Office of National Marine Sanctuaries
National Oceanic and Atmospheric Administration

STELLWAGEN BANK NATIONAL MARINE SANCTUARY

National Marine Sanctuaries

STATE OF THE SCIENCE REPORT

AN ADDENDUM TO THE STELLWAGEN BANK NATIONAL MARINE SANCTUARY 2020 CONDITION REPORT

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Cover photo: Two American lobsters (*Homarus americanus*) and a school of cunner (*Tautogolabrus adspersus*) use a historic shipwreck as home and habitat. The underwater photographer, Keith Ellenbogen, is the recipient of an Ernest F. Hollings Ocean Awareness Award to use the art of underwater photography to raise awareness about Stellwagen Bank National Marine Sanctuary. Photo: Keith Ellenbogen

Rationale

The Stellwagen Bank National Marine Sanctuary (SBNMS) management plan revision relies heavily on the findings from the 2020 condition report (NOAA Office of National Marine Sanctuaries, 2020). Knowledge and data gaps identified in the condition report help to highlight SBNMS science needs and guide the development of research action plans and strategies in the upcoming management plan. Since the condition report content was peer reviewed and finalized in 2018, a substantial body of new work by SBNMS staff and colleagues across the region has significantly increased our understanding of the sanctuary ecosystem. While this work will not be used to re-evaluate the status and trends of sanctuary resources in the condition report, we want to ensure that the best available science is considered in our management plan review and is what guides future sanctuary operations and management. The purpose of this document is to summarize SBNMS-related science published since the condition report content was finalized, with a focus on science potentially relevant for SBNMS management. The document is organized according to major topics found in the condition report (climate change, focal species, foundation species, etc.), although new, pertinent information was not available for all topics/species, and not all topics/species are included here. The document also includes a section for research conducted specifically in SBNMS that does not necessarily fall under an existing condition report topic.

Climate Change

Climate-driven changes are rapidly restructuring the Gulf of Maine (GOM) ecosystem, with extensive changes expected by 2050 (Pershing et al., 2019). Increasing temperatures and associated changes in oceanography, species distributions and ranges, and community structure suggest that the GOM is shifting from a subarctic temperate system to a warm temperate system (Pershing et al., 2019; Friedland et al., 2020). Record mean temperatures in the GOM over the last five years have been linked with changes in deep-water dynamics (Pershing et al., 2019; Record et al., 2019b). Weakening of the Atlantic Meridional Overturning Circulation has resulted in more northerly flow of the Gulf Stream, resulting in increased warm, slope water entering the GOM at depth through the Northeast Channel (Brickman et al., 2018; Caesar et al., 2018; Record et al., 2019b).

These changes in temperature and circulation are driving a number of ecosystem impacts with implications for SBNMS. Key components of the GOM/SBNMS prey base, *Calanus finmarchicus* and northern sand lance (*Ammodytes dubius;* hereafter sand lance), are shifting in abundance and distribution, with future changes predicted (Record et al., 2019b; Suca et al., 2021). Distribution shifts of dependent predators, including North Atlantic right and other baleen whales and Atlantic cod, are directly correlated or consistent with shifts in prey and climatic changes (Pershing et al., 2019; Record et al., 2019b; Davis et al., 2020). Commercially important fish species are experiencing changes to suitable thermal habitat, including range expansions, contractions, and habitat fragmentation (Pershing et al., 2019). Lobster and haddock, two economically important species in SBNMS, are experiencing habitat gains, while cod have experienced losses in thermal habitat (Friedland et al., 2020).

Model projections indicate potential impacts to the GOM lobster fishery by 2050. Under a "business as usual" climate scenario and projected temperature increases of 1–2°C, declines in lobster abundance of 42–62% relative to peak abundance, driven by lower recruitment and increased predation due to warming, are predicted (Le Bris et al., 2018).

Mid-Atlantic species, like butterfish, black sea bass, and longfin squid, are becoming more prominent and are expected to increase in abundance (McBride et al., 2018; Pershing et al., 2019; Friedland et al., 2020). Across the northeast shelf, significant changes in thermal regimes and more frequent extreme thermal events appear to have increased diversity and productivity over time, as most species of fish and macroinvertebrates have experienced increases in range, though changes varied by season (Friedland et al., 2020). Range expansions have also increased species interactions and, in some cases, competition (Friedland et al., 2020), though it is unclear how these shelf-level changes may manifest at the GOM/SBNMS scale.

Increased warming and longer summer durations may increase cold-stun stranding events on nearby Cape Cod for critically endangered Kemp's ridley sea turtles, which are sighted in SBNMS and may be expanding their range northward like many species. More stranding events were linked to warmer sea surface temperatures into late fall and, based on sea surface temperature projections, more than 2,300 Kemp's ridley sea turtles may cold stun annually by 2031 (Griffin et al., 2019).

There is also evidence of changing phenology (seasonal timing of recurring events) in the GOM, including later spring and fall phytoplankton blooms and earlier, higher peaks of *Calanus finmarchicus* abundance (Record et al., 2019a, 2019b; Staudinger et al., 2019). Changes to seasonal stratification and mixing, freshwater inputs, occurrence of larval fish, and fish migration are also occurring (Staudinger et al., 2019). Phenological changes influencing foraging and growth, predator-prey mismatches, or environmental cues may impact individual species, food webs, or overall ecosystems.

Pershing et al. (2019) used ensemble numerical models downscaled to the GOM to investigate climate-induced changes to physical conditions in the GOM by 2050, an important time point where impacts of different climate emission scenarios start to diverge. Models predicted a 1.1°C to 2.4°C increase in average temperature and a decrease in surface salinity under "business as usual" carbon emissions, which is expected to enhance water column stratification. SBNMS showed some of the greatest projected changes in the GOM. Model simulations supported continued increasing temperature and salinity in deep GOM basins, consistent with inflow of warm slope water. Further, models predicted an increase in current speed, particularly in the GOM Coastal Current, which may have important implications for transport of nutrients, phytoplankton, zooplankton, and larval fishes to SBNMS.

Ocean acidification in the GOM may impact several commercially and ecologically important species. Under a "business as usual" scenario, sea scallop biomass across George's Bank and the mid-Atlantic could decline more than 50% by 2100 (Rheuban et al., 2018). Stokesbury and Bethonney (2020) suggest using sea scallops as an indicator species for monitoring climate change impacts due to their sensitivity to warming and ocean acidification and their sedentary nature, which makes abundance surveys relatively straightforward. Exposure to higher pCO_2

had several impacts on lobsters, including slower development, decreased growth, increased susceptibility to shell disease, and increased mortality (McLean et al., 2018; Menu-Courey et al., 2019). Embryonic and larval development and survival showed variable and complex responses to warming and ocean acidification in several fish species, including Atlantic cod, Atlantic herring, and sand lance (Stiasny et al., 2016; Leo et al., 2018; Sswat et al., 2018; Murray et al., 2019). Impacts to these commercially and ecologically important species may impact fisheries and ecosystem structure in SBNMS. While ocean acidification in the larger GOM appears to be buffered at present, these conditions could impact species in SBNMS in the future. Given this buffering capacity, temperature effects are likely to have greater impact before pH does, though the interaction between these two factors could have a greater impact than either alone (Pershing & Stamieszkin, 2020).

In addition to having dramatic effects on ecosystems, commercial fishing and whaling have also reduced the impact of harvested species on carbon and nutrient recycling, drastically decreasing carbon sequestration opportunities (Pershing et al., 2010; Pershing & Stamieszkin, 2020). Pershing et al. (2010) estimated that rebuilding baleen whale populations could remove 1.66×10^5 tons of carbon each year through sinking whale carcasses, an estimate comparable to existing carbon sequestration projects. These results emphasize the value of whale conservation and the ecosystem services they can provide.

Foundation Species

Calanus finmarchicus

Observations and analysis of *C. finmarchicus* in relation to changing oceanography suggest that two distinct oceanographic pathways (western and eastern GOM), which differ in timing, seasonality, and environmental influences, drive abundance of *C. finmarchicus* in the GOM (Record et al., 2019b). In the western GOM, including near SBNMS, coastal amplification and transport of *C. finmarchicus* by the Maine Coastal Current has sustained and increased winter and spring abundance of *C. finmarchicus*. These processes continue to buffer against general declines in abundance observed throughout the GOM from summer to winter and the northern range shift predicted for *C. finmarchicus*. In contrast, the eastern GOM shows higher impact of climate-driven changes in oceanography. Deep-water warming and more warm slope water entering the GOM likely contribute to direct and indirect effects on *C. finmarchicus* abundance through reduced supply and declines in general condition (i.e., decreased diapause, increased metabolic demand; Record et al., 2019b). These shifts in *C. finmarchicus* are linked with changes in North Atlantic right whale distribution, with particularly clear correlations between *C. finmarchicus* and North Atlantic right whale abundance in the eastern GOM. The importance of *C. finmarchicus* in defining the GOM and the entire North Atlantic biome was highlighted by Pershing and Stamieszkin (2020).

Sand Lance

Sand lance are important forage fishes across the northern hemisphere and a key component of the SBNMS food web. A synthesis of available literature found that 72 predators (45 species of fishes, two squids, 16 seabirds, and nine marine mammals) across the Northwest Atlantic Ocean, many of which are found in SBNMS, were found to consume sand lance (Staudinger et al., 2020). Sanctuary research on spatial relationships between sand lance and top predators in SBNMS showed strong, consistent collocation among humpback whales, great shearwaters, and sand lance across seasons and years, suggesting that the abundance and distribution of humpback whales and great shearwaters is tightly linked to that of sand lance in SBNMS (Silva et al., 2020). Sand lance were the primary prey source for young great shearwaters sampled in and around SBNMS based on fecal DNA analysis (Powers et al., 2020). High collocation among these three species typically occurred on or near southern Stellwagen Bank, suggesting this area is a persistent hot spot for sand lance and predators.

Notable progress has been made in understanding sand lance ecology, phenology, and environmental drivers of distribution and abundance, including factors that influence interannual population fluctuations. Sanctuary-led sampling (standardized and opportunistic) and modeling showed significant spatial variation in sand lance presence and abundance. Sand lance abundance increased from north to south, consistent with collocation studies (Silva et al., 2020, 2021). Sand lance presence on Stellwagen Bank coincided with *C. finmarchicus* abundance, which dominated sand lance gut contents from winter to spring, accounting for up to 78% of diet by biomass (Suca et al., 2021). Spatial differences in *C. finmarchicus* availability on Stellwagen Bank appeared to drive spatial differences in sand lance lipid accumulation. Lipid content was significantly higher in fish from northern Stellwagen Bank, likely due to localized increases in *C. finmarchicus* transported by the Western Maine Coastal Current to the northwest corner of the bank (Suca et al., 2021).

Work suggests that the timing of sand lance feeding, growth, lipid accumulation and spawning may be linked to the phenology of *C. finmarchicus*. Feeding incidence (percent of stomachs with prey) peaked from March–May, coincident with the annual peak in *C. finmarchicus* abundance. Multiple years of observations showed that sand lance in SBNMS entered a dormancy period in late summer, marked by a cessation of feeding and lipid accumulation and increased time in the sediment starting in August, concurrent with reaching maximum size and lipid content. From August–October, lipid/energy reserves are dedicated to gonad development in preparation for spawning over a 1–2 week window in late November when water temperatures near 10°C (Murray et al., 2019; Suca et al., 2021). This work suggests projected decreases in *C. finmarchicus* availability in the Gulf of Maine may negatively impact sand lance body condition and reproduction, which may have important implications for predators and SBNMS ecosystem structure.

Based on the above observations in SBNMS and using Northeast Fisheries Science Center spring bottom trawl survey data from 1968–2019, Suca et al. (2021) showed that the three main drivers of sand lance abundance across the Northeast Shelf were *C. finmarchicus* abundance (lagged 3–4 years), Atlantic herring abundance (lagged 2–3 years) and the proportion of warm slope water entering the Northeast Channel (unlagged).

Sand lance abundance was negatively correlated with Atlantic herring abundance (2–3 year lag) throughout the time series. Atlantic herring consume larval and juvenile sand lance, exerting top-down control on sand lance populations. The lag represents the abundance of herring when sand lance caught in the survey were larvae and juveniles and were susceptible to predation by herring.

Sand lance abundance was positively correlated with *C. finmarchicus* abundance at a 3–4 year time lag. The time lag represents abundance of *C. finmarchicus* available to the parents of fish collected in the survey data, and supports the hypothesis (parental condition hypothesis) that higher abundance of *C. finmarchicus* available to parents results in more or better quality eggs of sand lance that are caught 3–4 years later in the survey. Results suggest *C. finmarchicus* abundance is linked with adult sand lance condition, suggesting that projected declines in *C. finmarchicus* abundance in the GOM will lead to decreases in high-quality prey for sand lance, decreasing parental condition and spawning output.

Sand lance abundance was negatively correlated with the proportion of warm slope water, consistent with other changes occurring throughout the GOM, including declines in abundance of *C. finmarchicus*, the primary prey of sand lance (Record et al., 2019b). Increasing warm slope water could impact sand lance in two ways: indirectly, through decreasing prey availability to spawners—thus lowering parental condition and spawning output—or through a direct negative effect on over-winter survival of adult sand lance via elevated bottom temperatures and lower winter prey availability. Here, it appears that increasing warm slope water had a direct deleterious effect on adult sand lance survival and abundance. During wintertime, post spawning, sand lance are at their lowest lipid content/energy reserves, making them susceptible to overwinter conditions and more sensitive to increased temperatures and prey shortages. Given the increasing proportion of warm slope water since 2009, sand lance are more likely to endure winter conditions with consistently high temperatures, increasing overwinter mortality for the species.

Lab studies also provide evidence of sand lance vulnerability to increasing temperatures as well as ocean acidification. Synergistic, negative effects of increased temperature and CO_2 decreased survival of sand lance embryos. Further, higher CO_2 concentrations delayed hatching, reduced energy reserves, and reduced embryonic growth. When compared with other species, these results suggest that sand lance may be one of the most ocean-acidification-temperature sensitive species studied to date (Murray et al., 2019).

Modeling work suggests that the future of sand lance across the Northeast Shelf, and therefore, SBNMS, is uncertain, due to observed and predicted climate-related changes to hydrography and prey availability. Using the relationships between sand lance, herring, *C. finmarchicus*, and slope water, projections of sand lance abundance under different climate scenarios (2020–2100) show that, on average, 95% of years and 97% of years under Representative Concentration Pathway 4.5 and 8.5 (i.e., "business as usual"), respectively, had both a negative sand lance and negative Atlantic herring anomaly. These predictions show that the Northeast Shelf will be in a state of low adult abundances of the two most dominant lipid-rich forage fish for much of the 21st century, a state rarely seen before (only six years from 1968–2008 had negative anomalies for both species), suggesting major changes to the forage fish complex and food web on the Northeast Shelf (Suca et al., 2020).

Work is ongoing to identify the role SBNMS plays as a sand lance source/sink for the region. Preliminary modeling suggests that most sand lance hatched on Stellwagen Bank are transported by currents to southern areas, while most sand lance that settle on Stellwagen Bank are supplied by areas to the north (Baumann et al., 2020). The projected shift in sand lance abundance and in the forage fish community warrant continued monitoring of forage fish and predator populations.

Focal Species

North Atlantic Right Whale

The status of the North Atlantic right whale is more dire than previously thought. In July 2020, the International Union for Conservation of Nature changed the status of North Atlantic right whales from endangered to critically endangered. In October 2020, NOAA Fisheries revised their 2018 population estimate from 412 to 383 individuals, and reported a preliminary abundance estimate of 366 individuals alive at the beginning of 2019. Ten deaths were documented in 2019, therefore, the best abundance estimate for the end of 2019 is 356 individuals.

Table 1. Births, deaths, and new injuries to North Atlantic right whales since 2018. Source: Pettis et al., 2018, 2020, 2021

Year	Births	Deaths	New Injuries	Detailed Information
2018	0	3	17	All deaths occurred in U.S. waters and cause of death was entanglement in all cases. Fifteen injuries were due to entanglement and two were due to vessel strikes.
2019	7	10	9	Cause of death information is available for four cases; three were caused by vessel strikes and one was caused by entanglement. All injuries were due to entanglement (four were observed with gear, five were observed with injuries but no gear present).
2020	10	2	13	One death was attributed to a vessel strike, and one was a possible birth injury/dystocia. Injuries were due to entanglement (four with gear attached, six with injuries but no gear present) and vessel strikes (three individuals).
2021	15	1	2	One death was a newborn calf vessel strike.

A transboundary (U.S. and Canada) North Atlantic right whale Unusual Mortality Event, declared in 2017, is ongoing. Of 33 North Atlantic right whales confirmed dead since 2017, 23 were necropsied and 19 of those died as a direct result of human activities (eight entanglements, 19 vessel strikes). Further, 15 live, free-swimming whales have been documented with serious entanglement or vessel-strike-related injuries since 2017. The total number of North Atlantic right whales involved in the Unusual Mortality Event is now 48 (33 dead, 15 seriously injured), which represents more than 10% of the population. NOAA Fisheries considers this a “significant setback to the recovery of such a critically endangered species” (NOAA Fisheries, 2021).

Entanglement in fishing gear is the leading cause of serious injury and mortality among North Atlantic right whales in recent years (Sharp et al., 2019; Moore et al., 2021). While birth rates have been correlated with stochastic prey availability to females (Meyer-Gutbrod & Greene, 2018) and nutrition is a factor in reproductive success (Moore et al., 2021), adult female mortality due to direct anthropogenic causes is the main factor driving low birth rates (Corkeron et al., 2018). Further, poor body condition of lactating females due to decreased prey availability or quality influences calf body length and may cause reductions in calf growth rates and, potentially, calf survival (Christiansen et al., 2020). Mortality due to entanglements and vessel strikes is also impacting North Atlantic right whale reproductive success (Moore et al., 2021).

Pace et al. (2020) recently reported on cryptic or unobserved mortality of North Atlantic right whales. Observed deaths from 1990–2017 substantially underestimated modeled estimates of mortality, with only 36% of estimated deaths detected, suggesting that observed mortality is a poor indicator of annual mortality estimates. During the same time period, there was a substantial mismatch between causes of serious injuries observed in living whales and causes of death determined from necropsied whales. Entanglement accounted for 54 of 62 or 87% of serious injuries in living whales, but only 20 of 41 or 49% of deaths in examined carcasses. The 62 seriously injured whales were not seen again, and could reasonably be presumed dead, suggesting that (1) observed percentages of causes of death cannot be used to estimate relative causes of cryptic mortality, (2) cryptic deaths from entanglement are much greater (more than double) than cryptic deaths due to other causes, and (3) entanglement mortality is widely underestimated. This work implies that entanglement impacts to the North Atlantic right whale population are even greater than currently estimated, which should be considered in management strategies.

Myers and Moore (2020) used three case studies from Maine and Massachusetts lobster fisheries to demonstrate that reductions in lobster fishing effort may support higher profits and help prevent entanglements. Fishing effort in the Maine lobster fishery was about 7.5 times higher than the Canadian GOM lobster fishery to harvest the same amount of landings, suggesting an overcapacity in the Maine fishery that could lead to resource overexploitation. Further, reductions in fishing effort in Maine and Massachusetts, either through reductions in numbers of traps or area closures, were correlated with record high landings. Reducing effort in the lobster fishery may increase fishing profits, increase long-term sustainability of the lobster fishery, and support North Atlantic right whale protections.

Most current management strategies to protect North Atlantic right whales are largely static and have relied on historic habitat use (e.g., the assumption that whale habitat use is predictable over space and time based on historical sightings data). Since 2010, however, North Atlantic right whales have drastically shifted their distribution to new areas where protections to minimize entanglements and vessel strikes do not yet exist (Davies & Brillant, 2019). Major distribution changes include declines in North Atlantic right whale sightings per unit effort in the Bay of Fundy and Great South Channel, increases in sightings per unit effort in Cape Cod Bay (Davies et al., 2019; Ganley et al., 2019; Record et al., 2019b), and newly documented use of the Gulf of St. Lawrence and areas south of Nantucket (Leiter et al., 2017; Davies & Brillant, 2019). Passive acoustic monitoring along the U.S. Eastern seaboard also shows a distribution shift, with fewer acoustic detections in the GOM (except for Massachusetts Bay) and more detections in the Gulf of St. Lawrence, southern New England, and the mid-Atlantic (Davis et al., 2017; Simrad et al., 2019). In Massachusetts Bay, North Atlantic right whale acoustic occurrence has increased during "off-season" time periods (summer–fall) (Charif et al., 2019), reflecting a change in North Atlantic right whale phenology in relation to Massachusetts Bay as part of overall distribution shifts throughout the GOM.

Shifts in habitat use of North Atlantic right whales have been largely linked to recent, rapid changes in climate and resulting shifts in their primary prey, *C. finmarchicus* (Record et al., 2019b); relationships between declining *C. finmarchicus* and North Atlantic right whales in the eastern GOM are clearer than in the western GOM. In Cape Cod Bay, increased *C. finmarchicus* abundance in early winter coincides with increased observations of North Atlantic right whales earlier in the year (Record et al., 2019b; Ganley et al., 2019). Further, recent modeling work accounting for monthly differences in detection probability in Cape Cod Bay suggests that more North Atlantic right whales use Cape Cod Bay than have been previously documented, particularly in January and February (Ganley et al., 2019). Trap-pot fishing is still allowed in Cape Cod Bay during January. The higher-than-perceived whale abundance during January suggests that entanglement risk is also higher than previously thought during this time (Ganley et al., 2019).

Notably, while North Atlantic right whale abundance has increased in Cape Cod Bay over the last decade (Mayo et al., 2018; Ganley et al., 2019; Record et al., 2019b), reasons for the increase are not clear, as North Atlantic right whale abundance does not correlate directly with *C. finmarchicus* abundance in Cape Cod Bay, and may be more related to availability of several zooplankton prey species. Given the rapid shifts in North Atlantic right whale distribution, dynamic forecasting of habitats and implementation of management measures will be critical for protecting this species.

Humpback Whale

New population estimates for GOM humpback whales suggest the population has been slowly growing since 2009, consistent with its Endangered Species Act status change and delisting (Robbins & Pace, 2018a). Given the slow population increase since 2009, Robbins and Pace (2018b) evaluated the effectiveness of two federal rules designed to reduce serious injury and mortality due to entanglement, the 2009 sinking ground line rule and the 2015 vertical line rule. Model results suggest no change in population survival rates in response to the 2009 ground line rule, but an apparent increase in survival from 2015–2016 coinciding with the 2015 vertical line rule. Further work is required to determine if the increase in survival is specific to entanglement or may involve other factors.

Despite population growth, GOM humpback whales still face considerable adverse impacts in SBNMS. Hill et al. (2017) documented vessel-related injuries to humpback whales in and around SBNMS using photos taken from 2004–2013 to better understand vessel-whale interactions. 14.7% of individuals (n=92) showed injuries consistent with one or more vessel strikes, with 10% of injuries deemed "fresh" and considered to have occurred in or around SBNMS. Vessel collision rates reported here are likely underestimates, given that blunt force trauma and death could not be detected. Notably, none of the injuries documented in this study were reported to NOAA. From 2004–2013, NOAA OLE received only one report of a humpback whale vessel strike in/near SBNMS. This work suggests that current surveillance and enforcement in SBNMS are inadequate to protect humpback whales from vessel strikes and supports the need for increased on-the-water education through SBNMS's Boater Outreach for Whale Watching program. Hill et al. (2017) recommended that guidelines and a management strategy be developed for all classes of vessels transiting in the vicinity of whales (not just those whale watching).

Humpback whale distribution in SBNMS is tightly linked to sand lance, and both species are strongly collocated on the southwest corner of Stellwagen Bank (Silva et al., 2020). Modeling work using SBNMS survey data shows a clear correlation between abundance of sand lance and humpback whales and provides fine scale (~1km) probability estimates of the occurrence of whale aggregations across the bank (Silva et al., 2021). Humpback whale aggregations are most likely to occur on southern Stellwagen Bank in areas of high sand lance abundance that also overlap a high-density area of fixed fishing gear (Silva et al., 2021).

Wiley et al. (2003) also identified the southwest corner of Stellwagen Bank as a high-risk area for entanglement. Southern SBNMS has persisted as a reliable sand lance, humpback whale, and fixed fishing gear hot-spot for nearly two decades, suggesting increased protections for this area would be valuable.

Wise et al. (2019) measured levels of metals in skin biopsies of humpback (and fin and minke) whales in the GOM. Data showed that humpback whales in the GOM were exposed to metal levels much higher than baleen whales in other regions. Metals found in biopsies included aluminum, chromium, and nickel, which can cause significant toxicity.

Odontocetes

Habitat modeling and passive acoustic monitoring have increased our understanding of odontocete use of SBNMS. Silva et al. (2019a) used opportunistic sighting data to model distributions of harbor porpoise and Atlantic white-sided dolphins, the two most commonly sighted odontocete species in SBNMS. Distributions differed by month and by species, but both showed associations with sand habitat, suggesting that sand lance may be important prey.

Passive acoustic monitoring from ocean gliders produced the first documentation of acoustic occurrence of dolphin species in Massachusetts Bay (Silva et al., 2019b). Dolphins were detected on 73% of deployment days, showed a consistent presence over two consecutive winter seasons, and were detected more frequently within SBNMS near southern Stellwagen Bank. Data also suggest annual site fidelity to the Stellwagen Bank area. This work suggests dolphins use the sanctuary area more than previously thought and warrants continued investigation into ecosystem and human impacts.

Great Shearwater

New work by SBNMS staff and colleagues has advanced knowledge of great shearwater diet, habitat use, and contaminant exposure. Great shearwaters in SBNMS are strongly collocated with sand lance, particularly near the southwest corner of Stellwagen Bank (Silva et al., 2020). Analysis of six years of satellite telemetry also shows overlap between great shearwater core use areas and sand lance habitat throughout the GOM (Powers et al., 2020). Fecal DNA analysis confirmed that sand lance were the primary food for great shearwaters in the GOM. Two years of stable isotope data from feathers, red blood cells, and plasma suggest great shearwater long-term diets are relatively stable in terms of trophic level, but small, seasonal short-term diet shifts were detected in GOM birds (Hong et al., 2019). Based on gonad development observed during necropsies of stranded or bycaught great shearwaters, 0–2 year old birds dominate in the southern GOM, suggesting that SBNMS serves as a winter "nursery" for this species (Powers et al., 2020).

Robuck et al. (2020) documented exposure of great shearwaters in Massachusetts Bay to contaminants of emerging concern, including emerging and legacy per- and polyfluoroalkyl substances and microplastics (Robuck, 2020). A 10-year time series showed per- and polyfluoroalkyl substance levels were associated with reduced organ weights and fat depth (Robuck, 2020), warranting further investigation given the importance of lipids for seabird migration and reproduction. Necropsies of great shearwaters revealed that 98% of juveniles from Massachusetts Bay were found to contain ingested plastics (Robuck et al., 2020).

New understanding of great shearwater habitat use, diet, and environmental exposure to contaminants combined with their unique life history characteristics support continued monitoring of this species as an important ecological indicator in SBNMS, particularly given the climate-driven shifts in diet and breeding responses seen in other GOM seabirds (Scopel et al., 2019).

Atlantic Cod

The most recent stock assessment indicates that GOM Atlantic cod are overfished and overfishing is occurring (Northeast Fisheries Science Center [NEFSC], 2020). The stock shows truncated size and age structure, consistent with a population experiencing high mortality and low recruitment. Research is needed on natural mortality, biases and uncertainty in catch estimates, stock structure, and potential causes of low stock productivity (NEFSC, 2020).

New research has confirmed the importance of SBNMS as a winter spawning ground for GOM Atlantic cod. Zemeckis et al. (2019) used a combination of passive acoustic monitoring from mobile and stationary platforms, tagging, and acoustic telemetry to identify the spatial and temporal distribution of cod spawning during winter in Massachusetts Bay. Fish presence inferred from acoustic telemetry and detections of cod grunts (male spawning vocalizations) indicate spawning primarily occurs from early November through January with a peak in mid-December. Several spawning hot spots were identified, including an area surrounding liquefied natural gas terminals (see NOAA Office of National Marine Sanctuaries (2020) for a map of this location) and the northwest corner of Stellwagen Bank. Based on strong evidence from all technologies, Zemeckis et al. (2019) recommended that the area surrounding the northwest corner of Stellwagen Bank be included in the seasonal closed area for Atlantic cod. In a subsequent study, a 10-year time series (2007–2016) of passive acoustic monitoring data from Massachusetts Bay confirmed the northwest corner of Stellwagen Bank as one of the areas of highest cod acoustic spawning activity (Caiger et al., 2020). A decline in grunt presence over the same 10-year time period correlated with declines in spawning stock biomass (Caiger et al., 2020), suggesting that this spawning ground may account for a critical component of the remaining stock's reproductive capacity and highlighting the need for continued protections. A general relationship between increasing sea surface temperature and interannual grunt rate and grunt presence suggests that temperature could be an important driver of Atlantic cod spawning or acoustic activity.

Work by Stanley et al. (2017) indicates that the effective communication space of cod in SBNMS is significantly reduced by increasing levels of underwater sound, mostly due to the presence of large vessel traffic. At a spawning site near the northwest corner of Stellwagen Bank, the number of automatic identification system (AIS) tracked vessels was positively correlated with sound pressure levels and negatively correlated with the effective vocalization radius for cod and haddock. Reductions in communication space during a time of high vocalization and critical biological activity (spawning) could impact cod reproductive success and survival.

Dean et al. (2019) used otolith analysis to classify cod as winter or spring spawners. Results showed that cod that spawn in spring outside SBNMS have lower mortality and were larger and older than cod spawning in winter partly in SBNMS, but contributed less than 2% to annual recruitment in the GOM. This further emphasizes the importance of further protections for winter spawning cod in SBNMS to sustain stock reproductive potential.

Lobster

Spatial variability in climate effects and local oceanographic conditions are driving lobster population trajectories across the northeast. Lobster abundance has increased in SBNMS and the northern GOM, mainly driven by increased recruitment and expanded juvenile thermal habitat due to warming (Le Bris et al., 2018; Mazur et al., 2020; Friedland et al., 2020). Successful recruitment relies on successful larval settlement, which occurs between 12°C and 20°C (Goode et al., 2019). Warming has expanded suitable thermal habitat for juveniles (above 12°C) to SBNMS and northward, accounting for increased abundance in the GOM stock in recent years. However, if temperatures in SBNMS continue to warm and regularly exceed the 20°C threshold, abundances will likely decline as seen in the southern New England stock (Le Bris et al., 2018; Goode et al., 2019). Further, predicted increases of strong stratification in the southwest GOM and SBNMS, which will cause bottom temperatures to remain colder and warm more slowly than surface temperatures, may inhibit larval settlement (Goode et al., 2019).

Benthic Biodiversity

Recent work using advanced next-generation DNA sequencing techniques characterized benthic communities of microorganisms (prokaryotic and eukaryotic) from sediment samples collected in northwest SBNMS. Polinski et al. (2019) identified organisms from 127 phyla, including 59 Bacteria, nine Archaea, 18 Animalia, 14 Chromista, eight Protozoa, two Plantae, and 17 Fungi phyla, across three sites and two seasons (summer and fall). Of these 127 phyla, 115 had not been found in SBNMS at the time of the 2010 management plan. The most abundant phylum of Archaea, Thaumarchaetoa, is important in global carbon and nitrogen cycles and is likely to be impacted by climate change due to its temperature-dependent distribution; thus, this phylum may represent an important indicator for impacts of warming on the benthic prokaryotic community. Sites and seasons showed similar organism abundances, but high biodiversity and heterogeneity across sites were driven by differences in rare microorganisms.

Heinrichs et al. (2020) quantified the relative abundance and biodiversity of the sediment microbial community at three sites in northwest SBNMS in two seasons (summer and fall), focusing specifically on bacteria, including those with potential biomedical applications (antibiotic compounds). Microbial community structure at all taxonomic levels (phylum, class, genus, species) differed significantly between seasons. Biodiversity was significantly higher in summer compared to fall for bacteria classes. *Streptomyces*, a genus known for producing a large percentage of secondary metabolites used in chemotherapy, immunosuppressants, and other drugs, was the fourth most abundant genus and was found at all sites in all seasons, but showed significant seasonal and spatial differences in abundance.

Ongoing work by Bucci et al. (2020) is characterizing and comparing microbial abundance and biodiversity in SBNMS, both inside and outside the Western Gulf of Maine Closure Area, an area that overlaps the sanctuary and is closed to bottom trawling. Preliminary results suggest differences in microbial communities between open and closed areas and the presence of bacterial strains (*Streptomyces*) relevant for biomedical and public health applications. Further work is warranted to explore impacts of open and closed fishing areas to the microbial community and the possibility of marine bioprospecting to support ecological and health studies.

These studies greatly expand knowledge of benthic ecology and biodiversity in SBNMS and highlight opportunities for future work and applications.

Human Impacts

Soundscapes

Haver et al. (2019) provide baseline soundscape information and comparisons for three U.S. national parks and SBNMS using acoustic data collected as part of the Noise Reference Station Network (Haver et al., 2018). Anthropogenic sound dominated the SBNMS soundscape. SBNMS had the highest sound levels of all sites, mainly attributable to year-round vessel traffic and seasonal weather patterns, with band levels higher in winter and spring due to wind and storms. Occurrence of humpback whale vocalizations suggests that higher sound levels in SBNMS could mask more humpback whale calls compared with other sites. Unique seasonal, diel, and spectral ambient sound level patterns across all four sites highlights the need for continued, standardized monitoring of soundscapes to document ecological changes and to appropriately tailor management actions.

Habitat Impacts

Goode et al. (2021) evaluated impacts of the GOM lobster fishery on essential fish habitat, including SBNMS, using the Swept Area Seabed Impact and National Marine Fisheries Service Vertical Line models. Impacts were primarily localized to coastal areas and mid-coast Maine, with minimal impacts on essential fish habitat predicted for SBNMS and most of the GOM due to small trap footprints and large area fished. However, it is unclear how limitations in data and model resolution may under- or overestimate impacts in SBNMS.

Recreational Fishing

Haddock have become a more popular target in Gulf of Maine and SBNMS recreational fisheries in recent years due to increased abundance and regulations on Atlantic cod. Haddock was the second most kept species in SBNMS from 1998–2016 by charter and party boats, composing 23% and 36.5% of landings from charter and party boats, respectively (Schwarzmann et al., 2020). Further, haddock caught in SBNMS recreational fisheries accounted for a large percentage of haddock caught in statistical area 514 (area including SBNMS, as defined by NOAA NEFSC for reporting and research), with 62.4% and 44.3% of charter and party boat haddock catch from statistical area 514 coming from SBNMS. However, given overlap between haddock and cod in some areas, fishing regulations placed on haddock to reduce impacts to cod have resulted in high discard rates for haddock. Capizzano et al. (2019) combined electronic tagging with representative fishery-dependent survey data to estimate a fishery-scale discard mortality rate for haddock released in the GOM recreational fishery. Mean discard mortality of haddock in the GOM recreational fishery was 63% for 2015 and was significantly influenced by season and length class, with increased mortality for smaller fish in autumn. Further, survival modeling indicated that mortality occurred primarily after release and not during capture and handling.

Other Fisheries

Winter Flounder Spawning Habitat in SBNMS

The southwest corner of Stellwagen Bank was newly identified as an offshore spawning area for winter flounder (Fairchild et al., 2017). Winter flounder are within the top 10 species in terms of pounds landed over sand habitat in SBNMS (Silva et al., 2020), and documentation of spawning activity further highlights the ecological importance of sand habitat to SBNMS and the GOM.

Thorny Skate Habitat Use in SBNMS

Thorny skates are primarily found in the GOM, including SBNMS. Thorny skates are critically endangered and overfished despite the lack of a directed fishery, and little is known about their movements and habitat use. Kneebone et al. (2020) used conventional tag-recapture analyses and pop-up satellite archival transmitting tags to investigate the horizontal movements, dispersal, and habitat use of thorny skate in the US GOM. Thorny skates tagged in SBNMS, including in Stellwagen Basin and the Western Gulf of Maine Closure Area, were relatively sedentary, exhibiting relatively small-scale movements and using SBNMS year round, though there was some evidence of a seasonal depth shift, perhaps related to temperature. Warming bottom temperatures have been linked with a recent range contraction of thorny skates into the western GOM. SBNMS may become a particularly important habitat for thorny skates as temperatures continue to increase.

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