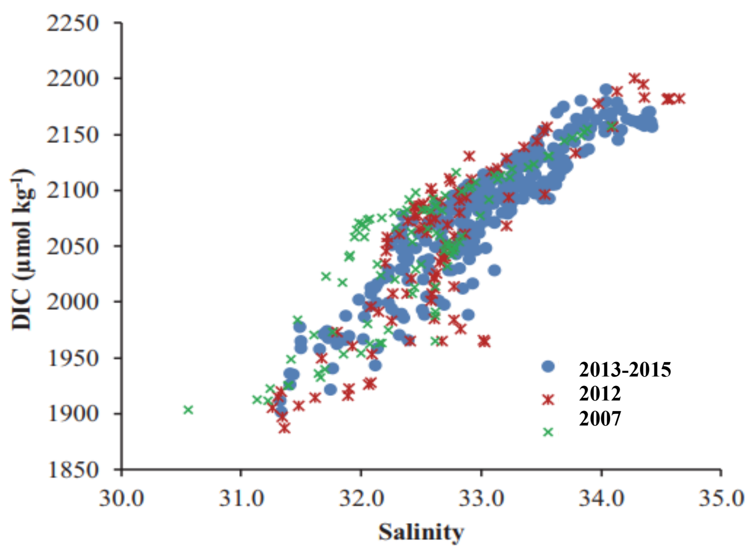

Figure 8. Comparison of DIC and salinity measurements from 2013-15 and the GOMECC 1 (2007) and GOMECC 2 (2012) studies. GOMECC data include all stations in the Gulf of Maine. Image: Wang et al. 2017

Q4: Are other stressors, individually or in combination, affecting water quality, and how are they changing?

See section on contaminants (Q6).

Q13: What are the levels of human activities that may adversely influence water quality and how are they changing?

See section on contaminants (Q6).

Chapter 3

HABITAT QUALITY

Q5: What is the integrity of major habitat types and how is it changing?

Water masses with distinct physical and biological characteristics form pelagic habitat types for many marine species. On the seafloor, substrate types and the complexity of the ocean floor determine the major benthic habitat types. Changes to the water mass that impact the integrity of pelagic habitat types are mentioned in "Water quality," Q3 and "Living resources," Q7.

Impacts to the structural integrity of the seafloor are largely attributed to mobile fishing gear, especially bottom trawling and dredging, which can have a direct negative impact to biogenic structure (e.g., sponges, hydrozoans, bryozoans, amphipod tubes, holothurians, shell aggregates; Auster et al. 1996, Jennings & Kaiser 1998) and the species which depend on those benthic communities.

Changes are occurring in the distribution of coastal vegetated habitat types with documented losses and fragmentation reported. In 2010, the State of the Gulf of Maine Report (Coastal Ecosystems and Habitats) classified the status and trends for the extent and distribution of salt marsh and seagrass in the Gulf of Maine as poor condition due to human impacts.

There is currently insufficient data available within the IEA data to determine trends in habitat condition for benthic habitat types.

Q6: What are contaminant concentrations in sanctuary habitats and how are they changing?

IEA data does not at this point have any synthesis products for contaminants. Information on contaminants can be found in Jones (2011) and Harding (2013). The trends for harmful algal blooms, fecal-borne microbial pollution, and pathogenic *Vibrio* spp. are all increasing in the Gulf of Maine. In 2011, a well-documented raw sewage discharge event occurred in the southern Gulf of Maine, releasing 300,000 tons of untreated sewage. Gulfwatch sites tracking contaminants in the tissue of blue mussels (*Mytilus edulis*) indicate that Massachusetts state waters have a high level of dichlorodiphenyltrichloroethane (DDT), chlordanes (CHLs), polychlorinated biphenyls (PCBs), dieldrin, and lead between 1993 and 2008. NOAA's Mussel Watch Program provides contaminant data for the Gulf of Maine from 1986 to 2012 (Fig. 9).

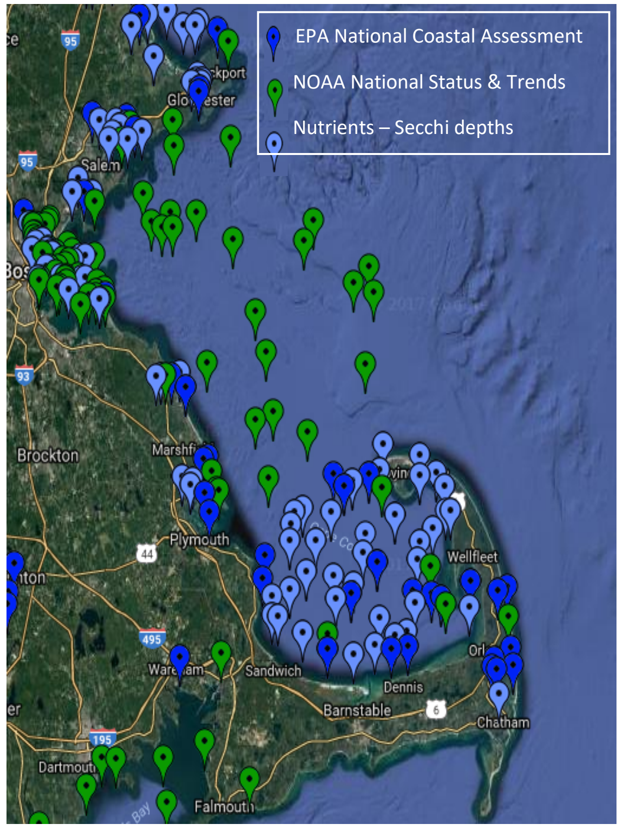

Figure 9. Water quality and contaminant sampling sites within the southwest Gulf of Maine region. Image: Seascape Analytics.

Q14: What are the levels of human activities that may adversely influence habitats and how are they changing?

Clearly, commercial shipping and boating-based activities such as whale watching and fisheries provide an extremely important benefit to the region in terms of employment, revenues, and as a source of high-quality food. Since the last condition report in 2006, employment in the three main marine sectors (shipping, seafood, and boating) declined due to the economic recession but show an upturn in 2011 (Fig. 10). Data on patterns of human activities at sea are available to support impact assessments linking changing human pressures and habitat condition (Fig. 11). More recent data are required to examine the trends to 2017.

Incidental environmental impacts are associated with the provision of these important services. Fishing removes marine fauna intentionally through harvesting (and via bycatch) and bottom trawling and dredging fishing gear can have adverse effects on geological features and associated benthic faunal assemblages (Auster et al. 1996, Jennings & Kaiser 1998). From 2007 to 2011, relative to other regions of the Gulf, the southwest region experienced intermediate levels of scallop and clam dredging; low levels of otter trawling; low-intermediate levels of potting; and intermediate-high levels of gill and seine netting based on the spatial distribution of landings (NEFSC Ecosystem Assessment Program). The Swept Area Seabed Impact (SASI) method for analyzing the effects of fishing was applied by New England Fishery Management Council (NEFMC Habitat Plan Development team) using susceptibility and recovery scores assigned individually for each combination of habitat and gear type for both physical habitat and their associated benthic communities (Fig. 12). The primary assumption of SASI is that area swept, when adjusted for gear contact with the seabed, is a proxy for seabed impact. Further, seabed impact as modified to account for the vulnerability of habitat features encountered is taken as a suitable proxy for the adverse effect of fishing on fish habitat.

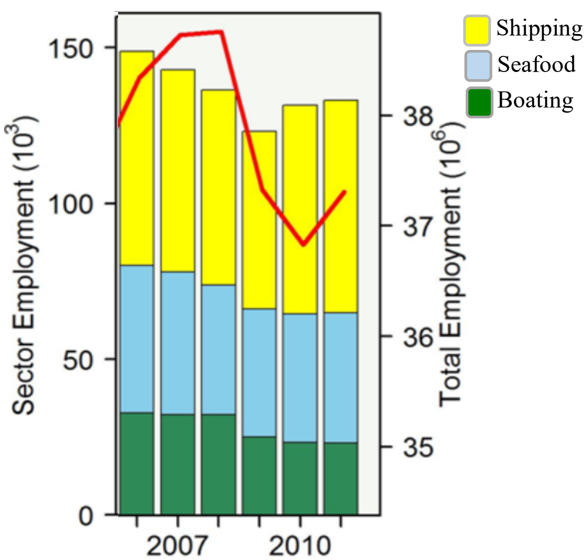

Figure 10. Employment in boating, seafood, and shipping sectors of the economy (2006-2011). Red line indicates total employment in States abutting the Northeast U.S. Continental Shelf Large Marine Ecosystem, and corresponds to the right y-axis. Image: NOAA

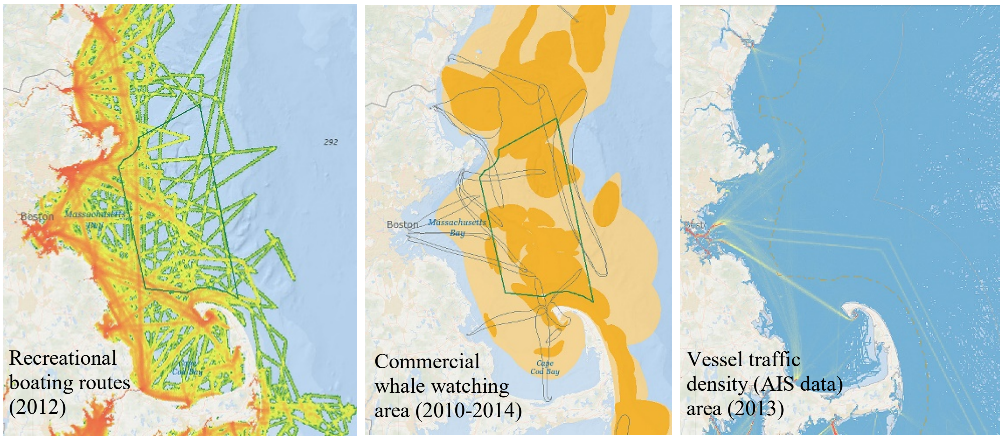

Figure 11. Examples of data on patterns of human activities at sea available to support impact assessments linking changing human pressures and habitat condition. Image: Northeast Ocean Data Portal and NOAA Marine Cadastre

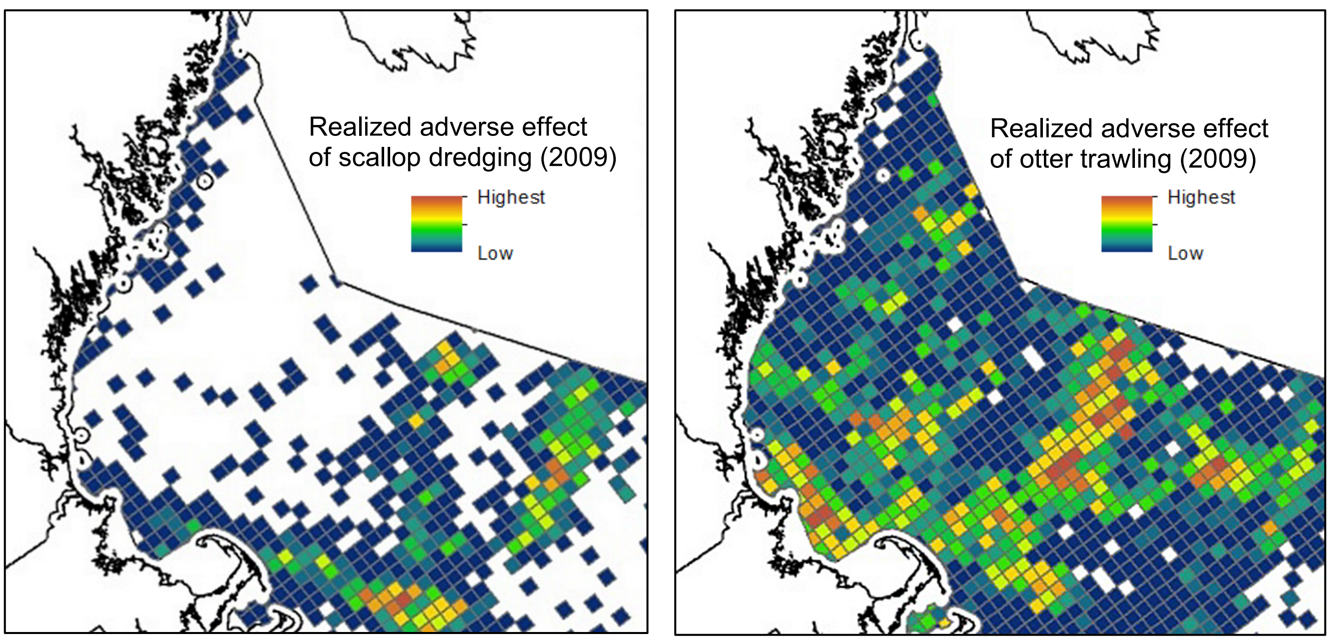

Figure 12. Modeled realized adverse effects on seafloor structure and biological communities for scallop dredging and otter trawling in 2009. Image: NEFMC 2011

Chapter 4

LIVING RESOURCES

Q7: What is the status of keystone and foundation species and how is it changing?

Fish

Distribution models developed by NEFSC (Kleisner et al. 2017) have projected a future loss in suitable thermal habitat for key northern species including Acadian redfish, American plaice, Atlantic cod, haddock, and thorny skate, but potential gains for some species including spiny dogfish and American lobster. Geographical ranges of 48 species recorded from trawls in 1970s (baseline) and again from 2013-2015 (recent) were mapped using kernel density estimation methods. Kernel density maps were used to spatially characterize distributions for a species based on the probability of a species being found at a location. Of the 48 species modeled, 24 species had shifted northeasterly into deeper water, 18 species shifted their distribution northeasterly into shallower water, and six species had moved along the shelf to the southwest, mostly into shallower water. The northward shift of fish species, as well as predicted negative and positive effects, is now well-reported in the scientific literature (Nye et al. 2009, Lucey & Nye 2010, Hare et al. 2016).

Thirty-one of these species showed mapped distributions in the Stellwagen Bank National Marine Sanctuary region (Table 2). Eleven species exhibited high overlap showing no clearly discernible change in geographical range for Stellwagen Bank National Marine Sanctuary; eight species showed range expansion (gains) in the sanctuary area in 2014-2015 compared with the 1970s; and 12 species showed a contraction in their geographical range in 2013-2015 compared with their distribution in the 1970s (Figs. 13–15).

Broader scale changes in the composition of communities and species interactions such as predator-prey relationships are expected with as-yet unknown socio-ecological consequences. Anticipation of these changes has important implications for industries and resource management linked directly or indirectly to fish distributions. Analyses of multi-decadal fish and zooplankton populations revealed a general pattern of approximate decadal rise and fall in species abundance (Pershing et al. 2005, Perretti et al. 2017). The high faunal productivity phase began in 1987 and returned to lower than average around 2000 (Fig. 16). In the Gulf of Maine, the high copepod abundance phase began in 1991 and ended in 2001. It is likely that increased primary and secondary productivity in the planktonic and/or benthic food of fish drive the observed cyclical patterns in fish population dynamics. Research suggests that the productivity cycles and trophic cascades are linked to the dynamics of the North Atlantic Oscillation whereby copepod abundance is higher in years with higher North Atlantic Oscillation index (Conversi et al. 2001, Greene et al. 2012). At broader time scales, the Atlantic Multi-Decadal Oscillation will also influence biological patterns through changes to temperature, salinity, and the effects on water stratification (Nye et al. 2014) (Fig. 17).

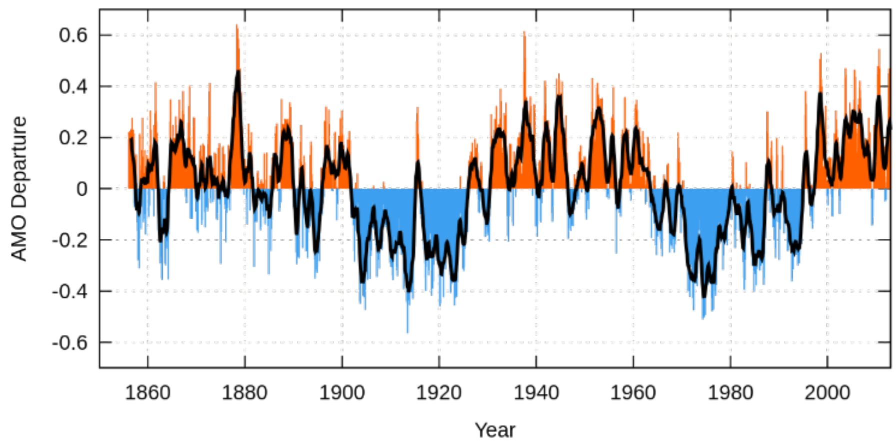

Figure 17. Atlantic Multi-decadal Oscillation time series (1856–2013) with a 12-month moving average (black line). Image: NOAA, USGS

This broad spatio-temporal pattern is important context for assessments of condition for Stellwagen Bank National Marine Sanctuary where reporting periods may fall somewhere in one decadal regime, or data may span parts of two different regimes. Analyses of trends in biological populations must therefore be interpreted within this broader temporal context of regime dynamics. In addition, determining the relative importance of fishing pressure and climate forcing in biological dynamics and the strength of interaction between the two ecosystem drivers is still under investigation for the Gulf of Maine, but is likely to be very significant for ecosystem functioning (Nye et al. 2013). For example, analyses led by NEFSC found that human pressures, especially high fishing pressure, in the Northeast Atlantic region were able to explain considerably more of the variation in ecological indicators of ecosystem health than environmental pressures (Large et al. 2015) suggesting that human activities have significantly altered the ecosystem structure and functioning of the Northeast U.S. shelf ecosystem.

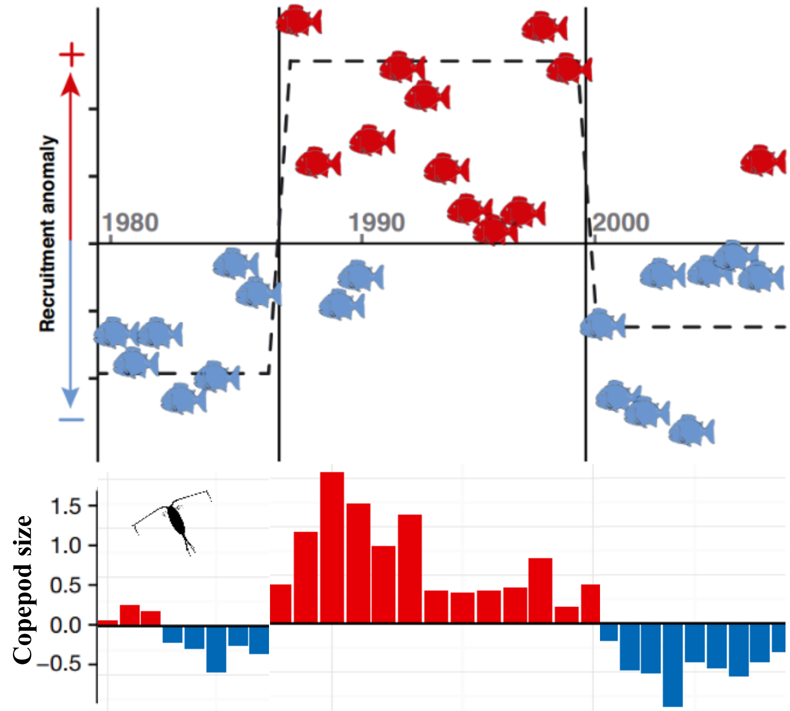

Figure 16. Top: Fish recruitment success regimes on the Northeast US Continental Shelf (1980 to 2008). Bottom: Average annual anomaly in the copepod size index (small copepod anomaly – large copepod anomaly). Image: Perretti et al. 2017

Another potential ecological indicator is the trophic level of a species. The trophic level of a species is a measure of its relative position in the food web and is an important aspect of understanding not only the implied size of species in an ecosystem, but also the transfer of energy in the system. We can determine the trophic level of a species from examining its diet. The mean trophic level is an indicator of how much energy is transferred to species feeding higher up in the food web and is a component of ecological integrity that can be disrupted by fishing activity or other disturbances. Mean trophic level for all fish from the bottom trawl surveys has remained relatively stable in the Gulf of Maine between 2006 and 2014 (Fig. 17).

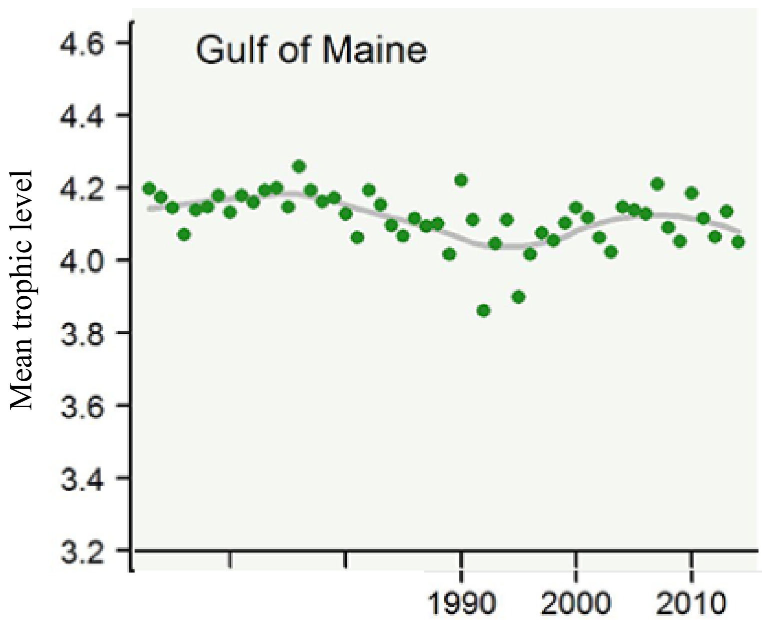

Figure 17. Mean trophic level of all finfish species caught in fall bottom trawl surveys. Image: NOAA

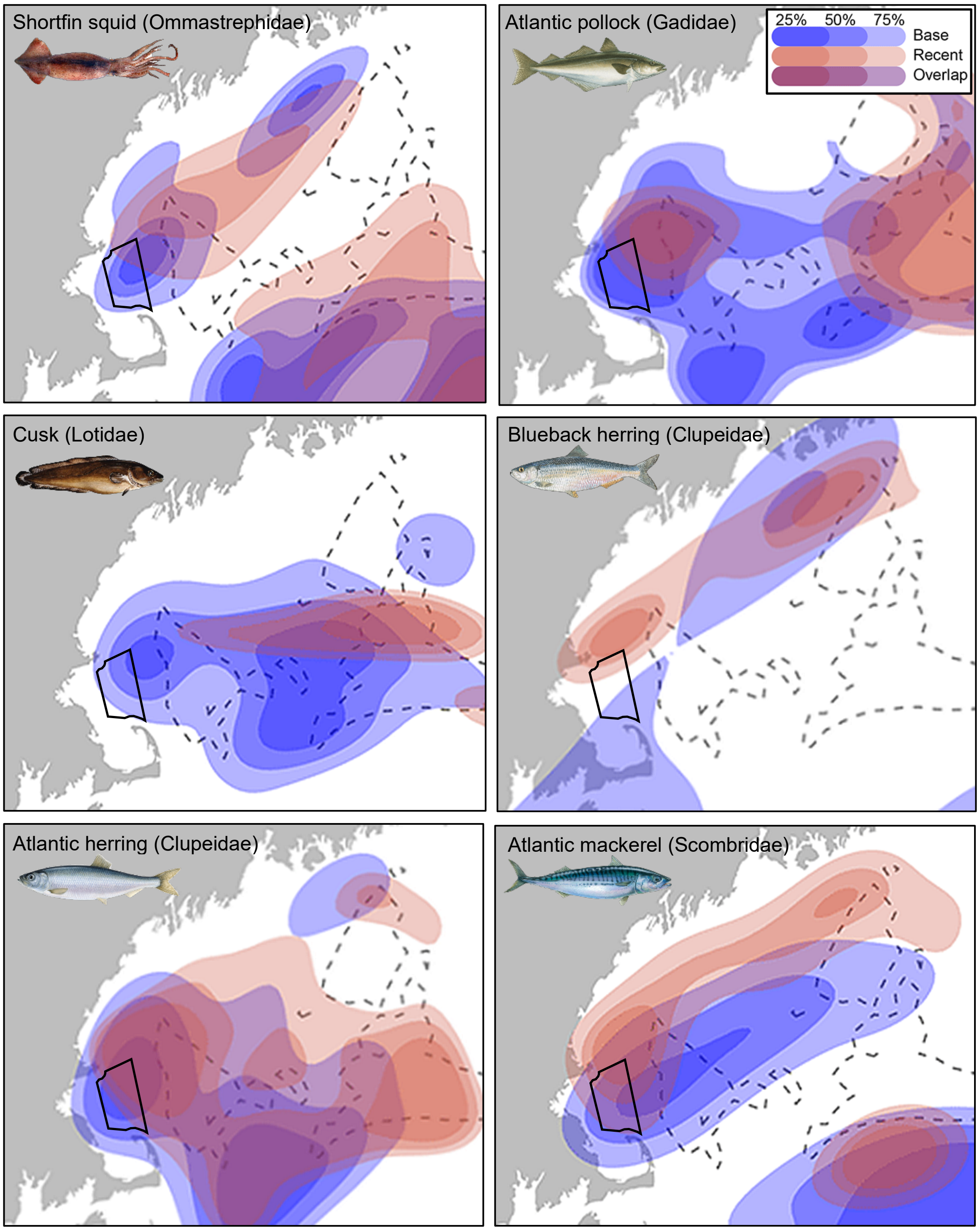

Figure 13. Kernel density plots illustrate contraction of species distribution away from Stellwagen Bank National Marine Sanctuary from the 1970s to 2015. Three levels of probability contours were mapped (25%, 50% and 75%) for species distributions recorded in the 1970s trawl data (blue shading=base) and for the 2013-2015 data (orange=recent). The 25% kernel defines the core area of the distribution and the 75% defines the broader outlying extent of the distribution. Overlap between the 1970s and recent years is colored with purple. Spatial uncertainty in models were not reported at the source. Image: Seascape Analytics, using NOAA maps

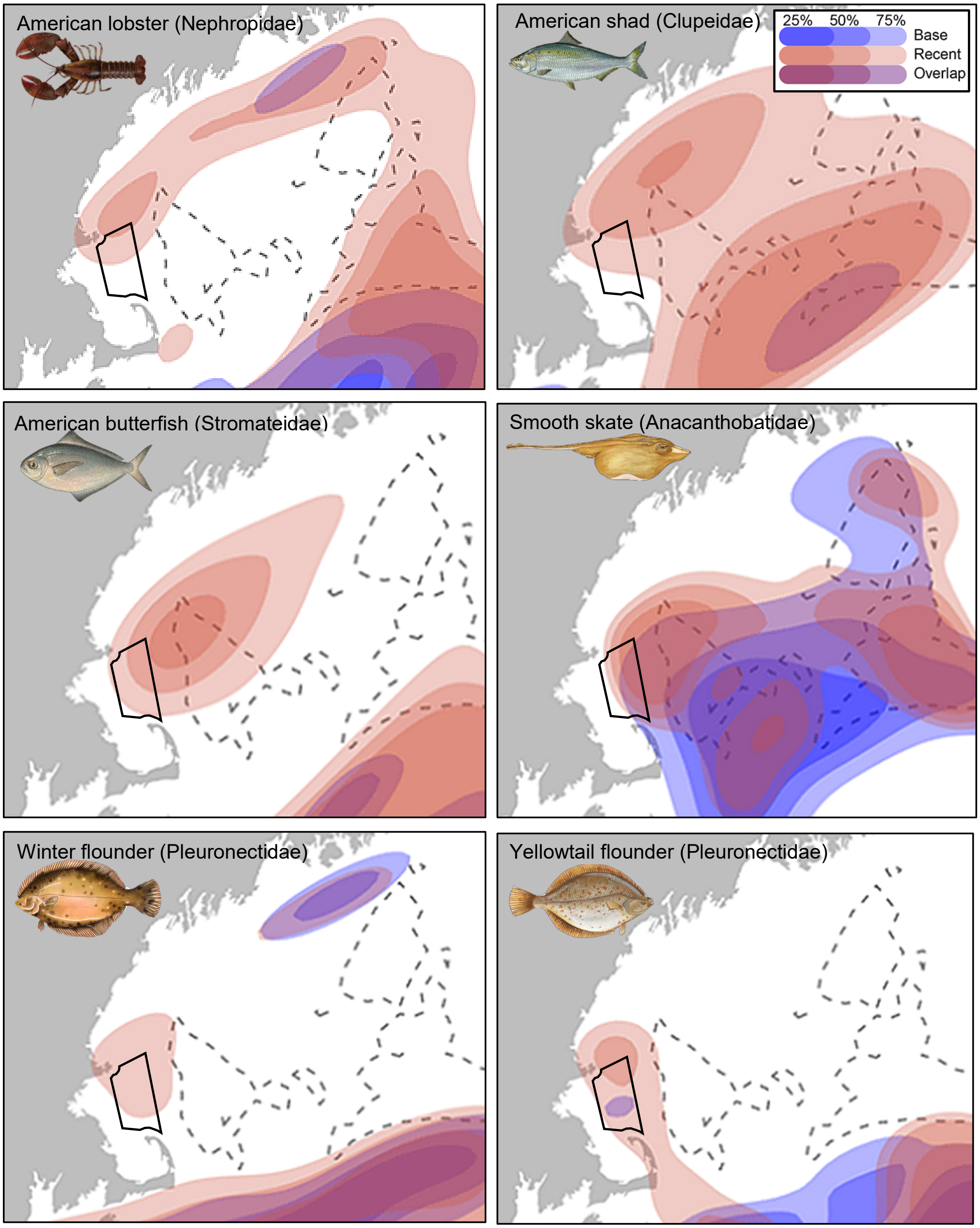

Figure 14. Kernel density plots illustrating expansion of species distribution into Stellwagen Bank National Marine Sanctuary from the 1970s to 2015. Three levels of probability contours were mapped (25%, 50% and 75%) for species distributions recorded in the 1970s trawl data (blue shading=base) and for the 2013-2015 data (orange=recent). The 25% kernel defines the core area of the distribution and the 75% defines the broader outlying extent of the distribution. Overlap between the 1970s and recent years is colored with purple. Spatial uncertainty in models were not reported at the source. Image: Seascape Analytics using NOAA maps

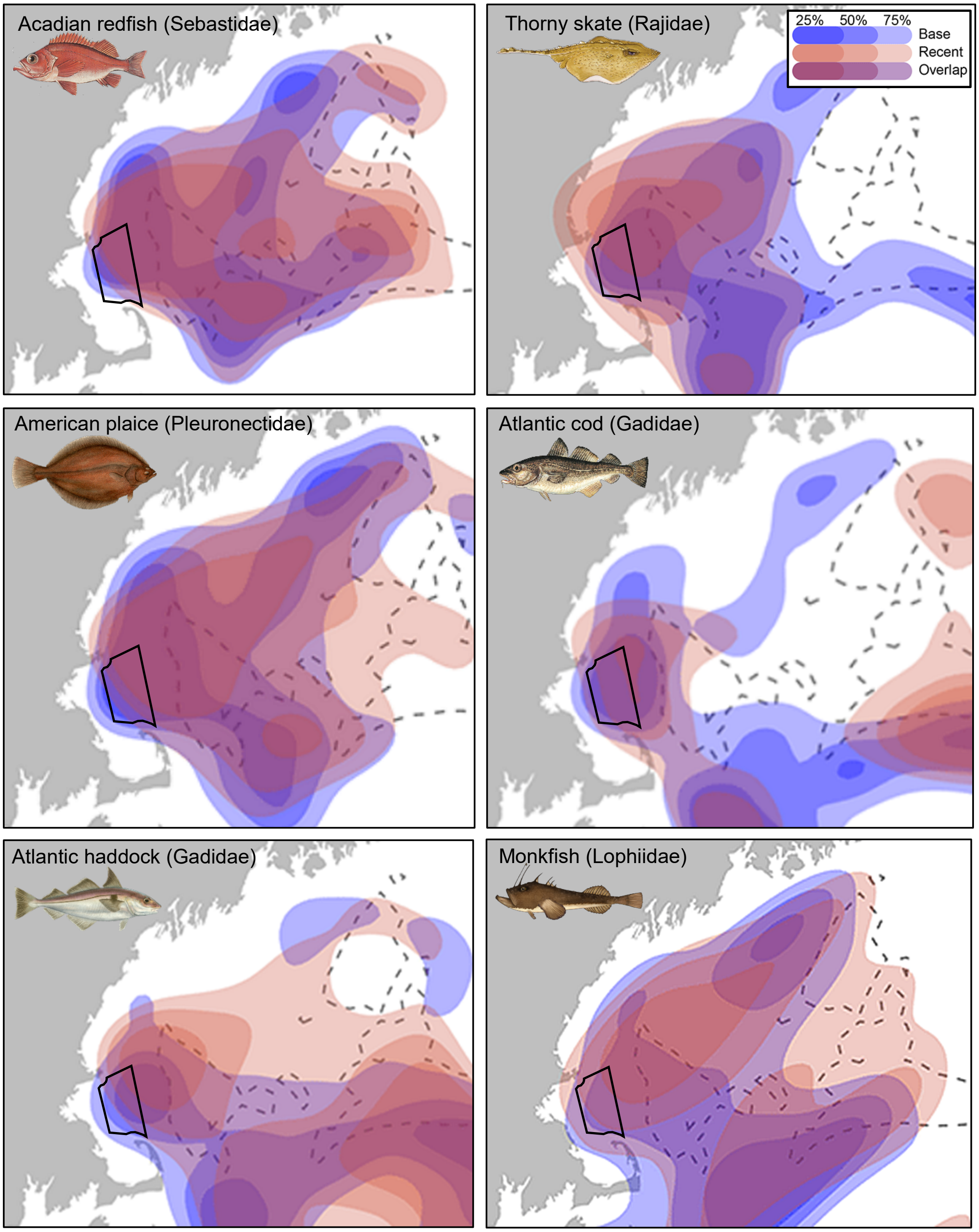

Figure 15. Kernel density plots illustrating high overlap in species distributions in the Stellwagen Bank National Marine Sanctuary region from the 1970s to 2015. Three levels of probability contours were mapped (25%, 50% and 75%) for species distributions recorded in the 1970s trawl data (blue shading=base) and for the 2013-2015 data (orange=recent). The 25% kernel defines the core area of the distribution and the 75% defines the broader outlying extent of the distribution. Overlap between the 1970s and recent years is colored with purple. Spatial uncertainty in models were not reported at the source. Image: Seascape Analytics using NOAA maps

Table 2. Changes in distribution patterns for 31 species recorded in the Stellwagen Bank National Marine Sanctuary region in the southern Gulf of Maine. Descriptions are visual interpretations of the kernel density maps provided by NOAA NEFSC Current Conditions of the Northeast Shelf Ecosystem – Spring 2016 Update.

Species	**Changes in distribution in southern Gulf of Maine (GoM) (1970s to 2015)**	**Stellwagen Bank National Marine Sanctuary**
	Regional geographical patterns	***Overlap, gain or loss***
Acadian redfish	Slight northward shift, high overlap	**High overlap**
Alewife	High overlap	**High overlap**
American lobster	No overlap, new range extended into western GoM and Stellwagen region	**Gain**
American plaice	High overlap	**High overlap**
American shad	No overlap, new range extended into western GoM and Stellwagen region	**Gain**
Atlantic cod	High overlap, core area range contraction, and fragmented core areas in GoM	**High overlap**
Atlantic herring	Overlap but northeastward shift to include deeper waters	**Overlap/loss**
Atlantic mackerel	Overlap but northwestward shift to shallower waters	**Overlap/loss**
Blueback herring	No overlap, but shift to northwestern shallower waters	**No overlap/loss**
Butterfish	No overlap, new range extended into western GoM and Stellwagen region	**No overlap/gain**
Cunner	No overlap, possible contraction of range out of GoM	**No overlap/loss**
Cusk	No overlap, retraction of range, and shift to deeper GoM waters	**No overlap/loss**
Haddock	High overlap, range expansion, and slight northward shift	**High overlap/loss**
Longhorn sculpin	Overlap, range shift westward into southern GoM	**High overlap/gain**
Monkfish	High overlap, expansion into deeper central GoM	**High overlap**
Ocean pout	High overlap, little change	**High overlap**
Pollock	Reduced overlap with range contraction and core area shifting northwards	**Overlap/loss**
Red hake	Overlap, range expansion north and northeast to deeper waters	**High overlap/loss**
Sand lance	No overlap, dramatic range contraction, and shift to offshore waters	**No overlap/loss**
Sea raven	High overlap with range contraction and slight northward shift	**High overlap/loss**
Sea scallop	Small overlap in central and northern Stellwagen region	**Overlap/gain**
Shortfin squid	Slight overlap, northward shift	**Overlap/loss**
Silver hake	High overlap	**High overlap**
Smooth skate	Slight overlap, northwest shift to shallower waters	**Overlap/gain**
Spiny dogfish	High overlap, slight northward shift of core area	**High overlap**
Thorny skate	High overlap, range contraction to shallower waters in the southern GoM	**High overlap**
White hake	High overlap	**High overlap**
Winter flounder	No overlap, recent expansion to southwestern GoM including Stellwagen	**Gain**
Witch flounder	High overlap	**High overlap**
Wolffish	High overlap, range contraction with slight northward shift of core habitat	**High overlap/loss**
Yellowtail flounder	Low overlap, expansion into shallower southwest GoM including Stellwagen	**Overlap/gain**

Plankton

From 2006 phytoplankton (primary production) in the Gulf of Maine exhibited an increase above the long-term average (± 1 SD) to 2011 and then declined to relatively stable average conditions between 2012 and 2016 (Fig. 18). This is likely to be driven by inter-decadal patterns in local and regional water conditions.

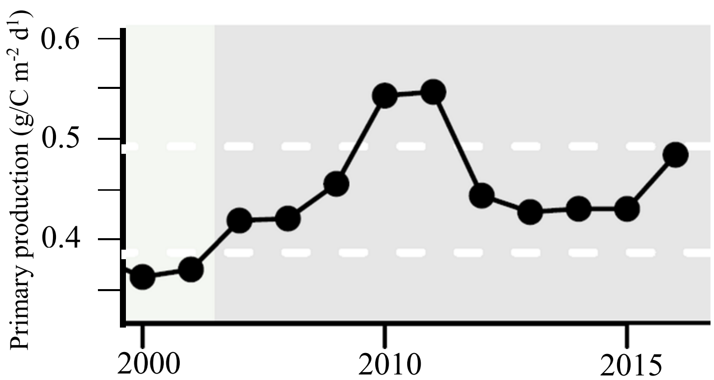

Figure 18. Phytoplankton productivity in the Gulf of Maine from 2000 to 2016. Dashed white horizontal lines indicate ± 1 standard deviation from the long-term time series mean. (Image: State of the Ecosystem report, NOAA NMFS NEFSC)

Several species of zooplankton, such as *Calanus* spp., are important components of the North Atlantic food web and a primary prey for endangered North Atlantic right whales (Mayo & Marx 1990, Meyer-Gutbrod & Greene 2014) and many species of forage fish. Changes in zooplankton abundance will have important ecological consequences for the Gulf of Maine ecosystem. *Calanus finmarchicus* is one of the most commonly found species of zooplankton in the Gulf of Maine. Several species of harvested fish depend on the lipid-rich calanoid copepods and their eggs as prey, including cod, herring, haddock, mackerel and red fish. Other key predators are seabirds such as Leach's storm petrel, as well as planktonic invertebrates such as siphonophores and euphausiids.

IEA analyses revealed a recent significant decline in the abundance of both *Calanus finmarchicus* and *Pseudocalanus* in the fall sampling season. No significant trend was detected for spring abundance, which is the time when right whales begin feeding in the Gulf of Maine (Fig. 19). Interpolated maps of *C. finmarchicus* (Figure 20) suggest a contraction in the regional abundance in spring 2005 to 2014 compared with the previous decade (1995 to 2004) and a considerable broad geographical reduction in density in the southern Gulf in fall 2005 to 2014 compared with 1995 to 2004. Models by NEFSC (Grieve et al. 2017) forecast that future temperature and salinity conditions will result in a gradual decrease in *C. finmarchicus* densities, with a high greenhouse gas emissions scenario decreasing density of this species by as much as 50% by the end of this century. Mapped predictions indicate that the Stellwagen region will experience less decline than the deeper central and northern Gulf waters. In Wilkinson Basin in the western Gulf of Maine, *C. finmarchicus* has persisted in large concentrations despite recent significant warming (Ji et al. 2017).

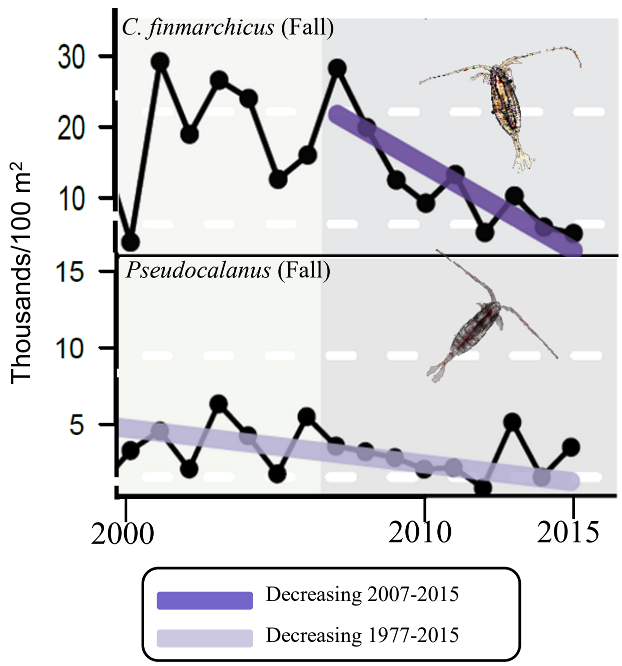

Figure 19. Declining (fall season) abundance of calanoid copepods in the Gulf of Maine. Image: State of the Ecosystem report, NOAA NEFSC

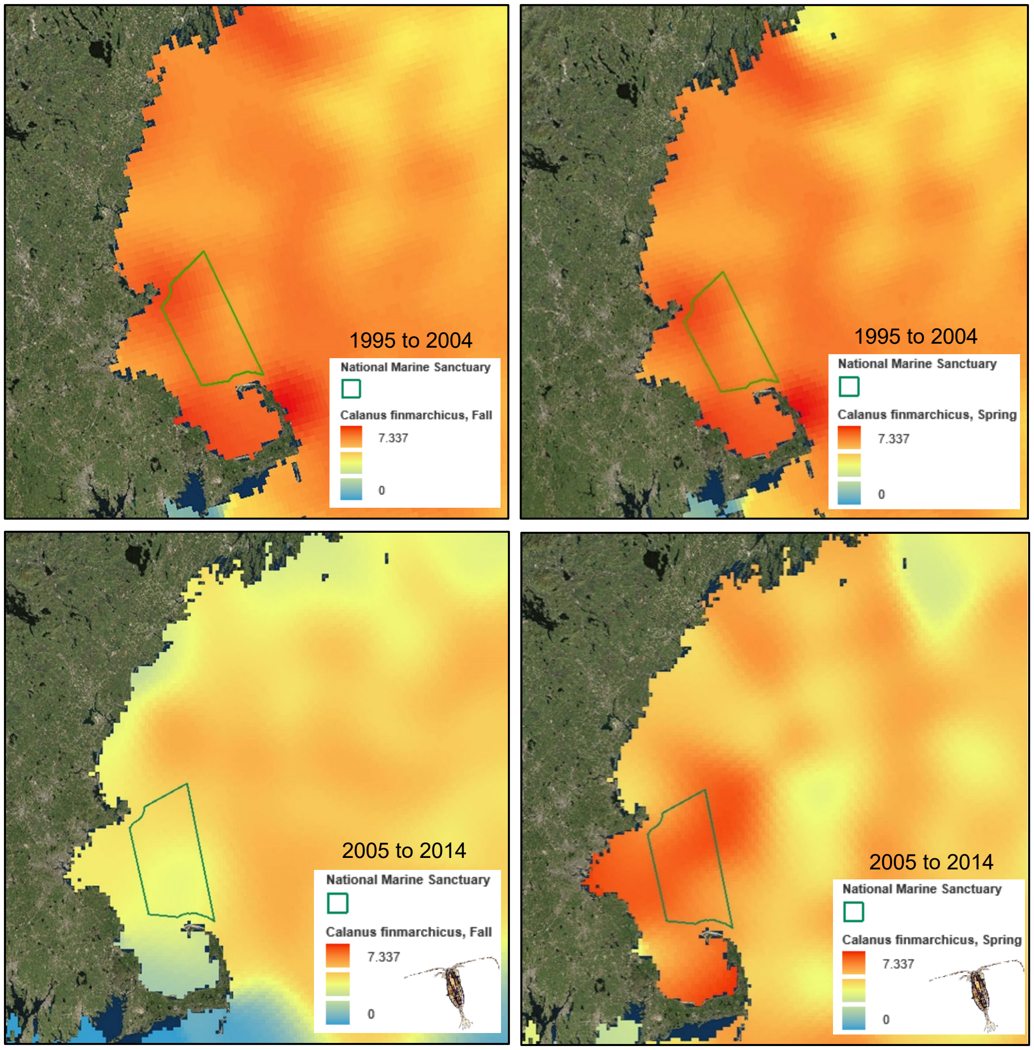

Figure 20. *Calanus finmarchicus* abundance (per cubic meter log-transformed) in fall and spring surveys in the southern Gulf of Maine in the survey period 1995-2004 (top) and 2005-2014 (bottom). Image: NEFSC & Northeast Ocean Data Portal

Further analyses are required to understand the ecological consequences for the spatio-temporal changes that are represented in Figure 20.

Biomass for six major trophic (functional) groups (see Table 3) for the Gulf of Maine show long-term increases in both seasons for benthos and meso-planktivores and statistically significant recent (2006-2016) increases for spring benthos, fall meso-planktivores and benthivores in both spring and fall sampling seasons (Fig. 21). Only macro-planktivores experienced statistically significant declines in both seasons since 2006. IEA data showing an increase in benthic biomass and benthivore biomass has led researchers to suggest that the benthic influence on food webs may be increasing relative to the pelagic productivity.

Table 3. Major functional groups in the Gulf of Maine used to examine ecological change by the Northeast Integrated Ecosystem Assessment.

Group (Description)	N species	Major species in the group
Benthos (bottom dwellers)	7	scallops, surfclam, quahog, mussels, whelks, conchs, sand dollars and urchins
Meso-planktivores (eat copepods)	7	Atlantic herring, butterfish, Atantic mackerel, menhaden, river herrings and shad
Macro-planktivore (eat large zooplankton)	6	white hake, longfin and shortfin squids, searobins, sculpin, lumpfish
Macro-zoopiscivores (eat large zooplankton, shrimp, and fish)	12	redfish, windowpane, cusk, pollock, red hake, clearnose, little, and smooth skates, smooth dogfish, buckler dory, blackbelly rosefish
Benthivores (eat bottom dwellers)	24	lobster, haddock, yellowtail, winter, and witch flounders, barndoor skate, ocean pout, black sea bass, scup, tilefish, tautog, cunner, blue crab, red crab, other crabs
Piscivores (eat fish)	13	monkfish, winter and thorny skates, silver and offshore hake, Atlantic cod, halibut, fourspot flounder, spiny dogfish, summer flounder, bluefish, striped bass, weakfish

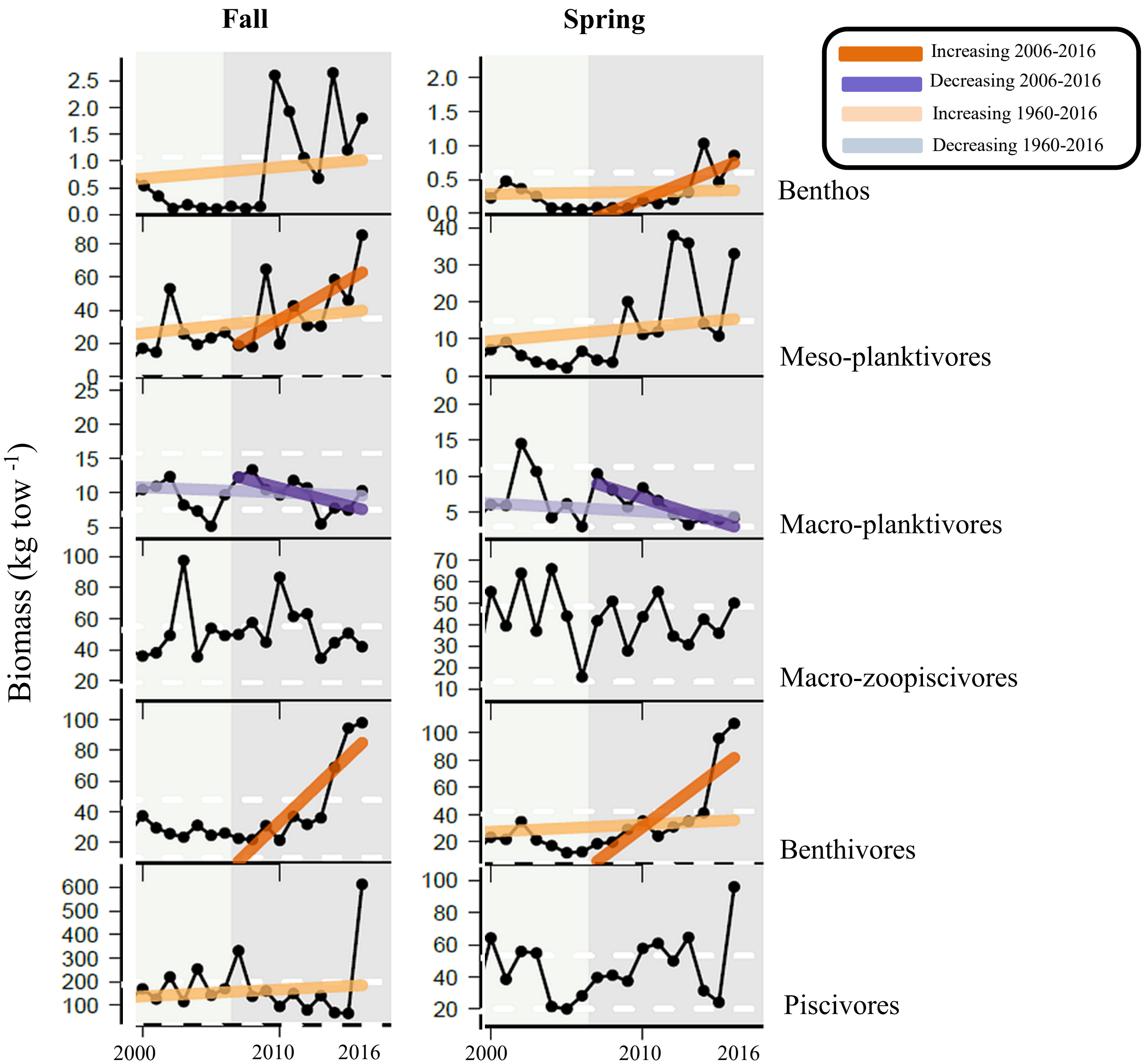

Figure 21. Fall and spring trends in biomass for key trophic groups sampled from the Gulf of Maine fisheries-independent (NEFSC) bottom trawls (2000-2016). Dashed white horizontal lines indicate ± 1 standard deviation from the long-term time series mean. Gray shaded time period is the most recent decade (2006-2016). Image: State of the Ecosystem report, NOAA NEFSC

Q8: What is the status of other focal species and how is it changing?

North Atlantic right whales (*Eubalaena glacialis*) are among the most endangered large whale populations in the world and have been listed as endangered under the Endangered Species Act since 1970. The population increased steadily from 1990 to 2010, but by

2014 the population is estimated to have decreased back to the population size estimated in 2006 (Fig. 22). Latest NOAA Fisheries model estimates for 2015 predict 458 individuals (Pace et al. 2017).

Terns are important indicators of the state of the environment and iconic bird species in the Gulf of Maine. Arctic terns (*Sterna paradisaea*) have experienced a significant decline in population size in the Gulf of Maine region while common terns (*S. hirundo*) have been steadily increasing since 2005 (Fig. 22).

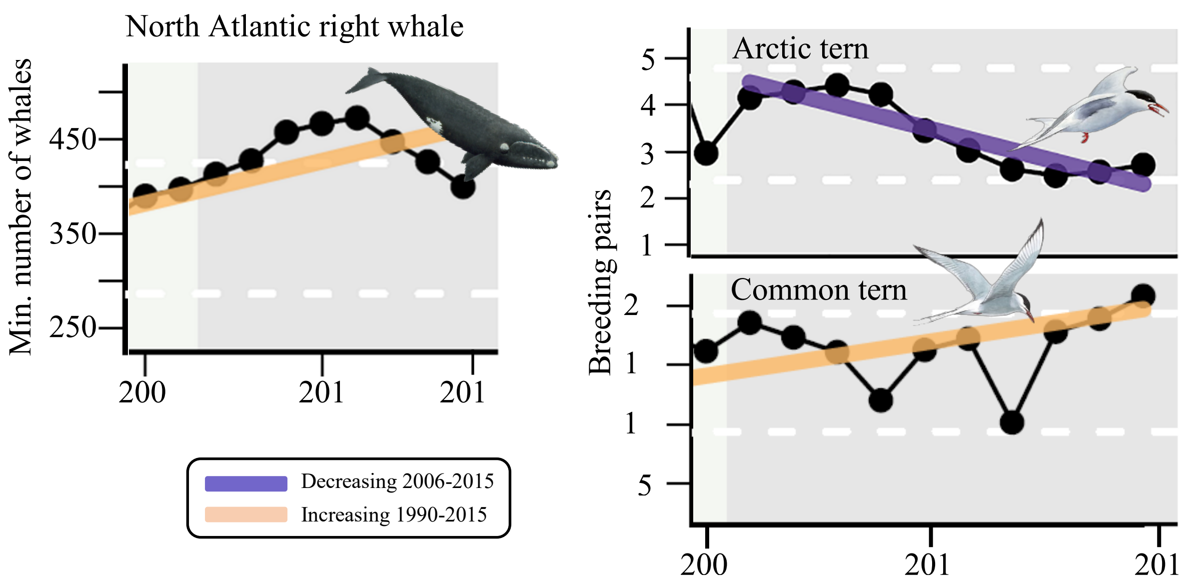

Figure 22. North Atlantic right whale estimated population (2005 to 2014) and tern breeding population size (2005-2015). Dashed white horizontal lines indicate ± 1 standard deviation from the long-term time series mean. Gray-shaded time period is the most recent years (2007-2014). Image: State of the Ecosystem report, NOAA NEFSC

Q9: What is the status of non-indigenous species and how is it changing?

More than sixty non-native marine species that cause or are likely to cause harm to ecosystems, economies, or public health have been reported in the Gulf of Maine (Table 4). These species have mostly come from Europe, Asia, and the Pacific Ocean, transported inadvertently through commercial shipping (Brawley et al. 2009). It is thought that human activity is leading to an increase in the number and abundance of invasive species in the Gulf of Maine. Some species may proliferate with warming waters. However, for most invasive species it is not yet clear how climate change will influence their population dynamics and extent, although some invasive species are shifting northward. Introduced seaweeds in Maine have increased particularly in the Casco Bay area. Colonial ascidians, Asian shore crab, mitten crab, a red alga

(*Grateloupia turuturu*), and lionfish may become more abundant in the region. Sites in New Hampshire and Maine have experienced 27-fold increases of the green alga *Codium fragile* over a 22-year period, along with its associated epiphyte *Neosiphonia harveyi* (Mathieson et al. 2008).

Table 4. Marine invasive species in the Gulf of Maine.
Source: State of the Gulf of Maine report 2010

TAXONOMIC GROUP	NUMBER
Crustacea	13
Rhodophyceae	11
Tunicata	7
Mollusca	6
Phaeophyceae	5
Hydrozoa	3
Bryozoa	3
Protista	3
Cnidaria	2
Polychaeta	2
Platyhelminthes	2
Diatomacea	2
Kamptozoa	1
Nematoda	1
Porifera	1
Cholorophyceae	1
Virus	1
TOTAL	64

Q10: What is the status of biodiversity and how is it changing?

Fish

The best example of a well-documented pattern of distribution and abundance at Gulf-wide scale is for fishes, which have been sampled by fishery-independent assessment surveys for more than 40 years (Incze et al. 2010) (Figure 24). There are four sources for fisheries trawl data: NEFSC, North East Areas Monitoring and Assessment Program (NEAMAP), Massachusetts Division of Marine Fisheries (MDMF), and Maine and New Hampshire state trawls. Each set of data sources have used standardized survey designs and data collection methodologies. Results were normalized to account for vessel and gear differences within each data source. According to IEA analyses, the number of species has steadily increased in the Gulf of Maine over the long term in the spring, and over the most recent decade in both the fall and spring surveys (Figure 23). Comparing fish species richness from trawl samples may provide a useful surrogate for patterns of ecosystem biodiversity, but further studies will be needed to determine trends in benthic species diversity. Recent synthesis by the Census of Marine Life may provide a reliable baseline for future studies.

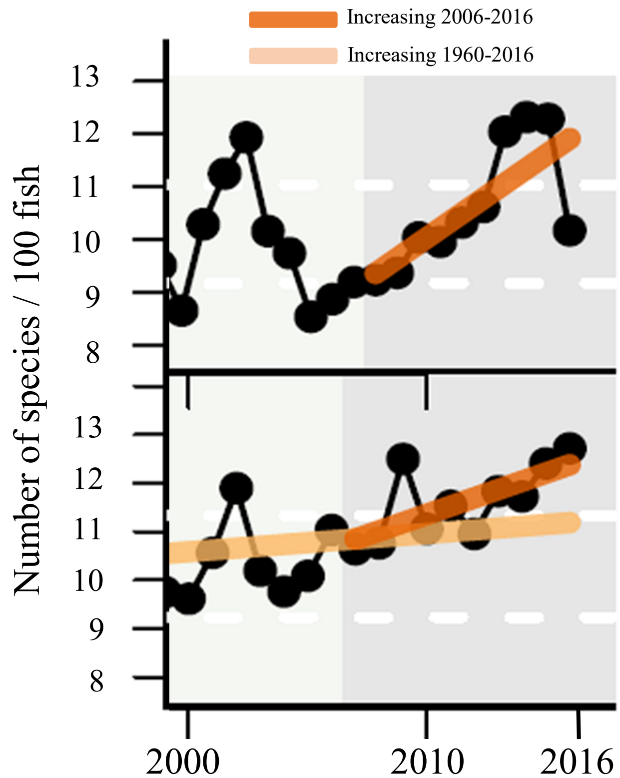

Figure 23. Fish species richness estimated as the mean number of species found in a random sample of 100 fish at a station for the Gulf of Maine portions of NEFSC surveys. Dashed white horizontal lines indicate ± 1 standard deviation from the long-term time series mean. Image: State of the Ecosystem report, NOAA NEFSC

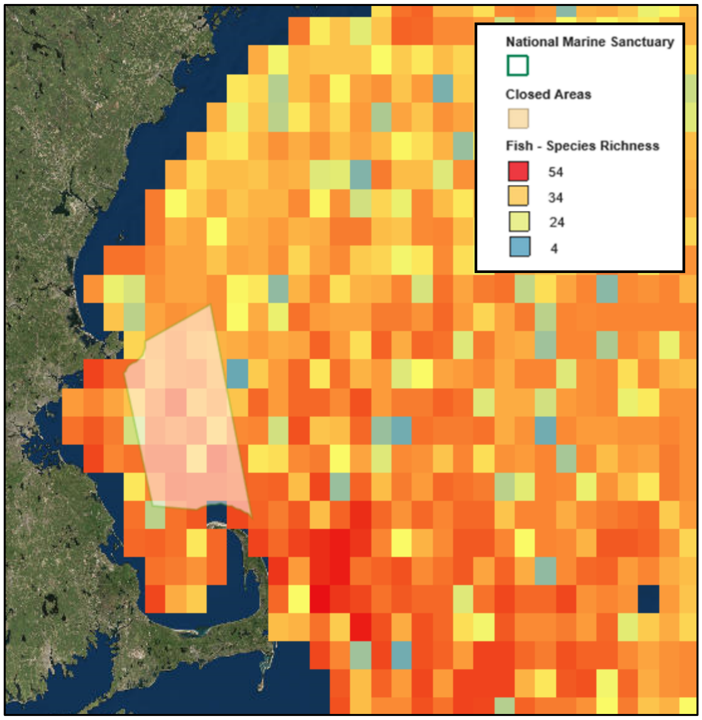

Figure 24. Number of fish species from all NEFSC fisheries-independent bottom trawls (1970-2014). For all fish species together (82 species) total species richness maps are calculated in GIS by summing the number of individual species present in each cell. A species was considered present in a cell if its biomass in that cell was greater than 1.5 kg. Each map cell is 10 km x 10 km. Image: Marine-life Data & Analysis Team (MDAT) data described by Curtice et al. 2016 and Fogarty & Perretti 2016

Q15: What are the levels of human activities that may adversely influence living resource quality and how are they changing?

Shipping and boating introduce noise pollution (Figure 25) and occasionally ships strike large marine animals such as whales. There is some evidence that recently introduced (2008) vessel speed restrictions have reduced the incidence of mortality by ship strike (Figure 26). Fishing gear also accounts for an increasing number of incidents of injury and mortality to cetaceans.

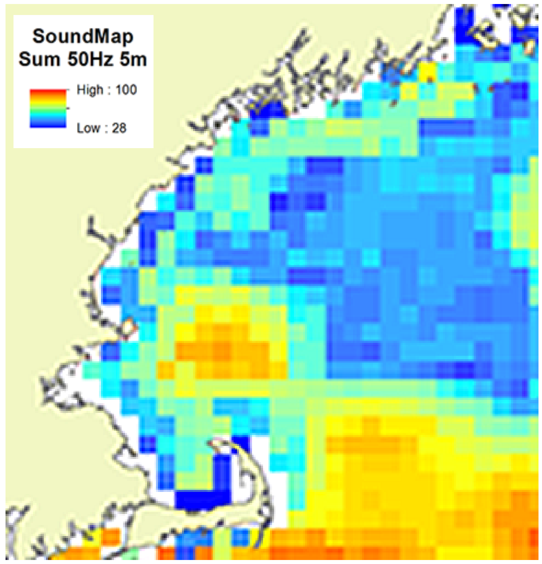

Figure 25. Modeled sound levels as a function of vessel traffic for different vessel types at 5 m depth and 50 Hz. Image: NOAA

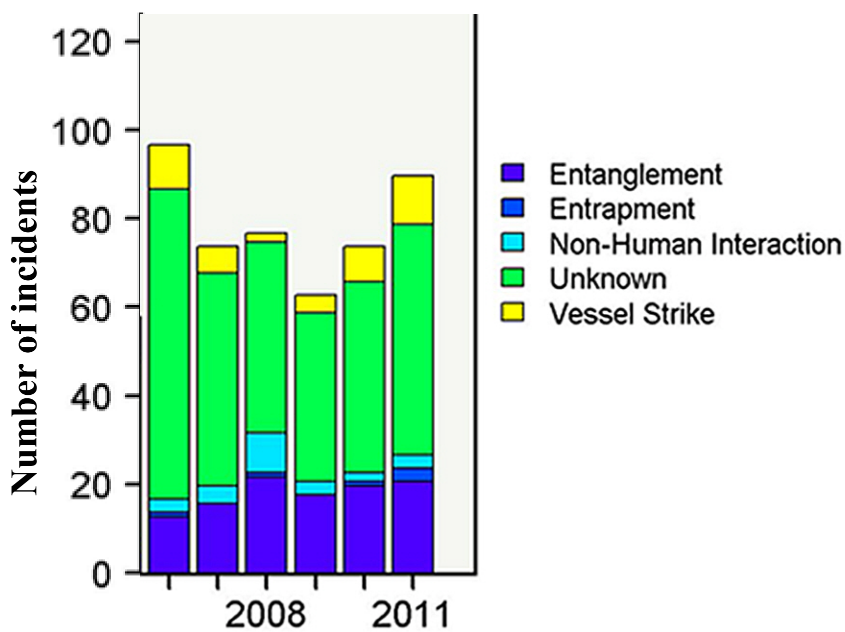

Figure 26. Number of incidents involving large whale injury and mortality by incident category. Image: NOAA

Commercial fishing is a major factor in structuring the biological communities in the Gulf of Maine and takes place over a considerable area and more intensively near densely population urban centers (Fig. 27) in the southwest region of the Gulf. Based on the weight of landings since 2006, the catch from the Gulf of Maine commercial fishery has declined for pelagic species and increased for crustaceans while remaining relatively stable for all principle species combined (Fig. 28). Change in catch for individual species is beyond the scope of this paper, but the data are available (NEFSC).

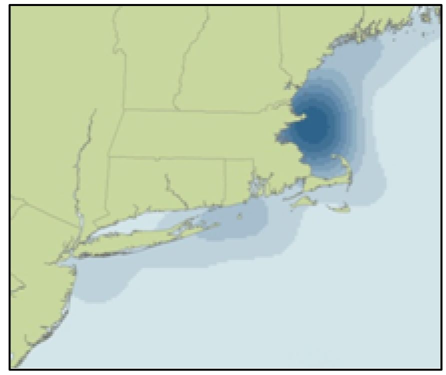

Figure 27. Concentration of fishing days for fixed-area fishers. Image: NOAA

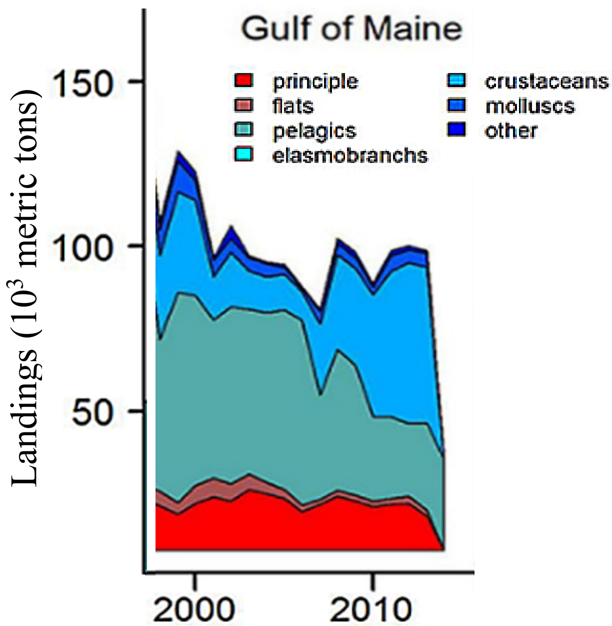

Figure 28. Landings (live weight) for the Gulf of Maine production unit. The groups represented are: principal groundfish (i.e., Atlantic cod, haddock, pollock, silver hake, red hake, white hake, red fish, and monkfish), flatfish (i.e., summer flounder, winter flounder, yellowtail flounder), pelagics (i.e., Atlantic herring, Atlantic mackerel), elasmobranchs (i.e., spiny dogfish, winter skates), crustaceans (i.e., American lobsters, red crab), mollusks (i.e., Atlantic scallops, ocean quahogs, surfclams), and other. Note: landings of lobster are underrepresented in the time series. Image: NOAA

Comparison of the fishing boat at-sea traffic between the 2006-2010 period and the 2011-2014 based on vessel monitoring system location data indicate a reduction in the fishing boat activity in the region of Stellwagen Bank National Marine Sanctuary. When the boat traffic density data are refined to only show the density of fishing boats that are travelling more slowly than 4 knots (the speed associated with deployed gears), 2011-2014 patterns are similar suggesting that the uncorrected data do also provide a reliable picture of the spatial patterns of relative fishing intensity (Fig. 29). The data also suggest a relatively high level of compliance with fishery closures (Northeast Multispecies Closed Areas). However, there are special programs that allow some fisheries, including groundfish, herring, surfclam/ocean quahog, and scallop, to access some parts of these closed areas under certain conditions. Vessels may transit the areas that are closed provided that their fishing gear is stowed according to regulations. Visual comparison for scallop fishing intensity suggests that fishers were not exploiting the offshore grounds as much in the 2011-2014 period compared with 2006-2010 (Fig. 32) whereas for monkfish fishers are working more intensively on offshore grounds (Fig. 30).

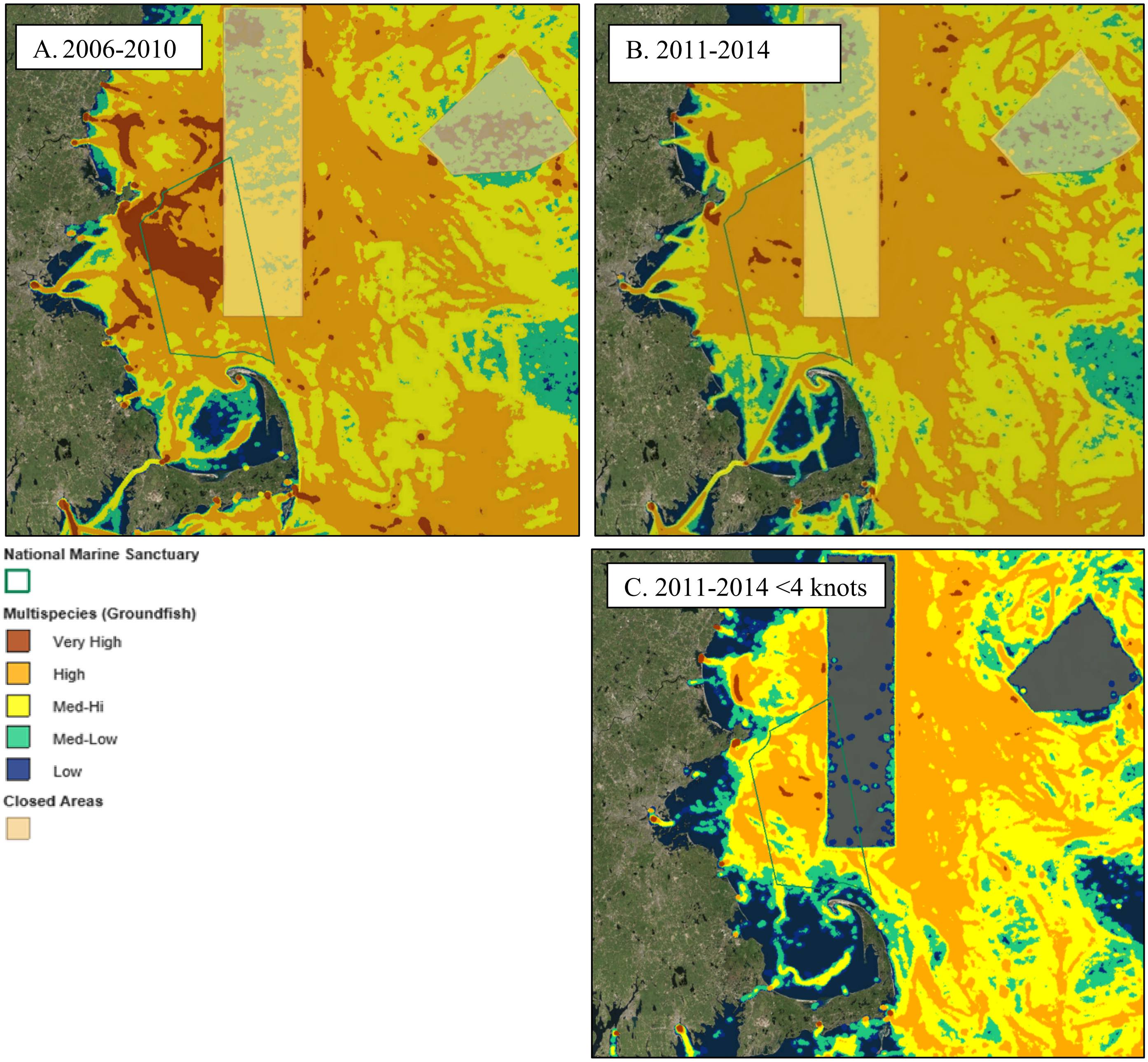

Figure 29. Multispecies (groundfish) fishing density for: (A) All fishing vessels including transiting (2006-2010); (B) all fishing vessels including transiting (2011-2014); and (C) fishing vessels presumed to be actively fishing (moving at < 4 knots) (2011-2014) based on fishing vessels with vessel monitoring systems. Image: Seascape Analytics using NOAA data

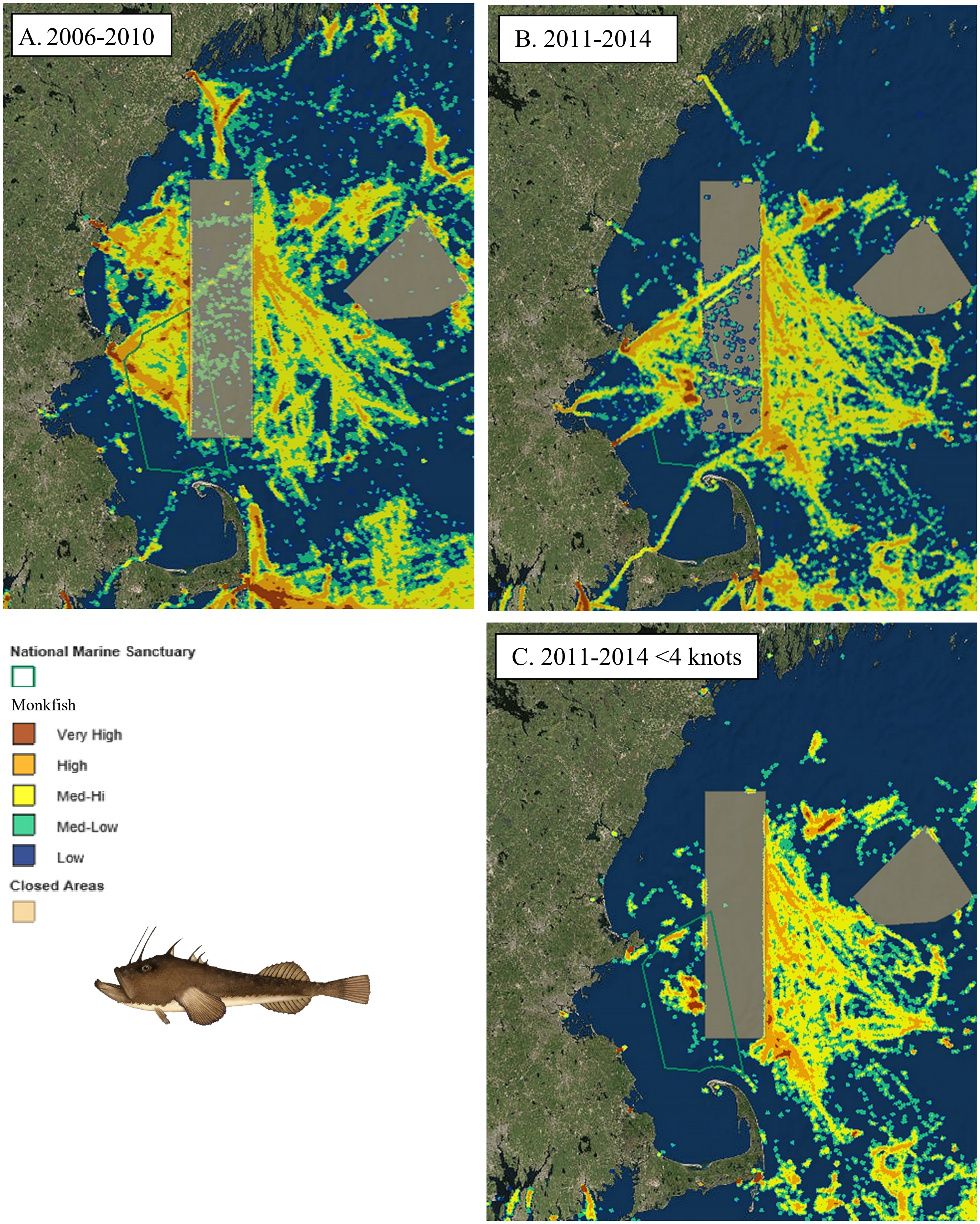

Figure 30. Monkfish fishing density for: (A) All fishing vessels including transiting (2006-2010); (B) all fishing vessels including transiting (2011-2014); and (C) fishing vessels presumed to be actively fishing (moving at < 4 knots) (2011-2014) based on fishing vessels with vessel monitoring systems. Image: Seascape Analytics using NOAA data

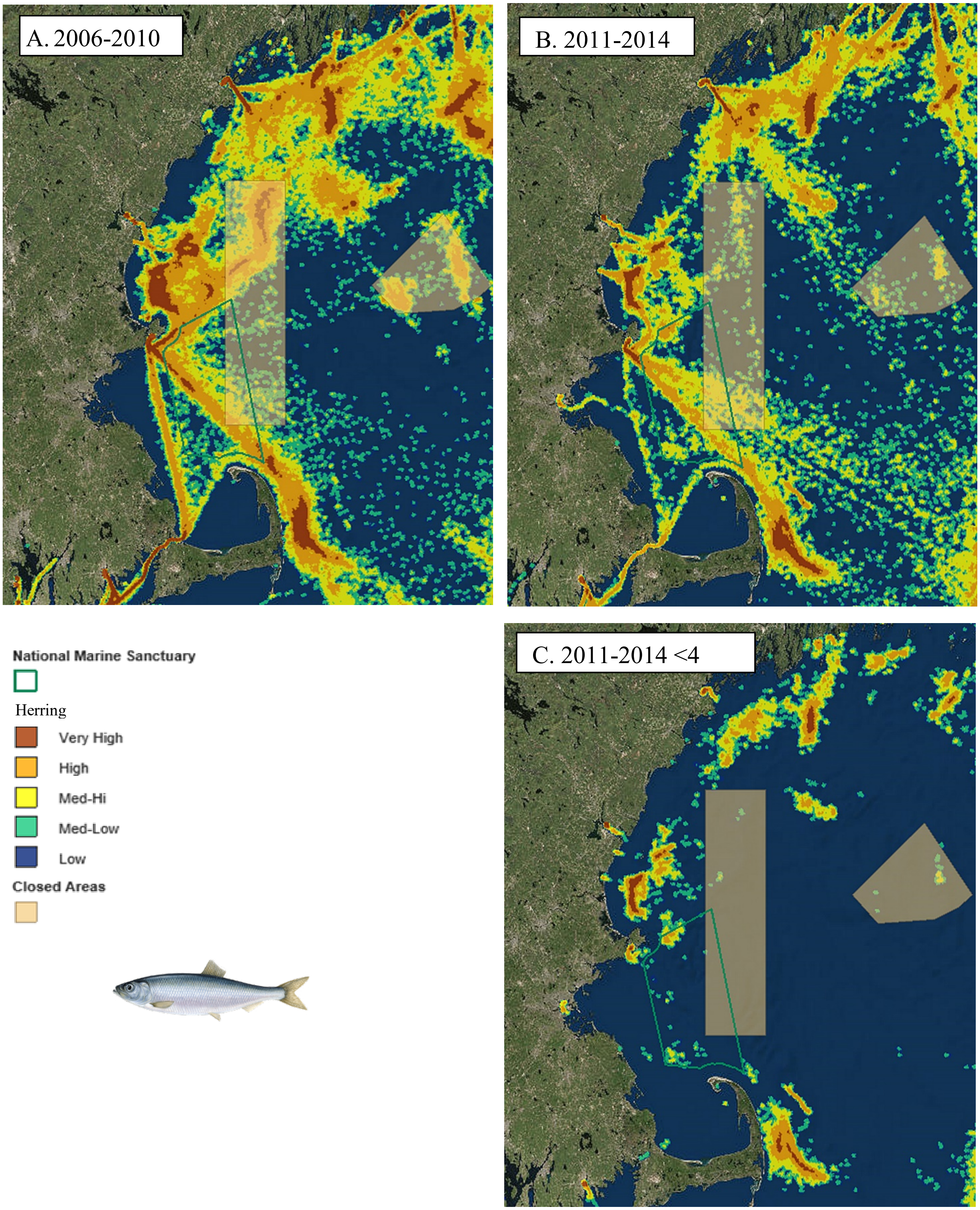

Figure 31. Herring fishing density for: (A) All fishing vessels including transiting (2006-2010); (B) all fishing vessels including transiting (2011-2014); and (C.) fishing vessels presumed to be actively fishing (moving at < 4 knots) (2011-2014) based on fishing vessels with vessel monitoring systems. Image: Seascape Analytics using NOAA data

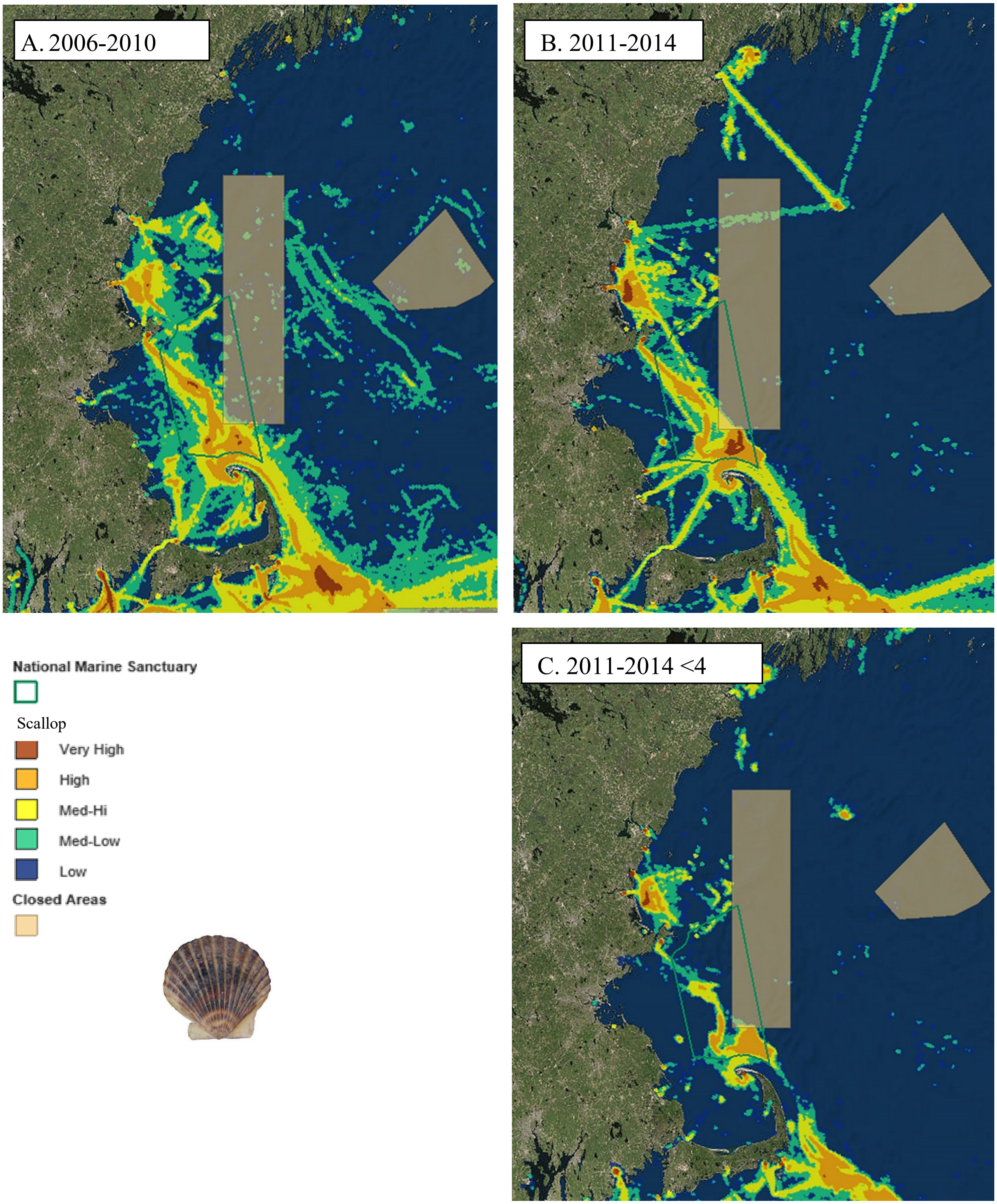

Figure 32. Scallop fishing density for: (A) All fishing vessels including transiting (2006-2010); (B) all fishing vessels including transiting (2011-2014); and (C) fishing vessels presumed to be actively fishing (moving at < 4 knots) (2011-2014) based on fishing vessels with vessel monitoring systems. Image: Seascape Analytics using NOAA data

Recreational fishing has increased over the long term, according to numbers of angler trips and anglers. However, there has been a significant decline over the past 10 years which may have started with the 2008 economic collapse, though recovery of recreational indices has not matched recovery in the wider economy (Fig. 33). Surveys also suggest an increase in the number of caught fish being released rather than harvested (Fig. 34).

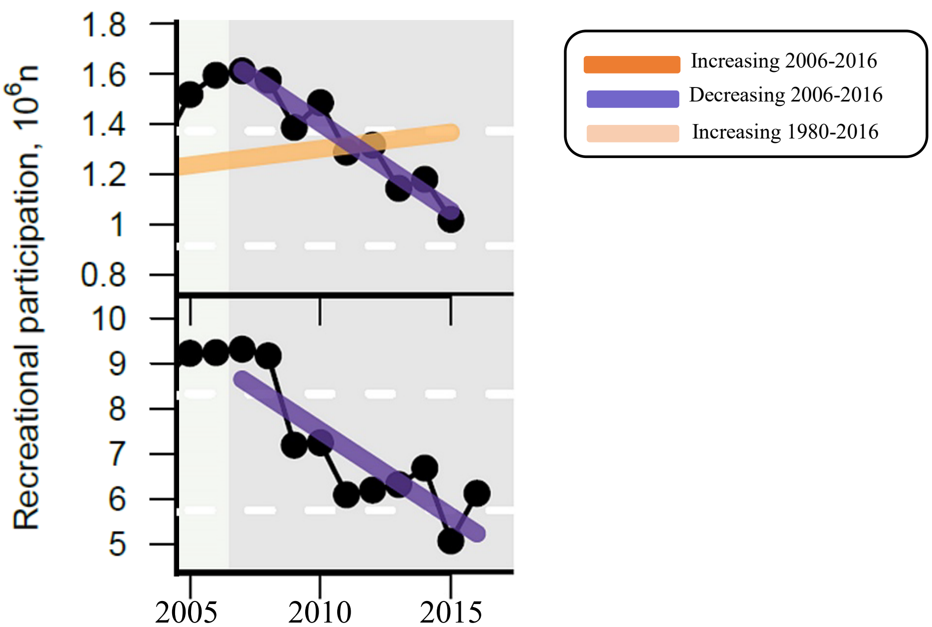

Figure 33. Recent decline in the number of: (A) anglers and (B) number of fishing trips in the Gulf of Maine recreational fishery. Image: State of the Ecosystem report, NOAA NEFSC

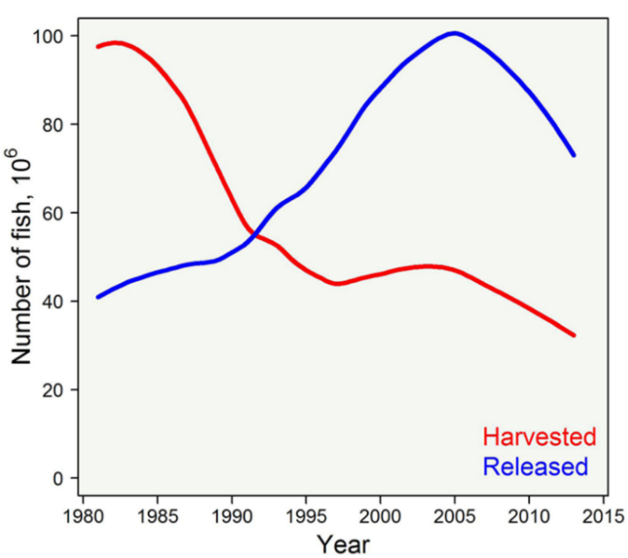

Figure 34. Trends in the number of fish caught and released in the recreational fishery (1980-2015) Image: NOAA

ACKNOWLEDGEMENTS

The majority of the information summarized in this report was gained from the "State of the Ecosystem - Gulf of Maine and Georges Bank" report produced by the Ecosystem Dynamics and Assessment Branch of NOAA's Northeast Fisheries Science Center (April 06, 2017). The report was based on best practices for Integrated Ecosystem Assessment (IEA) developed through the International Council for the Exploration of the Sea (ICES) Working Group for the Northwest Atlantic Regional Sea (WGNARS), a joint working group of the U.S. and Canada. Funding and intellectual support from the NOAA Fisheries Integrated Ecosystem Assessment Program was essential to the production of this report. We thank Sean Lucey (NOAA NEFSC) for guidance on additional data sources as well as the MDAT project team. Where IEA data did not provide sufficient information to address condition report questions then other NOAA Fisheries and NCCOS reports were reviewed together with summaries provided by the State of the Gulf of Maine report. The Northeast Ocean Data portal was also a source of regional information.

GLOSSARY OF ACRONYMS

CHL – chlordane
CO_2 – carbon dioxide
DDT – dichlorodiphenyltrichloroethane
DIC – dissolved inorganic carbon
DIN – dissolved inorganic nitrogen
DIP – dissolved inorganic phosphorus
EPA – United States Environmental Protection Agency
GoM – Gulf of Maine
HAB – harmful algal bloom
ICES – International Council for the Exploration of the Sea
IEA – integrated ecosystem assessment
MDAT – Marine-life Data and Analysis Team
MDMF – Massachusetts Division of Marine Fisheries
NCCOS – National Centers for Coastal Ocean Science
NEAMAP – North East Areas Monitoring and Assessment Program
NEFMC – New England Fishery Management Council
NEFSC – NOAA's Northeast Fisheries Science Center
NOAA Fisheries – NOAA's National Marine Fisheries Service
NO_3 – nitrate
NOAA – National Oceanic and Atmospheric Administration
PCB – polychlorinated biphenyl
$pCO_{2,sw}$ – partial pressure of seawater CO2
SASI – Swept Area Seabed Impact
$Si(OH)_4$ – silicate
WGNARS – Working Group for the Northwest Atlantic Regional Sea
WGOM – western Gulf of Maine
Ω_{AR} – aragonite saturation state

LITERATURE CITED

Anderson, D.M., B.A Keafer, J.L. Kleindinst, D.J. McGillicuddy Jr, J.L. Martin, K. Norton, … and B. Butman. 2014. *Alexandrium fundyense* cysts in the Gulf of Maine: long-term time series of abundance and distribution, and linkages to past and future blooms. *Deep Sea Research Part II: Topical Studies in Oceanography*, 103, 6-26.

Auster, P.J., R.J. Malatesta, R.W. Langton, L. Watting, P.C Valentine, C.L.S Donaldson, … and Babb, W.G. 1996. The impacts of mobile fishing gear on seafloor habitats in the Gulf of Maine (Northwest Atlantic): implications for conservation of fish populations. *Reviews in Fisheries Science* 4: 185–202.

Brawley, S.H, J. Coyer, A.M.H. Blakesee, G. Hoarau, L.E. Johnson, J.E. Byers, … and J. L. Olsen. 2009. Historical invasions of the intertidal zone of Atlantic North America associated with distinctive patterns of trade and emigration. *Proceedings of the National Academy of Science* 106: 8239–8244.

Conversi, A., S. Piontkovski, and S. Hameed. 2001. Seasonal and interannual dynamics of *Calanus finmarchicus* in the Gulf of Maine (Northeastern US shelf) with reference to the North Atlantic Oscillation. *Deep Sea Research Part II: Topical Studies in Oceanography* 48: 519–530.

Curtice, C., J. Cleary, E. Shumchenia, and P.N. Halpin. 2016. Marine-life Data and Analysis Team (MDAT) technical report on the methods and development of marine-life data to support regional ocean planning and management. *Marine-life Data Analysis Team (MDAT).* Online access: http://seamap.env.duke.edu/models/MDAT/MDAT-Technical-Report.pdf

Fay, G., J.S. Link, and J.A. Hare. 2017. Assessing the effects of ocean acidification in the Northeast US using an end-to-end marine ecosystem model. *Ecological Modelling* 347: 1–10.

Fernandes, L.F., K.A. Hubbard, M.L. Richlen, J. Smith, S.S Bates, J. Ehrman, … and K. Libera. 2014. Diversity and toxicity of the diatom *Pseudo-nitzschia* Peragallo in the Gulf of Maine, Northwestern Atlantic Ocean. *Deep Sea Research Part II: Topical Studies in Oceanography* 103: 139–162.

Fogarty, M. and C. Perretti. 2016. Distribution and biomass data for fish species along the US east coast from about Cape Hatteras north to waters in the state of Maine, created by the Northeast Fisheries Science Center for the Northeast Regional Ocean Council. Online access: http://www.northeastoceandata.org/data-explorer/?fish

Gledhill, D.K., M.M. White, J. Salisbury, H. Thomas, I. Mlsna, M. Liebman, … and S.C. Doney. 2015. Ocean and coastal acidification off New England and Nova Scotia. *Oceanography* 28: 182–197.

Greene, C.H., B.C. Monger, L.P. McGarry, M.D. Connelly, N.R. Schnepf, A.J. Pershing, … and R.S. Pickart. 2012. Recent Arctic climate change and its remote forcing of Northwest Atlantic shelf ecosystems. *Oceanography* 25: 208–213.

Grieve, B.D., J.A. Hare, and V.S. Saba. 2017. Projecting the effects of climate change on *Calanus finmarchicus* distribution within the US Northeast Continental Shelf. *Scientific Reports* 7: 6264.

Gulf of Maine Council on the Marine Environment (GOMC). 2010. The Gulf of Maine in context: State of the Gulf of Maine report. Retrieved from http://www.gulfofmaine.org.

Harding, G. 2013. Toxic Chemical Contaminants: Review. State of the Gulf of Maine Report. Gulf of Maine Council on the Marine Environment. Online access: https://gulfofmaine.org/public/state-of-the-gulf-of-maine/

Hak, J.C. and P.J. Comer. 2017. Modeling landscape condition for biodiversity assessment: Application in temperate North America. *Ecological Indicators* 82: 206-216.

Hare, J.A, W.E. Morrison, M.W. Nelson, M.M. Stachura, E.J. Teeters, R.B. Griffis, et al. 2016. A Vulnerability Assessment of Fish and Invertebrates to Climate Change on the Northeast U.S. Continental Shelf. *PLoS ONE* 11: e0146756.

Harvey, C.J., C.R. Kelble, and F.B. Schwing. 2016. Implementing "the IEA": using integrated ecosystem assessment frameworks, programs, and applications in support of operationalizing ecosystem-based management. *ICES Journal of Marine Science*, *74*(1), 398-405.

Incze, L.S., P. Lawton, S.L. Ellis, and N.H. Wolff. 2010. Biodiversity knowledge and its application in the Gulf of Maine area. In McIntyre, A.D. (Ed.) *Life in the World's Oceans: Diversity, Distribution, and Abundance* (pp. 43–63). Oxford, UK: Blackwell Publishing.

Jennings, S. and M.J. Kaiser. 1998. The effects of fishing on marine ecosystems. *Advances in Marine Biology* 34: 203–314.

Ji, R., Z. Feng, B.T. Jones, C. Thompson, C. Chen, N.R. Record, and J.A. Runge. 2017. Coastal amplification of supply and transport (CAST): a new hypothesis about the persistence of *Calanus finmarchicus* in the Gulf of Maine. *ICES Journal of Marine Science* 74: 1865–1874.

Jones, S. 2011. Microbial Pathogens and Biotoxins. State of the Gulf of Maine Report. Gulf of Maine Council on the Marine Environment. Online access: https://gulfofmaine.org/public/state-of-the-gulf-of-maine/

Kleindinst, J.L., D.M. Anderson, D.J. McGillicuddy, R.P. Stumpf, K.M. Fisher, D.A. Couture, J.M. Hickey, and C. Nash. 2014. Categorizing the severity of paralytic shellfish poisoning outbreaks in the Gulf of Maine for forecasting and management. *Deep Sea Research Part II: Topical Studies in Oceanography* 103: 277–287.

Kleisner, K.M., M.J. Fogarty, S. McGee, J.A. Hare, S. Moret, C.T. Perretti, and V.S. Saba. 2017. Marine species distribution shifts on the US Northeast Continental Shelf under continued ocean warming. *Progress in Oceanography*, 153, 24-36.

Large, S.I., G. Fay, K.D. Friedland, and J.S. Link. 2015. Quantifying patterns of change in marine ecosystem response to multiple pressures. *PLoS One*, *10*(3), p.e0119922.

Levin, P. S., M.J. Fogarty, S.A. Murawski, and D. Fluharty. 2009. Integrated ecosystem assessments: developing the scientific basis for ecosystem-based management of the ocean. *PLoS Biology* 7: 23–28.

Li, W.K.W., R.A. Andersen, D.J. Gifford, L.S. Incze, J.L. Martin, C.H. Pilskaln, … and N.H. Wolff. 2011. Planktonic microbes in the Gulf of Maine area. *PloS ONE* 6: e20981.

Liebman, M., G. Benoy, J.S. Latimer, and S. Bricker. 2012. Eutrophication. State of the Gulf of Maine Report. Gulf of Maine Council on the Marine Environment. Online access: https://gulfofmaine.org/public/state-of-the-gulf-of-maine/

Lo, T.T. and H.H. Hsu. 2010. Change in the dominant decadal patterns and the late 1980s abrupt warming in the extratropical Northern Hemisphere. *Atmospheric Science Letters* 11: 210–215.

Lucey, S.M. and J.A. Nye. 2010. Shifting species assemblages in the northeast US continental shelf large marine ecosystem. *Marine Ecology Progress Series*, 415, 23-33.

Mathieson, A.C, J.R. Pederson, C.D. Neefus, C.J. Dawes, and T.L. Bray. 2008. Multiple assessments of introduced seaweeds in the North Atlantic. *ICES Journal of Marine Science* 65: 730–741.

Mayo, C.A. and M.K. Marx. 1990. Surface foraging behaviour of the North Atlantic right whale, *Eubalaena glacialis*, and associated zooplankton characteristics. *Canadian Journal of Zoology*, 68(10), 2214-2220.

McGillicuddy Jr., D.J., D.W. Townsend, R. He, B.A. Keafer, J.L. Kleindinst, Y. Li, … and D.M. Anderson. 2011. Suppression of the 2010 *Alexandrium fundyense* bloom by changes in physical, biological, and chemical properties of the Gulf of Maine. *Limnology and Oceanography* 56: 2411–2426.

Meyer-Gutbrod, E.L. and C.H. Greene. 2014. Climate-Associated Regime Shifts Drive Decadal-Scale variability in recovery of North Atlantic Right Whale Population. *Oceanography* 27: 148–153.

Morse, R.E., K.D. Friedland, D. Tommasi, C. Stock, and J. Nye. 2017. Distinct zooplankton regime shift patterns across ecoregions of the US Northeast continental shelf Large Marine Ecosystem. *Journal of Marine Systems* 165: 77–91.

NEFMC. 2011. Omnibus essential fish habitat (EFH) Amendment 2 Final Environmental Impact Statement. Appendix D: The Swept Area Seabed Impact (SASI) approach: a tool for analyzing the effects of fishing on Essential Fish Habitat. New England Fishery Management Council.

NHDES (New Hampshire Department of Environmental Services). 2009. Numeric Nutrient Criteria for the Great Bay Estuary. Durham, NH: New Hampshire Estuaries Project, Department of Environmental Services, pp 73.

Nye, J.A., J.S. Link, J.A. Hare, and W.J. Overholtz. 2009. Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. *Marine Ecology Progress Series* 393: 111–129

Nye, J.A., R.J. Gamble, and J.S. Link. 2013. The relative impact of warming and removing top predators on the Northeast US large marine biotic community. *Ecological Modelling*, 264: 157–168.

Nye, J.A., M.R. Baker, R. Bell, A. Kenny, K.H. Kilbourne, K.D. Friedland, … and R. Wood. 2014. Ecosystem effects of the Atlantic multidecadal oscillation. *Journal of Marine Systems* 133: 103–116.

Pace, R.M, P.J. Corkeron, and S.D. Kraus. 2017. State-space mark-recapture estimates reveal a recent decline in abundance of North Atlantic right whales. *Ecology and Evolution* 7: 8730–8741.

Perretti, C.T., M.J. Fogarty, K.D. Friedland, J.A. Hare, S.M. Lucey, R.S. McBride, … and L.A. Smith. 2017. Regime shifts in fish recruitment on the Northeast US Continental Shelf. *Marine Ecology Progress Series*, *574*, 1-11.

Pershing, A.J., C.H. Greene, J.W. Jossi, L. O'Brien, J.K Brodziak, and B.A. Bailey. 2005. Interdecadal variability in the Gulf of Maine zooplankton community, with potential impacts on fish recruitment. *ICES Journal of Marine Science*, *62*(7), 1511-1523.

Reid, P.C., R.E. Hari, G. Beaugrand, D.M. Livingstone, C. Marty, D. Straile, … and R. Brown. 2016. Global impacts of the 1980s regime shift. *Global Change Biology* 22: 682–703.

Samhouri, J.F., A.J. Haupt, P.S. Levin, J.S. Link, and R. Shuford. 2013. Lessons learned from developing integrated ecosystem assessments to inform marine ecosystem-based management in the USA. *ICES Journal of Marine Science*, *71*(5): 1205-1215.

Thomas, A.C., R. Weatherbee, H. Xue, and G. Liu. 2010. Interannual variability of shellfish toxicity in the Gulf of Maine: time and space patterns and links to environmental variability. *Harmful Algae* 9: 458–480.

Thomas, A.C., A.J. Pershing, K.D. Friedland, J.A. Nye, K.E. Mills, M.A. Alexander, … and M.E. Henderson. 2017. Seasonal trends and phenology shifts in sea surface temperature on the North American northeastern continental shelf. *Elementa: Science of the Anthropocene*, *5*.

Townsend, D.W., N.D. Rebuck, M.A. Thomas, L. Karp-Boss, and R.M. Gettings. 2010. A changing nutrient regime in the Gulf of Maine. *Continental Shelf Research* 30: 820–832.

Townsend, D.W., D.J. McGillicuddy, M.A. Thomas, and N.D. Rebuck. 2014. Nutrients and water masses in the Gulf of Maine–Georges Bank region: variability and importance to blooms of the toxic dinoflagellate *Alexandrium fundyense*. *Deep Sea Research Part II: Topical Studies in Oceanography* 103: 238–263.

Wang, Z.A., G.L. Lawson, C.H. Pilskaln, and A.E. Maas. 2017. Seasonal controls of aragonite saturation states in the Gulf of Maine. *Journal of Geophysical Research: Oceans* 122: 372–389.

Xu, H., H.M. Kim, J.A. Nye, and S. Hameed. 2015. Impacts of the North Atlantic Oscillation on sea surface temperature on the Northeast US Continental Shelf. *Continental Shelf Research* 105: 60–66.

NATIONAL MARINE SANCTUARIES

AMERICA'S UNDERWATER TREASURES