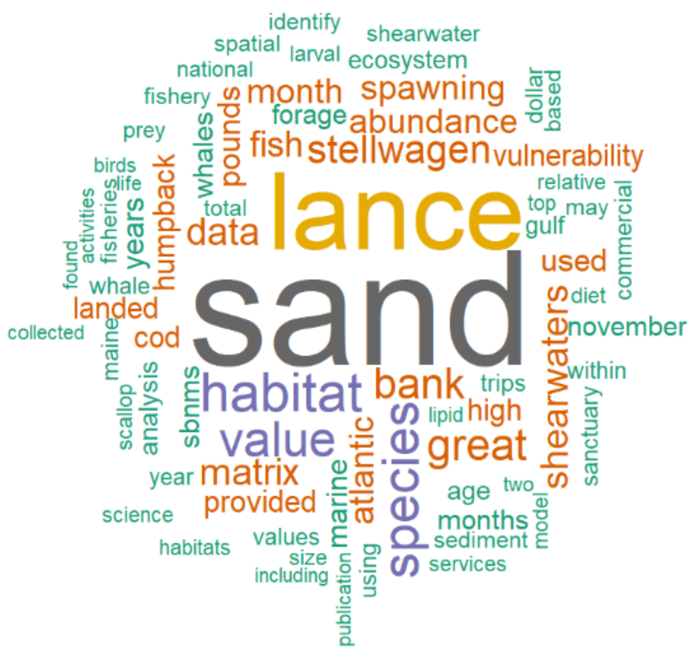
OCS Study
BOEM 2022-041

Assessing the Biological and Oceanographic Processes that Drive Fisheries Productivity in New England Sand Shoals and the Potential for Dredging-Related Disruption



U.S. Department of the Interior
Bureau of Ocean Energy Management
Sterling, VA

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Assessing the Biological and Oceanographic Processes that Drive Fisheries Productivity in New England Sand Shoals and the Potential for Dredging-Related Disruption

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DISCLAIMER

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REPORT AVAILABILITY

To download a PDF file of this report, go to the U.S. Department of the Interior, Bureau of Ocean Energy Management Data and Information Systems webpage (http://www.boem.gov/Environmental-Studies-EnvData/), click on the link for the Environmental Studies Program Information System (ESPIS), and search on 2022-041. The report is also available at the National Technical Reports Library at https://ntrl.ntis.gov/NTRL/.

CITATION

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ABOUT THE COVER

A word cloud highlights the most frequently used words in this report, underscoring important topics and themes throughout this study.

ACKNOWLEDGMENTS

We thank Dann Blackwood, Kevin Powers, Peter Hong, Chris Murray, Lucas Jones, Linda Welch, Sara Williams, Kent Hatch, Anna Robuck, and Peter Trull for their significant contributions to this study. Many thanks to Stellwagen Bank National Marine Sanctuary, specifically Pete DeCola, Ben Haskell, Anne-Marie Runfola, Anne Smrcina, Elizabeth Stokes, and Alan Collette for their support on this project and S4 and program volunteers who helped collect these data.

Contents

List of Figures

List of Tables

List of Abbreviations and Acronyms

Short Form	Long form
BOEM	Bureau of Ocean Energy Management
CTD	conductivity, temperature, depth
FOO	Frequency of occurrence
GARFO	Greater Atlantic Regional Fisheries Office
GIC	global of colocation
GIS	geographic information system
GSI	Gonado-somatic indices
IA	Interagency Agreement
MBL	Marine Biological Laboratory
MIMES	Multiscale Integrated Model of Ecosystem Services, Boston University
NCCOS	National Center for Coastal Ocean Science
NEFSC	Northeast Fisheries Science Center (NOAA)
NEG	Northeast Gateway
NMFS	National Marine Fisheries Service (NOAA)
NOAA	National Oceanic and Atmospheric Administration
PTT	Platform transmitting terminals
SBNMS	Stellwagen Bank National Marine Sanctuary
SNP	Single nucleotide polymorphisms
STEM	science, technology, engineering, and math
µatm	units of microatmospheres
UConn	University of Connecticut
UD	utilization distribution
VTR	Vessel trip report

1 Summary

Coastal erosion and immersion threaten beach habitat, the species that depend on that habitat, and the recreational and economic activities that beach habitat and waterfront locations support. It also impacts human structures that have been placed in harm's way. Climate change, in the form of higher sea level, stronger storms and changing currents, is accelerating erosion and emersion in parts of the U.S. Though coastal habitats and economies can be protected through beach nourishment using offshore sand deposits, when done poorly, it can harm offshore sand habitats that support a different set of fish and wildlife populations, ecosystem functions, and economic activities.

The Bureau of Ocean Energy Management (BOEM) proactively sought to assess the potential of sand dredging to disrupt marine habitats and ecosystem service provided by sand habitat by entering into an Interagency Agreement (IA agreement M17PG00019/P00002**)** with the National Oceanic and Atmospheric Administration (NOAA) National Ocean Services (NOS) Office of National Marine Sanctuaries Stellwagen Bank National Marine Sanctuary (SBNMS). The agreement enabled collaborative research to address critical knowledge gaps relative to the productivity and ecology of sand habitat. Collaborators included Boston University, Center for Coastal Studies (Provincetown, MA), the University of Connecticut, the University of Massachusetts Dartmouth, and the Woods Hole Oceanographic Institution.

Though SBNMS' federal designation as a national marine sanctuary prohibits the removal of sand resources from the sanctuary, the long-term databases already in existence made it the ideal natural laboratory for studying the value of sand habitat, the potential consequences of sand habitat disruption, and the possibility of identifying temporal windows during which disruption might be reduced. Existing long-term SBNMS databases related to this project include (1) commercial fisheries catch and dollar value derived from data provided by the National Marine Fisheries Services (NMFS) Greater Atlantic Regional Fisheries Office (GARFO), (2) the ability to link fisheries and economic data with the sanctuary's multi-beam derived sediment maps identifying sand, gravel and mud habitats, (3) the sanctuary's ongoing research into northern sand lance (*Ammodytes dubius*; hereafter, sand lance) forage fish (the presumed foundational species supporting sanctuary productivity, which is dependent on sand substrate for survival), (4) an ongoing study of great shearwater (*Ardenna gravis*) seabird habitat use (derived from satellite tagged and/or tracked birds) and foraging and/or feeding behavior (based on stable isotope analysis of blood, feather and exhaled gas samples, and fecal DNA) obtained from birds captured at sea, (5) an extensive dataset on humpback whale (*Megaptera novaeangliae*) abundance and distribution in the sanctuary provided by the Center for Coastal Studies.

Before our research, little was known about the productivity and ecology of offshore sand habitats, or what opportunities might allow sand removal while limiting ecological disturbance and disruption of commercial fisheries. Under a separate agreement with BOEM, data and findings from this report were used in collaboration with Boston University to develop an ecosystem services model to create a decision support tool that would examine the cost and benefits for various sand removal scenarios under consideration. An additional goal was to provide methodologies that could be used by other science teams to investigate and understand the impacts and opportunities relative to sand removal specific to their region. Sand lance forage fish proved to be a major component of sand habitat productivity, so much of our effort focused on investigating sand lance.

The resulting project, "Productivity and Ecology of Sand Habitats," was conducted from 2018 to 2020 and contained the nine objectives listed below.

1. Monitoring abundance and distribution of sand-dependent forage species at existing sentinel sites (those already monitored by SBNMS) and sites designated by BOEM as areas with sand shoals and features of interest
2. Document diets, feeding success, and nutritional condition of sand-dependent forage species to identify bottom-up drivers of abundance and distribution
3. Identify the spawning and/or reproductive cycle of sand-dependent forage species
4. Identify origin of sand-dependent forage species using genetic analysis to localize fish origin
5. Model larval movements using the appropriate oceanographic model to determine if an array of sandy geomorphological features are sources or sinks for productivity
6. Develop a Sand Lance Life History Matrix and Ecosystem Services Vulnerability Matrix
7. Identify the relationships among sand habitat, sand lance forage fish, and commercial fisheries
8. Gather spatial and behavioral telemetry data on select species used to identify habitat use, ecosystem connectivity and site fidelity relative to sand habitat productivity
9. Create outreach and education products in support of the non-technical audience

Key findings from each of these objectives are listed below.

Objective 1: Monitoring abundance and distribution of sand-dependent forage species at existing sentinel sites and sites designated by the contracting officer's representative as areas with sand shoals and features of interest

a. Spatial distributions of sand lance, humpback whales, and great shearwaters were highly correlated. Monitoring the abundance and distribution of sand-dependent forage fish focused on sand lance. Sand lance, humpback whales, and great shearwaters (the latter two chosen because they are the most numerous representatives of their taxa) were counted during spring and fall at 44 standardized sites throughout the sanctuary. Data were analyzed using the Index of Global of Colocation (GIC), which ranges from "0" (two populations show no co-occurrence) to "1.0" (total co-occurrence). Overall GICs were: sand lance and great shearwaters; GIC = 0.99, sand lance and humpback whales; GIC = 0.99, demonstrating extremely high co-occurrence between sand lance and these top predators. See Silva et al. 2020.

b. Bayesian hierarchical modeling showed a positive correlation between sand lance and humpback whale abundance. A Bayesian hierarchical modeling approach was used to explore the influence of sand lance on humpback whales at multiple spatial and temporal scales, while accounting for sampling variability and uncertainty. Results showed a statistically clear positive correlation between sand lance and humpback whales, supporting previous work and confirming the continued importance of sand lance as the primary food source of humpback whales in recent years. See Silva et al. 2021.

c. Standardized shipboard transects for seabirds in SBNMS showed most species aggregated over sand habitat.

Thirty-one standardized seabird surveys (April through December 2012–2017; eight species; 12,733 sightings) were conducted along predetermined track lines. Species counts and sediment data were aggregated over grid cells for analysis. All species except black-backed and herring gulls selected habitat with greater than 60% sand.

Objective 2: Document diets, feeding success, and nutritional condition of sand-dependent forage species to identify bottom-up drivers of abundance and distribution

a. The copepod *Calanus finmarchicus* dominated sand lance diet by biomass and/or feeding occurred primarily from December–July.

Identification of sand lance stomach contents indicated that feeding occurred primarily from December to July. *Calanus finmarchicus* dominated the diet by biomass in all months with the exceptions of February and November where *Metridia* spp. and *Centropages* spp. dominated, respectively.

b. Sand lance demonstrated a protracted lipid accumulation window (February–August) followed by a sharp decline in lipid content in the fall after spawning.

Lipids were extracted from 197 sand lance collected in 2019. A generalized additive model including month fit with a cyclic cubic regression spline identified a protracted lipid accumulation window (February – August). Sand lance then ceased feeding, used lipids, and began gonad development in the fall, followed by a sharp decline in lipid content in the fall after spawning. The abundance of *Calanus finmarchicus* strongly influenced sand lance parental condition and recruitment due to its association with the ability of sand lance to accumulate lipids for spawning and over winter survival.

c. Sand lance on Stellwagen Bank **showed a boom-and-bust population pattern that is dependent on external input of larvae from other areas**. Analysis of otoliths from 300 fish indicated that: (1) sand lance represent a boom-and-bust population pattern that is dependent on external input, (2) most individuals are either age-2 or age-3, (3) spring is the primary growing season, with fish beginning to reach their annual asymptotic length in June and reaching maximum size in August, (4) larval sand lance were planktonic for 50 to 85 days before settling on Stellwagen Bank. See Suca et al. 2021.

Objective 3: Identify the spawning and/or reproductive cycle of sand-dependent forage species.

a. Sand lance on Stellwagen Bank are spawning once per year during a narrow window at the end of November. The spawning pattern of sand lance on Stellwagen Bank was documented during five consecutive years: 2016–2020, inclusive. We found (1) spawning on Stellwagen Bank occurred during a narrow, two-week period at the end of November, (2) temporal patterns in sand lance gonado-somatic index (a measure of reproductive activity) showed a sudden increase and then immediate decrease at the end of November, which is consistent with a single, short spawning peak, (3) histological analyses of oocytes of pre-peak, and post-spawning females showed a single cohort of secondary oocytes ripening and then disappearing, and (4) post-spawn females had ovaries consisting only of primary oocytes which are the reservoir for next year's spawning. Hence, our analyses confirmed that sand lance on Stellwagen Bank are spawning only once per year during a narrow window at the end of November.

b. Sand lance reproductive success is exceptionally CO_2 sensitive compared to other fish species. Effects of ocean acidification and oceanic warming on the reproduction of sand lance was evaluated using wild, spawning-ripe adults collected from SBNMS and fertilized embryos were reared (University of Connecticut; Baumann lab) at three pCO$_2$ conditions (400, 1,000, and 2,100 µatm) crossed with three temperatures (5°C, 7°C, and 10°C). Exposure to future pCO$_2$ conditions consistently resulted in severely reduced embryo survival. Sensitivity to elevated pCO$_2$ was highest at 10°C, resulting in up to an 89% reduction in hatching success between control and predicted end-of-century pCO_2 conditions. Moreover, elevated pCO_2 conditions delayed hatching, reduced remaining endogenous energy reserves at hatch, and reduced embryonic growth. Our results suggest that sand lance is exceptionally CO_2 sensitive compared to other fish species. See Murray et al. 2019.

Objective 4: Identify origin of sand-dependent forage species using genetic analysis to localize fish origin.

a. Genetic analysis confirmed that sand lance on Stellwagen Bank are sand lance (*Ammodytes dubius*) and not American sand lance (*Ammodytes americanus*) (the two species in the western North Atlantic).

b. Sand lance form two genetically distinct supergroups. We used Low Coverage Whole Genome Sequencing to understand sand lance connectivity among geographic areas. Data suggests that sand lance form two genetically distinct supergroups; one that occurs south of Nova Scotia, including Stellwagen Bank and another group further north including the Gulf of St. Lawrence and Newfoundland.

Objective 5: Model larval movements using the appropriate oceanographic model to determine if an array of sandy geomorphological features are sources or sinks for productivity.

a. Stellwagen Bank larval sand lance originate from northerly spawning populations. The spatial origin and fate (source and/or sink) of sand lance found on Stellwagen Bank was investigated using hydrodynamic drift simulations. Origin data suggest Stellwagen Bank sand lance population is highly connected to–and reliant on–spawning populations immediately to the north in the coastal and northern Gulf of Maine.

b. Partial self-recruitment occurred in some years, with self-recruitment highest on the southwest corner of Stellwagen Bank.

c. Fate data suggest that sand lance spawned on Stellwagen Bank are exported to suitable habitats in areas to the south and southeast of the bank, thereby potentially contributing to large but interannually variable settlement pulses on Nantucket Shoals, Georges Bank, and southern New England waters, including areas currently under development for offshore wind energy production. Available monitoring records of larval sand lance abundance on Stellwagen Bank (2008–2016) suggested that years of exceptional transport from far away areas in the northern Gulf of Maine produce exceptional larval pulses, thus highlighting the potential role of variable transport patterns in generating the large spatiotemporal fluctuations typical for this important forage fish.

Objective 6: Sand lance life history matrix

a. Sand lance vulnerability matrix. We used our accumulated knowledge (literature and research specific to SBNMS) on sand lance life history (e.g., spawning, somatic growth, lipid accumulation, etc.) to create a monthly vulnerability matrix that could identify tradeoffs to different life stages of sand lance at different times of year in relation to disruption by human activity, such as dredging. We found that important life history activities occurred in almost all months. However, we suspect sand lance would be least biologically vulnerable to disruption during August and September because growth is completed, feeding has slowed, lipid concentration is high, and no spawning or larval settlement is occurring. However, because sand lance are buried in the sediment during much at that period, they might be extremely vulnerable to mechanically induced injury or mortality, such as that caused by dredging operations.

b. Ecosystem Services Vulnerability Matrix. We created a monthly Ecosystem Services Vulnerability Matrix based on ecosystem components that directly or indirectly benefit from sand lance or sand habitat and could be disrupted by sand dredging operations. Ecosystem categories included humpback whales, great shearwaters, whale watching trips, cod spawning, cod landings, scallop landing, lobster landing, trap pot fishery trips, gillnet fishery trips, scallop dredge fishery trips, bottom longline fishing trips, and otter trawl fishing trips.

c. Overall. Vulnerability for each month was calculated as the sum value for all sand lance or sand habitat-related ecosystem services occurring during that month. To rank Overall Vulnerability, we created five equal interval classes as follows: VL = 0-19; L = 19.1-38, M = 38.1-57, H = 57.1-76, VH = 76.1-95 (maximum possible sum). All month's services fell into the Medium risk category. However, all months had at least three Very High ranking activities and/or services. Further, the time period where sand lance may be least vulnerable to disturbance (August–September) is the time of highest vulnerability for other ecosystem services dependent on sand habitat.

Objective 7: Identify the relationships among sand habitat, sand lance forage fish, and commercial fisheries.

Since 2010, sand habitat has provided the greatest pounds landed and dollar value for commercial fisheries in all years and in all months in SBNMS. To examine the importance of sand habitat to commercial fisheries, Vessel Trip Report data for SBNMS were obtained from the Greater Atlantic Regional Fishery Office (Gloucester, Massachusetts) for the years 2007–2016, the most recent years in which data were available. These data were analyzed relative to habitat type by overlaying catch data on sediment maps provided by the US Geological Survey (USGS). Sand habitat provided the most pounds landed for 8 of the 19 species examined, including the highly valuable blue-fin tuna and scallop fisheries. Sand habitat was the second most productive habitat in 10 other species, including cod and haddock. Thus, sand habitat was highly productive for 18 of the 19 species. Relative to total pounds landed by commercial fisheries in SBNMS for the years 2007–2016, sand habitat provided the greatest contribution (67,441,139 lbs; 46%), followed by gravel (51,055,032 lbs; 34%) and mud (30,116,863 lbs; 20%). Relative to the dollar value of commercial fishery catch in SBNMS for the years 2007–2016, sand habitat provided the greatest dollar value ($73,297,830; 44%), followed by gravel ($53,032,721; 32%) and mud ($39,296,415; 24%) Since 2010, sand habitat has provided the greatest dollar value in all years and in all months.

Objective 8: Gather spatial and behavioral telemetry data on select species used to identify habitat use, ecosystem connectivity and site fidelity relative to sand habitat productivity.

a. Satellite telemetry indicated most great shearwater seabirds in the Gulf of Maine aggregated over sand habitat. From 2013 to 2018, we tagged 58 great shearwater seabirds (~10/year) with Solar PTT-100 15-gram platform transmitting terminals (PTTs) and tracked them to identify habitat use. Data indicated that (1) Within the Gulf of Maine, great shearwaters preferentially used shallow (<100 m) coarse grained sand habitat, (2) the physical habitat selected by great shearwaters was spatially aligned with that of sand lance, (3) necropsy of bycaught great shearwaters from the same area demonstrated that most (89%) of the birds were young (0–2 years of age), suggesting that the Gulf of Maine serves an a nursery for great shearwaters.

b. DNA from fecal samples of captured birds indicated that sand lance is the most common prey item. Captured birds were also sampled for food habits. We used fecal DNA to investigate the frequency of occurrence of prey items for 35 birds caught in 2017 and 2018. Results showed that while in the Gulf of Maine, great shearwaters fed primarily on sand lance. The frequency of occurrence for sand lance (71.4%) was almost twice that of the next most frequent prey item (48.6%, Atlantic menhaden [*Brevoortia tyrannus*]).

c. NMFS trawl data showed great shearwater habitat use coincided with sand lance. Using results from NMFS bottom trawl survey, 67% of trawl locations containing sand lance fell within great shearwater foraging hotspots, while far fewer locations containing mackerel and herring fell within foraging hotspots (36% and 37%, respectively). These data suggest that sand lance and the sand habitats that support sand lance are key factors in shearwater habitat use. See Powers et al. 2020; Hong et al. 2019; Powers et al. 2017).

Objective 9: Create outreach and education products in support of the non-technical audience.

Outreach and education was an important component of the project. We created an information video developed by Jim Toomey, the creator of the highly popular *Sherman's Lagoon* comic strip, which featured the importance of sand habitat and sand lance forage fish, and the collaboration between BOEM and SBNMS to produce high quality data for decisions about ocean mining of sand habitat. The video can be viewed at https://www.boem.gov/marine-minerals/marine-mineral-research-studies/studying-sand-lance**.** We also created a Twitter account (@trackseabirds) to keep the public aware of the project and associated seabird information. Over 1,030 people are following the account. For public schools, we created a free, outreach program allowing teachers to plot great shearwater movements based on PTT-derived data on specially designed charts. The program was presented at the 43 Annual Meeting and Conference of Massachusetts Marine Educators in Woods Hole, Massachusetts (May 4, 2019). Teachers were able to request the unit, charts and location data for plotting bird movements and learning about sand habitats. The project supports Science, Technology, Engineering and Math (STEM) goals in education. For commercial fishing stakeholders, we produced two stories for the Cape Cod Commercial Fishermen's Association e-newsletter based on the findings from this project. One story focused on sand lance [1] and the other on great shearwaters[2]. A presentation featuring our STEM education program was made at the 2020 World Seabird Twitter Conference. Finally, we worked with Blackbeard Biologics to create a citizen science focused program to make frequent and multiple conductivity, temperature, and depth (CTD) casts to help monitor climate change conditions in the sanctuary and New England waters. Participants made their own CTD units and deployed them from whale watching boats operating in Massachusetts, New York, and Maine. COVID-19 restrictions cancelled excursions in 2020. Six whale watching companies participated in the project in 2021 and conducted a total of 38 CTD casts to collect water quality data across the Gulf of Maine.

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[1] See https://capecodfishermen.org/item/plumbsandeels0429?category_id=9

[2] See https://capecodfishermen.org/news

2 Objective 1: Monitoring Abundance and Distribution

Objective 1: Monitoring abundance and distribution of sand-dependent forage species at existing sentinel sites and sites designated by the COR specified areas with sand shoals and features of interest.

2.1 Species Co-occurrence

Counts of SEABed Observation and Sampling System (SEABOSS)-captured sand lance and concurrent counts of humpback whales and great shearwater seabirds were conducted during spring and fall at 44 monitored stations (Figure 1 and Figure 2) from 2013–2019. Data were used to map the mean (center of gravity) and variance (inertia) of the sampled populations, which were used to calculate the global index of colocation (GIC) for sand lance and/or humpback whales, sand lance and/or great shearwaters and humpback whales and/or great shearwaters (Figure 2). GIC index ranges from 0 (two populations show no co-occurrence) to 1.0 (total co-occurrence). Overall GICs were: sand lance and great shearwaters; GIC = 0.99, sand lance and humpback whales; GIC = 0.99, demonstrating extremely high co-occurrence between sand lance and these top predators (Figure 3). Humpback whales and great shearwaters were chosen as the most numerous top predators in the study area.

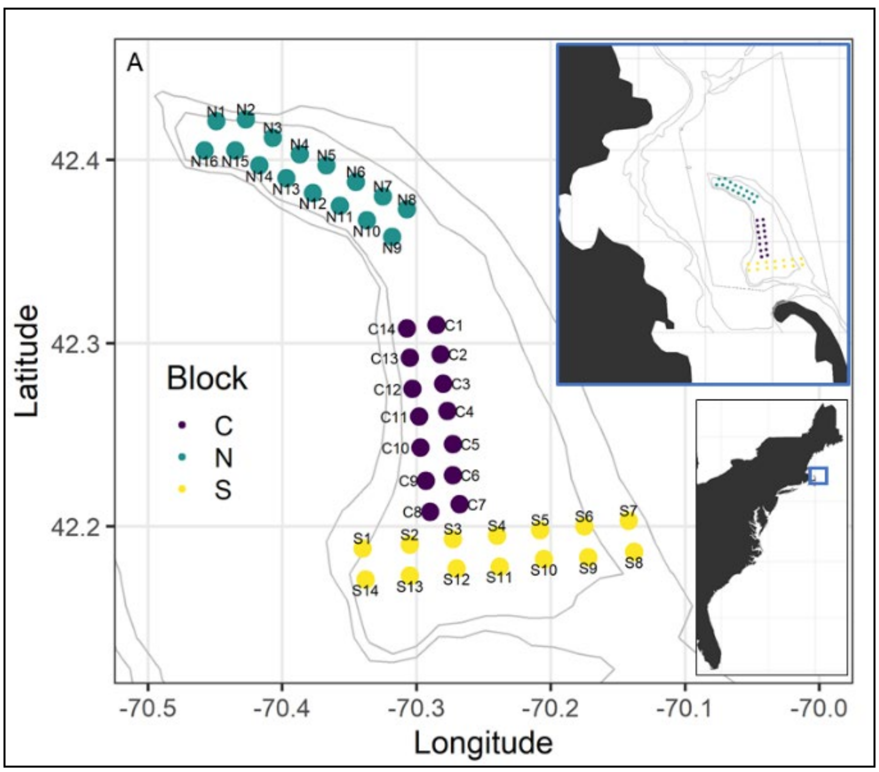
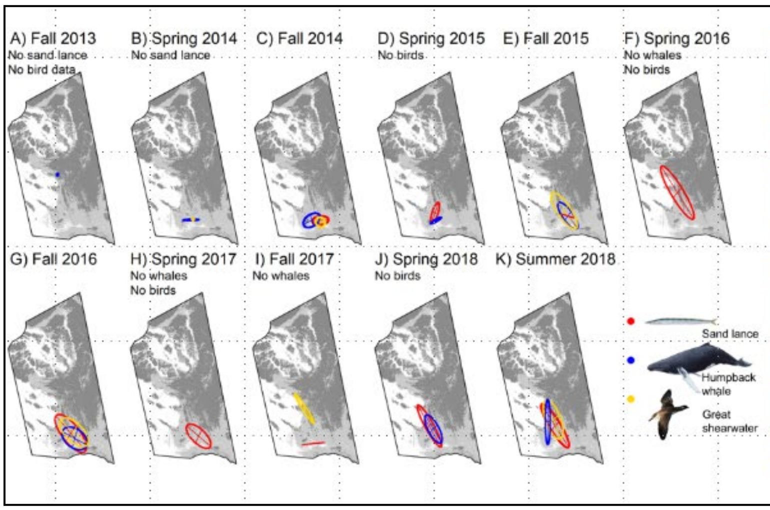


Figure 1. Survey design used in the global index of colocation (GIC) and Bayesian analyses (see Figure 6)

Map shows Stellwagen Bank proper and the 44 sites included in the survey. Sites are organized into three blocks: North (N-green), Central (C-purple), and South (S-yellow). Sites within blocks were ~1km apart and were designed to sample all potential sand lance benthic habitat. Thin gray lines represent the 50m (outer) and 40m (inner) isobaths. Inset maps show the survey location within Stellwagen Bank National Marine Sanctuary (rectangular boundaries) off the coast of Massachusetts (top) and the location of the study site off the northeast US From Silva et al. 2021.

Figure 2. SEABOSS deployment
The field team working to recover the SEABOSS after sampling the sediment for sand lance. Photo: Steve DeNeef.



Cruise	Sand lance and humpbacks	Sand lance and shearwaters	Humpbacks and shearwaters
Fall 2013	No sand lance	No sand lance	No birds
Spring 2014	No sand lance	No sand lance	Not enough data *
Fall 2014	0.7	0.99	0.64
Spring 2015	0.78	No birds	No birds
Fall 2015	Not enough data†	Not enough data†	0.95
Spring 2016	No whales	No birds	No whales/birds
Fall 2016	0.96	0.98	0.97
Spring 2017	No whales	No birds	No whales/birds
Fall 2017	No whales	Not enough data†	No whales
Spring 2018	0.96	No birds	No birds
Summer 2018	0.92	0.97	0.95
Total	0.99	0.99	0.98

Figure 3. Spatial overlap and corresponding global index of colocation (GIC) for sand lance and/or humpback whales, sand lance and/or great shearwaters and humpback whales/great shearwaters for the years 2013–2018
Colored cross-hairs and circles represent the mean location (center of gravity) and variance (inertia), respectively, of sampled populations. From Silva et al. 2020.

See Silva et al. 2020 (abstract is below).

Abstract: Spatial relationships between predators and prey provide critical information for understanding and predicting climate-induced shifts in ecosystem dynamics and mitigating human impacts. We used SBNMS as a case study to investigate spatial overlap among sand lance (*Ammodytes dubius*), a key forage fish species, and two protected predators: humpback whales (*Megaptera novaeangliae*) and great shearwaters (*Ardenna gravis*). We conducted six years (2013–2018) of standardized surveys and quantified spatial overlap using the global index of collocation. Results showed strong, consistent collocation among species across seasons and years, suggesting that humpback whales and great shearwater distributions are tightly linked to sand lance. We propose that identifying sand lance habitats may indicate areas where humpbacks and shearwaters aggregate and are particularly vulnerable to human activities. Understanding how sand lance influence predator distributions can inform species protection and sanctuary management under present and future scenarios.

2.2 Sand Habitat, Sand Lance, and Humpback Whale Abundance

To gain further insights into the interaction among sand lance and top predators, we obtained the number of individually identified humpback whales sighted in the study area for the years 2013–2018, along with their sex and age class (i.e., calf, juvenile, mature, male and/or female) (data from the Center for Coastal Studies; Dr. Jooke Robbins).

Preliminary analysis indicates a positive correlation between the number of individual whales seen in a year and the number of sand lance captured in SEABOSS grab samples (Figure 4 and Figure 5). The association was seen across sex and age classes (mature females, juveniles, calves) (Figure 5).

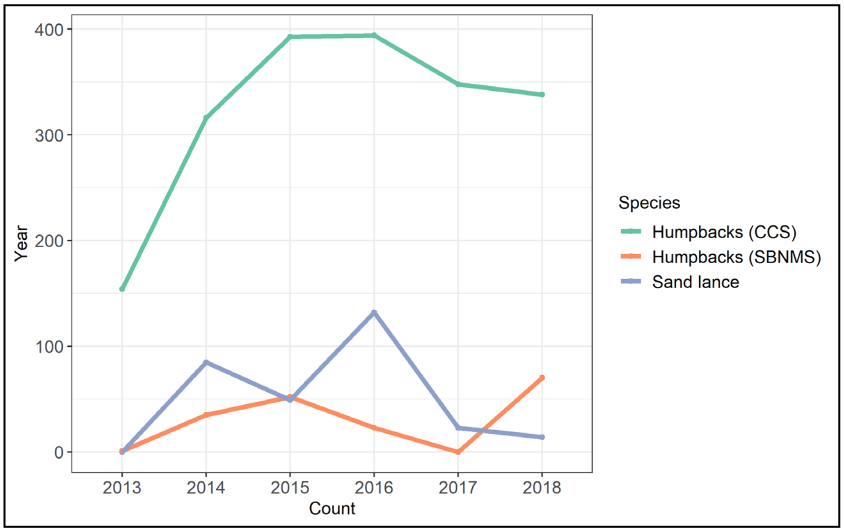


Figure 4. Number of sand lance caught at SEABOSS stations compared to the number of individually identified humpback whales (CCS) and the number of whales recorded at SEABOSS stations (SBNMS)

The number of individually identified whales per year by sex and age class. Data on individually identified whale provided by J. Robbins, Center for Coastal Studies, Provincetown, Massachusetts.

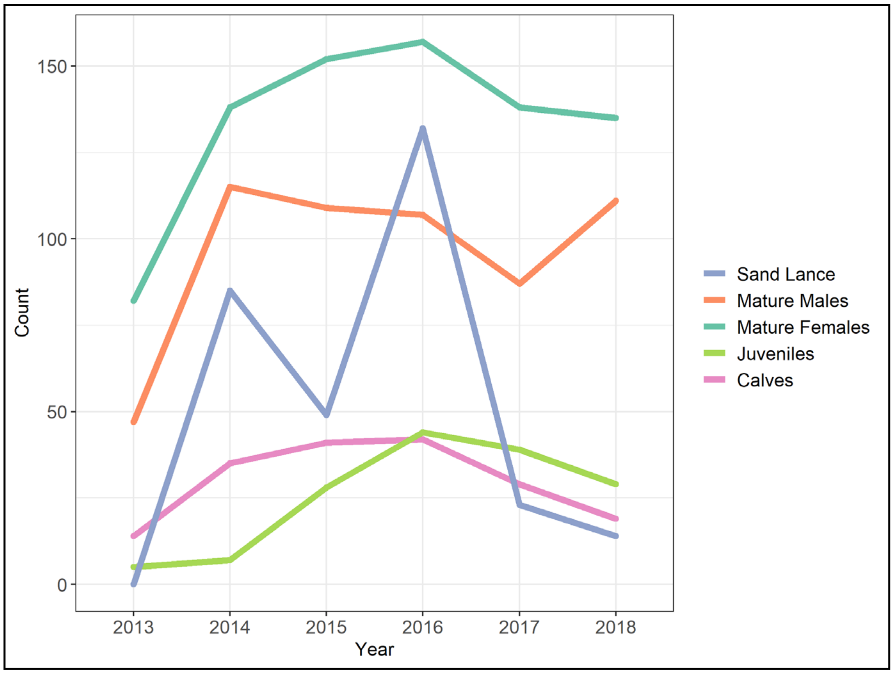


Figure 5. The number of sand lance captured at all SEABOSS sites, by year, as compared to the number of individually identified humpback whales by age class (mature female, mature male, juvenile and calf)

All but mature males followed trends in sand lance abundance. Data on individually identified whale provided by J. Robbins, Center for Coastal Studies, Provincetown, Massachusetts.

2.3 Bayesian Model for Prediction of Sand Lance and Humpback Whales

We used a subset of our long-term standardized survey data (2013–2019) from SBNMS and a Bayesian hierarchical modeling approach to explore the influence of sand lance on humpback whales at multiple spatial and temporal scales while accounting for sampling variability and propagating uncertainty. We developed zero-inflated Poisson mixed effects models for both sand lance and humpbacks, using modeled sand lance abundance as a predictor in the whale model. Results showed a positive correlation between sand lance and humpback whales (Figure 6 and Figure 7). Regional mean abundances of both species increased from north to south, though site-level variation within regions showed more variability. Results suggest annual variation in abundance of both species, with potentially different influences. This model can be used as a framework for further model development to include influence of environmental variables, larger geographic scope, and predictive capabilities.

See Silva et al. 2021; the abstract is provided below.

Abstract: The primary prey of humpback whales in the southwestern Gulf of Maine is sand lance. Despite this established relationship, we lack models to further understand the influence of sand lance on humpback whales or to predict humpback abundance or distribution in response to climate-related changes in sand lance abundance or distribution. We used a subset of long-term standardized survey data (2013–2019) from SBNMS and a Bayesian hierarchical modeling approach to explore the influence of sand lance on humpback whales at multiple spatial and temporal scales while accounting for sampling variability and propagating uncertainty. We developed zero-inflated Poisson mixed effects models for both sand lance and humpbacks, using modeled sand lance abundance as a predictor in the whale model. Results showed a statistically clear positive correlation between sand lance and humpback whales.

Regional mean abundances of both species increased from north to south, though site-level variation within regions showed more variability. Results suggest annual variation in abundance of both species, with potentially different influences. We demonstrate one management application of our method by examining entanglement risk for humpback whales. Whale aggregations were more likely to occur in a high-density area of fixed fishing gear that overlaps with an area of higher sand lance abundance. Our work suggests that humpback whale distribution in the larger Gulf of Maine may be impacted by climate-related fluctuations in sand lance abundance. Predicting future distributions of humpback whales is important for ecosystem-based management, including mitigation of human impacts, and our work serves as a foundation for further model development.

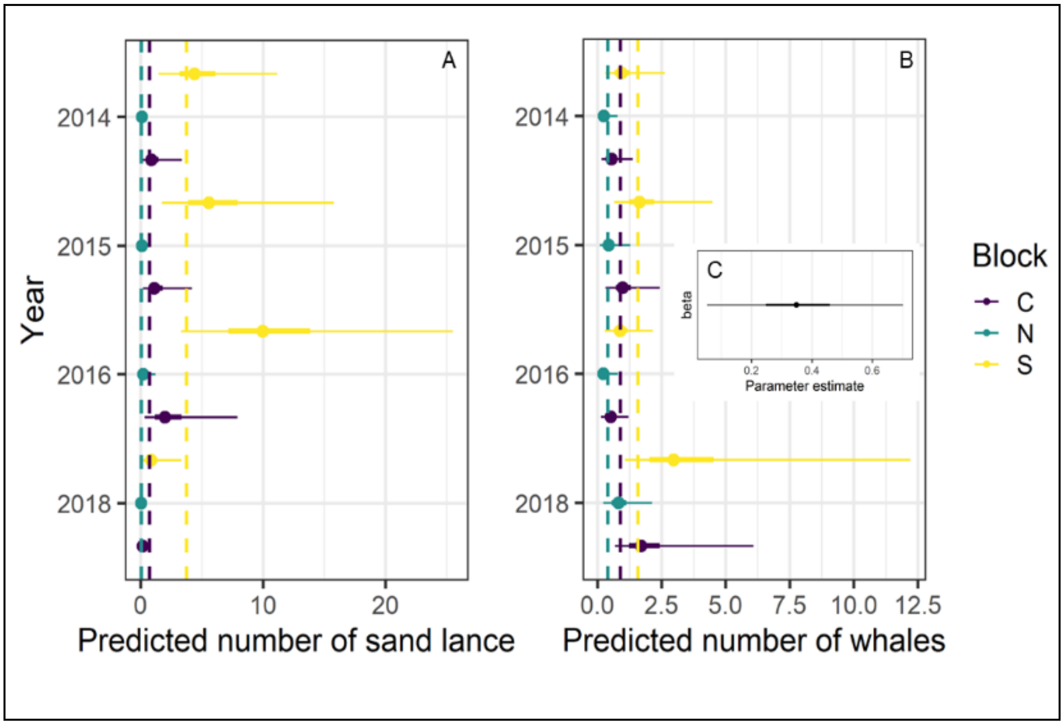


Figure 6. Predicted numbers of sand lance and humpback whales by block and year analyzed (see Figure 2)

Dashed vertical lines represent median abundance estimates for each block (N = green, C = purple, S = yellow). Points represent median abundance estimates for each block in each year. Thicker lines represent 50% Bayesian credible intervals and thinner lines represent 95% Bayesian credible intervals. A) Predicted numbers of sand lance. B) Predicted number of humpback whales. C) Parameter estimate for the influence of sand lance abundance on humpback abundance. This relationship was used to estimate block median abundance for humpbacks (dashed vertical lines) in (B). From Silva et al. 2021.

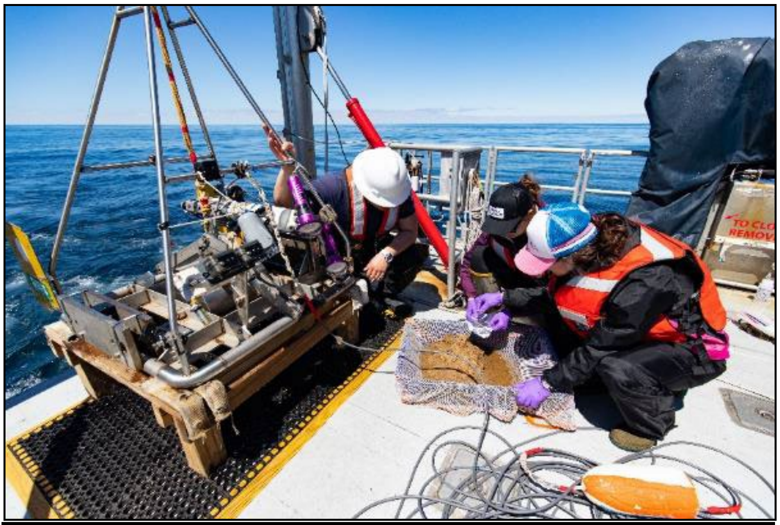


Figure 7. Counting sand lance
Researchers sifting through sand sampled using the SEABOSS to document presence and abundance of sand lance. Photo: Steve DeNeef.

2.4 Sand Habitat, Sand Lance, and Seabirds

We investigated the associations among sand habitats, sand lance fishes and seabirds using shipboard surveys, animal telemetry, and prey species as identification through DNA in fecal material. Telemetry and fecal analysis were confined to great shearwaters.

2.4.1 Shipboard Surveys

Thirty-one standardized surveys were conducted using expert citizen scientists along predetermined track lines (Figure 8) (April through December; 2012–2017). Birds, identified to species, were counted within 300m of the track line (n= 12,733). For analysis, we created grid cells of approximately 4’ longitude and 4’ latitude along the track lines. Cells were binned by sediment type based on the percentage of sand contained, using ten percent increments (i.e. 10% sand, 20% sand, etc.) Percent sand was calculated from sediment data contained in unpublished raster files provided by NOAA’s National Centers for Coastal Ocean Science for the Northeast and Mid-Atlantic areas of the US continental shelf. Habitat selection was determined by calculating the percent of sightings that occurred within each sediment bin. Species were great shearwater Corey’s Shearwater (*Calonectris borealis*), Wilson’s Storm Petrel (*Oceanites oceanicus*), Northern Gannet (*Morus bassanus*), Razorbill Auk (*Alca torda*), Common Murre (*Uria aalge*), Great Black-backed Gull (*Larus marinus*) and Herring Gull (*Larus argentatus*). Cells with greater than 60% sand were over selected by all species except herring and black-backed gulls (Figure 9)

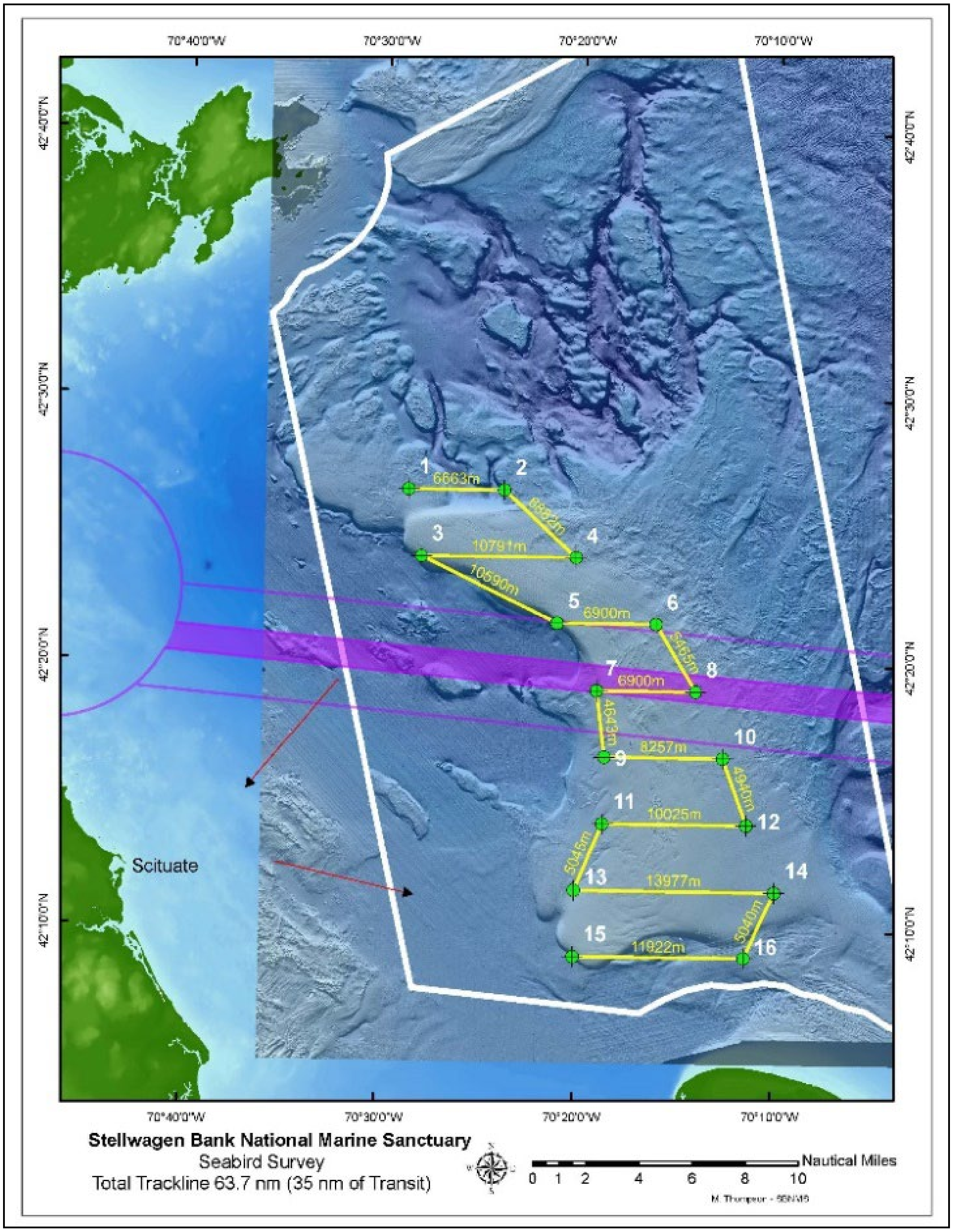


Figure 8. Track lines used for standardized seabird surveys within the Stellwagen Bank National Marine Sanctuary

Sightings were made from the flybridge and recorded with 300m of one side the vessel (glare dependent). Analysis consisted of surveys departed from Scituate, Massachusetts aboard the 15m NOAA R/V *Auk*.

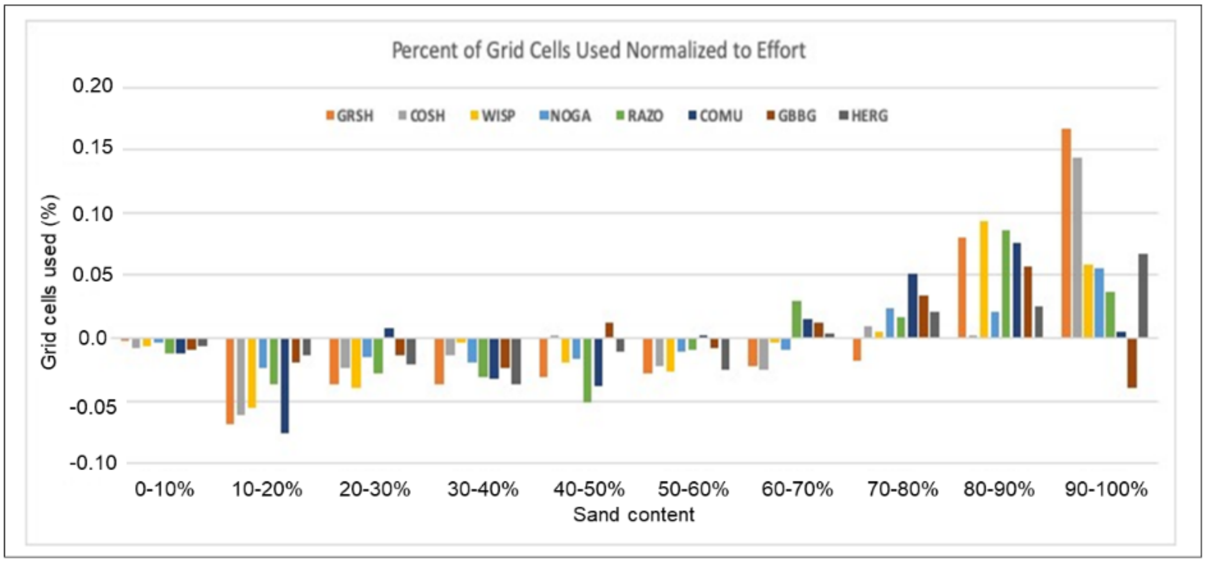


Figure 9. Percent of seabird sightings, by species, relative to amount of sand habitat contained within grid cells

Grid cells were 4' longitude and 4' latitude created along the standard survey track line. Cells were binned in 10% sand increments. Analysis was based on 12,733 sighting from 31 cruise (2012–2107). All species except black-backed and herring gulls selected for cells with greater than 60% sand.

2.4.2 Telemetry

From 2013 to 2018, we tagged 58 great shearwaters (~10/year) with Solar PTT-100 15-gram PTTs from Microwave Telemetry [3]. Birds were in the SBNMS off the Massachusetts coast or the coastal waters east of Cape Cod, Massachusetts (~41.3° to 43.0° latitude, −70.5° to −69.5° longitude). PTTs had a duty cycle of 24 hours on (i.e., continuous). Captured birds were weighed and placed in aluminum foil lined cages to collect fecal material for DNA analysis. More details can be found in Powers et al. (2017) and Powers et al. (2020) (see Objective 8). Argos locations were analyzed using Bayesian switching state-space model (see Powers et al. 2017) and a Time Local Convex Hull (T-LoCoH, http://tlocoh.rforge.r-project.org) method (see Powers et al. 2020).

The main findings were as follows:

1. Within the Gulf of Maine, great shearwaters preferentially used shallow (<100 m) course grained sand habitat (Powers et al. 2017 and Powers et al. 2020, Figure 5 in Powers et al. 2020).
2. The physical habitat selected by great shearwaters was spatially aligned with that of sand lance (Powers et al 2020).
3. Necropsy of bycaught great shearwaters from the same area demonstrated that most (89%) of the birds were young (0–2 years of age), suggesting that the Gulf of Maine serves an a nursery for great shearwaters (Powers et al. 2020).

For a full accounting of telemetry results, see Objective 8: Gather spatial and behavioral telemetry data on select species used to identify habitat use, ecosystem connectivity and site fidelity relative to sand habitat productivity.

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[3] 8835 Columbia 100 Parkway, Suites K & L, Columbia, MD 21045, USA; https://www.microwavetelemetry.com/

2.4.3 Prey Selection Based on DNA Analysis of Fecal Samples

We used fecal DNA to investigate the frequency of occurrence of prey items for 35 birds caught in 2017 and 2018. The frequency of occurrence for sand lance (71.4%) was almost twice that of the next most frequent prey item (48.6%, Atlantic Menhaden (*Brevoortia tyrannus*)) (Table 1).

Table 1. Food habits of great shearwaters

Prey group	Common name	Count	FOO
Ammodytes spp.	Sand lance	25	71.4%
Brevoortia tyrannus	Atlantic menhaden	17	48.6%
Scomber scombrus	Atlantic mackerel	11	31.4%
Leucoraja erinacea	Little skate	7	20.0%
Peprilus triacanthus	Atlantic butterfish	3	8.6%
Clupea harengus	Atlantic herring	2	5.7%
Squalus acanthias	Spiny dogfish	2	5.7%
Morone saxatilis	Striped bass	1	2.9%
Merluccius bilinearis	White hake	1	2.9%
Pleuronectiformes	Flatfishes (flounders)	1	2.9%
Tautogolabrus adsperus	Cunner	1	2.9%

Notes: Number of samples (count) and frequency of occurrence (FOO) of prey groups representing food habits of great shearwaters. Data were derived from metagenomic analysis of 35 successfully sequenced fecal samples collected in waters off MA, USA. From Powers et al. 2020.

2.5 Sediment Grain Size and Sand Lance

We explored the relationship between sediment grain size and the number of sand lance captured. Most of the 44 sites monitored with SEABOSS were in the "coarse" grain size category (Figure 10), therefore analysis by grain size was compromised. Preliminary examination suggested that Zone (Central, North South; see Figure 1) was the best predictor of sand lance abundance.

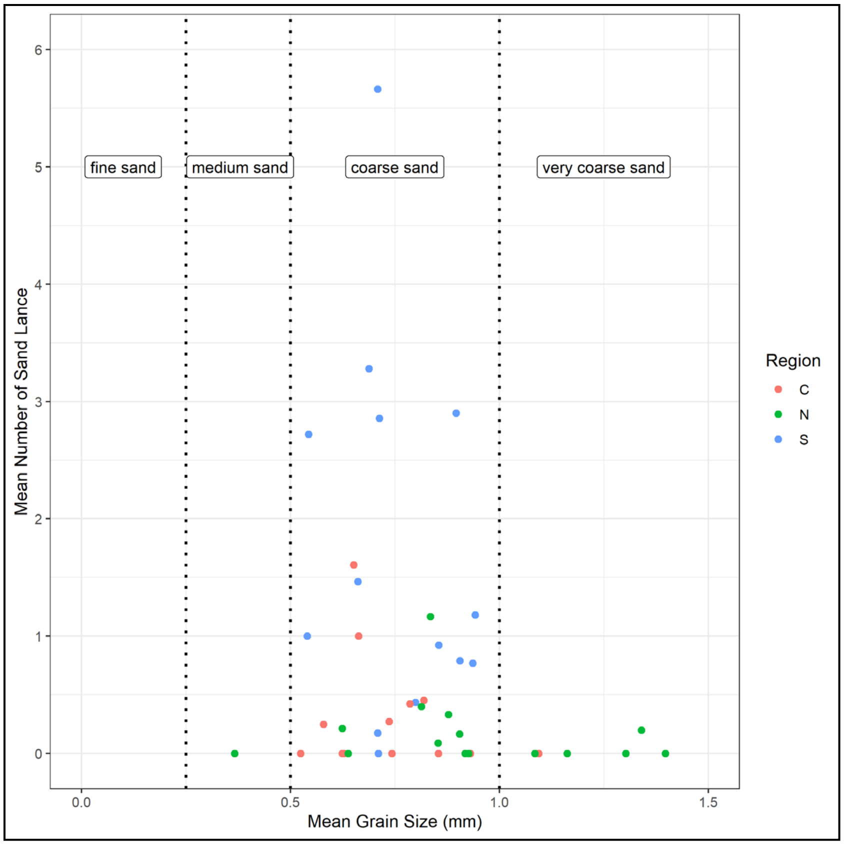


Figure 10. Number of sand lance captured at SEABOSS monitoring sites based on gain size and zone (central, north, and south)

3 Objective 2: Bottom-Up Drivers of Abundance and Distribution

Objective 2: Document diets, feeding success, and nutritional condition of sand-dependent forage species to identify bottom-up drivers of abundance and distribution.

3.1 Age Structure

Six hundred sand lance caught by grab or trawl (Figure 11) Oct–Dec 2014–2016 were weighed, measured, and otoliths were extracted. Three hundred were selected for age analysis. Extracted otoliths were mounted on microscope slides using thermoplastic cement. Otoliths were then polished briefly with 9 µm lapping film and subsequently imaged under 6x magnification. Using ImagePro® Premier, otolith length, width, and area were measured and the center and each winter ring (translucent) marked. Age 0 fish had already one winter ring on the edge, age-1 fish had two winter rings etc.

Figure 11. Examples of adult (left) and young of the year (year 0) settler sand lance captured in beam trawl tows
Photos: Tammy Silva

The results below (Figures 12–17) show the arrival of a large year class in 2014, with below-average body size. That strong year class can be seen in 2015 and 2016. Results suggest the boom-and-bust pattern of a population that is dependent on external input. It is consistent with patterns observed in other sand lance populations, e.g., in the North Sea.

One hundred and ten individual adults caught in 2019 were aged; 20 fish per month for the months of March, April, June, August, and 30 individuals in November. Most individuals (n=99) were either age-2 or age-3. Length by month data suggest spring is the primary growing season, with fish beginning to reach their annual asymptotic length in June and reaching maximum size in August (Figure 18). Larval durations of recent settlers were also estimated from otolith microstructure analysis. Larval sand lance were planktonic for 50 to 85 days before settling on Stellwagen Bank (Figure 19).

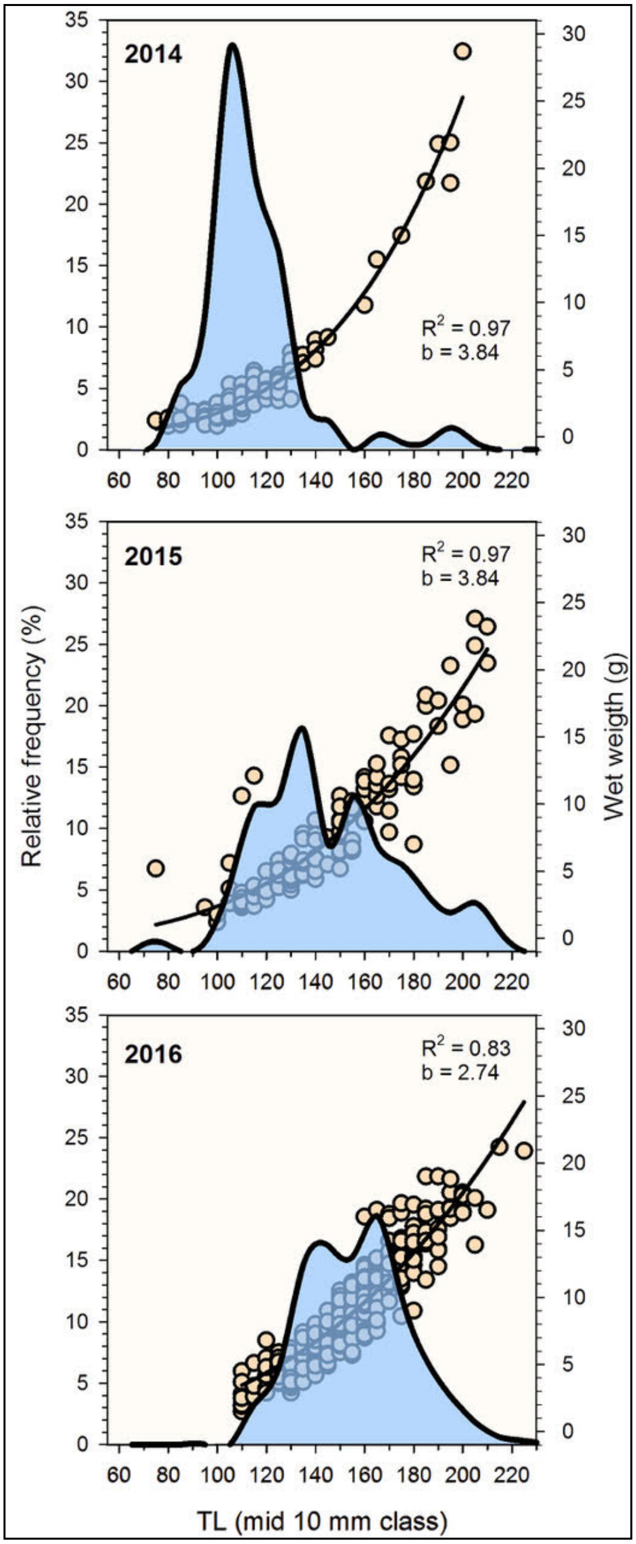


Figure 12. Relative length frequency distributions of sand lance caught on Stellwagen Bank in fall-winter 2014–2016 (blue shading) and the relationship between TL–wet weight (ww = a*TL^b).

Though 2014 was dominated by the small (0-group) cohort (note higher b exponent), 2015–2016 featured mostly larger (older) individuals (note lower b exponent) N_{2014} = 168, N_{2015} = 127, N_{2016} = 333.

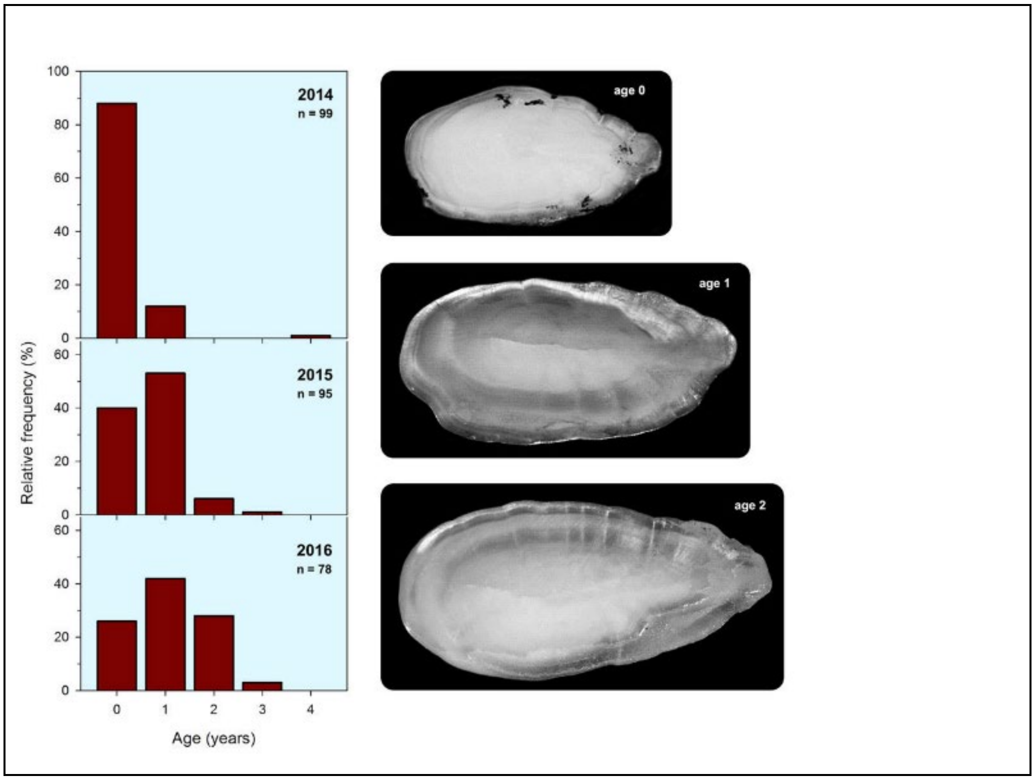


Figure 13. Otolith-based age distributions of sand lance on Stellwagen Bank in 2014–2016 (scaled to population sample)

In 2014, catches were almost exclusively dominated by the new age-0 cohort, with very few older individuals. That strong year class is apparent as age-1 in 2015 and age-2 in 2016. These findings are consistent with the hypothesis that large pulses arrive in the sanctuary and then slowly dissipate.

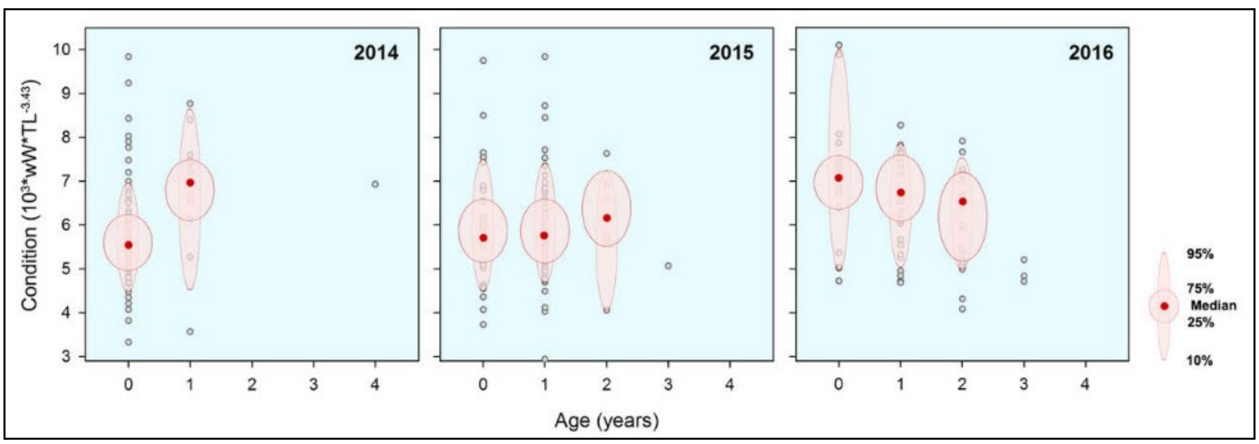


Figure 14. Age-specific condition of sand lance 2014–2016.Significant Age x Year interaction

Lowest condition for age-0 in 2014, (GLM by year) significantly below the age-1 condition. No age effect in 2015, 2016. GLM by age shows that both age-0 and age-1 fish had sig higher condition in 2016 (comp. 2014, 2015).

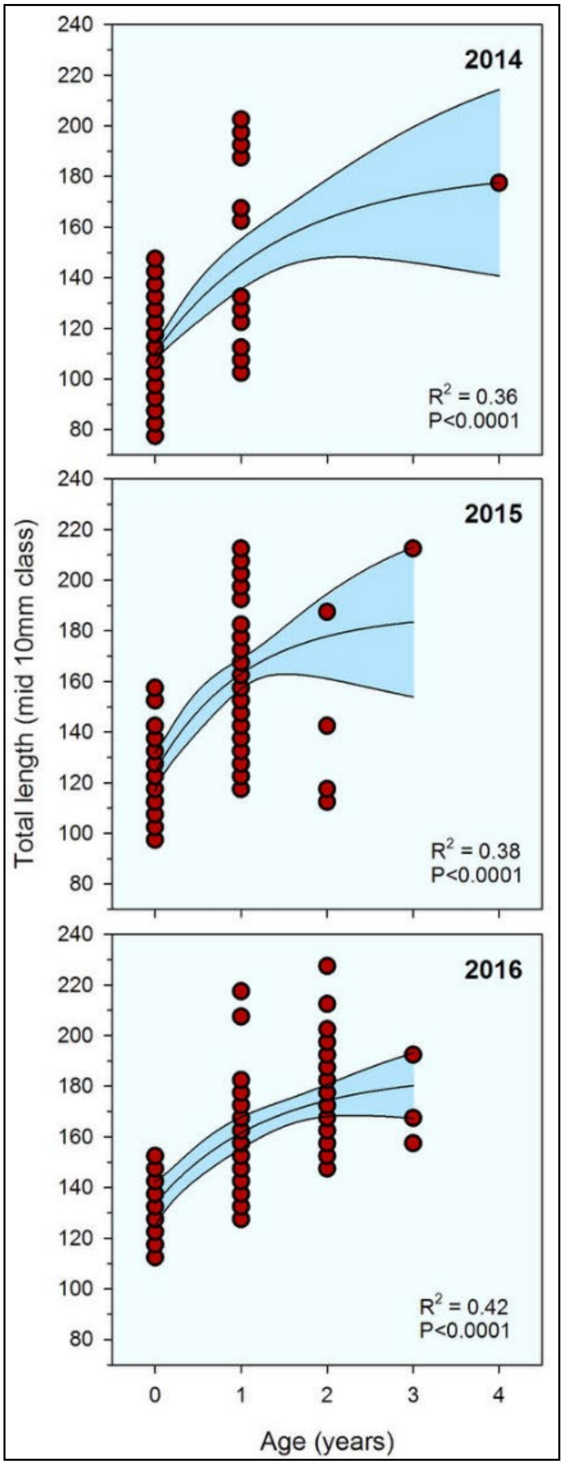


Figure 15. Age-length population growth curve for sand lance caught on Stellwagen Bank

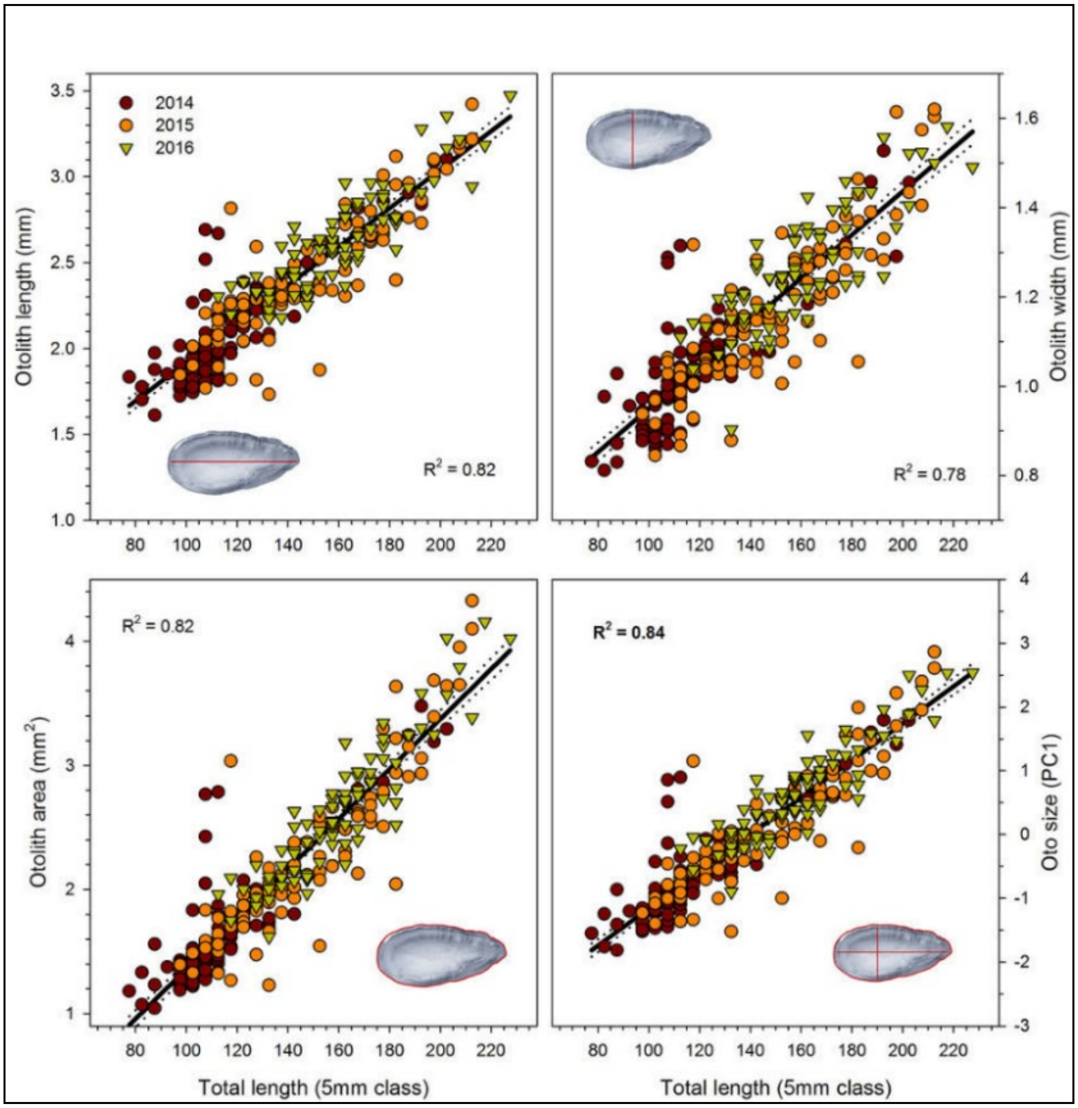


Figure 16. Relationship between sand lance body size and otolith size (A: otolith length, B: otolith width, C: otolith area) and fish size. (D) all three combined)

Otoliths can be used a reliable proxy for body size.

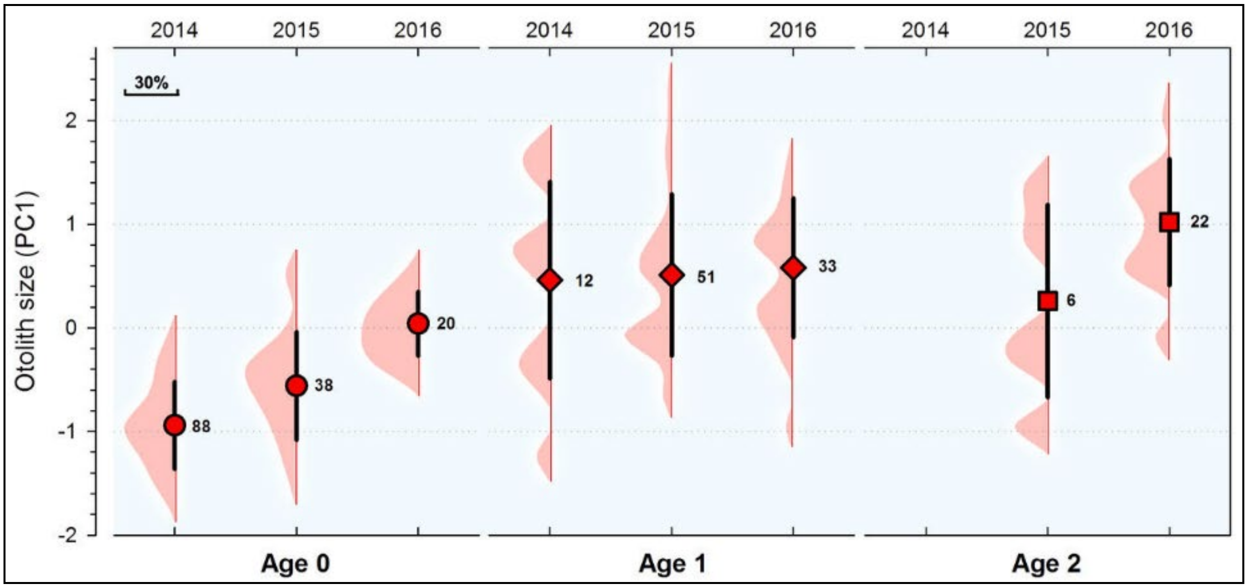


Figure 17. Otolith size by age group and year

(1) Small initial body size (otolith size) of initial 2014 cohort (2) significant increase in age-0 otolith size from 2014 to 2015 to 2016 and (3) significant increase in age-2 otolith size from 2015 to 2016. Shading equals relative frequency, symbol and error bars equal means +/- 1 SD.

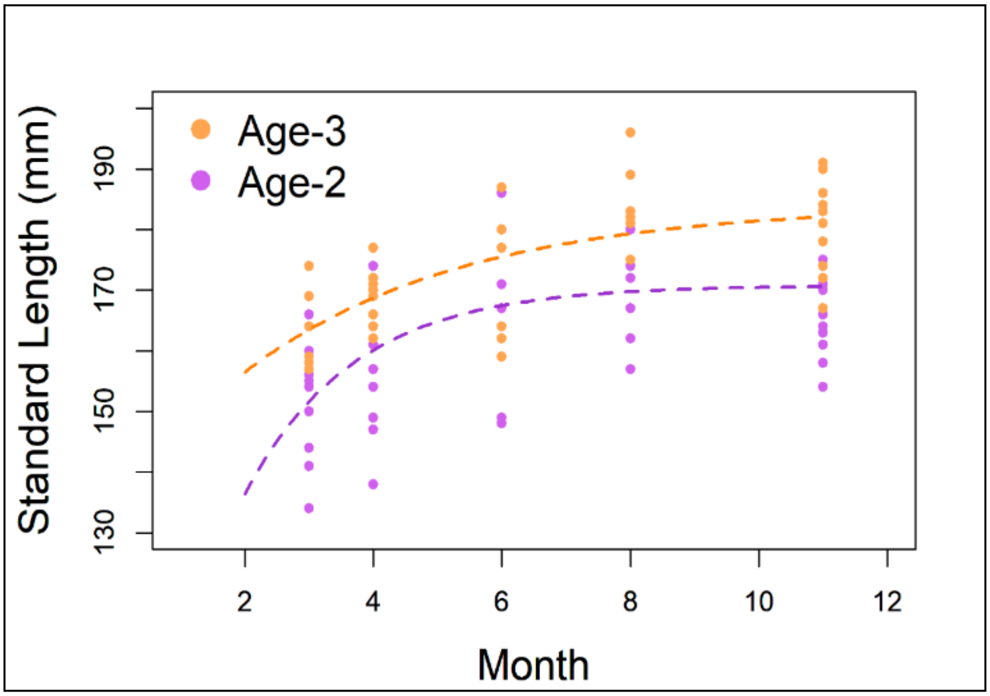


Figure 18. von Bertalanffy curves fitted to length by month for age-2 and age-3 for adult sand lance collected in 2019

Most growth occurred from February to August. From Suca et al. 2021.

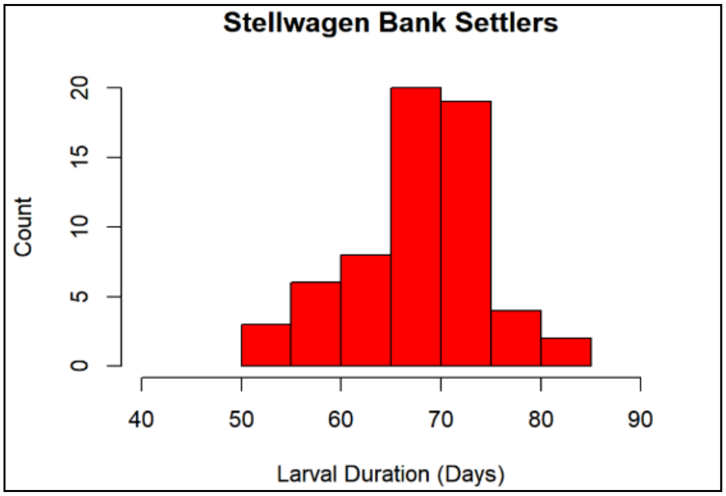


Figure 19. Histogram of larval duration of recent settlers collected on Stellwagen Bank in May, June, and July 2019

Days to settlement was analyzed using otolith rings. Larval sand lance were planktonic for 50 to 85 days before settling on Stellwagen Bank.

3.2 Feeding and Diet

Stomach contents were identified from sand lance collected in 2019 (Figure 20). Of 202 fish dissected, a total of 70 individuals contained prey. Feeding occurred primarily from December to July (Figure 21). The copepod *Calanus finmarchicus* dominated the diet by biomass in all months with the exceptions of February where the copepod *Metridia* spp. Dominated and November when the copepod *Centropages* spp. Dominated prey biomass, although the number of prey items available were low in November. The diet by number was more mixed, with *Calanus* and small calanoids representing nearly the same proportion. *Metridia* and *Temora* were also abundant by number in February and June, respectively (Figure 22 and Figure 23).

Figure 20. Studying sand lance diet

Science team members prepare to conduct a CTD cast and zooplankton tow to document environmental conditions and food availability for sand lance. Photo: Steve DeNeef

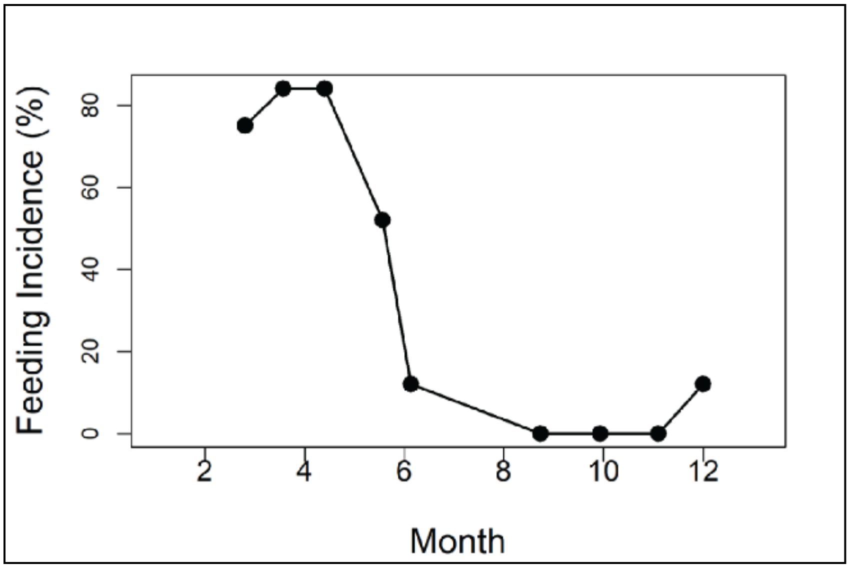


Figure 21. Analysis of sand lance stomach contents.
Stomach content analysis (n=202) indicated that sand lance fed primarily from December to July. From Suca et al. 2021.

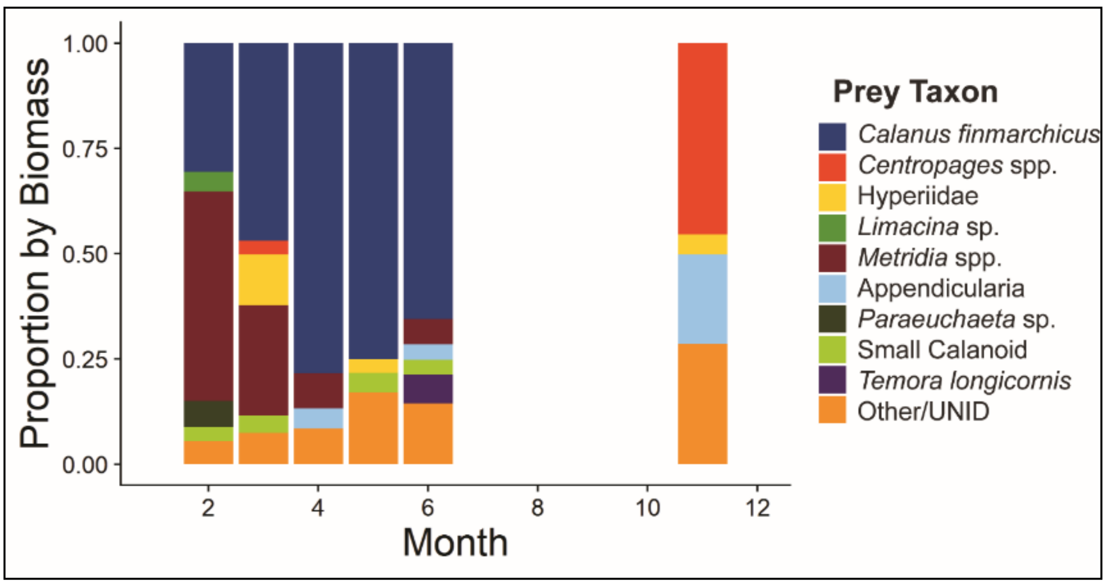


Figure 22. Diet by biomass by month of adult sand lance (n=70) collected in 2019
Calanus finmarchicus was the dominant prey item. No data collection occurred in January, July, and December. No prey were observed in August, September, and October. From Suca et al. 2021.

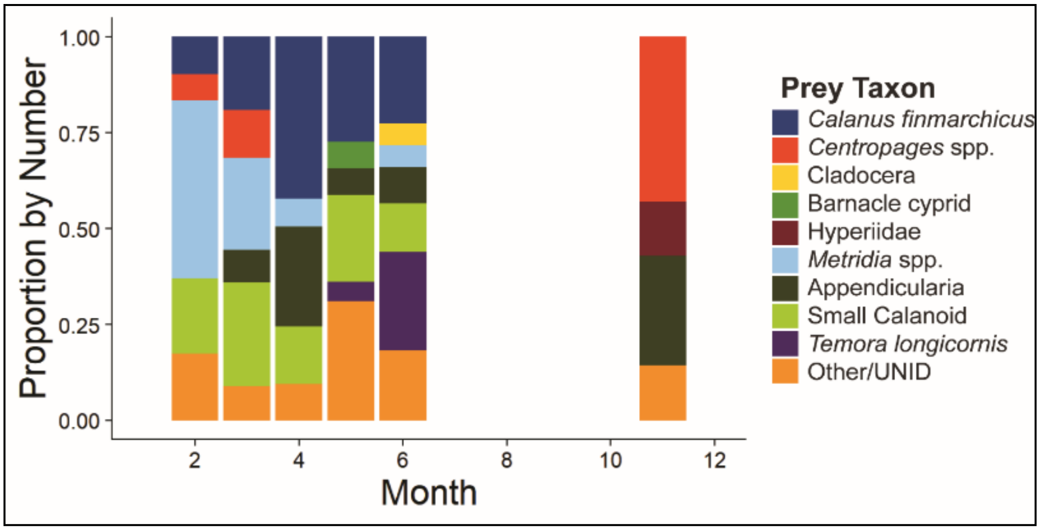


Figure 23. Diet by number by month of adult sand lance (n=70) collected in 2019

No data collection occurred in January, July, and December. No prey were observed in August, September, and October. From Suca et al. 2021.

3.3 Nutritional Condition

Lipids were extracted from 197 sand lance collected in 2019. A generalized additive model including month fit with a cyclic cubic regression spline identified a protracted lipid accumulation window (February–August) followed by a sharp decline in lipid content in the fall after spawning. Intra-bank "region" (i.e., north, central, south) was also included as a factor. Fish collected from the northern portion of the bank had significantly higher lipid content than those from the central and south, which showed no difference (Figure 24). This is consistent with the northern portion of the bank having a higher mean *Calanus* abundance in March, May, and June (Figure 24 and Figure 25), and exhibiting different water mass properties than the south (the central stations are often closer to southern water mass properties but vary) (Figure 26).

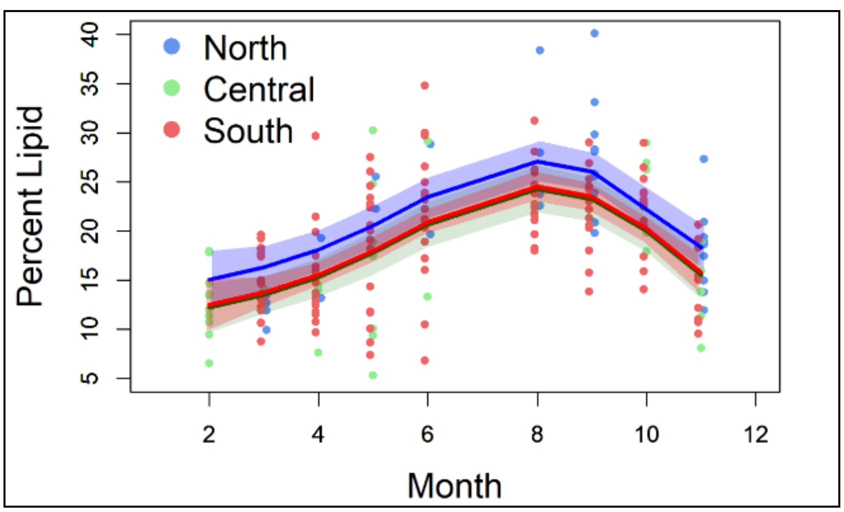


Figure 24. Whole body percent lipid by month and region of sand lance collected in 2019

Solid lines represent fitted values of region-specific monthly lipid content of sand lance from a generalized additive model. Body lipid content increased from February to July and decreased from August to November. Sand lance were not collected in December or January. Shading represents the 95% confidence interval. From Suca et al. 2021.

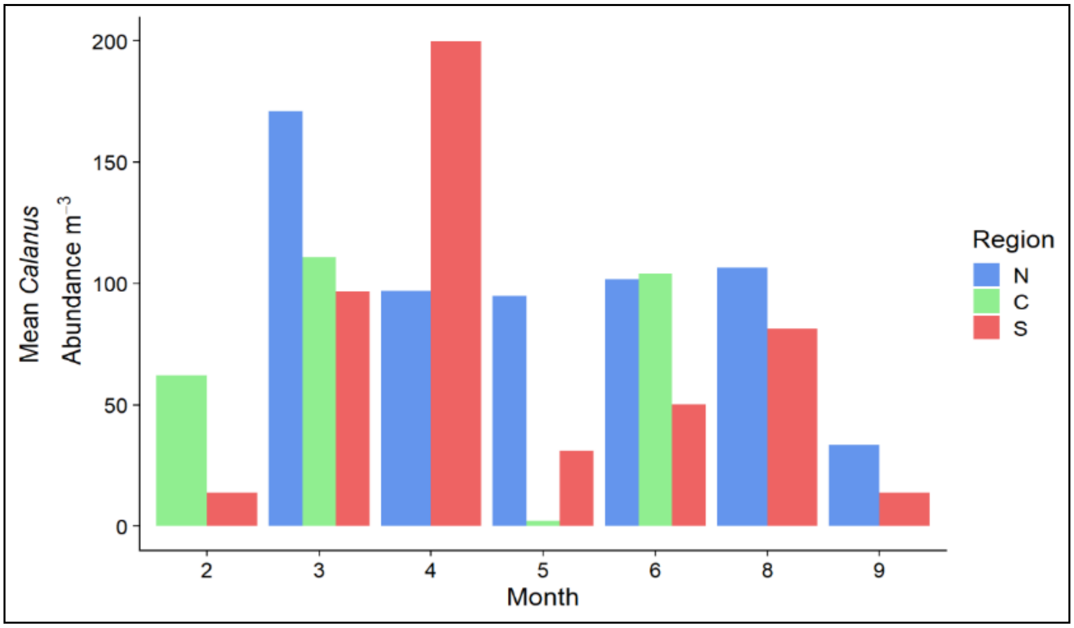


Figure 25. Mean *Calanus* abundance by region and month from vertical zooplankton samples in 2019

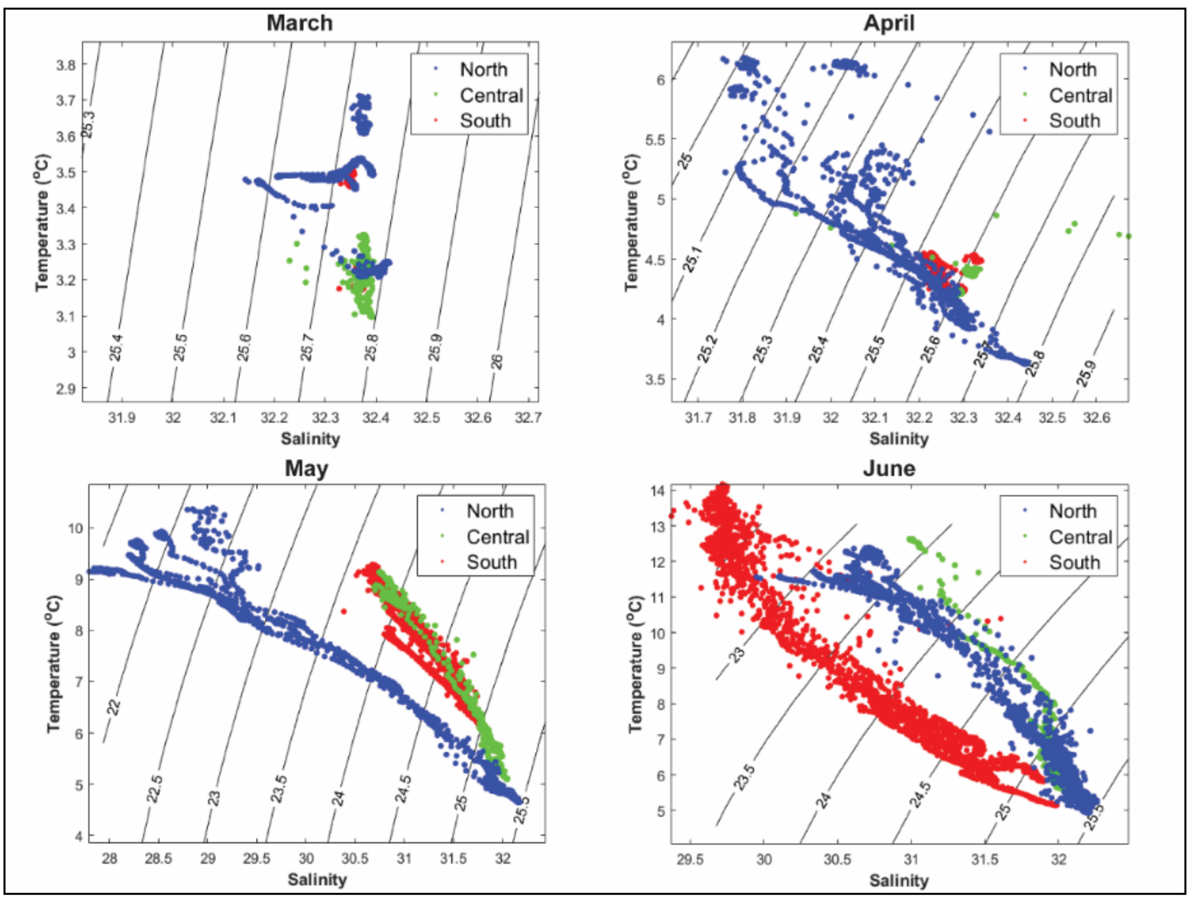


Figure 26. Monthly temperature-salinity plots of CTD casts on Stellwagen, color coded by region
Solid lines represent isopycnals. See Suca et al. 2021; the abstract is provided below. Abstract: Sand lance (*Ammodytes dubius*) and Atlantic herring (*Clupea harengus*) represent the dominant lipid-rich forage fish species

throughout the Northeast US shelf and are critical prey for numerous top predators. However, unlike Atlantic herring, there is little research on sand lance or information about drivers of their abundance. We use intra-annual measurements of sand lance diet, growth, and condition to explain annual variability in sand lance abundance on the Northeast US Shelf**.** Our observations indicate that sand lance feed, grow, and accumulate lipids in the late winter through summer, predominantly consuming the copepod *Calanus finmarchicus*. Sand lance then cease feeding, utilize lipids, and begin gonad development in the fall. We show that the abundance of *Calanus finmarchicus* strongly influences sand lance parental condition and recruitment. Atlantic herring can mute this effect through intra-guild predation. Hydrography further impacts sand lance abundance as increases in warm slope water decrease overwinter survival of reproductive adults. The predicted changes to these drivers indicate that sand lance will no longer be able to fill the role of lipid-rich forage during times of low Atlantic herring abundance—changing the Northeast US shelf forage fish complex by the end of the century.

4 Objective 3: Spawning and/or Reproductive Cycle

Objective 3: Identify the spawning and/or reproductive cycle of sand-dependent forage species.

The spawning pattern of sand lance on Stellwagen Bank was documented during five consecutive years: 2016–2020, inclusive. Our work resulted in the first definitive proof of sand lance spawning in this area. Current literature describes a long spawning season for sand lance (i.e., end of October to February), but we consistently found a much narrower spawning window of about two weeks at the end of November. In 2017, we measured temporal patterns in sand lance gonado-somatic index, which showed a sudden increase and then immediate decrease at the end of November, which is consistent with a single, short spawning peak (Figure 27). Furthermore, histological analyses of oocytes of pre-peak, and post-spawning females showed a single cohort of secondary oocytes ripening and then disappearing (Figures 28–31). Post-spawn females had ovaries consisting only of primary oocytes which are the reservoir for next year's spawning (Figure 28). Hence, our analyses confirmed that sand lance on Stellwagen Bank are spawning just once per year during a narrow window at the end of November.

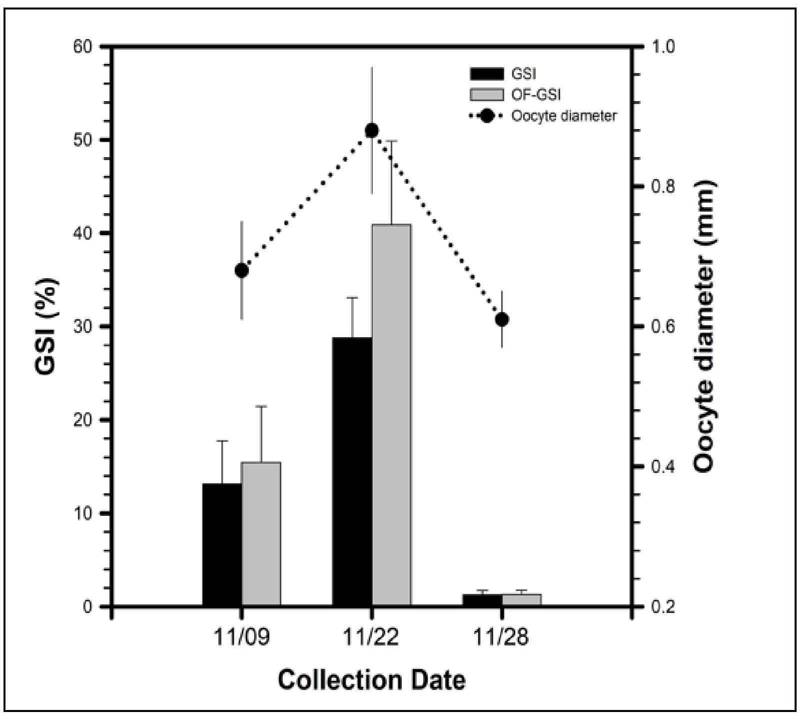


Figure 27. Development of whole body (black bars) and empty body (gray bars) gonado-somatic indices (GSI) during the late fall 2017

Black circles denote the size of oocytes. Error bars are 1 SD. Data are consistent with a single spawning event.

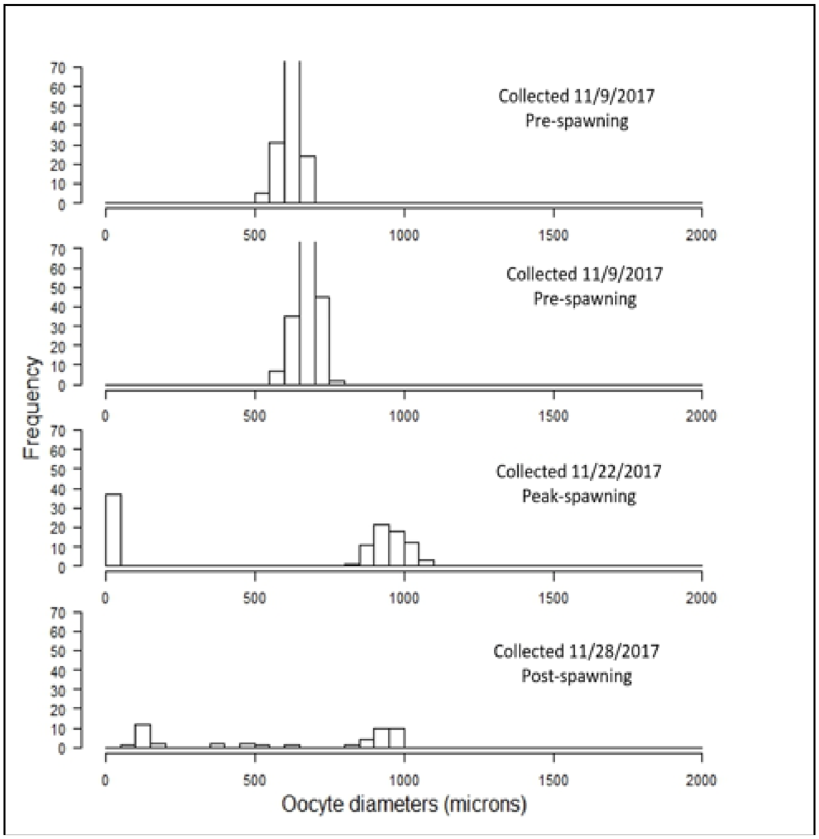


Figure 28. Frequency distribution of oocytes in sand lance in pre-, peak, and post-spawning females from November 2017

Data are consistent with a single spawning event.

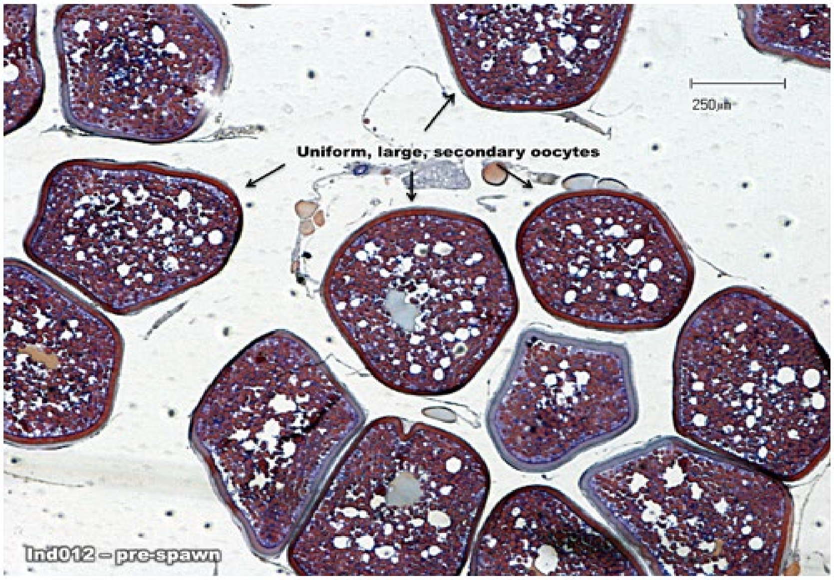


Figure 29. Histology of the ovary of a sand lance female prior to spawning

All oocytes are of the same size and developmental stage, supporting the single, narrow spawning window for this species.

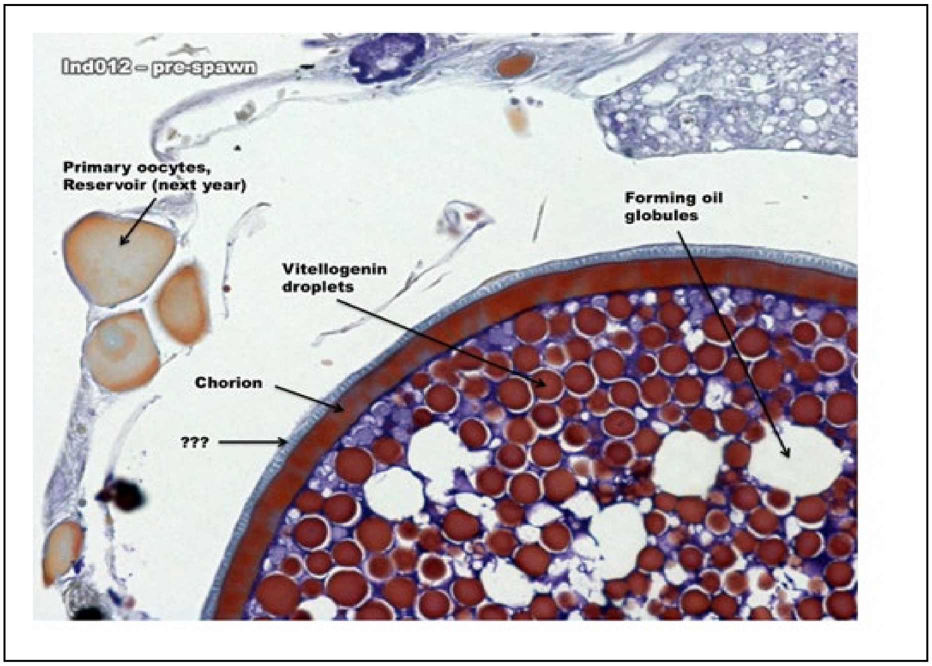


Figure 30. Histology of a secondary oocytes in a pre-spawning sand lance female from November 2017

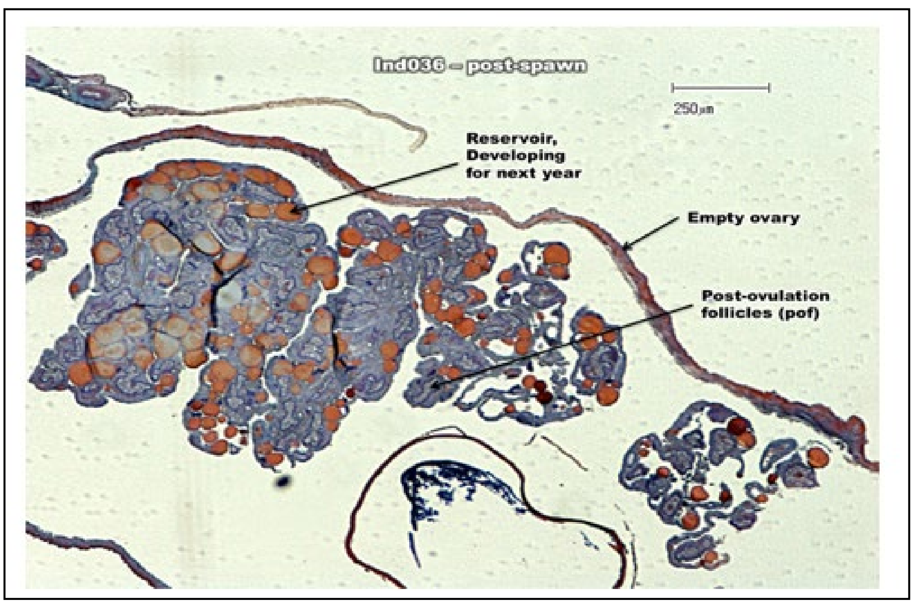


Figure 31. Histology of the ovary of a sand lance female post-spawning at the end of November 2017

Only small, primary "reservoir" oocytes remain. This is consistent with a single spawning peak.

In addition, our work on sand lance spawning contributed to our understanding of the effects of ocean acidification and oceanic warming on the reproduction of sand lance (Figure 32). Over the course of two years, we conducted factorial pCO_2 × temperature exposure experiments on offspring of the sand lance. Wild, spawning-ripe adults were collected from SBNMS and fertilized embryos were reared at three pCO_2 conditions (400, 1,000, and 2,100 µatm) crossed with three temperatures (5°C, 7°C, and 10°C).

Exposure to future pCO_2 conditions consistently resulted in severely reduced embryo survival. Sensitivity to elevated pCO_2 was highest at 10°C, resulting in up to an 89% reduction in hatching success between control and predicted end-of-century pCO_2 conditions (Figure 32). Moreover, elevated pCO_2 conditions delayed hatching, reduced remaining endogenous energy reserves at hatch, and reduced embryonic growth. Our results suggest that sand lance is exceptionally CO_2 sensitive compared to other fish species, though pCO_2 conditions experienced by sand lance in their natural environment (SBNMS) are currently unknown.

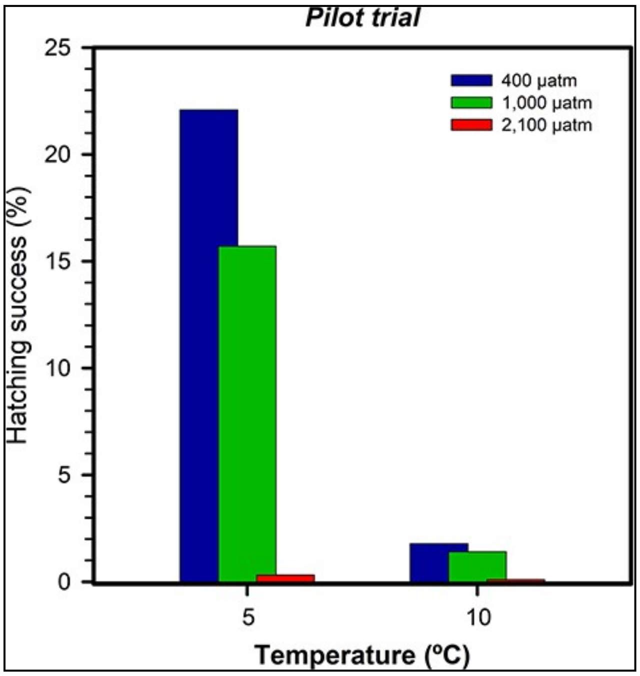


Figure 32. Sand lance hatching success. ***A. dubius***
Mean embryo survival (%) of offspring reared at 400 µatm (blue, left bar), 1,000 µatm (green, central bar) and 2,100 µatm pCO_2 (red, right bar) and two temperatures from the pilot trial. From Murray et al. 2019.

As previously reported, sand lance spawning occurs during a narrow window at the end of November when water temperatures are trending towards 10°C. Trawls conducted in 2020 supported those finding, with samples obtained on 19 November containing males, but not females, in spawning condition (water temperature 10.5°C). Sampling on 27 November had both sexes in full spawning condition (water temp 10.2°C). Fish were strip spawned on the R/V *Auk* and taken to the Baumann lab at the University of Connecticut (UConn) (Avery Point) for larval rearing and experimentation (Figure 33).

Figure 33. Spawning at sea: field work focused on sand spawning

Left: strip spawning-ripe sand lance onboard the vessel for transportation to the lab. Right: sand lance eggs. Photo: Hannes Baumann.

See Murray et al. 2019; the abstract is provided below.

Abstract: Sand lances of the genus Ammodytes are keystone forage fish in coastal ecosystems across the northern hemisphere. Because they directly support populations of higher trophic organisms such as whales, seabirds or tuna, the current lack of empirical data and, therefore, understanding about the climate sensitivity of sand lances represent a serious knowledge gap. Sand lances could be particularly susceptible to ocean warming and acidification because, in contrast to other tested fish species, they reproduce during boreal winter months, and their offspring develop slowly under relatively low and stable pCO_2 conditions. Over the course of 2 years, we conducted factorial pCO_2 × temperature exposure experiments on offspring of the sand lance, *Ammodytes dubius*, a key forage species on the northwest Atlantic shelf. Wild, spawning-ripe adults were collected from Stellwagen Bank National Marine Sanctuary (Cape Cod, USA), and fertilized embryos were reared at three pCO_2 conditions (400, 1000 and 2100 μatm) crossed with three temperatures (5, 7 and 10 C). Exposure to future pCO_2 conditions consistently resulted in severely reduced embryo survival. Sensitivity to elevated pCO_2 was highest at 10 C, resulting in up to an 89% reduction in hatching success between control and predicted end-of-century pCO_2 conditions. Moreover, elevated pCO_2 conditions delayed hatching, reduced remaining endogenous energy reserves at hatch and reduced embryonic growth. Our results suggest that the sand lance is exceptionally CO_2-sensitive compared to other fish species. Whether other sand lance species with similar life history characteristics are equally CO_2-sensitive is currently unknown. But the possibility is a conservation concern, because many boreal shelf ecosystems rely on sand lances and might therefore be more vulnerable to climate change than currently recognized. Our findings indicate that life history, spawning habitat, phenology and developmental rates mediate the divergent early life CO_2 sensitivities among fish species.

5 Objective 4: Origin Identification

Objective 4: Identify origin of sand-dependent forage species using genetic analysis to localize fish origin.

To investigate the relationship of sand lance occurring on Stellwagen Bank to that of sand lance throughout the western North Atlantic, we obtained fin clips samples from 490 individual sand lance , spanning almost the entire known distributional range of this species. In addition, we included 10 and 15 outgroup samples from congener species *A. personatus* (Pacific) and *A. americanus* (nearshore Atlantic), respectively. In collaboration with Prof. Therkildsen's Population Genomics Lab (Cornell University), we subsampled and extracted DNA from 315 individuals using Quiagen Easy Kits and protocol. Samples were checked for DNA yield and were then further prepared for sequencing by attaching individually barcoded libraries to each sample.

In March 2020, we submitted these samples to the sequencing facility of Novogene[4] . Out of an abundance of caution and to preserve the ability to adjust sequencing procedures, we first proceeded to have them sequence three of the required five HiSeq sequencing lanes—the remaining samples will be sequenced after results of the Q/C of the first batch are available.

In May 2020, we received the first sequences from Novogene, ~350GB of data. We proceeded to request and receive access to UConn's High Performance Computing Cluster, which is required for these kinds of bioinformatic analyses. Again, we are using the currently most powerful genomic approach (Low coverage whole genome sequencing) to go after our central question of sand lance connectivity. At its extremes, we may see complete genetic homogenization across the species distribution or high local clustering of each population. Homogeneous genomes would point to strong connectivity including the potential to repopulate an area after local disappearance of sand lance. If populations are genetically clustered, it means they retain independence from each other and therefore cannot be assumed to simply get replenished from outside sources. This analysis was been slowed by COVID-19 restrictions that prevent laboratory access and analysis.

A main finding from preliminary genetic analysis of single nucleotide polymorphisms (SNPs) suggests that sand lance form two genetically distinct supergroups, one that occurs south of Nova Scotia, including Stellwagen Bank and another group further north including Gulf of St. Lawrence and Newfoundland (Figure 34).

[4] Novogene Corporation, Inc., 8801 Folsom Blvd, Suite 290, Sacramento, California.

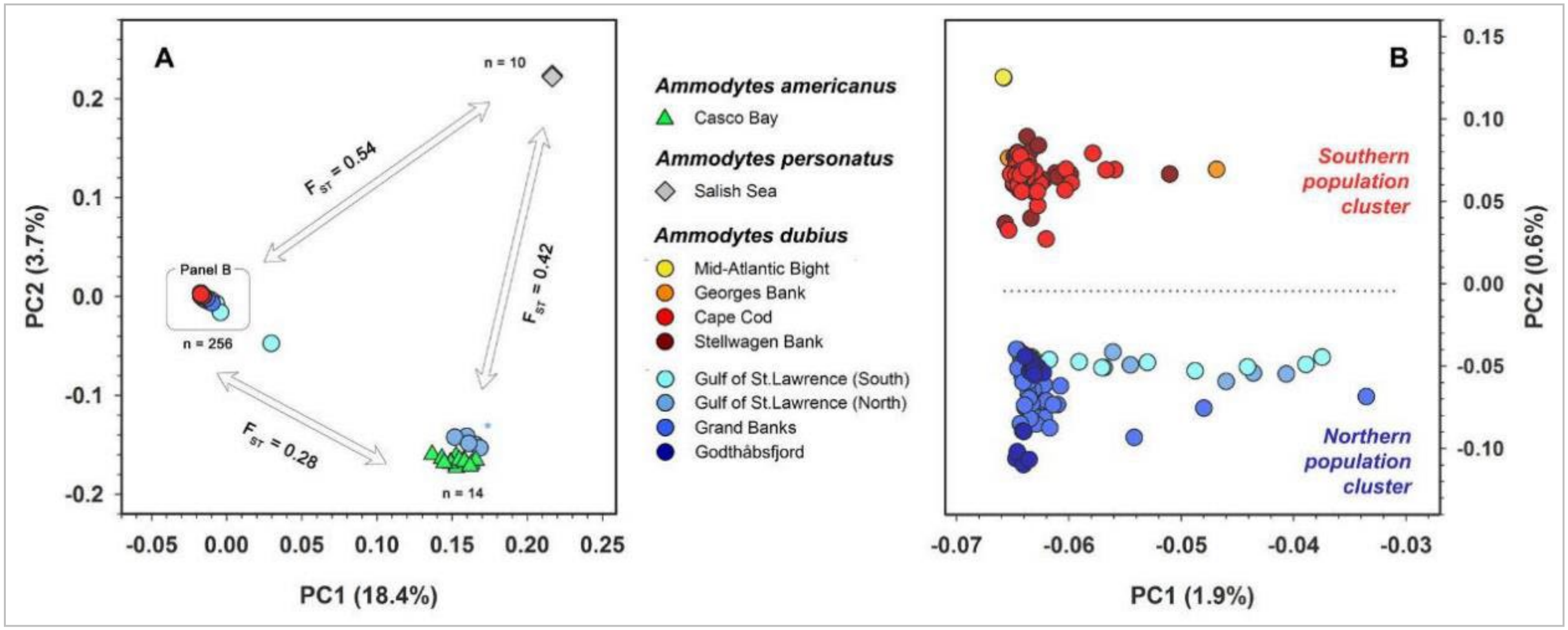


Figure 34. Genetic separation of *Ammodytes* species based on >38M single nucleotide polymorphisms (SNPs) identified using low coverage, whole genome sequencing and subsequent principal component analysis (PCA).

(A) Separation of congeners *A. americanus, A. personatus,* and *A. dubius* along the first two principal components (PCs), explaining a cumulative 22.1% of the variability. Numbers next to the arrows denote the metric of genetic separation (FST-values), with numbers of sequenced specimens given next to each group (Asterisk refers to 5 specimens from the northern Gulf of St. Lawrence that were likely *A. americanus* but were mis-identified as *A. dubius*). (B) PCA of *A. dubius* from 8 locations across the species geographical distribution, explaining a cumulative 2.5% of the overall variability. Along PC2, a complete separation occurred between specimens north vs. south of the Scotian shelf, referred to here as Northern and Southern population clusters, respectively (from Jones et al. in submission)

6 Objective 5: Model Larval Movements

Objective 5: Model larval movements using the appropriate oceanographic model to determine if an array of sandy geomorphological features are sources or sinks for productivity.

To investigate the spatial origin and fate (source and/or sink) of sand lance found on Stellwagen Bank (Figure 35), we performed long-term (1990–2016) hydrodynamic drift simulations (Figure 36). To accomplish this, we seeded 1,230 Lagrangian drifters on Stellwagen Bank in each of four depths: 5, 15, 25, 35m. We created backward (n=8) and forward (n=7) scenarios in each of 27 years and tracked them for 68 and 85 days backward (spatial origin) or forward (spatial fate) (see Section 3.1).

Our findings suggest that the Stellwagen Bank sand lance population is highly connected to–and reliant on–spawning populations immediately to the north in the coastal and northern Gulf of Maine. This also indicates the potential for partial self-recruitment back to the bank (Figure 37 and Figure 38). Self-recruitment was highest on the southwest corner of Stellwagen Bank, where our sampling also demonstrated the most consistent sand lance abundance. We further found that the productive Stellwagen Bank spawning ground likely exports most of its offspring to suitable habitats in areas to the south of the bank, thereby potentially contributing to large, but interannually variable settlement pulses on Nantucket Shoals, Georges Bank, and southern New England waters, including areas currently under development for offshore wind energy production (Figure 39). Available monitoring records of larval sand lance abundance on Stellwagen Bank (2008–2016) suggested that years of exceptional transport from far away areas in the northern Gulf of Maine produce exceptional larval settlement pulses, thus highlighting the potential role of variable transport patterns in generating the large spatiotemporal fluctuations typical for this important forage fish (Figure 40). A recent publication of this work (Suca et al. 2022) can be found in Appendix E.

Figure 35. Fish larvae captured during a bongo net tow
Photo: Tammy Silva

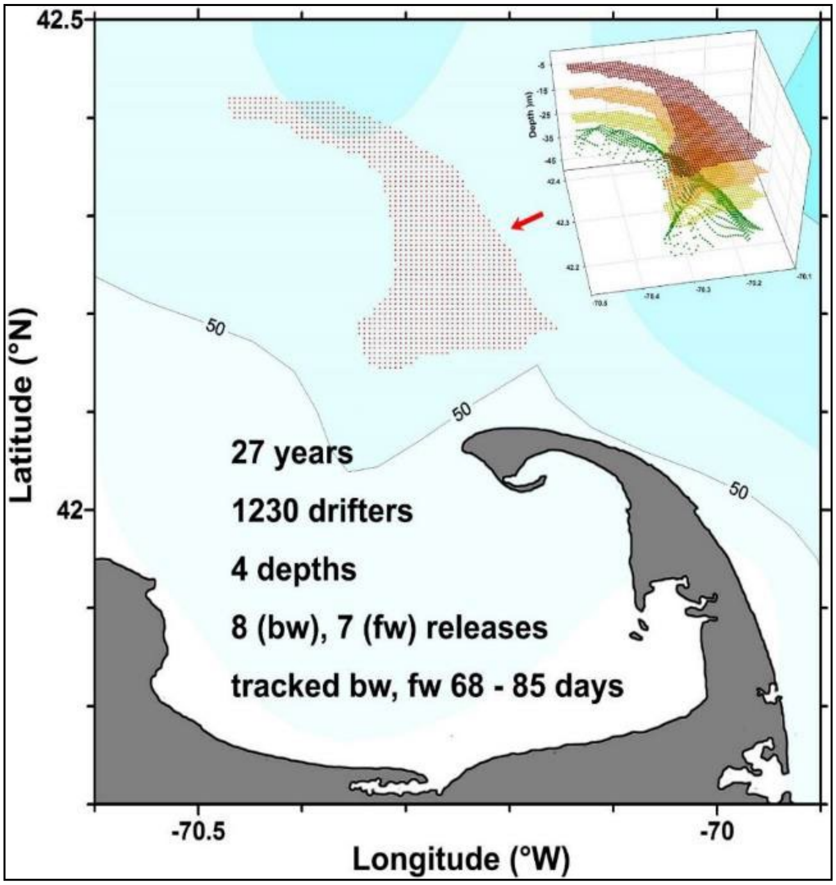


Figure 36. Set-up of the hydrodynamic drift simulations
We seeded 1,230 Lagrangian drifters (red dots) on Stellwagen Bank in each of four depths (5, 15, 25, 35m, inset), 8 or 7 releases (backward, forward tracking, respectively) and each of 27 years, and tracked them for 68 and 85 days backward (spatial origin) or forward (spatial fate).

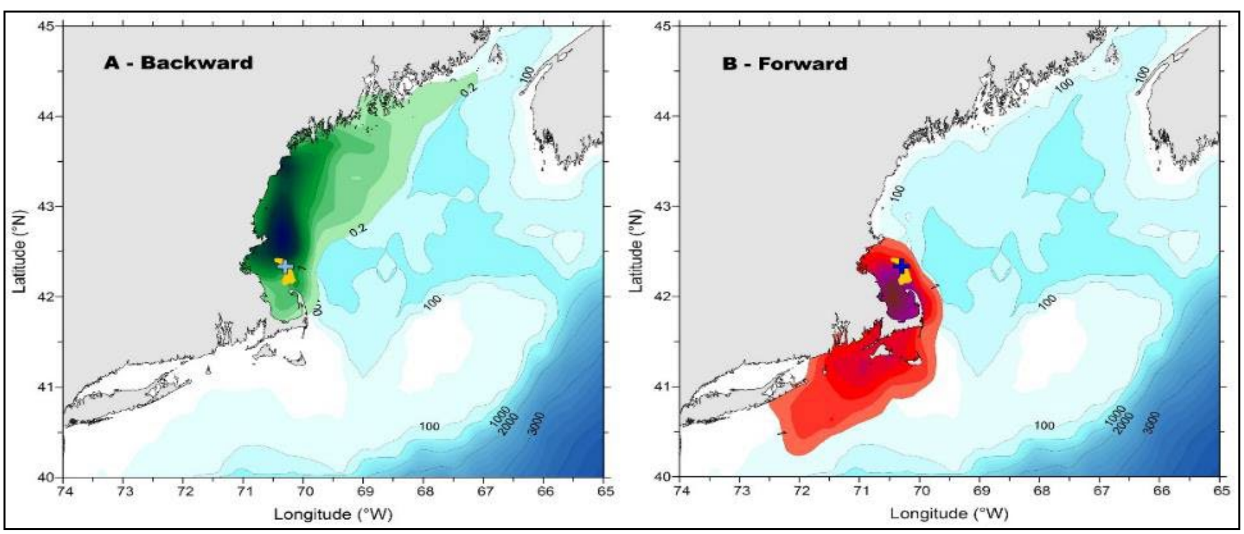


Figure 37. Aggregate backward (A) and forward (B) drift simulations to infer the spatial origin (A) and fate (B) of northern sandlance larvae settling (A) or produced (B) on Stellwagen Bank NMS.
We seeded 1,230 Lagrangian drifters (yellow area) in each of 27 years (1990–2016), each of four depths (5, 15, 25, 35m) and (A) each of 8 days (17–31 March) or (B) each of 7 days (1–13 Jan), and then tracked backward or forward

for 68 and 85 days. Contours represent total aggregate percentages of particle distributions across all years and releases. Results indicate that sand lance on Stellwagen Bank originate in coastal and northern Gulf of Maine and that sand lance spawned on Stellwagen Bank exported south and southeast to coastal Cape Cod, Great South Channel and southern New England. There is some retention in the southwest corner area of Stellwagen Bank. From Suca et al. 2021**.**

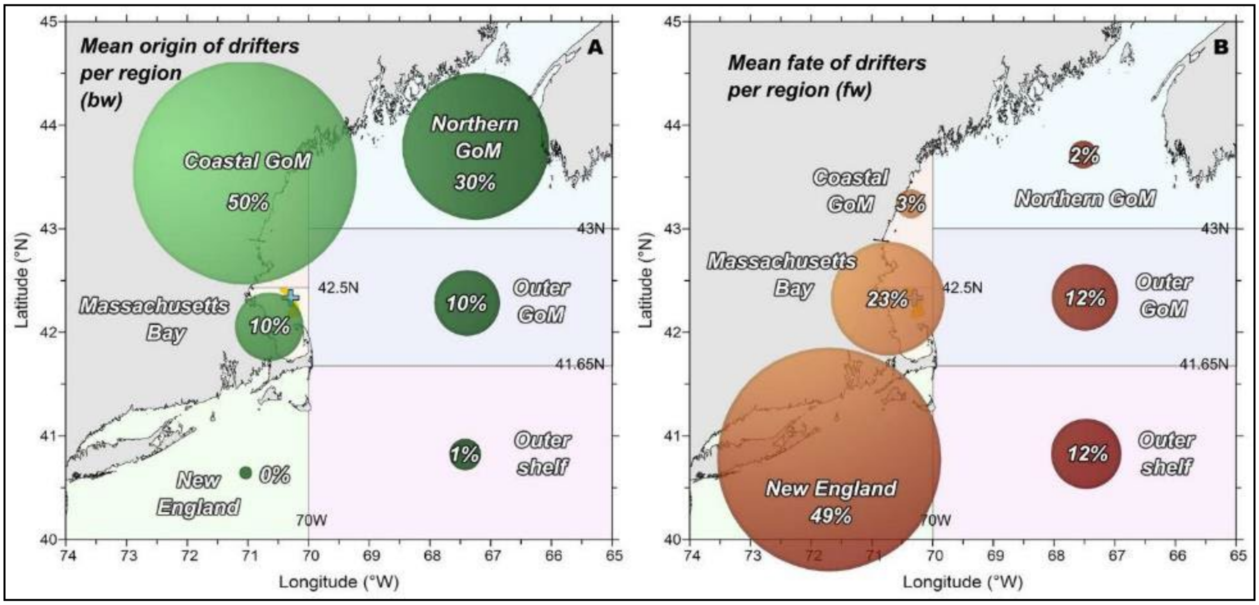


Figure 38: Bubble plot of the mean percentage of drifters (across all years, releases, periods, 15- to 35-m depths) in (A) backward projections and (B) forward projections

Bubble sizes are scaled to percentages. Sand lance on Stellwagen Bank are sourced primarily from coastal and northern Gulf of Maine, with some retention in the Bank's southwest corner. Sand lance spawned on Stellwagen Bank populate southern New England waters (i.e., east of Cape Cod, Great South Channel, Long Island, and south).

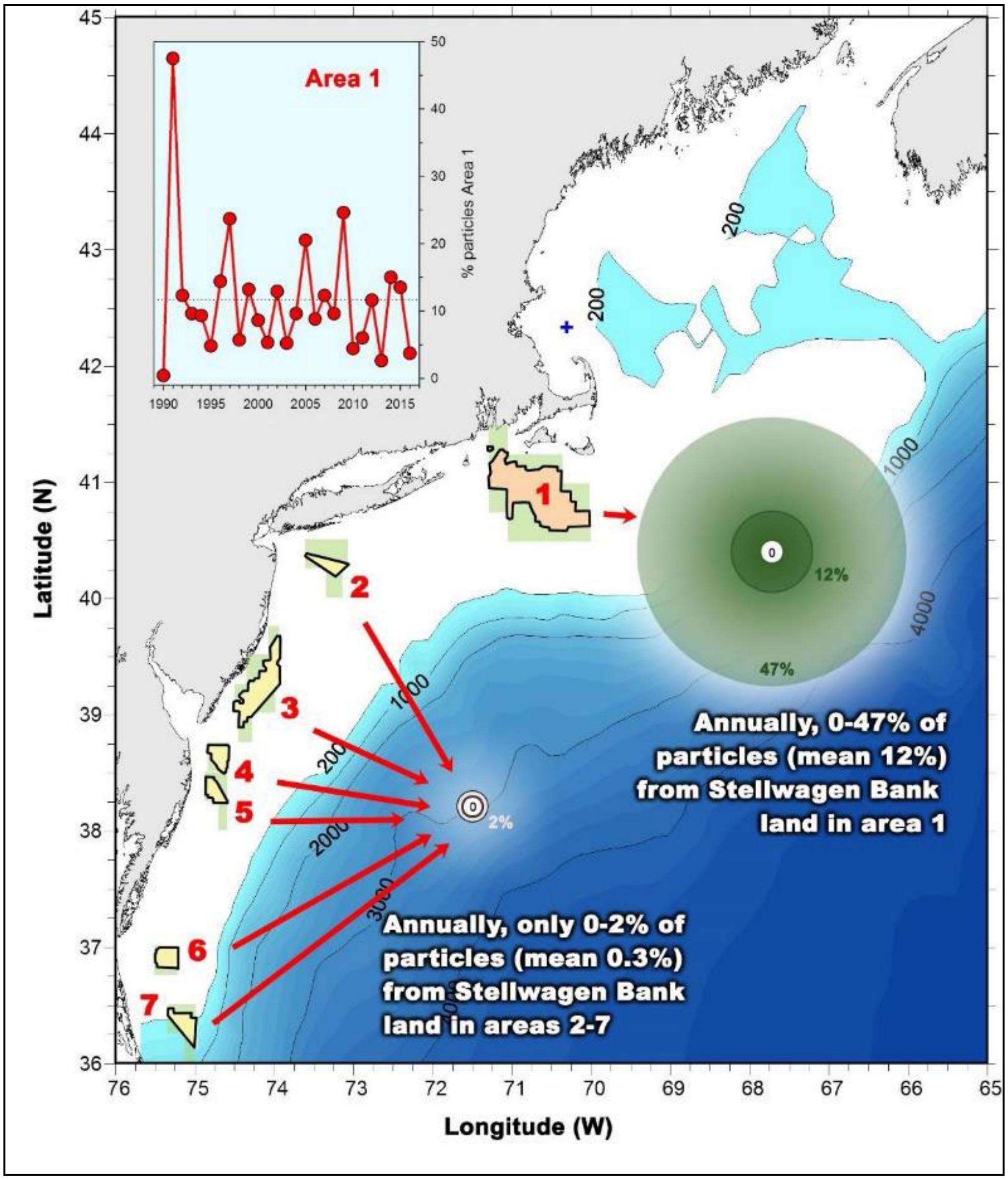


Figure 39. Percentage of Stellwagen produced sand lance larvae drifting into BOEM Wind Lease areas at the time of settlement (68–85d), inferred from forward runs

Black outlines show wind energy areas 1–7 along the mid-Atlantic Bight (green squares = grid cells used to include drifters). Circles show minimum, mean, and maximum percentages of drifters. Inset shows time-series of area 1.

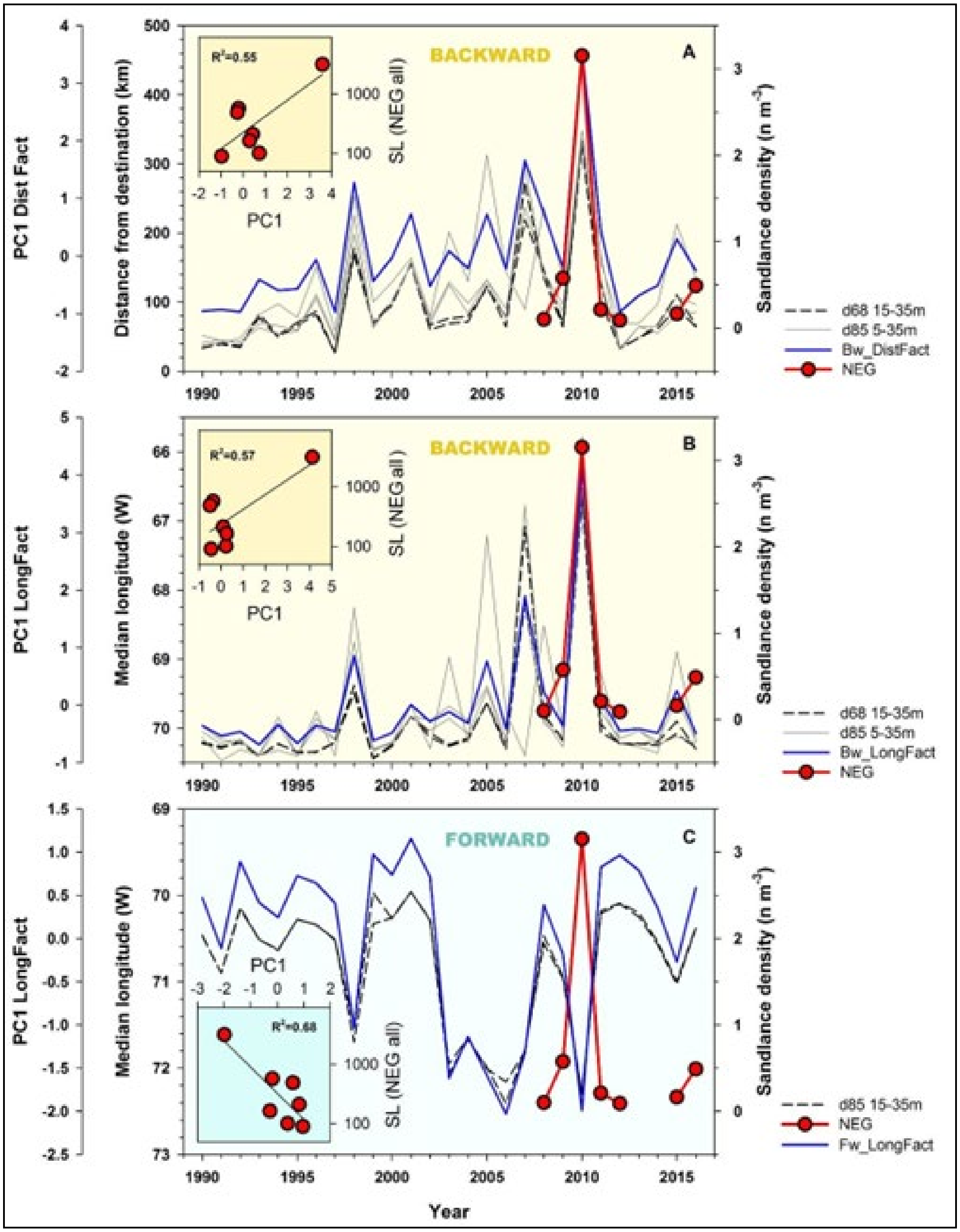


Figure 40. Time-series of drifter-derived proxies of interannual variability in backward and forward simulations (gray, black lines) and their relationship to independent measurements of larval sand lance occurrence (yolksac, post-yolksac) at the Northeast Gateway facility near Stellwagen Bank (red circles, lines; 2008–2016)

(A) Median distance of drifters from the mean arrival destination on Stellwagen Bank for different drift depths and tracking periods (but across all release days), (B) Median longitude of drifters from different depths and backward tracking periods (but across all release days), (C) mean longitude of drifters from different depths and forward tracking periods (but across all release days). The blue lines in each plot show the time-series of first principal component scores, calculated from all individual drifter time-series. Inserts show correlations between PC scores and the Feb-Apr sand lance larval abundance (ind m^{-3}) recorded by NEG.

7 Objective 6: Sand Lance Life History Matrix

Objective 6: Sand lance life history matrix.

7.1 Sand Lance Vulnerability Matrix

We used our accumulated knowledge (literature and research specific to SBNMS) on sand lance life history (e.g., spawning, somatic growth, lipid accumulation, etc.) to create a sand lance vulnerability matrix. The matrix identifies risk tradeoffs and potential impacts to different life stages of sand lance at different times of year in relation to disruption by human activity such as dredging. We assigned a value to each event / activity indicating its importance during each month. Values ranged from zero for a month in which a life history activity did not occur to five for a month during which an activity was extremely important for sand lance survival and reproduction. For example, spawning activity received a value of 5 in November, when our data indicates all spawning occurs and 0 in January–September when there is no likelihood of spawning behavior. October and December received values of 4, to account for potential variability in spawning behavior based on interannual or future changes in bottom temperature. We then used these values to create a monthly Life History Vulnerability Matrix (Figure 41). For ease of viewing, we color coded cells based on the value provided as follows: 5 = red, 4 = orange, 3 = light orange, 2 = yellow, 1 = light green, and 0 = dark green. Total vulnerability for each month was calculated by summing ranks for all life history activities occurring during that month and assigning a rank based on five equal interval classes: Very Low = 0–7; Low = 7.1–14, Medium = 14.1–21, High = 21.1–27, Very High = 27.1–35 (maximum possible sum). This method of ranking total vulnerability by summing ranks of all life history activities essentially represents an average monthly vulnerability, which may lessen the impact of extreme values. However, Very High risk of disruption of even one life history activity makes sand lance vulnerable. As another way of assessing risk, we also present the Total Very High Ranks, which was calculated by summing the number of Very High risk activities for each month.

Matrix categories were (1) spawning, (2) egg development, (3) larval settlement, (5) foraging for somatic growth and lipid accumulation, (6) lipid storage required for adult survival during non-feeding times, (7) lipid storage required for reproductive success and (8) bottom time depicting relative time sand lance spent buried in the sediment which might increase dredge-type disruption.

<u>Spawning</u>. Spawning occurred during a short window towards the end of November (see Objective 3). Therefore, we provided November with an index value of 5 (red), while the shoulder months of October and December were assessed as 4 (orange). All other months were assessed as having no impact (0, dark green).

<u>Egg Development</u>. We were unable to independently determine time to hatching. Literature suggests sand lance eggs, which adhere to the sediment, hatch approximately six weeks after laying (Smigielski et al. 1984). Therefore, because sand lance eggs are deposited on Stellwagen Bank in November or December (see Objective 3), we provided an index value of 5 (red) for the months of November–January, as times during which sand lance eggs would be extremely vulnerable to disturbance. To be conservative and to account for potential variability, we assigned February and March with index values of 3 (light orange) and April a value of 2. All other months (May–October) were considered to have no impact on sand lance eggs (0 value).

<u>Settlement</u>. Larval sand lance recruited to SBNMS are planktonic for 50–90 days (see Objective 5). Therefore, larval sand lance would be most likely to settle on Stellwagen Bank during March and April. During this period, disruptive activities could preclude local settlement. Therefore, we provided March and April with an index value of 5 (red). To be conservative and account for variability, we provided the shoulder months of February and May with an index value of 4 and June with a value of 3. All other months were considered to have no impact on larval settlement and were given values of 0 (dark green).

Foraging. Sand lance forage primarily on *Calanus* copepods from December–July. It is during this time that somatic growth occurs and lipids are stored for spawning and adult survival during low-feeding months (August–November) (see Objective 2). Peak growth and lipid accumulation coincide with peak *Calanus* abundance in February–April and we provided these months with index values of 5 (red). January and May were assigned values of 4 (orange) consistent with those months historically lower, but still important, *Calanus* abundance, followed by June, July and December (3; light orange) November (2; yellow) and August–October (1; light green).

Reproductive Success. Sand lance are capital breeders, with fecundity and reproductive success depending on lipids accumulated before spawning (see Objective 2). Therefore, feeding and lipid accumulation during the foraging months of January–July are critical to reproductive success. We provided a value of 5 for March–June when lipid accumulation was highest and a value of 4 for the slower accumulation months of February and July. August to November demonstrated little lipid accumulation and received values of 1, while the slightly increased periods of December and January received values of 2.

Adult Starvation. Adult sand lance can be vulnerable to starvation. Sand lance feed very little from August through the November spawning period (see Objective 2). During this time, increased energy is devoted to egg and sperm production. By October and November, gonads fill most of the body cavity, severely reducing or negating nutrient intake. Following November spawning, adult sand lance are nutritionally depleted and dependent on remaining lipid stores and immediate foraging on available zooplankton species of low caloric value. Therefore, we assessed their vulnerability to starvation as 5 from November to March, with decreasing vulnerability in the following months (April–October) when high nutrient value *Calanus* become increasingly available.

The matrix allows us to examine tradeoffs with respect to risks and potential impacts of sand dredging on sand lance life stages at different times of year. Notably, no month had zero risk, and these risks and potential impacts likely vary annually. We suspect sand lance would be least biologically vulnerable to disruption during August and September because growth is completed, feeding has slowed, lipid concentration is high, and no spawning or larval settlement is occurring. However, because sand lance are buried in the sediment during much of that period, they might be extremely vulnerable to mechanically induced injury or mortality, such as that caused by dredging operations. Though sand lance will flee the substrate when disturbed, they attempt to re-bury within a few meters. In addition, our ability to capture sand lance via grab sample indicates not all sand lance flee the substrate when disturbed, though we acknowledge that grab sampling represents a very different disturbance than that of dredging and sand lance responses may differ. A more extensive Sand Lance Life History Vulnerability Matrix, including additional rationales for cell values, can be found in Appendix F.

Table 2. A qualitative, monthly, data-driven Sand Lance Life History Vulnerability Matrix indicating months during which key life history processes occur for sand lance and their potential vulnerability to disruption due to dredging or other human activities

Activity	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
SL spawning	0	0	0	0	0	0	0	0	0	4	5	4
SL daily bottom time	3	3	3	3	3	3	4	5	5	5	5	4
SL settlement	0	1	4	5	5	4	0	0	0	0	0	0
SL eggs	5	5	3	2	0	0	0	0	0	0	5	5
SL foraging	4	5	5	5	4	3	3	1	1	1	2	3
SL survivorship (lipids)	5	5	5	4	3	2	1	1	1	1	5	5
SL reproductive success (lipids)	2	4	5	5	5	5	4	1	1	1	1	2
TOTAL SL SUM VULNERABILITY	19.0	23.0	25.0	24.0	20.0	17.0	12.0	8.0	8.0	12.0	23.0	23.0
TOTAL SL VULNERABILITY RANK	M	H	H	H	M	M	L	L	L	L	H	H
TOTAL VH RANKS	2	3	3	3	2	1	0	1	1	1	4	2

Notes: Matrix ranges from no occurrence or disruption potential (value zero/color green) to high occurrence or disruption potential (value 5; color red). VL = Very Low, L = Low, M=Medium, H = High VH = Very High. Sand lance would be biologically most vulnerable to disruption from November to May and least during August and September. The full matrix, with supporting information relative to the values found in each cell, can be found in Appendix F.

7.2 Ecosystem Services Vulnerability Matrix

We created a monthly Ecosystem Services Vulnerability Matrix based on ecosystem components that directly or indirectly benefit from sand lance or sand habitat (e.g., commercial fisheries, commercial whale watching, top predator foraging), and could be disrupted by sand dredging operations (Table 3) to examine tradeoffs in risk to ecosystem services. This was developed because decisions on sand dredging must also include a range of activities that could be impacted and that would be considered in addition to that of sand lance.

We used our accumulated knowledge (literature and research specific to SBNMS) on marine life and human activities in SBNMS to assign a value to each month relative to its importance to that activity. Values ranged from 0 for a month in which an activity did not occur to 5 for a month during which an activity was extremely important as demonstrated by high occurrence (e.g., high occupancy by marine life or high effort by human activity). For example, we used the information on the bimodal peak in cod spawning (Zemeckis et al. 2019) to assign a value of 5 to the months of May and June, November and December, and 0 values for the months of February, March, August, and September, when spawning is not known to occur. When data existed, values were assigned quantitatively. For example, values for commercial fisheries were assigned by summing pounds landed for each month, finding the range of values across months, creating five equal size classes based on the range, and then assigning each month a value based on which class it fell into. Details on how values were determined for each ecosystem service are provided in Appendix VI. For ease of viewing, we color coded cells based on the value provided as follows: 5 = red, 4 = orange, 3 = light orange, 2 = yellow, 1 = light green, and zero = dark green. Total vulnerability for each month was calculated by summing ranks for all life history activities occurring during that month and assigning a rank based on five equal interval classes: VL = 0-12; L = 12.1-24, M = 24.1-36, H = 36.1-48, VH = 48.1-60 (maximum possible sum).

This method of ranking total vulnerability by summing ranks of all ecosystem activities essentially represents an average monthly vulnerability and very high-risk activities may appear lessened if many other lower risk activities occur in that month. However, Very High risk of disruption of even activity makes ecosystem services vulnerable. As another way of assessing risk, we also present the Total Very High Ranks, which was calculated by summing the number of Very High risk activities for each month.

We used the following ecosystem service categories to populate the matrix: humpback whales, great shearwaters, whale watching trips, cod spawning, cod landings, scallop landing, lobster landing, trap pot fishery trips, gillnet fishery trips, scallop dredge fishery trips, bottom longline fishing trips, and otter trawl fishing trips. These categories were selected based on their ecological, economic, and historical occurrence and importance to SBNMS and the Gulf of Maine region. For example, humpbacks and great shearwaters are the most common large whale and seabird in SBNMS and show strong overlap with sand habitat and sand lance (Objective 1). SBNMS is a premier whale watching destination and whale watching companies that visit SBNMS contribute $182 million in output to the local economy (Schwarzmann & Shea 2020). Cod, Scallops, and Lobster represent the highest value fisheries, and fishing gear types selected to examine trip effort are the most commonly fished gears in SBNMS. We note that there may be some redundancy and/or correlation between certain gears and landings, but we included both landings and gear to examine casse where trip effort may not be correlated with landings but fishing effort may still impact sand habitat and sand lance. For information specific to top predators see Objective 1. For information specific to commercial fisheries see Objective 7.

<u>Humpback whales</u>. We used daily sightings of individually identified humpback whales to identify the months with the highest occupancy of SBNMS (see Objective 1). Humpbacks occur in SBNMS at low levels from December to March. Numbers rapidly increase in April and are high through the summer months with a peak in July. Numbers gradually decrease through the fall until they reach minimum levels in December. Therefore, we provided a value of 1 for the months December–March, 3 for April and November, 4 for May/June and August–October, and 5 for July.

<u>Great shearwaters</u>. We used sanctuary sighting of great shearwater seabirds combined with our PTT tracking (Objectives 1, 9) to assign monthly matrix values based on occupancy. In general, great shearwaters arrive to the sanctuary in May, peak in August–October and depart in November. Therefore, we assigned values of 0 for December–April, 1 for May and November, 2 for June, 3 for July, and 5 for August–October.

<u>Whale watching trips</u>. We used the number of Stellwagen Bank whale watching trips per month to create matrix values for that activity. As part of a sanctuary whale watching report (Schwarzmann and Shea 2020), two whale watch companies operating in SBNMS provided estimates (one qualitative, one based on percentages) of the number of whale watching trips per month. Whale watching trips begin in April, peaks in July and August and cease in November. Therefore, we assigned matrix values of 0 for the months November–March; 3 for the shoulder months of April, May, and October; 4 for June and September; and 5 for the peak months of July and August.

<u>Cod Spawning</u>. Atlantic Cod have a bimodal spawning peak during the months of May-June and November-December (matrix value = 5). We provided a matrix value of 4 for the shoulder months of January, April, July, and October to account for variability and 0 for February, March, August, and September, when spawning is unlikely.

<u>Cod landings</u>. We used the number of pounds landed/month to create matrix values for the cod fishery. Landing date and location were taken from data provided by NOAA Fisheries and partitioned to be specific to the Stellwagen Bank area. (Objective 7). Landings in descending order were January, March, June and December (matrix value = 5), February and July (matrix value = 4), August, September and November (matrix value = 3) May and October (matrix value = 2) and April (matrix value = 1).

Scallop landing. We used the number of pounds landed per month to create matrix values for the scallop fishery. Landing date and location were taken from data provided by the NEFSC and partitioned to be specific to the Stellwagen Bank area. (Objective 7). Pounds landed in descending order were April (matrix value=5), May (matrix value = 4), June, July, February and March (matrix value = 2) and August through January (matrix value = 1).

Lobster landings. We used the number of pounds landed per month to create matrix values for the lobster fishery. Landing date and location were taken from data provided by NOAA Fisheries and partitioned to be specific to the Stellwagen Bank area. (Objective 7). Pounds landed in descending order were November and December (matrix value=5), October (matrix value=4), September (matrix value=3), January, July, August (matrix value=2), February-June (matrix value=1).

Scallop dredge fishery trips. Because the scallop dredge fishery interacts with the seabed where sand lance settle and live, and pounds landed might not be equal to fishing effort, we also used the above data to identify the number of scallop trips that occurred by month (Objective 7). Number of trips per month in descending order of effort were the following: April and May (matrix value = 5), June and July (matrix value = 4), March (matrix value = 3), February and August (matrix value = 2), and September–January (matrix value = 1).

Trap pot fishery trips. We used the same data to identify the number of trap pot fishery trips that occurred each month. In descending order of effort, these were: October and November (matrix value = 5), September and December (matrix value = 4), July and August (matrix value 3), January, May and June (matrix value = 2), and February–April (matrix value =1).

Gillnet fishery trips. We also used the NEFSC database to identify the number of gillnet trips that occurred each month (Objective 7). In descending order of effort these were: March, June, July, and December (matrix value = 5), January, February, August, and September (matrix value = 4), October and November (matrix value = 3), May (matrix value = 2), and April (matrix value = 1).

Bottom longline fishery trips. We used the NEFSC database to identify the number of trips that occurred each month (Objective 7). In descending order of effort these were: March (matrix value = 5), January and February (matrix value = 4), May and December (matrix value = 2), and March and June–November (matrix value = 1).

Otter trawl fishery trips. We also used the NEFSC database to identify the number of otter trawl trips that occurred each month (Objective 7). In descending order of effort these were: December–March and June (matrix value 5), July (matrix value = 4), August and November (matrix value = 3), May, September and October (matrix value = 2) and April (matrix value = 1).

Total Ecosystem Services Vulnerability for each month was calculated by summing the ranks for all sand habitat related ecosystem services occurring during that month. To rank Total Vulnerability, we created five, equal interval classes as follows: VL = 0-12; L = 12.1-24, M = 24.1-36, H = 36.1-48, VH = 48.1-60. Two months (June and July) were ranked as High, February ranked as Low, and all other months ranked as Medium risk. The matrix allows us to examine tradeoffs with respect to risks and potential impacts of sand dredging on ecosystem services that depend on sand habitat and/or sand lance, including commercial fishing, at different times of year. Notably, no month had zero risk and these risks and potential impacts likely vary annually. Further, months with the lowest risk of disturbance to ecosystem services throughout the year differed from months of lowest risk to sand lance life history stages, demonstrating the value in the matrices for examining tradeoffs associated with sand dredging at different times of year.

Table 3. A qualitative, monthly, data-driven Ecosystem Services Vulnerability Matrix indicating months during which key ecosystem services occur

Activity	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Humpbacks	1	1	1	3	4	4	5	4	4	4	3	1
Great shearwaters	0	0	0	0	1	2	3	5	5	5	1	0
Whale watching trips	0	0	0	3	3	4	5	5	4	3	0	0
Cod spawning	4	0	0	4	5	5	4	0	0	4	5	5
Cod landings	5	4	5	1	2	5	4	3	3	2	3	5
Scallop landings	1	2	2	5	4	2	2	1	1	1	1	1
Lobster landings	2	1	1	1	1	1	2	2	3	4	5	5
Trap pot fishery trips	2	1	1	1	2	2	3	3	4	5	5	4
Gillnet fishery trips	4	4	5	1	2	5	5	4	4	3	3	5
Scallop dredge fishery trips	1	2	3	5	5	4	4	2	1	1	1	1
Bottom longline fishery trips	4	4	5	1	2	1	1	1	1	1	1	2
Otter trawl fishery trips	5	5	5	1	2	5	4	3	2	2	3	5
TOTAL ECOSYSTEM SUM VULNERABILIY	29.0	24.0	28.0	26.0	33.0	40.0	42.0	33.0	32.0	35.0	31.0	34.0
TOTAL ECOSYSTEM VULNERABILITY RANK	M	L	M	M	M	H	H	M	M	M	M	M
TOTAL VH RANKS	2	1	4	2	2	4	3	2	2	2	3	5

Notes: Matrix values range from no occurrence or disruption potential (value zero/color green) to high occurrence or disruption potential (value 5; color red). VL = Very Low, L = Low, M=Medium, H = High VH = Very High. The full matrix, with supporting information relative to the values found in each cell, can be found in Appendix F.

Finally, we combined these two matrices to provide a rank for each month based on their calculated sensitivities to disruption of sand habitat, sand lance, and ecosystems services (Table 4). We calculated overall vulnerability by summing the ranks for total sl sum vulnerability and total ecosystem sum vulnerability and assigning ranks to each month based on five equal interval classes as follows: VL = 0-19; L = 19.1-38, M = 38.1-57, H = 57.1-76, VH = 76.1-95 (maximum possible sum). We note that the relative weights of influence of the sand lance and ecosystem services matrices differ; sand lance are considered far more extensively than any one ecosystem service and thus, the two matrices do not contribute equally to the Overall Vulnerability matrix, which could be perceived as valuing different ecosystem components differently. However, given the significance of sand habitat to all life history stages of sand lance and the importance of sand lance to numerous predators, giving more weight to sand lance in the Overall Vulnerability matrix is reasonable.

Table 4. Overall vulnerability

Overall Vulnerability Matrix	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Overall Vulnerability Sum	48.0	48.0	54.0	50.0	52.0	56.0	54.0	41.0	40.0	47.0	54.0	57.0
Overall Vulnerability Rank	M	M	M	M	M	M	M	M	M	M	M	M
Total VH Ranks	4	3	8	5	3	5	3	3	3	3	7	7

Notes: Overall Vulnerability for each month was calculated by summing the total sum ranks all categories in the Sand Lance Life History Vulnerability and Ecosystem Services Vulnerability matrices. All months were classified as Medium. However, all months have at least three activities or services that were ranked as Very High risk and three months (March, November, December) have seven Very High risk activities or services.

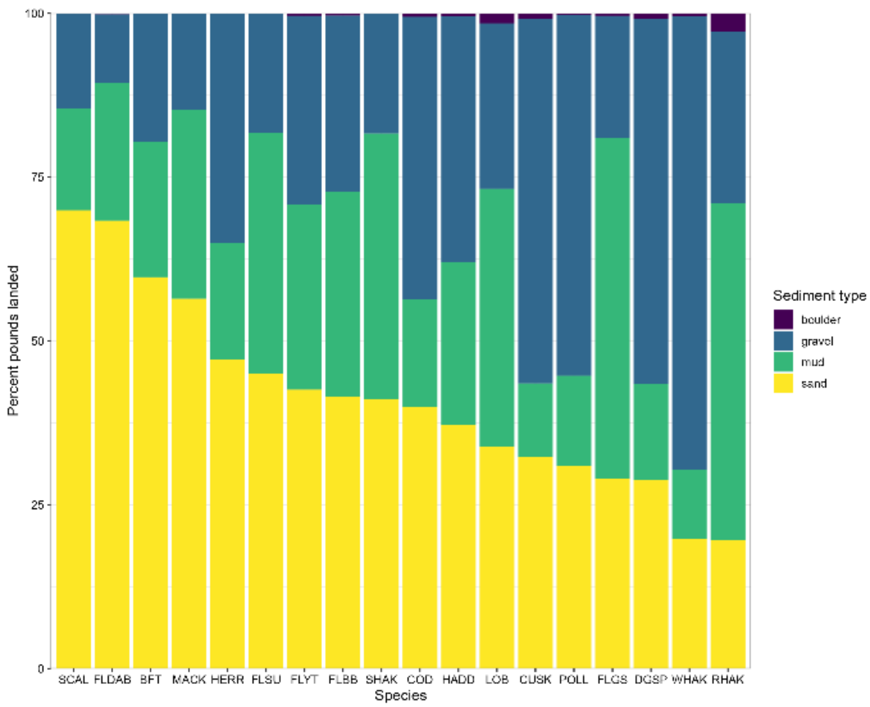
The vulnerability matrices and supporting information have been provided to the Boston University Multiscale Integrated Model of Ecosystem Services (MIMES) team for use by its MIMES modeling team for the development of its decision support tool. In addition, monthly meetings are occurring to discuss model inputs and validate the model's outputs. The full matrices with supporting information can be found in Appendix F.

8 Objective 7: Sand Habitat, Sand Lance Forage Fish, and Commercial Fisheries

Objective 7: Identify the relationship among sand habitat, sand lance forage fish, and commercial fisheries.

To examine the importance of sand habitat to commercial fisheries, Vessel Trip Report data for SBNMS were obtained from the Greater Atlantic Regional Fishery Office for the years 2007–2016, the most recent years in which data were available. These data were analyzed relative to habitat type by overlaying catch data on sediment maps provided by the USGS. Sediment maps consisting of sand, gravel, mud, and boulder habitat types were created by hydrographic survey and analyses specific to SBNMS, with a spatial resolution of 10m (cell size) (Valentine 2001). geographic information system (GIS) techniques were used to calculate the total pounds landed by habitat (sediment) type and to normalize the data to square kilometers of habitat. Boulder habitat was removed from the analysis because it contributed such a small fraction of habitat area and pounds landed. Dollar value (in 2017 dollars) for pounds landed were also provided by GARFO.

For 18 commercial fishes analyzed, 9 had the greatest landed pounds associated with sand habitat and sand habitat accounted for the second largest pounds landed in 8 other species (Figure 41, Table 5).



BFT Bluefin Tuna
COD Atlantic Cod
CUSK Cusk
DGSP Spiny Dogfish
HADD Haddock
HERR Herring
LOB Lobster
MACK Mackerel
FLBB Flounder Black Back Winter
FLDAB Flounder American Plaice Dab
FLGS Flounder Gray Sole Witch
FLYT Flounder Yellowtail
FLSU Flounder Summer
POLL Pollock
SCAL Sea Scallop
SHAK Hake Silver
WHAK Hake White
RHAK Hake Red

Figure 41. Percent pounds by species landed in sand, gravel, mud and boulder habitats for 18 commercial fish species for the years 2007–2016

Data calculated from National Marine Fisheries Service vessel trip reports. Data provided by the Greater Atlantic Regional Fisheries Office, Gloucester, Massachusetts.

Table 5. Pounds landed by habitat type showing the relative importance of sand habitat as compared to gravel, mud, and boulder habitats

		Percentage of Pounds Landed			
Species abbreviation	**Species name**	**Sand**	**Gravel**	**Mud**	**Boulder**
BFT	**Bluefin Tuna**	**59.7**	19.6	20.6	0
COD	Cod	39.9	43.2	16.4	0.5
CUSK	Cusk	32.3	55.6	11.3	0.9
DGSP	Spiny Dogfish	28.9	55.7	14.6	0.8
HADD	Haddock	37.2	37.6	24.8	0.4
HERR	**Herring**	**47.2**	35.1	17.7	0
LOB	Lobster	33.8	25.2	39.4	1.5
MACK	**Mackerel**	**56.4**	14.6	28.9	0
FLBB	**Flounder Black Back Winter**	**41.5**	26.8	31.4	0.3
FLDAB	**Flounder American Plaice Dab**	**68.4**	10.5	21	0.2
FLGS	Flounder Gray Sole Witch	29	18.7	51.9	0.4
FLYT	**Flounder Yellowtail**	**42.6**	28.8	28.2	0.4
FLSU	**Flounder Summer**	**45**	18.3	36.7	0
POLL	Pollock	31	55.1	13.7	0.2
SCAL	**Sea Scallops**	**69.9**	14.5	15.5	0
SHAK	**Hake Silver**	**41.1**	18.3	40.6	0.1
WHAK	Hake White	19.8	69.3	10.5	0.5
RHAK	Hake Red	19.6	26.2	51.4	2.8

Notes: Sand habitat provided the most pounds landed in 9 of the 18 species (bold blue text), including the highly valuable blue-fin tuna and scallop fisheries. In terms of pounds landed, sand habitat was the second most productive habitat in eight other species, including Cod and Haddock. Sand habitat was highly productive for 17 of the 18 species.

For 17 species, we calculated pounds landed in sand habitat by month for the years 2007–2016. Species for which sand habitat accounted for the greatest percentage of pounds landed are in blue. These data will inform decisions on the impact of sand disruption on particular species in specific time periods. An example of the analysis focused on the scallop fishery is in Figure 42 and Figure 43. Individual figures for all 17 species are contained in Appendix B.

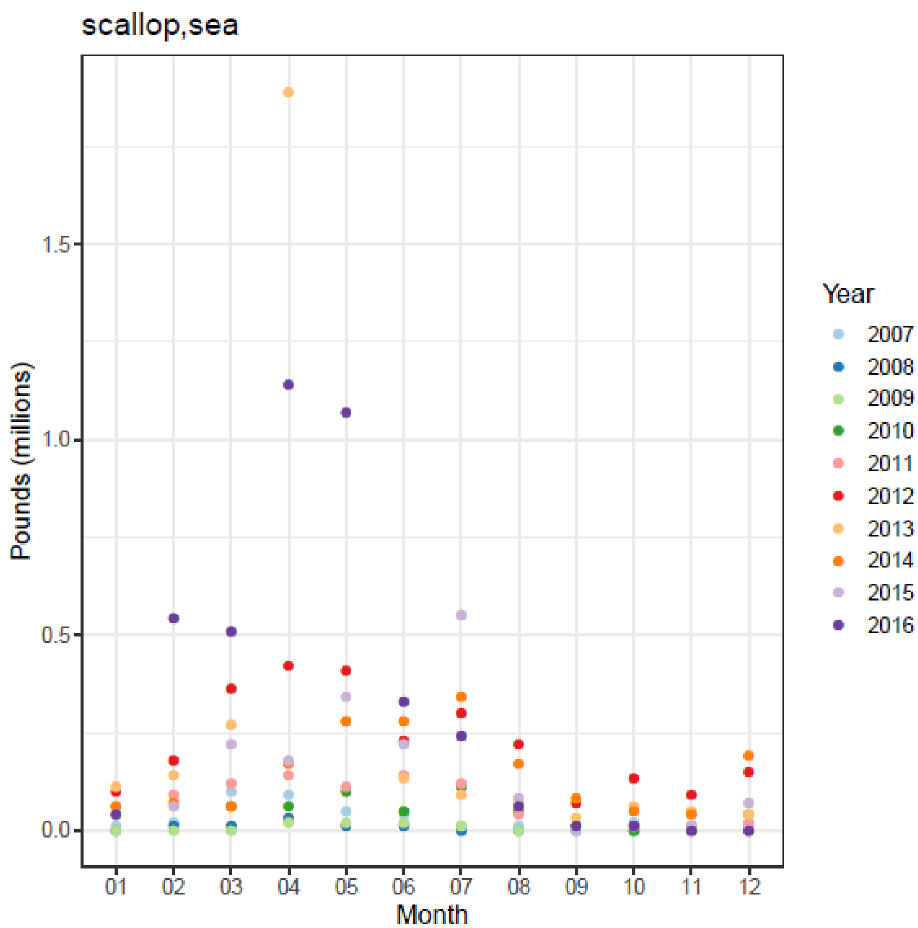


Figure 42. Pounds of Scallops landed in SBNMS from sand habitat, by month, for the years 2007–2016

Note breaks in lines where no data exists for that month and year.

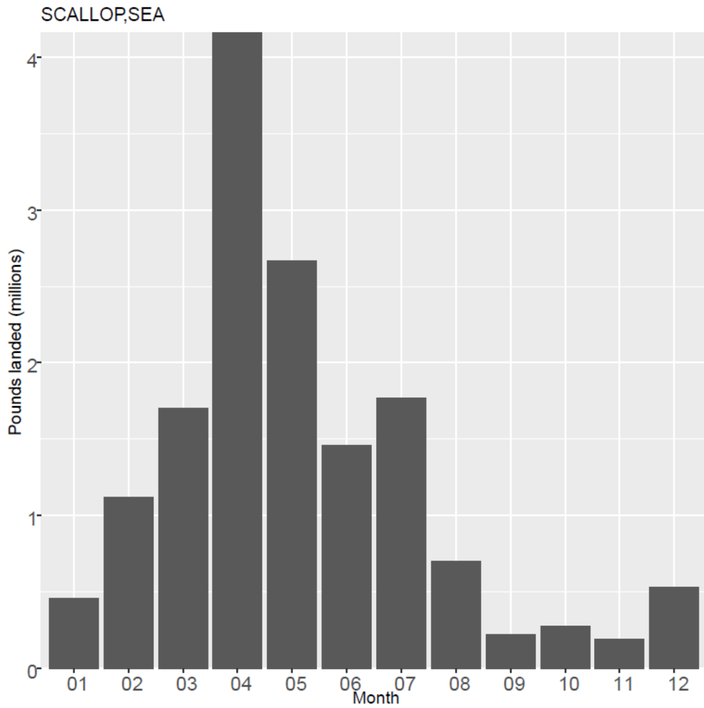


Figure 43. Pounds of scallops landed in SBNMS from sand habitat, by month, for the years 2007–2016

Relative to total pounds landed by commercial fisheries in SBNMS for the years 2007–2016, sand habitat provided the greatest contribution (67,441,139 lbs; 46%), followed by gravel (51,055,032 lb; 34%) and mud (30,116,863 lbs; 20%) (Figure 44).

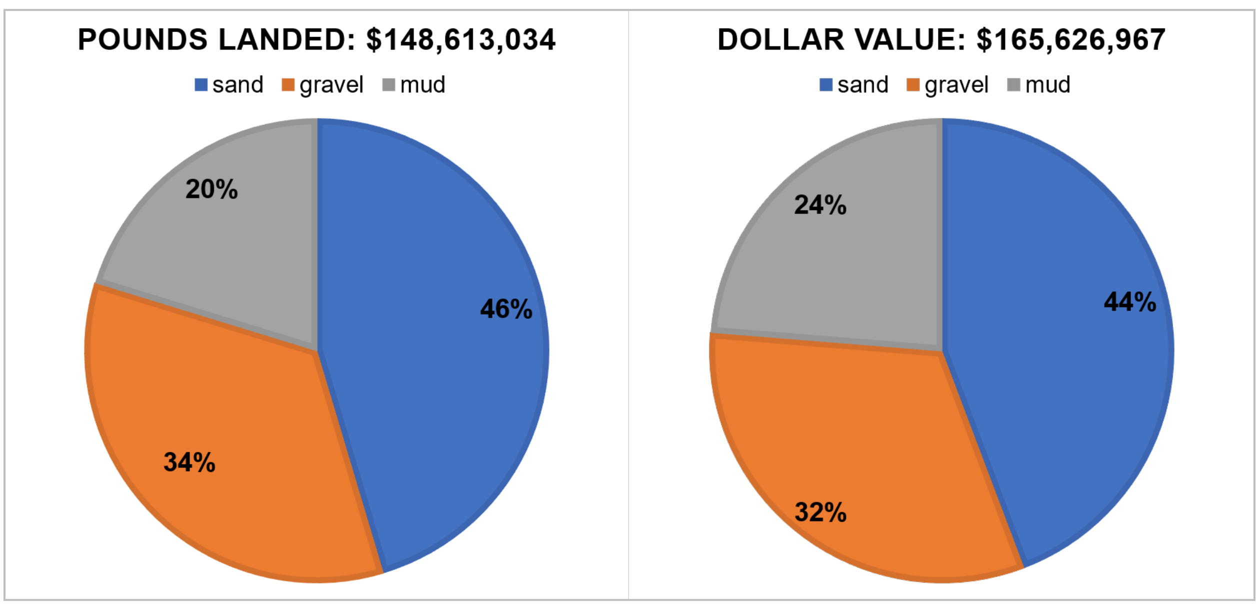


Figure 44. Aggregate commercial fisheries pounds landed and dollar value by habitat type (sand, gravel, and mud) in SBNMS for the years 2007–2016 combined

Sand habitat accounted for the most pounds landed and the greatest dollar value.

Relative to the dollar value of commercial fishery catch in SBNMS for the years 2007–2016, sand habitat provided the greatest dollar value ($73,297,830; 44%), followed by gravel ($53,032,721; 32%) and mud

($39,296,415; 24%) (Table 6; Figure 44). Since 2010, sand habitat has provided the greatest dollar value in all years (Figure 45) and in all months (Figure 46).

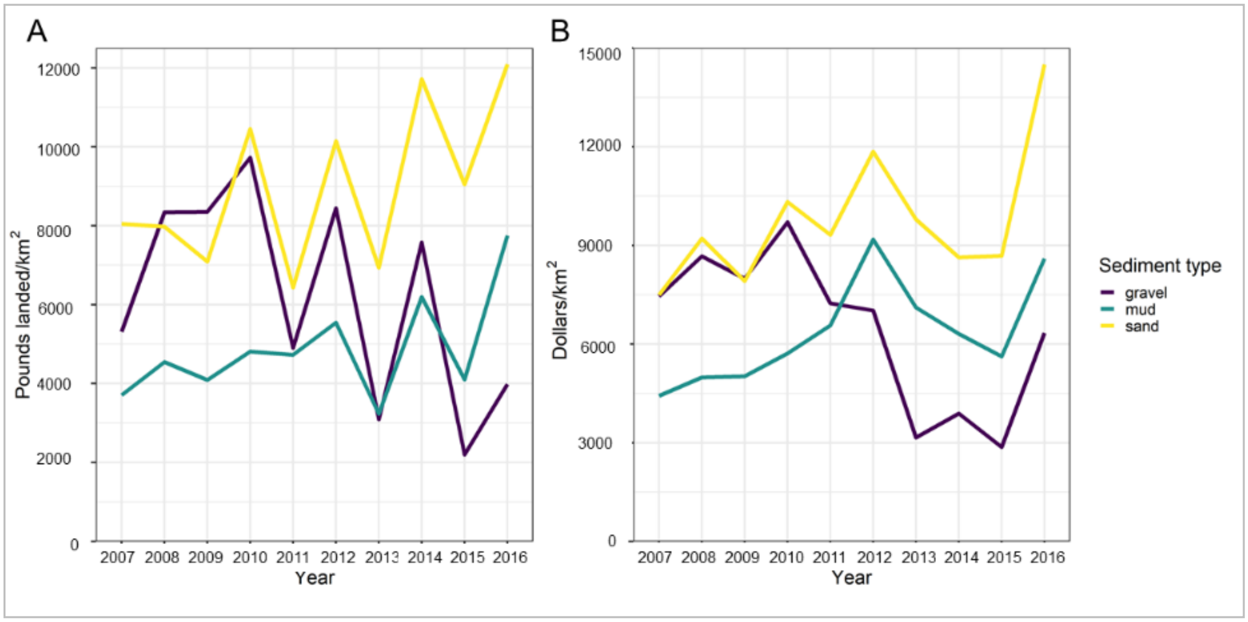


Figure 45. Pounds landed per square kilometer of sediment type (A) and dollar value per square kilometer of sediment type (B) for commercial fish species in SBNMS per year from 2007–2016

Boulder was removed from analysis because it contributed such a small fraction of pounds landed. In almost all years, sand habitat provided the greatest pounds and dollar value.

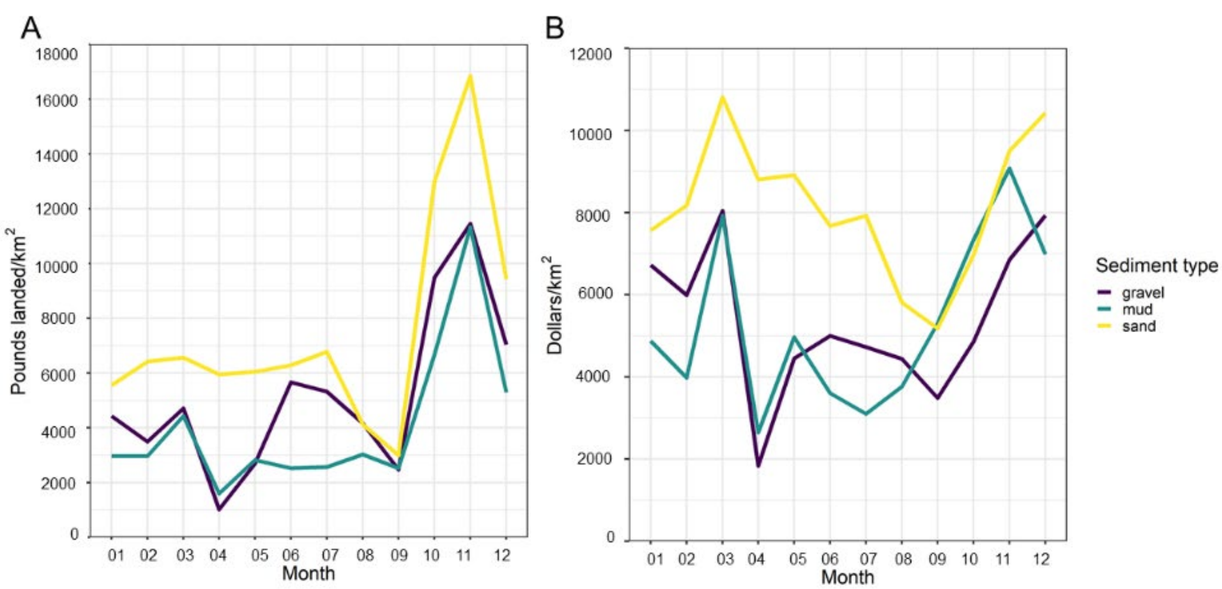


Figure 46. Pounds landed per square kilometer of sediment type (A) and dollar value per square kilometer of sediment type (B) for commercial fish species in SBNMS per month from 2007–2016

Boulder was removed from analysis because it contributed such a small fraction of pounds landed. In almost all months, sand habitat provided the greatest pounds and dollar value.

The top five species in terms of pounds landed and dollar value for the entire time period was conducted for the entire sanctuary and for each habitat type within the sanctuary. For all habitat types combined, the top five in pounds landed were Atlantic Cod, Atlantic Herring, Sea Scallops, Atlantic Mackerel, and Spiny Dogfish. The top five in dollar value were Atlantic Cod, Lobster, Sea Scallop, Yellowtail Flounder, and Haddock (Table 4). For sand habitat specifically, the top five species in pounds landed were sea scallops, Atlantic cod, Atlantic herring, Atlantic mackerel, and pollock and the top five species in dollar value were sea scallop, Atlantic cod, lobster, yellowtail flounder, and haddock (Table 6). Cod have provided the greatest dollar value (Schwarzmann and Shea 2020) and cod abundance and distribution has been directly linked to the availability of sand lance (Richardson 2014). These data provided to Boston University for use by its MIMES modeling team for the development of its decision support tool.

Table 6. Top five species in terms of pounds landed (top rows) and dollar value (bottom rows) by habitat type from 2007–2016

Sand		Gravel		Mud		SBNMS (all habitats)	
Species	Pounds landed (millions)	Species	Pounds landed (millions)	Species	Pounds landed (millions)	Species	Pounds landed (millions)
Sea Scallop	15.3	Atlantic Cod	15	Atlantic Cod	5.71	Atlantic Cod	34.8
Atlantic Cod	13.9	Atlantic Herring	10.2	Atlantic Herring	5.14	Atlantic Herring	29
Atlantic herring	13.7	Spiny Dogfish	6.71	Atlantic Mackerel	4.15	Sea Scallop	21.8
Atlantic mackerel	8.11	Pollock	5.59	Sea Scallop	3.39	Atlantic Mackerel	14.4
Pollock	3.71	Sea Scallop	3.17	Lobster	3.28	Spiny Dogfish	12
Species	Dollar value (millions)	Species	Dollar value (millions)	Species	Dollar value (millions)	Species	Dollar value (millions)
Sea scallop	22.2	Atlantic Cod	24.1	Lobster	12.7	Atlantic Cod	56.4
Atlantic cod	22.1	Lobster	8.69	Atlantic Cod	9.9	Lobster	33
Lobster	11.1	Sea Scallop	4.7	Sea Scallop	4.8	Sea Scallop	31.7
Yellowtail flounder	4.19	Pollock	3.43	Witch Flounder	2.65	Yellowtail Flounder	9.56
Haddock	2.48	Yellowtail Flounder	2.77	Yellowtail Flounder	2.56	Haddock	6.77

To document the importance of sand lance to commercial fisheries, diet information was leveraged from a study by the Northeast Fisheries Science Center. Diets of commercial fishes were documented by analyzing stomach contents of fish caught on the NEFSC bottom trawl survey from 1975–2015. Sand lance occurred in stomachs of 13 of 24 fish species sampled from Stellwagen Bank, including Atlantic Cod, Haddock, Yellowtail Flounder, Winter Skate, Thorny Skate, Spiny Dogfish, Silver Hake, Goosefish, Little Skate, Longhorn Sculpin, Pollock, Red Hake, and Sea Raven. Sand lance accounted for more than 20% of diet by mass for Atlantic Cod, Winter Skate, Little Skate, Longhorn Sculpin, and Spiny Dogfish. Sand lance accounted for ~17% and ~ 10% for yellowtail flounder and haddock, respectively, both of which, along with Atlantic cod, are within the top five species landed in sand habitat in terms of dollar value (Figure 47, Table 6).

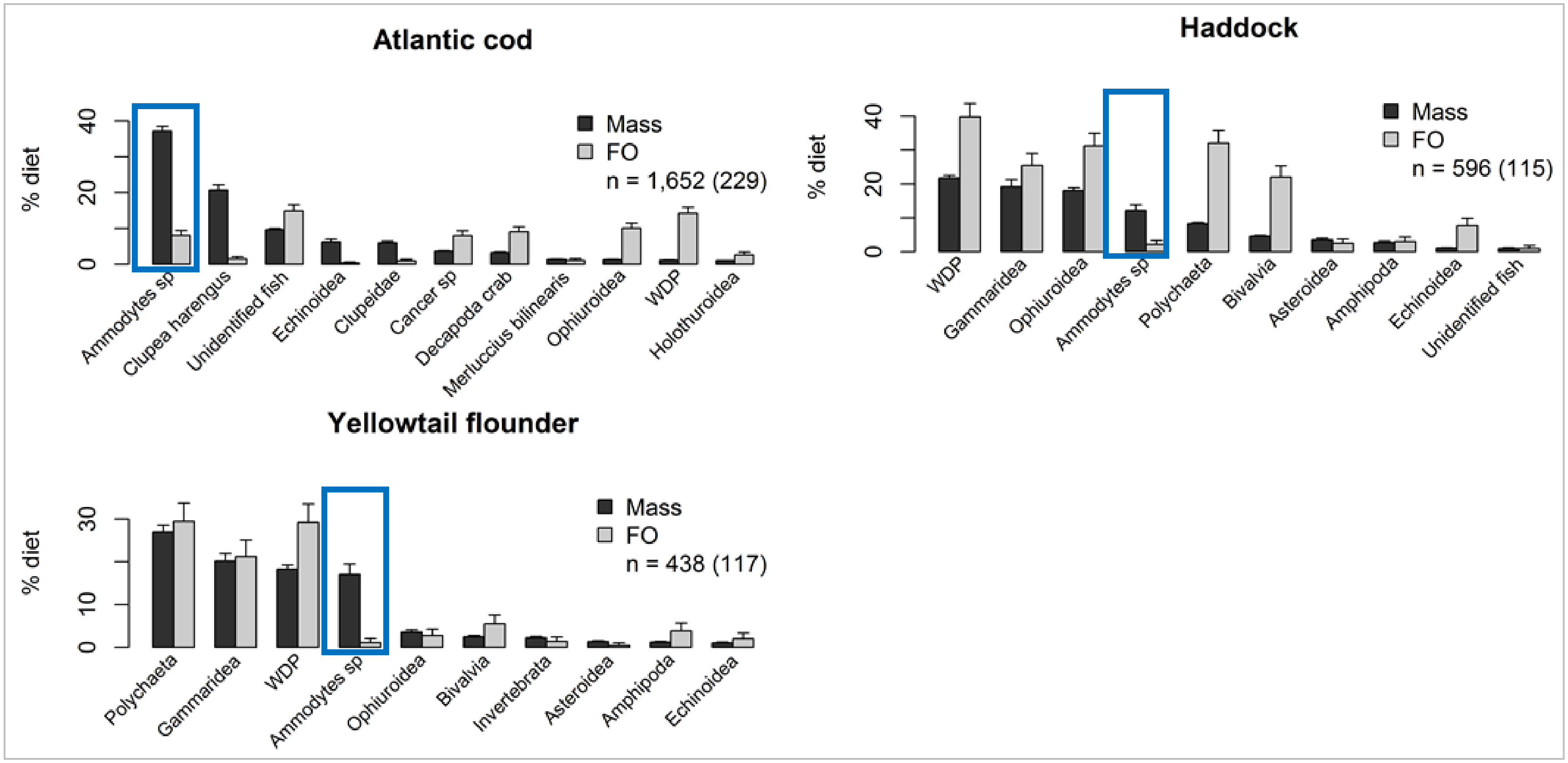


Figure 47. Diet information for species caught in SBNMS in the NEFSC trawl survey from 1975–2015

The percentage of prey species identified from stomach contents for Atlantic Cod (top), Yellowtail Flounder (center), and Haddock (bottom) are shown by %mass and frequency of occurrence (FO). All three species fall within the top five species landed in sand habitat in SBNMS by dollar value. Bars representing sand lance (*Ammodytes* sp.) are boxed in blue.

For Atlantic Cod, the percentage of sand lance in the diet by mass over decadal time scales appeared to be correlated with overall sand lance abundance, increasing from the 1970s to 1980s concurrent with an increase in sand lance abundance in the Gulf of Maine and Stellwagen Bank, decreasing in the 1990s, and increasing again in the 2000s.

In the mid-Atlantic, sand lance occurred in the diet (at least once) of 32 species, including Atlantic Cod, Silver Hake, Smooth Dogfish, Spiny Dogfish, Summer Flounder, Windowpane Flounder, Yellowtail Flounder, Atlantic Herring, and Atlantic Mackerel (Figure 48).

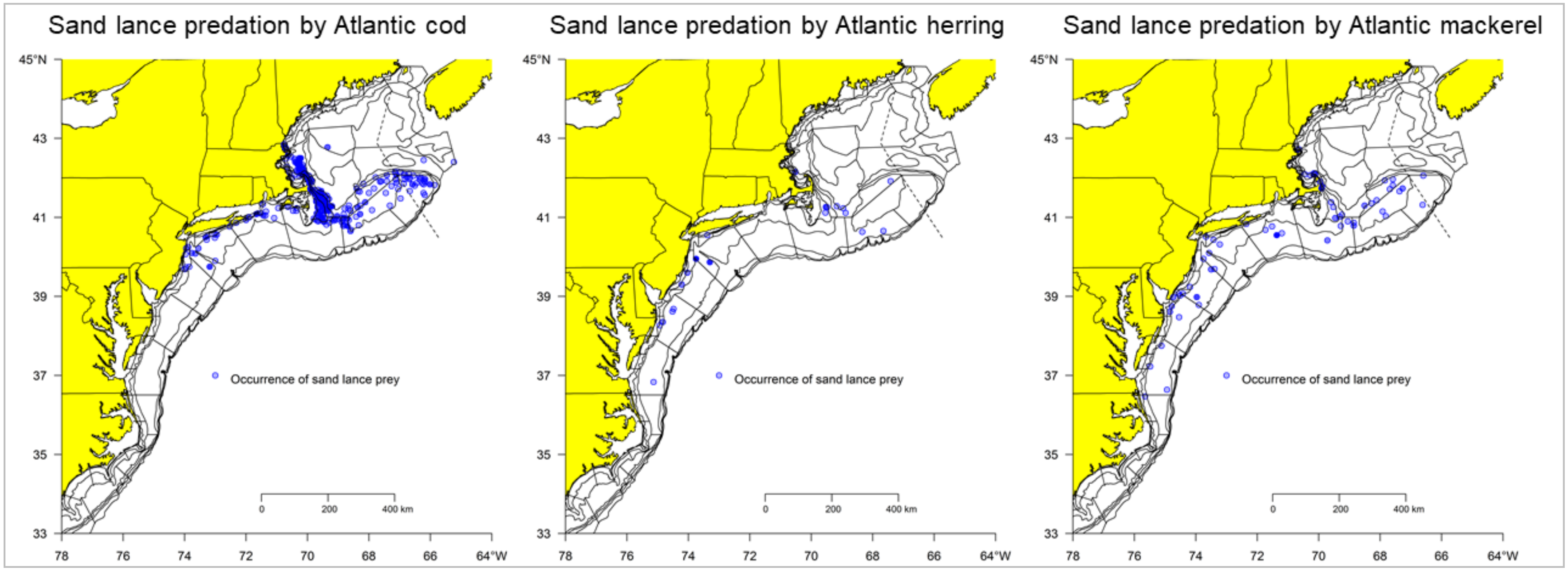


Figure 48. Occurrence of sand lance in stomach contents of Atlantic Cod (left), Atlantic Herring (center) and Atlantic Mackerel (right) across the mid-Atlantic from 1975–2015

9 Objective 8: Spatial and Behavioral Telemetry Data

Objective 8: Gather spatial and behavioral telemetry data on select species used to identify habitat use, ecosystem connectivity and site fidelity relative to sand habitat productivity.

From 2013 to 2018, we tagged 58 great shearwaters (~10/year) with Solar PTT-100 15-gram PTTs[5] to identify habitat use of an abundant and highly mobile top predator in the SBNMS and Gulf of Maine (Figure 49). Birds were tagged in the SBNMS off the Massachusetts coast or the coastal waters east of Cape Cod, MA (~41.3° to 43.0° latitude, -70.5° to -69.5° longitude). PTTs had a duty cycle of 24 hours on (i.e., continuous). Captured birds were weighed and placed in aluminum foil lined cages to collect fecal material for DNA analysis. More details can be found in Powers et al. 2017 and Powers et al. 2020 (see below). Argos locations were analyzed using Bayesian switching state-space model (Powers et al. 2017) and a Time Local Convex Hull[6] method (Powers et al. 2020) (Figure 50 and Figure 51).

Relative to food habits, fecal DNA analysis for prey items determined that, while in the Gulf of Maine, birds (n=35, 2017) foraged primarily on sand lance (Figure 54). Frequency of occurrence (FOO) of sand lance DNA in fecal samples (71.4%) was almost twice that of the next most frequent species (Atlantic menhaden [*Brevoortia tyrannus*], 48.6%) (Table 1). Relative to sand habitat, spatial occurrence of sand lance from bottom fish trawl survey data suggested these fish preferred shallow water (<100 m deep) with substrates having high sand content (>50%) of grain sizes in the range of 0.35 to 2 mm. These properties were also associated and spatially aligned with the collective hotspot range of great shearwaters (Figures 52, 53, and 55). 67% of locations containing sand lance fell within great shearwater foraging hotspots, while far fewer locations containing mackerel and herring fell within foraging hotspots (36% and 37%, respectively). These data suggest that sand lance and the sand habitats that support sand lance are key factors in shearwater habitat use (Figure 55) (see Powers et al. 2020).

Figure 49. A tagged great shearwater takes off in flight immediately after release
Photo: Steve DeNeef.

[5] Microwave Telemetry, 8835 Columbia 100 Parkway, Suites K & L, Columbia, Maryland, 21045, https://www.microwavetelemetry.com/

[6] T-LoCoH, http://tlocoh.rforge.r-project.org.

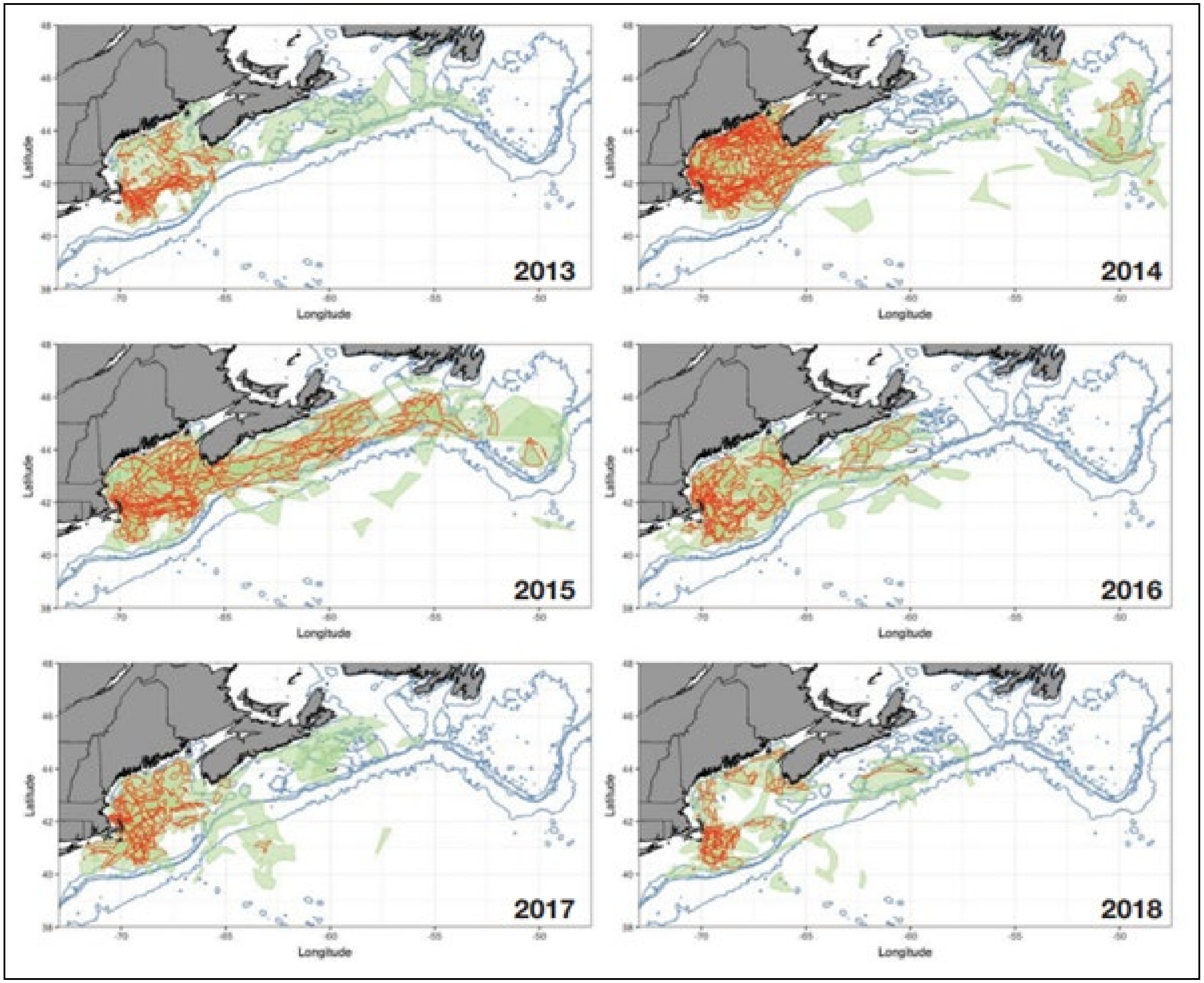


Figure 50. Plots of great shearwater 95% kernel utilization distributions (UDs) derived from convex hulls of individual birds tagged per year (2013–2018)

Individual UDs are filled in green. Red borders denote intersections of individuals within that year. In 2018, two UDs extended east of -45° longitude outside of the study area. From Powers et al. 2020.

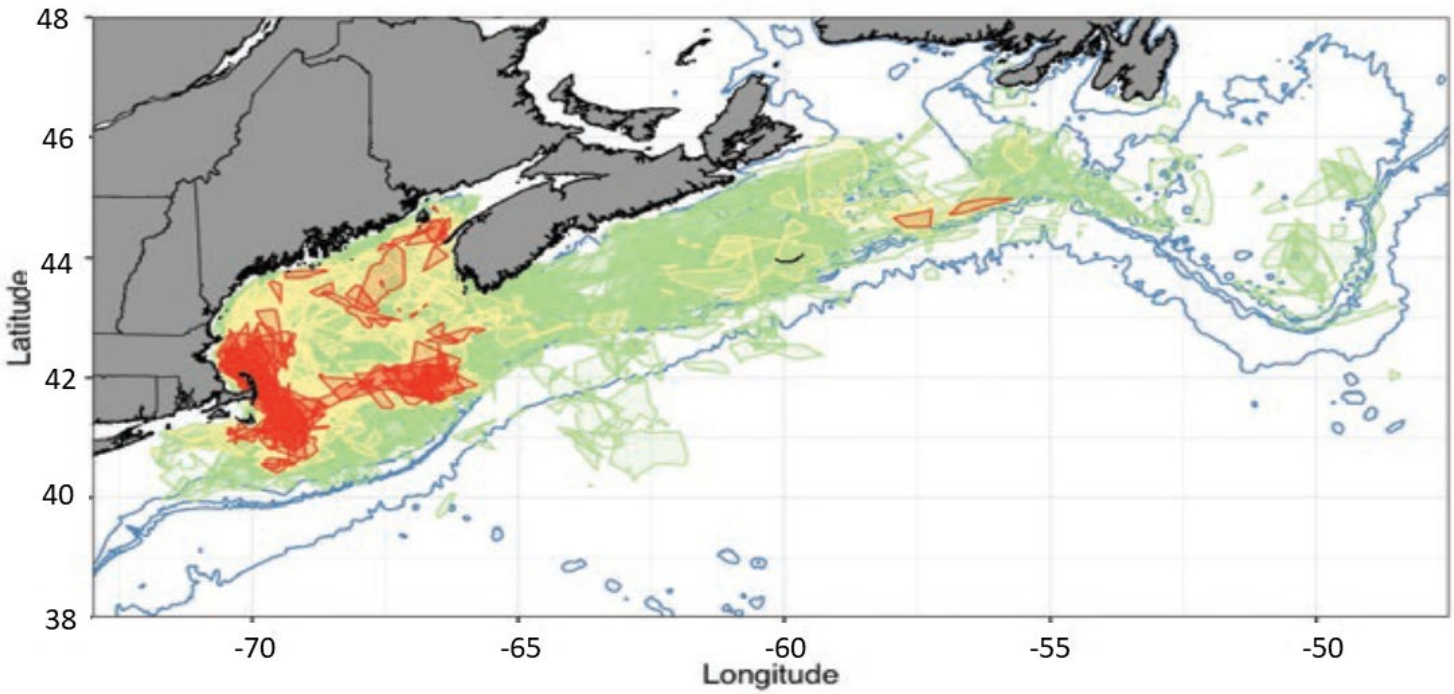


Figure 51. Aggregate plot of all individual utilization distributions of great shearwaters (n = 58) from 2013 to 2018 with kernel density groupings based on entire convex hull dataset

From Powers et al. 2020.

Figure 54. A great shearwater feasts on a sand lance
Photo: Elliot Hazen.

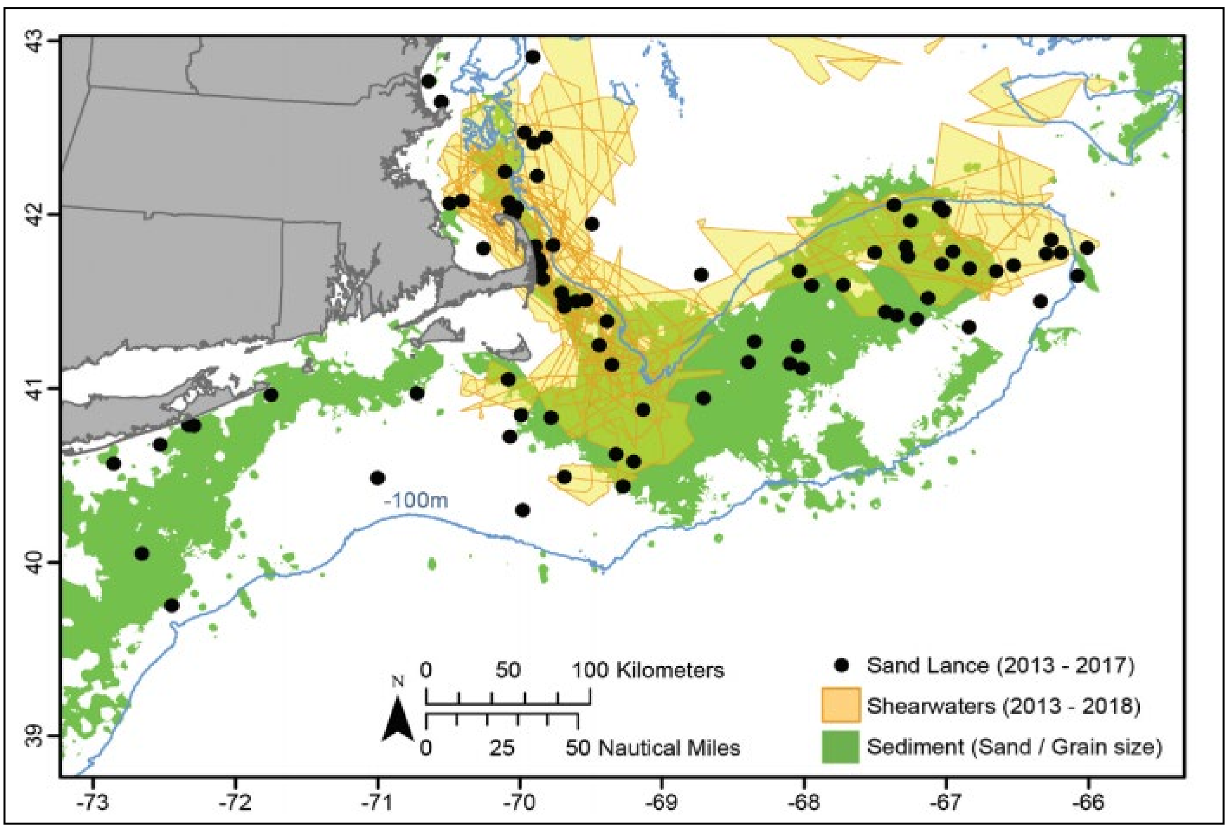


Figure 55. Plot of aggregate 25% kernel utilization distributions (UDs) of great shearwaters, sand lance trawl captures, and substrate properties common to both species in the southwestern Gulf of Maine and Georges Bank
Most sand lance (at least 64%) caught in US NOAA NMFS bottom fish trawl samples (2013–2017) occurred within the 100 m isobath over sediment with > 50% sand content and grain sizes ranging from 0.35–2.00 mm in diameter. Within the 25% kernel UD, 67% of sand lance captures occurred and 49% of shearwater hull locations intersected with these sediment properties. From Powers et al. 2020.

See Powers et al. 2020 for a full description of the methods and results; the abstract is provided below.

Abstract: Movements of Great Shearwaters Ardenna gravis wintering in the Northwest Atlantic showed age-based spatial and temporal flexibility, with foraging tactics linked to a defined physical preference of their primary prey. From 2013 to 2018, we tracked 58 Great Shearwaters during their wintering season using platform terminal transmitters deployed in the same area of the southwest Gulf of Maine. Utilization distributions (UDs) for individual birds were created from convex hulls, which were then combined for spatial and temporal analyses. Of the 95% kernel UDs, 55% were contained within the Gulf of Maine and the remainder extended to the Scotian Shelf off Nova Scotia and the Grand Banks off Newfoundland. Analysis of fecal DNA from tagged birds and others captured with them indicated that sand lance *Ammodytes dubius* were the primary prey while in the Gulf of Maine. This relationship was supported by the overlap of UDs and sand lance habitat. The spatial occurrence of sand lance from bottomfish trawl survey data demonstrated that these fish preferred shallow water (50%) and grain sizes ranging from 0.35–2.00 mm in diameter. These same properties were associated and spatially aligned with the collective 25% kernel UD of Great Shearwaters. Necropsy of bycaught Great Shearwaters from an area that overlapped in space and time with tagged individuals and sand lance habitat demonstrated that most birds (89%) were young (0–2 years), based on gonadal development, molt score, and/or bursa of Fabricius. Coupling demographic information from necropsies with spatial habits and movement timing of tagged birds suggests this region serves as a winter “nursery” for Great Shearwaters.

The results of stable isotope analysis can be found in Hong et al. 2019; the abstract is provided below.

Abstract: The great shearwater (*Ardenna gravis*) is a common pelagic bird with a distribution that spans almost the entire Atlantic basin, which in conjunction with its relatively high abundance, makes great shearwaters an effective bio indicator. We compared δ13C and δ15N values from the feathers, red blood cells (RBCs), and plasma of great shearwaters collected in 2014 and 2015 from the waters off Massachusetts and Cape Cod. The δ13C and δ15N values of RBCs were quite constant between sampling periods and years, suggesting a generally stable food web over that time period. However, the δ13C of plasma indicates a small seasonal change in diet between July and September for both years, with plasma δ15N values suggesting a slight increase in trophic level late in summer. Comparison of the δ15N of RBCs and plasma indicates that great shearwaters experienced a diet shift during the first few weeks of summer 2014, but not in 2015. Comparisons with other studies suggest that these shearwaters feed at a lower trophic level than great shearwaters sampled in the Bay of Fundy and that there is a decrease in δ13C with increasing latitude, which could indicate a more pelagic diet in northern waters. Stable isotope analysis of the sixth primary feathers provided evidence that these feathers are molted in the Northern Hemisphere and that the diet of great shearwaters shortly after arrival was different in 2014 and 2015. This study demonstrates that within species comparisons of tissue isotopic signatures over time and comparisons of isotopic signatures of tissues with different turnover rates, can detect changes in diet and be used as a tool to monitor for changes in marine food webs over time and space. The relevant signals remain informative even in the absence of species-specific data on tissue-diet discrimination factors, tissue turnover rates, or knowledge of dietary components and their stable isotopic signatures, suggesting dietary changes indicative of a corresponding change in the food web.

10 Objective 9: Outreach and Education

Objective 9: Create outreach and education products in support of the non-technical audience.

10.1 Information Video

We contracted with Jim Toomey, the creator of the highly popular *Sherman's Lagoon* comic strip, to create an informational video on the importance of sand habitat and sand lance forage fish, and the collaboration between BOEM and SBNMS to produce high quality data for decisions about dredging sand and its associated habitat. Because no mining or leasing activities are permitted in the Sanctuary, it is an ideal living laboratory to better understand sand lance populations and seafloor ecology. The video van be viewed at the website listed below.[7]

10.2 @trackseabirds Twitter Account

A Twitter account (@trackseabirds) (Figure 56) was developed to keep the public aware of the project and associated seabird information. Over 1,030 people are following the account as of 4/4/2022.

Figure 56. Screenshot of @trackseabirds Twitter account on 12/14/2021

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[7] See the website https://www.boem.gov/marine-minerals/marine-mineral-research-studies/studying-sand-lance

10.3 Public Schools

A free, outreach program allowing teachers to plot great shearwater movements based on PTT-derived data on specially designed charts (Figure 57) was created and piloted at five middle schools reaching approximately 350 students in grades 5 through 8. The program was presented at the 43rd Annual Meeting and Conference of Massachusetts Marine Educators in Woods Hole, Massachusetts (May 4, 2019). Teachers were able to request the unit, charts, and location data for plotting bird movements and learning about sand habitats. The project supports STEM goals in education.

Figure 57. A middle school student plots PTT-derived great shearwater location data on a laminated, reusable Gulf of Maine chart

Discussions focused on seabird movement, migration and habitat needs, including sand lance and sand habitat. The project supported STEM goals in education.

10.4 Naming Tagged Great Shearwaters

In 2018, satellite tagged great shearwaters were named for Cape Cod middle schools. Schools and other schools, were provided with free STEM-focused presentations (see above). In 2019, satellite tagged great shearwaters were named for Massachusetts Audubon Centers. Centers were given weekly updates on their birds' travels, which they posted on their websites. A free presentation about the project was also given to the sites.

In 2021, during Black Birder's Week, in partnership with the BlackAFinSTEM Collective, shearwater names were selected.[8]. The names ranged from witty puns to names recognizing Black leaders in aviation, science, and environmental education. The names were announced during a BlackAFinSTEM Facebook Live presentation. Names included Shearlock Holmes; Britney Shears; Shearly Temple; Sheari/Shuri (a character in the film "Black Panther"); and more.

[8] See https://www.blackafinstem.com/

Name	Recognition
Bessie	Bessie Coleman, the first Black woman and Native American woman to hold a pilot's license.
Jemison	Mae Carol Jemison, an engineer, physician, and former NASA astronaut who became the first Black woman to travel into space when she served as a mission specialist aboard the Space Shuttle Endeavour.
Ashanti	Ashanti Johnson, one of the first Black chemical oceanographers and recipient of the 2010 Presidential Award for Excellence in Science, Mathematics, and Engineering.
Arliner	Roger Arliner Young, the first African American woman to receive a PhD in Zoology and who worked on marine invertebrates at the Marine Biological Laboratory [MBL] on Cape Cod.
EE Just	Ernest Everett Just, a marine biologist and pioneer in studies of embryonic development in marine invertebrates at MBL, and a founder of Omega Psi Phi at Howard University.
Dioum	Baba Dioum, a Senegalese forestry engineer, whose statement "In the end, we will conserve only what we love, we will love only what we understand, and we will understand only what we are taught" is widely quoted.
Tuskegee	In honor of the Black World War II fighter pilots.
Naomi and Bonstance	Two names liked by the team, associated with beauty and grace.

10.5 2020 World Seabird Twitter Conference

A presentation featuring our STEM education program was made at the 2020 World Seabird Twitter Conference (Figure 58). The conference was entirely virtual on Twitter and international in scale and included over 180 presentations across 17 different time zones with thousands of participants viewing and interacting with content. Our presentation alone had over 7000 views on Twitter.

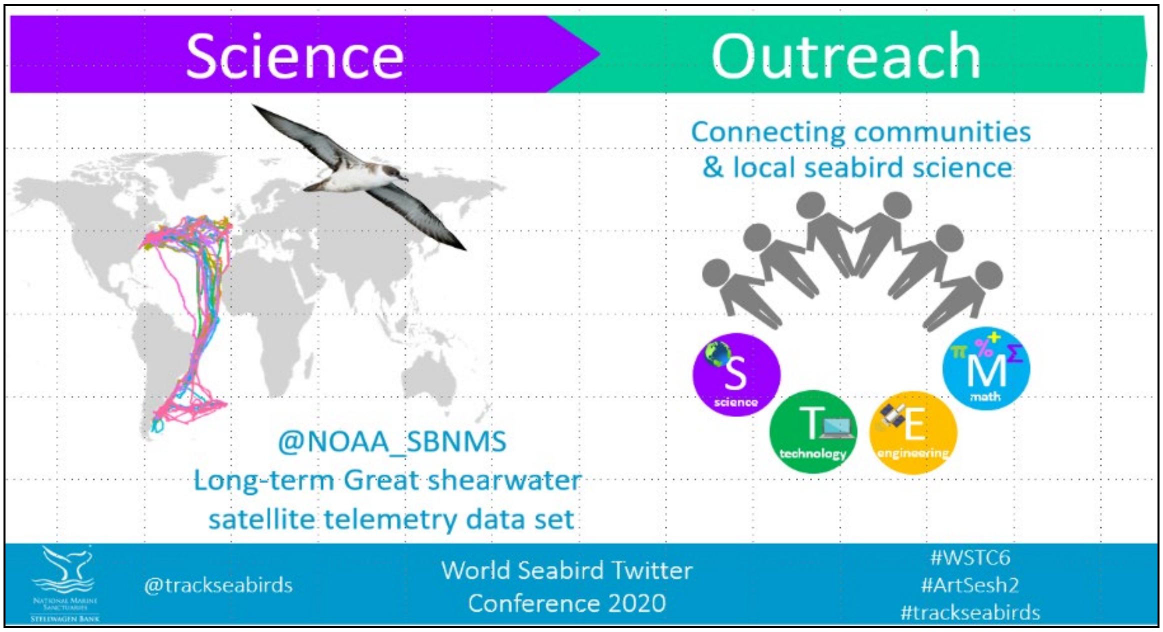

Figure 58. A presentation describing our BOEM-supported, STEM-focused education program was made at the 2020 World Seabird Twitter Conference

See https://www.seabirds.net/events/wstc/

10.6 Open CTD

Blackbeard Biologics conducted a three-day education session at the SBNMS that helped participants build open-source CTDs for biological sampling and classroom use (Figure 59). This workshop served as an introduction to the Open CTD to support the citizen science project with whale watching companies to monitor environmental conditions in SBNMS (see 10.7).

Figure 59. Build Your Own CTD session

Participants built their own open-source CTD at a three-day education session held at the SBNMS and conducted by Blackbeard Biologics.

10.7 Citizen Science

Andrew Thayler of Blackbeard Biologics conducted a virtual presentation for the Gulf of Maine Naturalists workshop. The talk focused on how to use OpenCTD: creating a low-cost, open-source oceanographic instrument for everyone. Mr. Thayler produced ten OpenCTDs units to be provided to naturalists for deployment during whale watching or other excursion types. This is part of the project's Citizen Science initiative. In 2020, COVID-19 restrictions cancelled excursions. But in 2021, six whale-watching companies participated , including participants in Maine, Massachusetts, and New York. A virtual orientation and training was provided to all participating naturalists (Figure 60). A total of 38 OpenCTD deployments were conducted by whale-watching companies throughout the 2021 season. Technical issues with the instrument and data logging resulted in 15 deployments from four companies with useable data (Figure 61). This first year of the project provided invaluable feedback on instrument design and will inform a complete instrument upgrade for next year. "Measuring the Ocean with OpenCTD & Professional Naturalists" is an ArcGIS® StoryMap featuring the project and the data collected can be found at the URL below[9]. See also the figures below.

Figure 60. Whale-watching naturalists attended the virtual Open CTD training with their instruments
Photo: Tammy Silva

[9] Visit https://storymaps.arcgis.com/stories/ef90c68de96b42a884cd36919dec508c

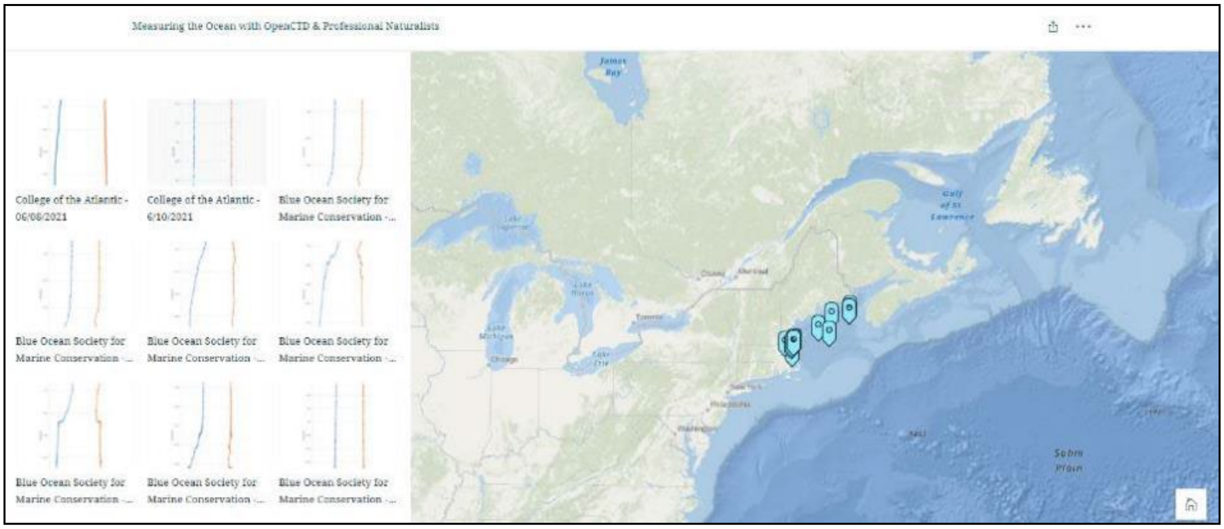

Figure 61. Data visualization of OpenCTD deployments in the Citizen Science program available as part of the StoryMap

The map on the right shows the location of all CTD deployments. Temperature and Salinity data collected during each deployment in visualized on the left and is linked with location in the StoryMap. A total of 38 deployments were conducted during this trial year of the program, resulting in 15 deployments (due to equipment issues) with useable data.

10.8 Video and Photography

Steve. DeNeef were cancelled due to COVID-19 restrictions. S. DeNeef joined the project in 2019 and 2021 and filmed surveys and sampling of sand lance on both SEABOSS and trawl trips as well as capturing, sampling, and tagging of great shearwaters. Photographs are available to BOEM.

10.9 Infographics

We summarized the major highlights of our study into two infographics for this report. The first describes the value of sand habitat from ecological and economic perspectives (Figure 62). The second describes the risk associated with disruption to sand habitat in each month of the year and highlights the occurrence of important ecological and economic activities (Figure 63).

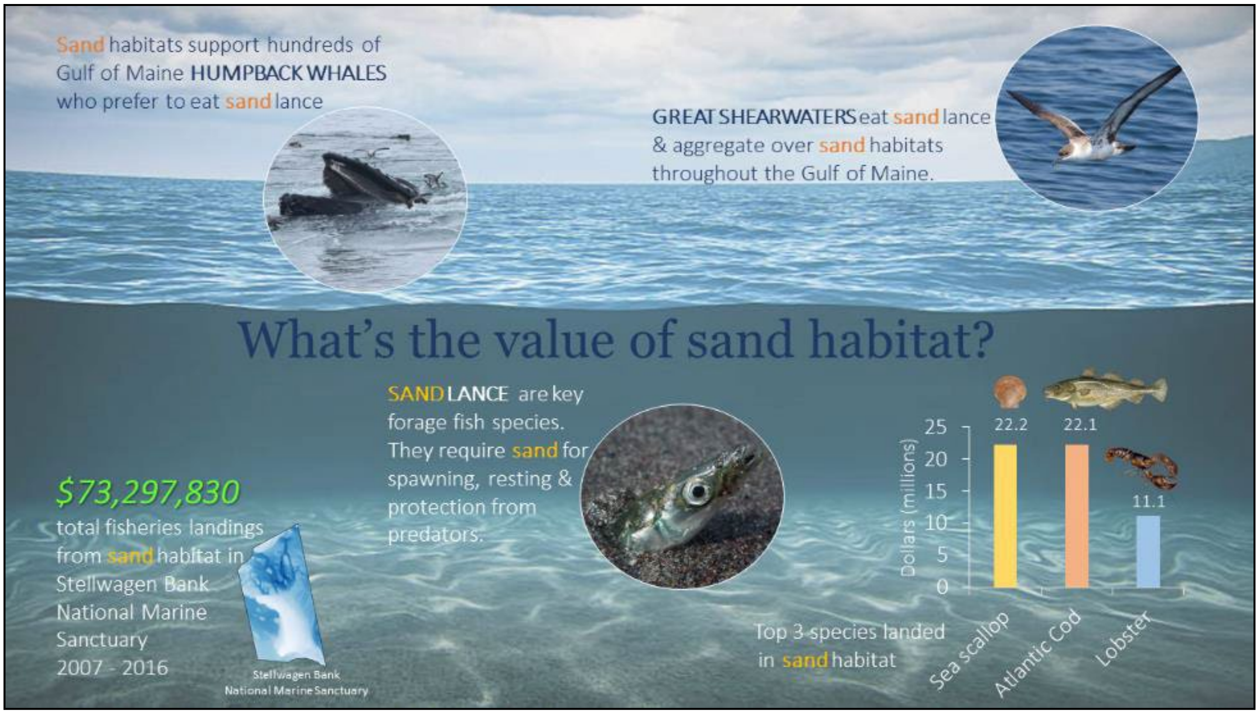

Figure 62. Infographic describing the value of sand habitat for the public

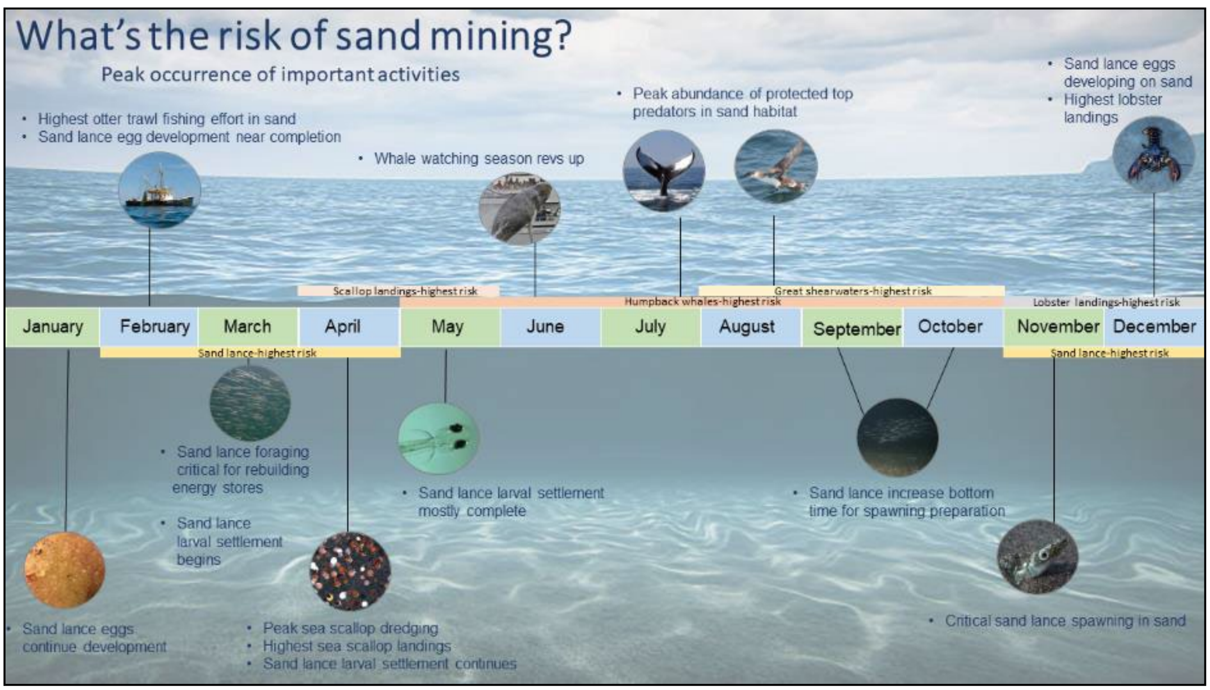

Figure 63. Infographic describing the risk associated with sand extraction throughout the year

11 Summary

Sand habitat plays critical ecological and economic roles; it supports the sand-dependent sand lance forage fish through all critical life history stages, and it turn provides prey and habitat for whales, seabirds, and commercial fishes, driving ecosystem services from fishing to whale watching and supporting coastal economies. Sand dredging operations should consider the ecological and economic tradeoffs related to both sand lance life history and ecosystem services identified here at monthly and annual scales. Potential areas of future work include: the ability of sand lance to adapt to climate change, impacts of physical disturbance to sand lance, and a similar study addressing the ecology of the coastal species, the American sand lance (*Ammodytes americanus*), whose range includes intertidal habitats is more likely to be impacted by sand dredging operations

12 References

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Appendix A: Full Vulnerability Matrices

A.1 Sand Land Life History Vulnerability Matrices

Table A-1. Sand lance spawning vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0	0	0	0	0	0	0	0	0	4	5	4

Source data: SBNMS / BOEM

Rationale: Spawning takes place during a short time window (few days) in mid-late November that is likely driven by water temperature. Climate change driven variability in bottom temperature could lead to earlier or later spawning periods encompassing October or December.

Rank calculation notes: Ranks based on data and observations during research cruises—not developed quantitatively / systematically.

Table A-2. Sand lance daily bottom time vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
3	3	3	3	3	3	4	5	5	5	5	4

Source data: SBNMS / BOEM

Rationale: Daily bottom time reflects several aspects of sand lance behavior including daily bottom use and aestivation. Sand lance spend time on / in the bottom for some period each day (nighttime and some daytime hours) - there is no 24 hour period where they do not use the bottom. During estivation (Aug-Nov), sand lance are on or in the bottom preparing to spawn and not using the water column to feed, which increases daily bottom time during these months.

Rank calculation notes: Ranks are scaled (not quantitatively / systematically) by how much time fish spend in / near sand in a 24-hour period.

Table A-3. Sand lance settlement vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0	4	5	5	4	3	0	0	0	0	0	0

Source data: SBNMS / BOEM

Rationale: Settlement refers to the transition from larval lifestyle in the water column to an adult-like lifestyle using the benthic and pelagic environments, which happens after an average of 68 days as a larval fish.

Rank calculation notes: Ranks based on otolith data and observations during research cruises—not developed quantitatively / systematically

Table A-4. Sand lance eggs vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
5	3	3	2	0	0	0	0	0	0	5	5

Source data: SBNMS / BOEM

Rationale: Eggs are deposited on the bottom in November and develop over several months. Temperature can influence all stages of development - colder bottom temperatures may prolong egg development and delay hatching.

Rank calculation notes: Ranks based on lab rearing studies and observations of larval sand lance during research cruises—not developed quantitatively / systematically

Table A-5. Sand lance foraging vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
4	5	5	5	4	3	3	1	1	1	2	3

Source data: SBNMS / BOEM

Rationale: Sand lance stomach contents show high feeding incidence from Feb - May, with highest rates in Feb - April, before tapering off before estivation Aug - October. Feeding begins again immediately after spawning in mid-November.

Rank calculation notes: Ranks based on stomach content analysis—not developed quantitatively / systematically.

Table A-6. Sand lance starvation (lipids) vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
5	5	5	4	3	2	1	1	1	1	5	5

Source data: SBNMS / BOEM

Rationale: Impacts to sand lance lipid accumulation were separated into impacts on survivorship and impacts to reproductive success (next row), based on seasonal behavioral changes. Sand lance put all energy into gonad development and stop feeding in August. After spawning in Nov, they have little lipid reserves and are just starting to ramp up foraging again. Disturbance (dredging) may result in stress and avoidance responses from sand lance leading to increased metabolic activity. Disturbance from Nov - March before sand lance have accumulated enough lipids may result in low resilience to stress and increased mortality.

Rank calculation notes: Ranks based on stomach content and lipid analysis—not developed quantitatively / systematically.

Table A-7. Sand lance vulnerability totals

Activity	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Rank calculation notes
TOTAL SL SUM VULNERABILITY	19.0	24.0	26.0	24.0	19.0	16.0	12.0	8.0	8.0	12.0	23.0	23.0	Total sand lance sum vulnerability was calculated by summing all ranks for each month
TOTAL SL VULNERABILITY RANK	M	H	H	H	M	M	L	L	L	L	H	H	Total sl vulnerability rankings were designated by summing all ranks for each month and assigning each month a rank based on the following equal size classes (created using the minimum (0) and maximum (35) possible sums: VL = 0-7; L = 7.1-14, M = 14.1-21, H = 21.1-27, VH = 27.1-35
TOTAL VH RANKS	2	2	4	3	1	1	0	1	1	1	4	2	Total Very High (VH) ranks is another way to think about risk. The summed total ranks above provide one objective way to look at risk, but by summing all values, the risk an activity presents may appear lessened if there are many other low risk activities occurring in that month. However, if a month has even one Very High-risk activity, this is an important consideration as sand lance would still be vulnerable. We present this alternative way to summarize vulnerability, Total VH Ranks, as the number of activities rated as Very High (VH) risk in each month.

A.2 Ecosystems Services Vulnerability Matrices

Table A-8. Humpback vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	1	1	3	4	4	5	4	4	4	3	1

Source data: Center for Coastal Studies

Rationale: Ranks were determined quantitatively based on data.

Rank calculation notes: Ranks based on stomach content analysis—not developed quantitatively / systematically. Ranks were assigned by calculating range of data, dividing range into 5 equal categories, assigning data to 1 of 5 categories based on its value.

Table A-9. Great shearwater vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0	0	0	0	1	2	3	5	5	5	1	0

Source data: SBNMS

Rationale: Ranks were determined using satellite telemetry data and historical sightings knowledge. Ranks for July–November based on the number of days satellite tagged shearwaters were located in SBNMS in that month and were determined quantitatively. Rank for July is likely an underestimate because tagging occurs in July. Ranks for Dec–June determined based on historical sighting knowledge. Birds migrate south in winter and start returning to GOM towards the end of May and into June. Rankings for May and June reflect the increase in birds during this time (early summer).

Rank calculation notes: Ranks for July–November were assigned using satellite telemetry data and by calculating range of data, dividing range into 5 equal categories, assigning data to 1 of 5 categories based on its value.

Table A-10. Whale watching trip vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0	0	0	3	3	4	5	5	4	3	0	0

Source data: ONMS WW company surveys

Rationale: Ranks were determined based on survey data from 2 whale watch companies where trip effort per month was either described: qualitatively either by ranking (0 trips, light, medium, busiest) or based on percentage of trips that occur in that month. No raw data (number of trips per month) was available to determine a quantitative ranking.

Rank calculation notes: Ranks were determined by ranking 'busiest' months as the most vulnerable (5), medium months as (4), light month as (3) and months with no trips as 0.

Table A-11. Cod spawning vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
4	0	0	4	5	5	4	0	0	4	5	5

Source data: Primary literature

Rationale: Rankings based on data from Zemeckis et al 2019 ICES J Mar Sci. Passive acoustic monitoring of cod grunts (reproductive vocalization) suggests peak spawning activity from early Nov - January with a peak in mid-December. Satellite tagging data shows presence of cod on spring spawning grounds from April–July (Zemeckis et al 2017 ICES J Mar Sci). Rankings based on summary in Dean et al 2019 ICES J Mar Sci.

Rank calculation notes: Rankings based on primary literature documenting peak winter spawning in Nov–Dec with some in Oct and Jan and peak spring spawning of cod in May–June with some in April and July.

Table A-12. Cod landings vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
5	4	5	1	2	5	4	3	3	2	3	5

Source data: VTR 2007–2016

Rationale: Ranks were determined quantitatively based on data.

Rank calculation notes: Ranks were assigned by calculating range of data, dividing range into 5 equal categories, assigning data to 1 of 5 categories based on its value.

Table A-13. Scallop landings vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	2	2	5	4	2	2	1	1	1	1	1

Source data: VTR 2007–2016

Rationale: Ranks were determined quantitatively based on data.

Rank calculation notes: Ranks were assigned by calculating range of data, dividing range into 5 equal categories, assigning data to 1 of 5 categories based on its value.

Table A-14. Lobster landings vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2	1	1	1	1	1	2	2	3	4	5	5

Source data: VTR 2007–2016

Rationale: Ranks were determined quantitatively based on data.

Rank calculation notes: Ranks were assigned by calculating range of data, dividing range into 5 equal categories, assigning data to 1 of 5 categories based on its value.

Table A-15. Trap pot fishery trips vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2	1	1	1	2	2	3	3	4	5	5	4

Source data: VTR 2007–2016

Rationale: Ranks were determined quantitatively based on data.

Rank calculation notes: Ranks were assigned by calculating range of data, dividing range into 5 equal categories, assigning data to 1 of 5 categories based on its value.

Table A-16. Gillnet fishery trips vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
4	4	5	1	2	5	5	4	4	3	3	5

Source data: VTR 2007–2016

Rationale: Ranks were determined quantitatively based on data.

Rank calculation notes: Ranks were assigned by calculating range of data, dividing range into 5 equal categories, assigning data to 1 of 5 categories based on its value.

Table A-17. Scallop dredge fishery trips vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	2	3	5	5	4	4	2	1	1	1	1

Source data: VTR 2007–2016

Rationale: Ranks were determined quantitatively based on data.

Rank calculation notes: Ranks were assigned by calculating range of data, dividing range into 5 equal categories, assigning data to 1 of 5 categories based on its value.

Table A-18. Bottom longline fishery trips vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
4	4	5	1	2	1	1	1	1	1	1	2

Source data: VTR 2007–2016

Rationale: Ranks were determined quantitatively based on data.

Rank calculation notes: Ranks were assigned by calculating range of data, dividing range into 5 equal categories, assigning data to 1 of 5 categories based on its value.

Table A-19. Otter trawl fishery trips vulnerability matrix

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
5	5	5	1	2	5	4	3	2	2	3	5

Source data: VTR 2007–2016

Rationale: Ranks were determined quantitatively based on data. These numbers represent vulnerability of otter trawl effort in terms of number of unique trips per month (docid in VTR data).

Rank calculation notes: Ranks were assigned by calculating range of data, dividing range into 5 equal categories, assigning data to 1 of 5 categories based on its value.

Table A-20. Ecosystem vulnerability totals

Activity	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Rank calculation notes
TOTAL ECOSYSTEM SUM VULNERABILIY	29.0	24.0	28.0	26.0	33.0	40.0	42.0	33.0	32.0	35.0	31.0	34.0	Total ecosystem sum vulnerability was calculated by summing all ranks for each monh
TOTAL ECOSYSTEM VULNERABILITY RANK	M	L	M	M	M	H	H	M	M	M	M	M	Total ecosystem vulnerability rankings were designated by summing all ranks for each month and assigning each month a rank based on the following equal size classes (created using the minimum (0) and maxiumum (60) possible sums: VL = 0-12; L = 12.1-24, M = 24.1-36, H = 36.1-48, VH = 48.1-60.
TOTAL VH RANKS	2	1	4	2	2	4	3	2	2	2	3	5	Total Very High (VH) ranks is another way to think about risk. The summed total ranks above provide one objective way to look at risk, but by summing all values, the risk an activity presents may appear lessened if there are many other low risk activities occuring in that month. However, if a month has even one Very High risk activity, this is an important consideration asthe ecosystem would still be vulnerable. We present this alternative way to sumarize vulnerability, Total VH Ranks, as the number of activities rated as Very High (VH) risk in each month.

Table A-21. Overall vulnerability matrix—sand lance life history matrix and ecosystem services matrix combined

Activity	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Rank calculation notes
OVERALL VULNERABILITY SUM	48.0	48.0	54.0	50.0	52.0	56.0	54.0	41.0	40.0	47.0	54.0	57.0	SL + ECOSYSTEM COMBINED SUM was calculated by summing the summed vulnerability ranks for the SL table and the ECOSYSTEM table
OVERALL VULNERABILITY RANK	M	M	M	M	M	M	M	M	M	M	M	M	Total sl + ecosystem vulnerability rankings were designated by summing the total sl sum vulnerability and total ecosystem sun vulnerability for each month and assigning each month a rank based on the following equal size classes (created using the minimum (0) and maxiumum (95) possible sums: VL = 0-19; L = 19.1-38, M = 38.1-57, H = 57.1-76, VH = 76.1-95.
TOTAL VH RANKS	4	3	8	5	3	5	3	3	3	3	7	7	Total Very High (VH) ranks is another way to think about risk. The summed total ranks above provide one objective way to look at risk, but by summing all values, the risk an activity presents may appear lessened if there are many other low risk activities occuring in that month. However, if a month has even one Very High risk activity, this is an important consideration as the entire ecosystem would still be vulnerable. We present this alternative way to sumarize vulnerability, Total VH Ranks, as the number of activities rated as Very High (VH) risk in each month which was created by summing the total VH ranks for the sl and ecosystem tables.

Appendix B: Catch Data Summaries for Commercial Fish Species 2007–2016 in SBNMS from VTR Data

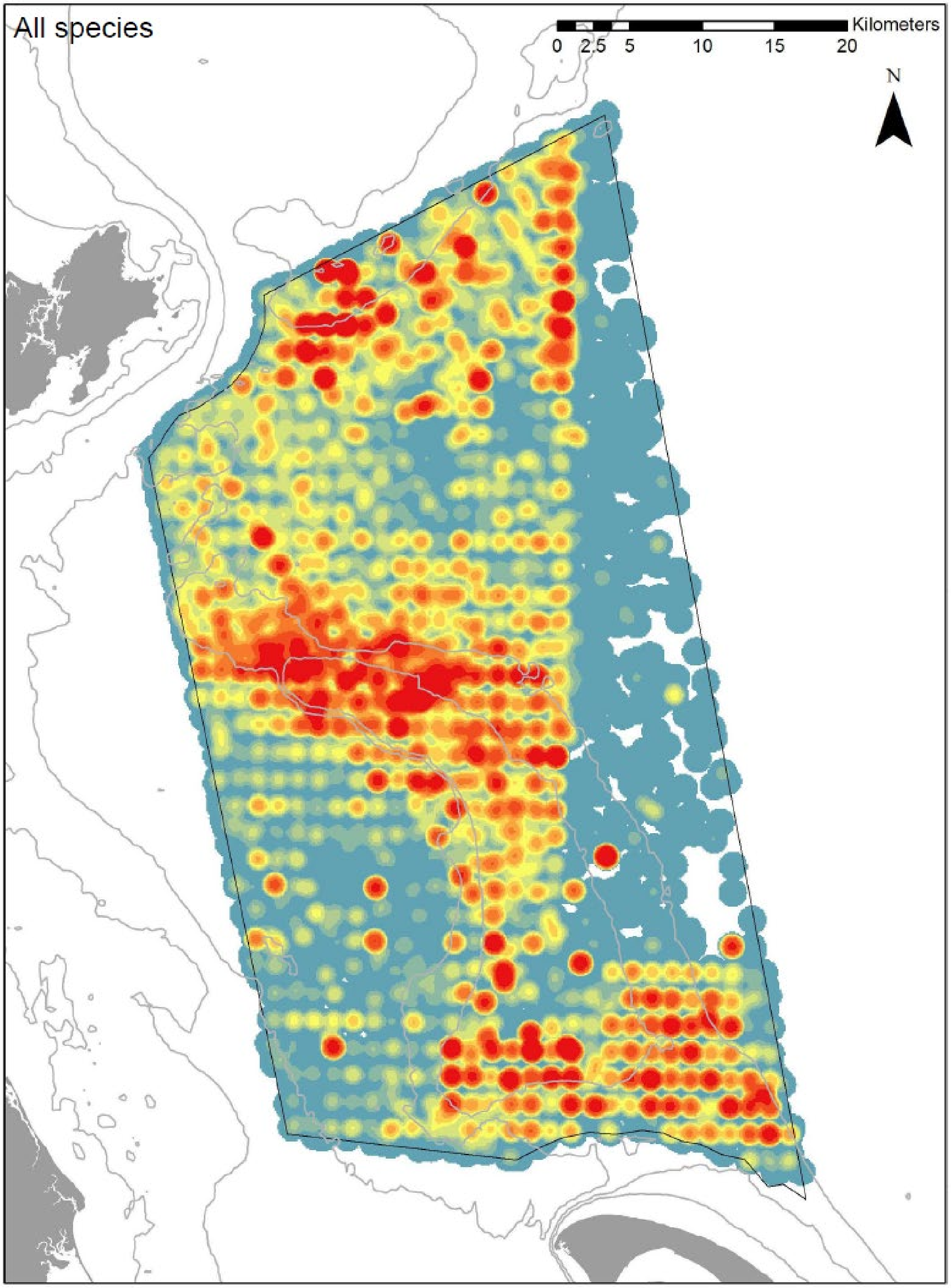

Figure B-1. Catch data summaries for all commercial fish species 2007–2016 in SBNMS from VTR data

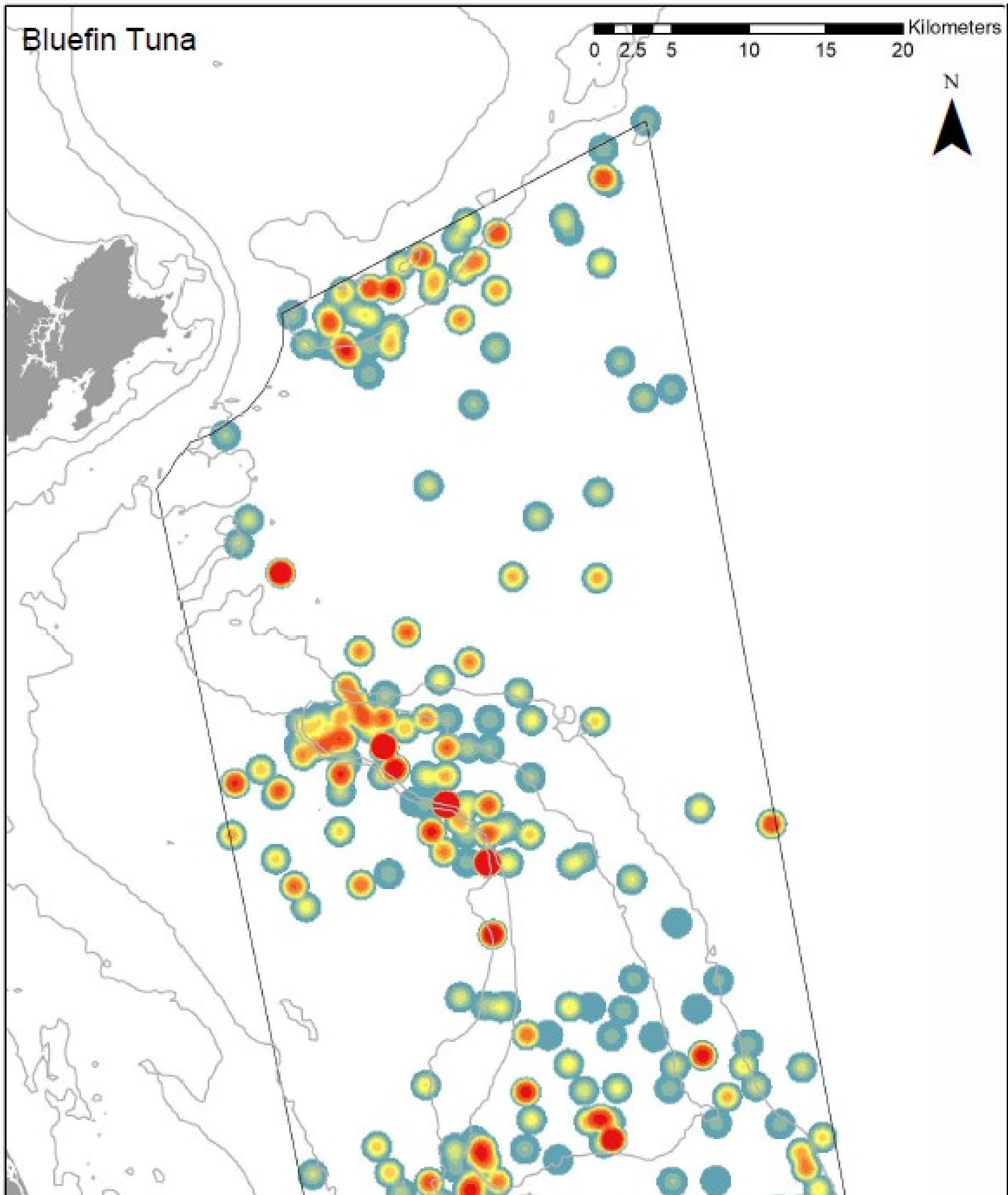

Figure B-2. Catch data summaries for bluefin tuna 2007–2016 in SBNMS from VTR data

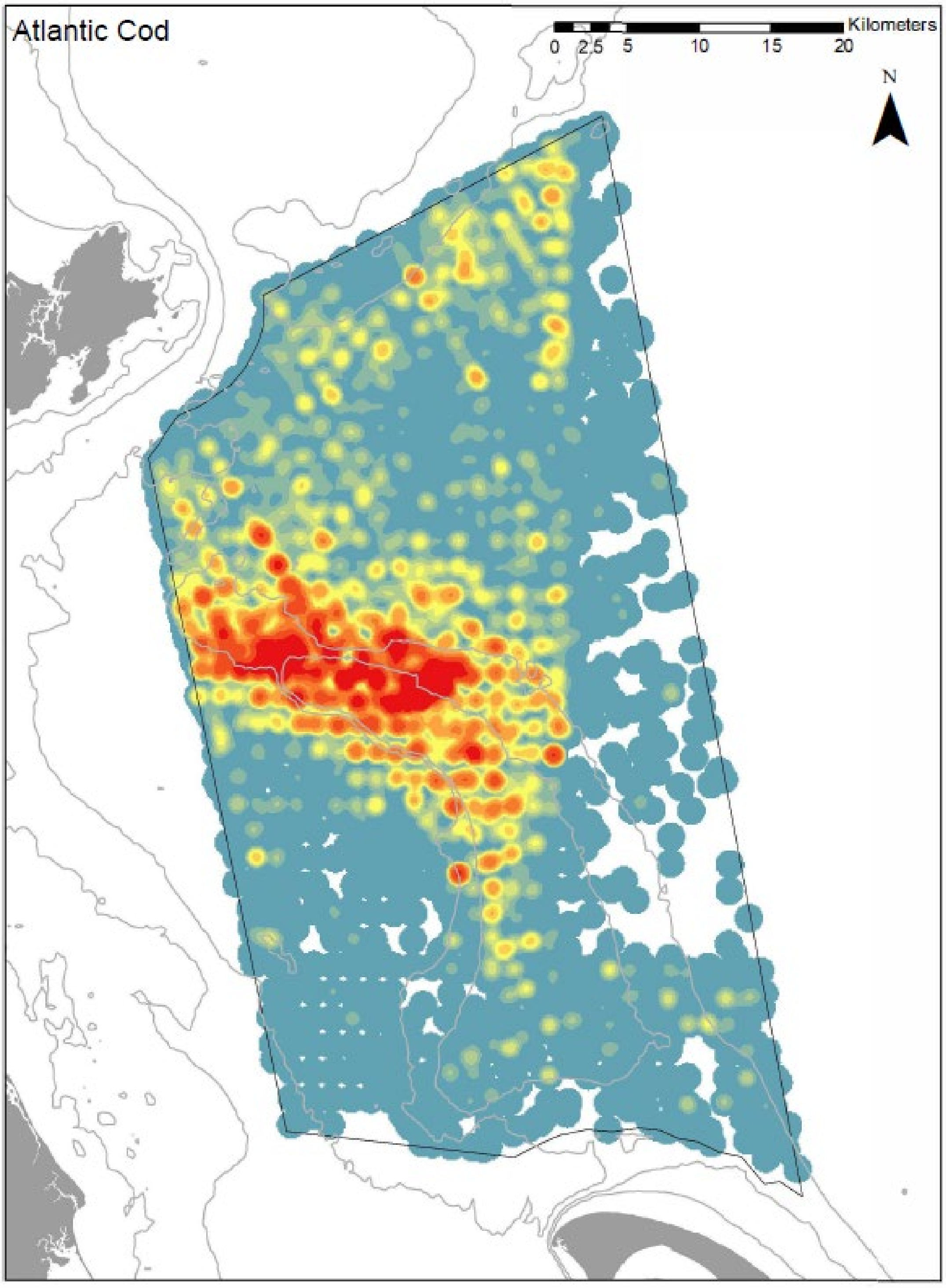

Figure B-3. Catch data summaries for Atlantic cod 2007–2016 in SBNMS from VTR data

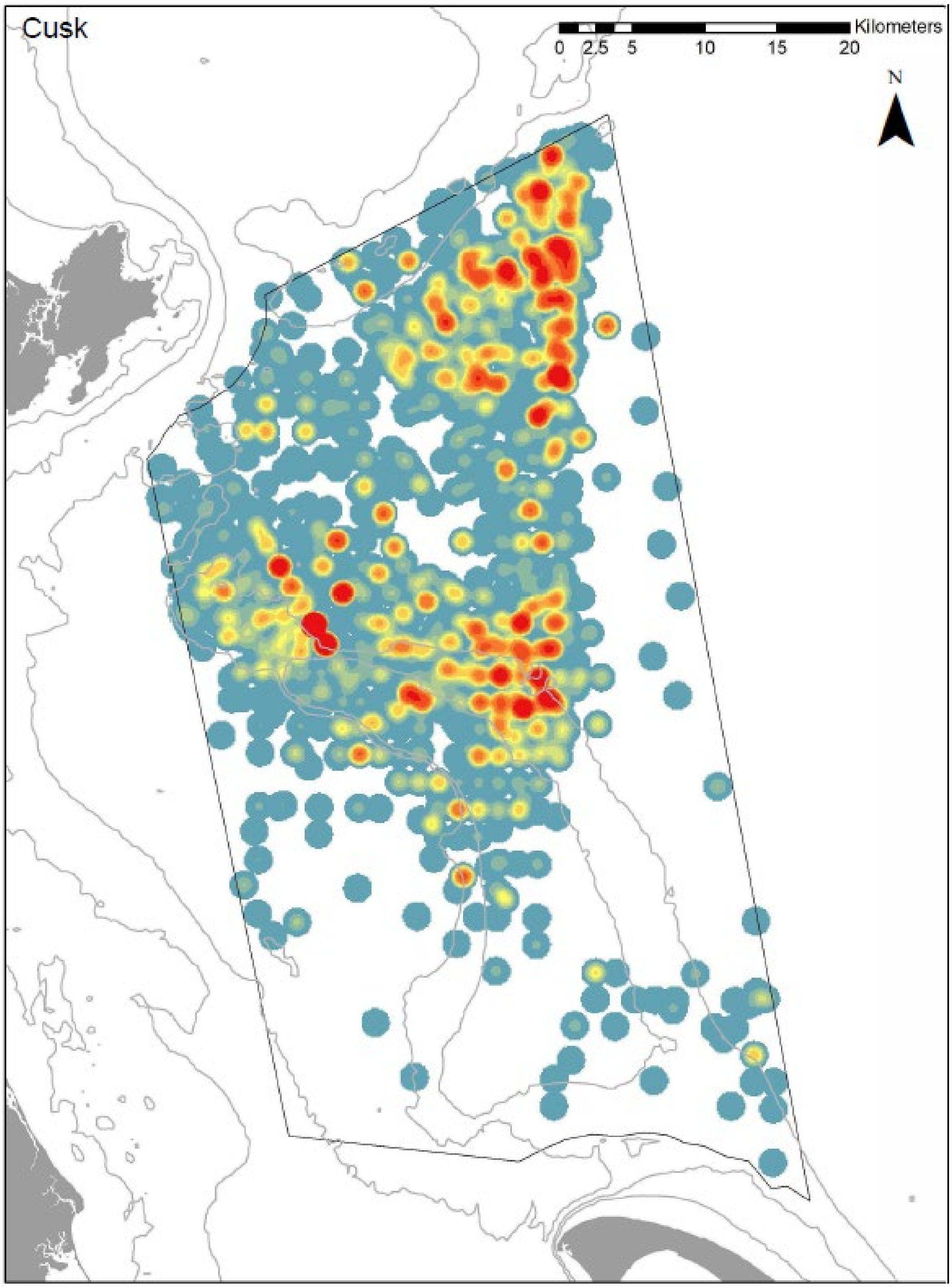

Figure B-4. Catch data summaries for cusk 2007–2016 in SBNMS from VTR data

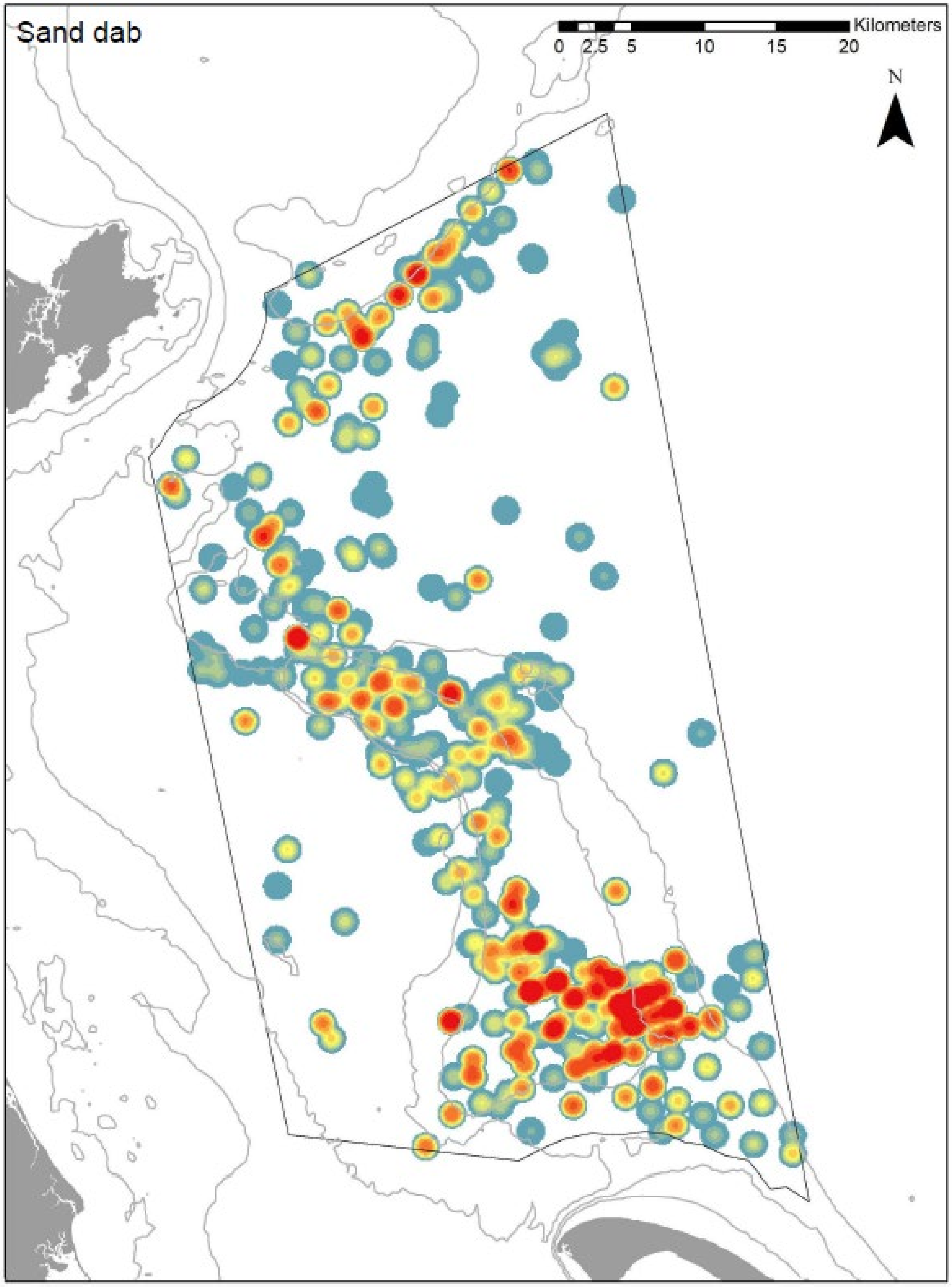

Figure B-5. Catch data summaries for sand dab 2007–2016 in SBNMS from VTR data

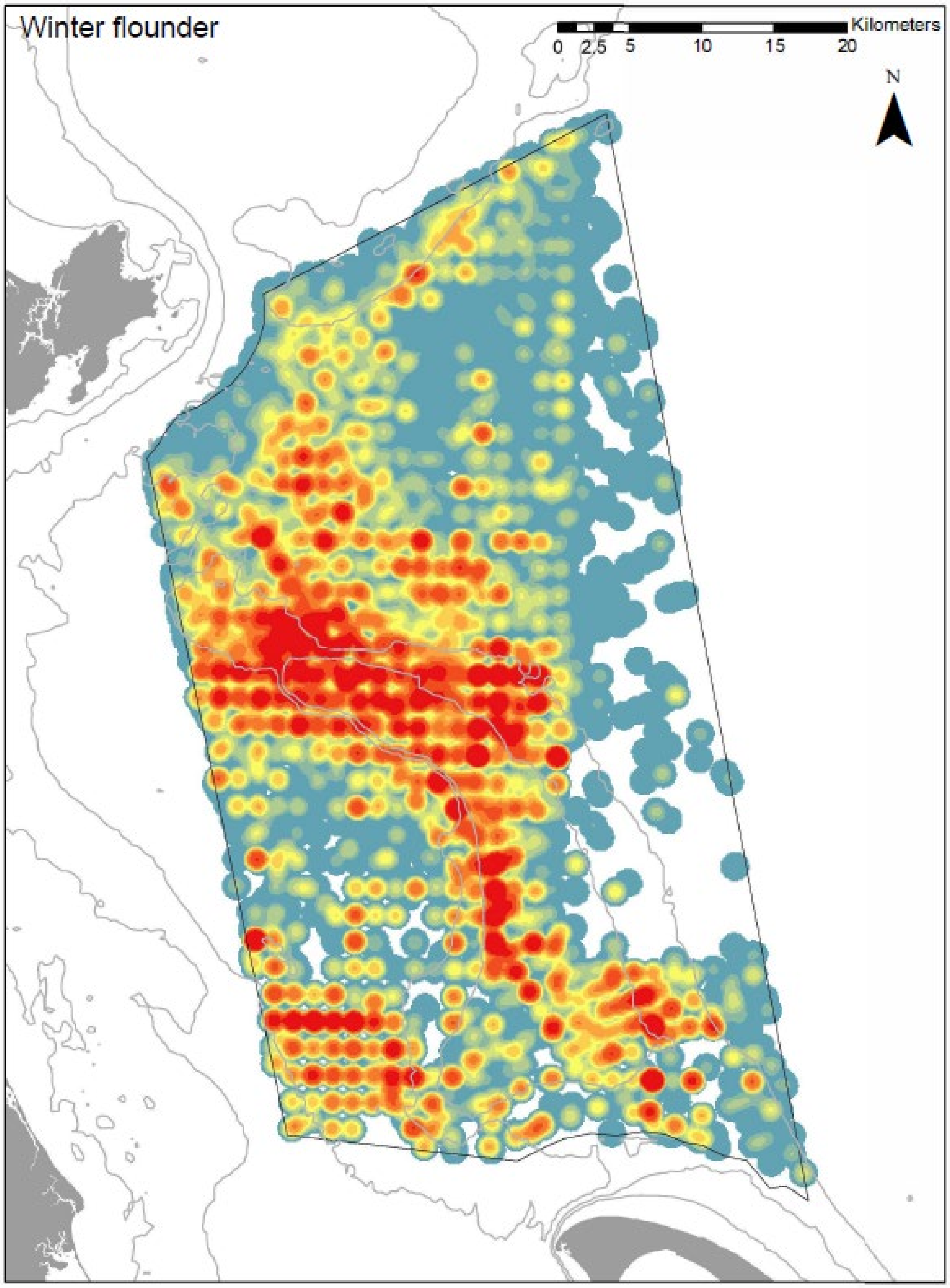

Figure B-6. Catch data summaries for winter flounder 2007–2016 in SBNMS from VTR data

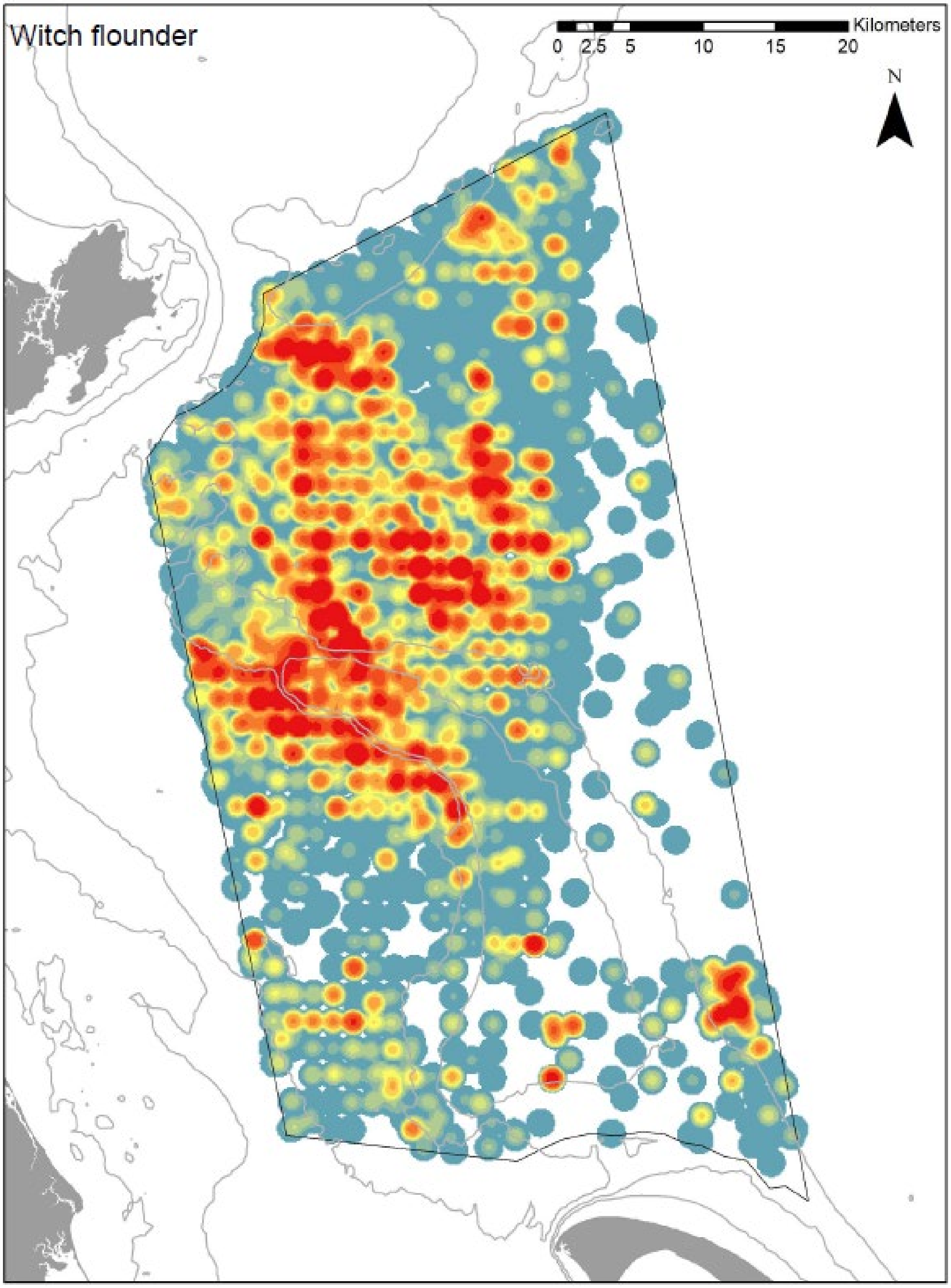

Figure B-7. Catch data summaries for witch flounder 2007–2016 in SBNMS from VTR data

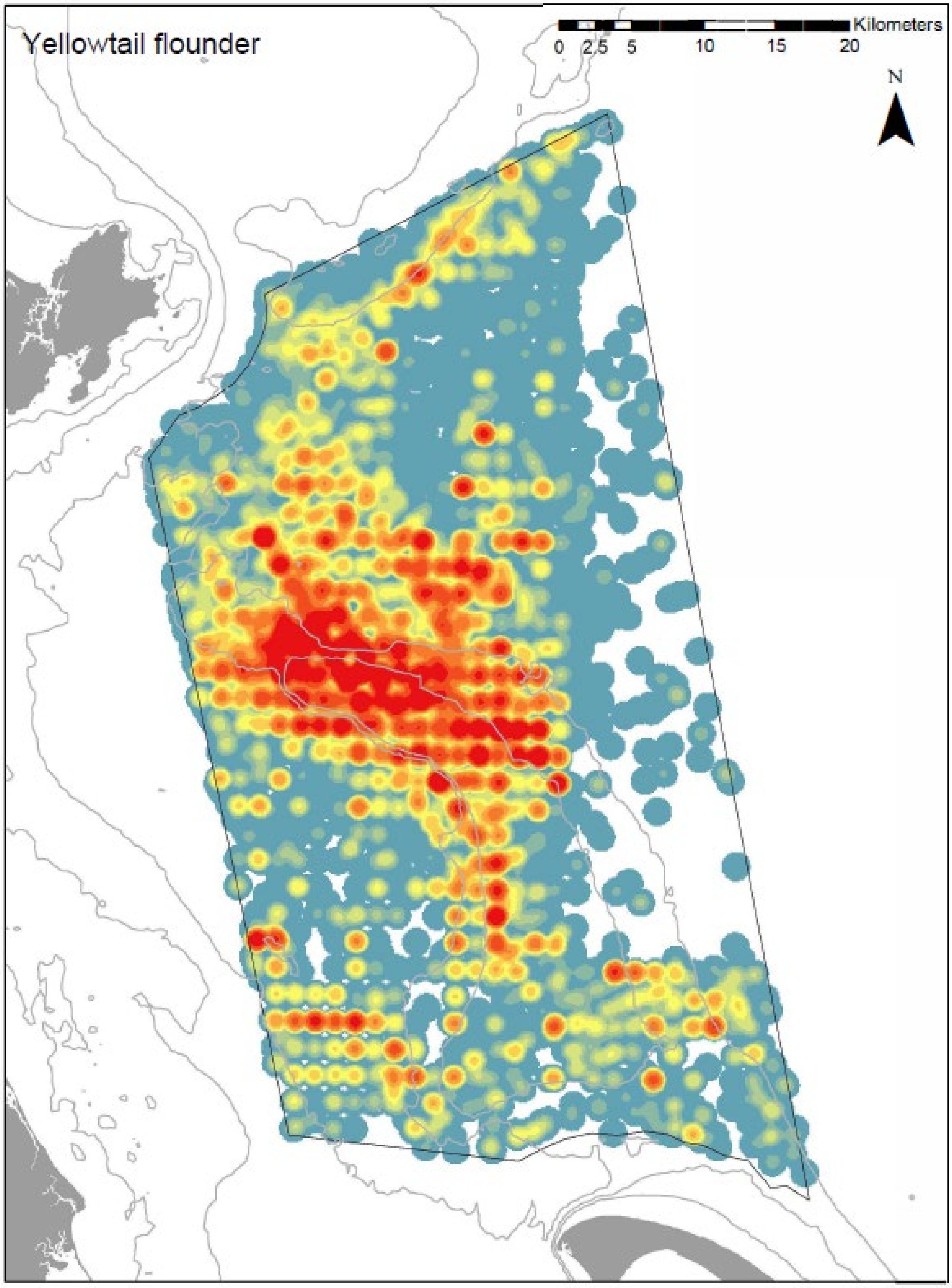

Figure B-8. Catch data summaries for yellowtail flounder 2007–2016 in SBNMS from VTR data

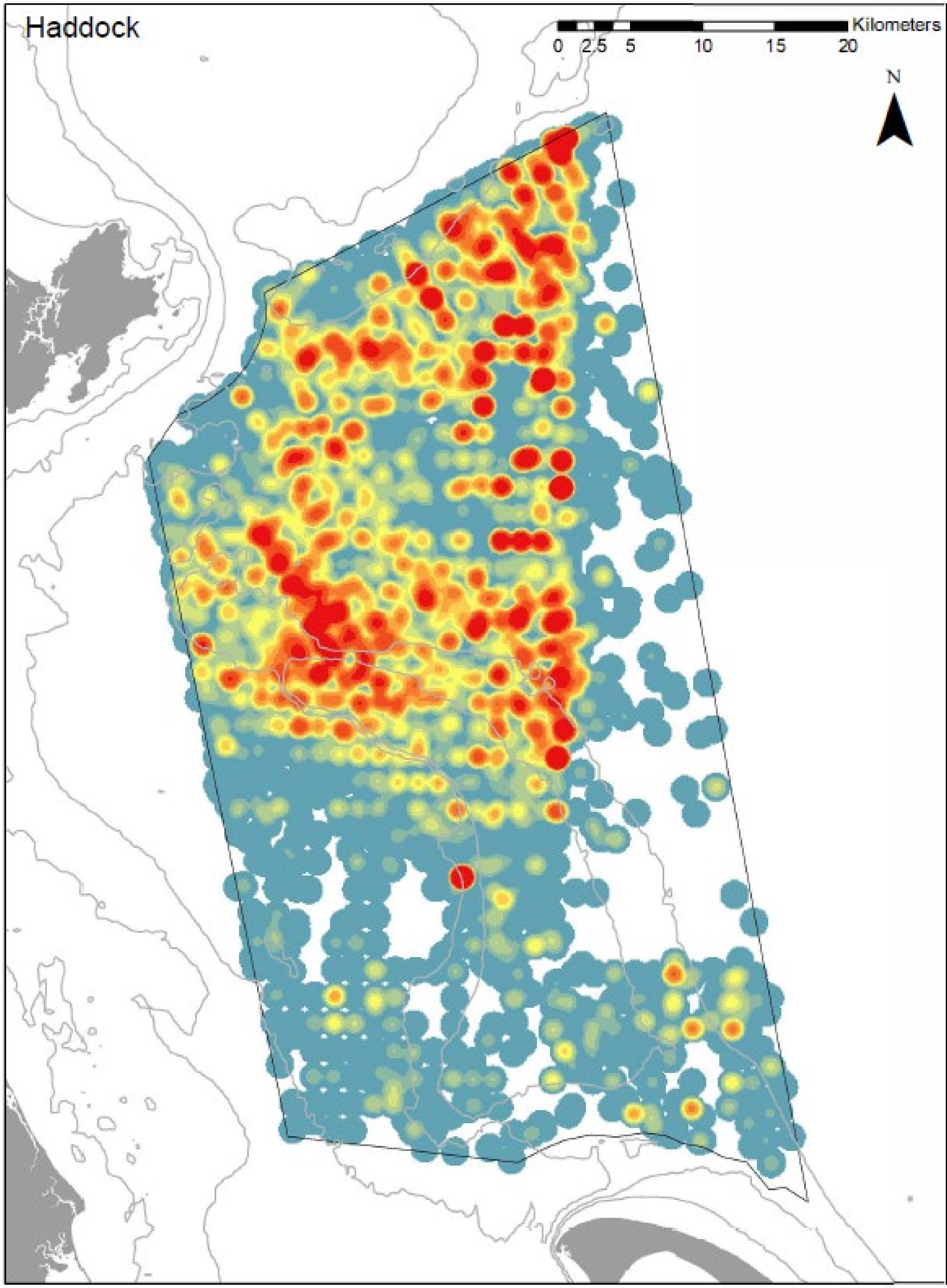

Figure B-9. Catch data summaries for haddock 2007–2016 in SBNMS from VTR data

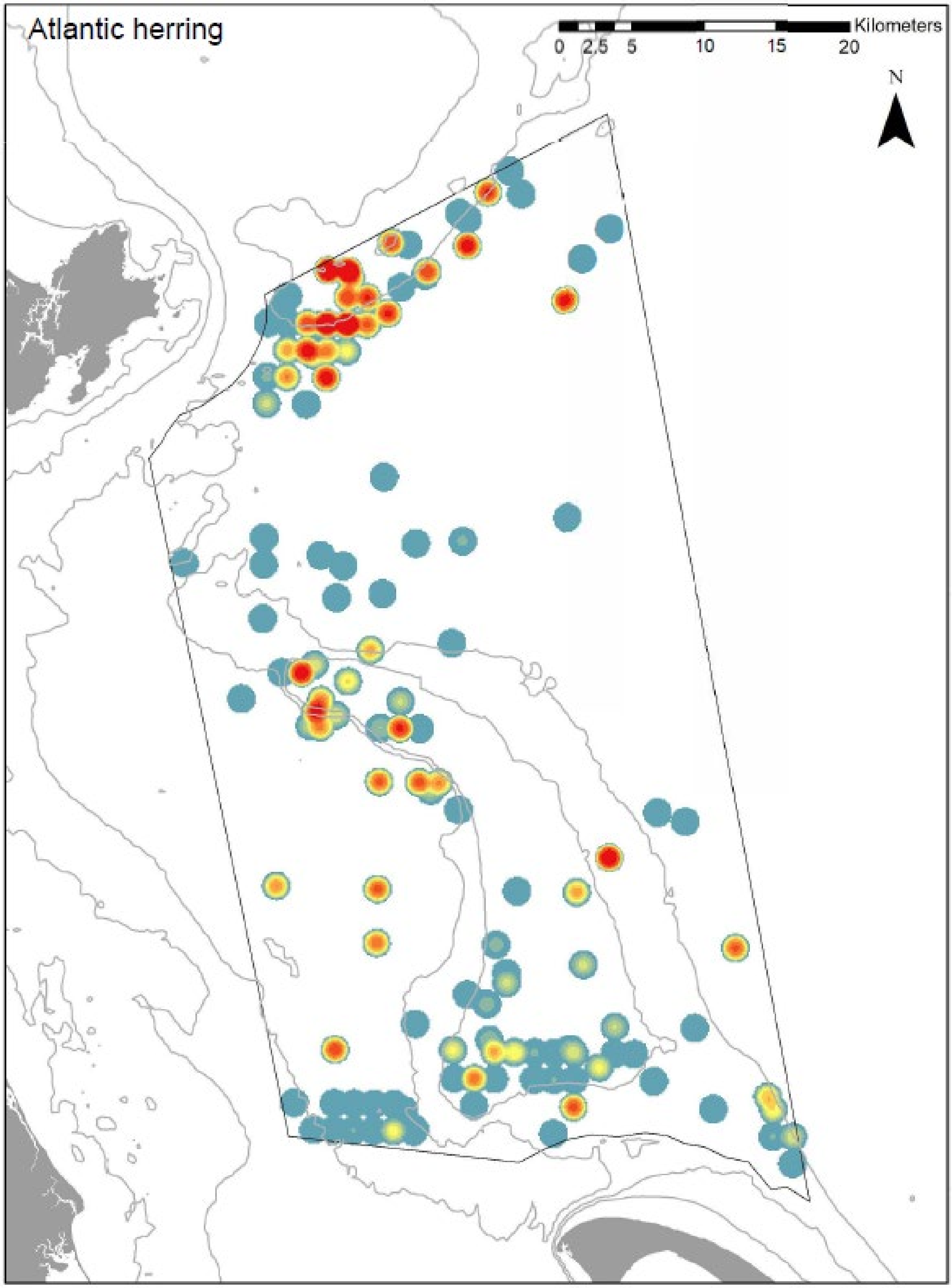

Figure B-10. Catch data summaries for Atlantic herring 2007–2016 in SBNMS from VTR data

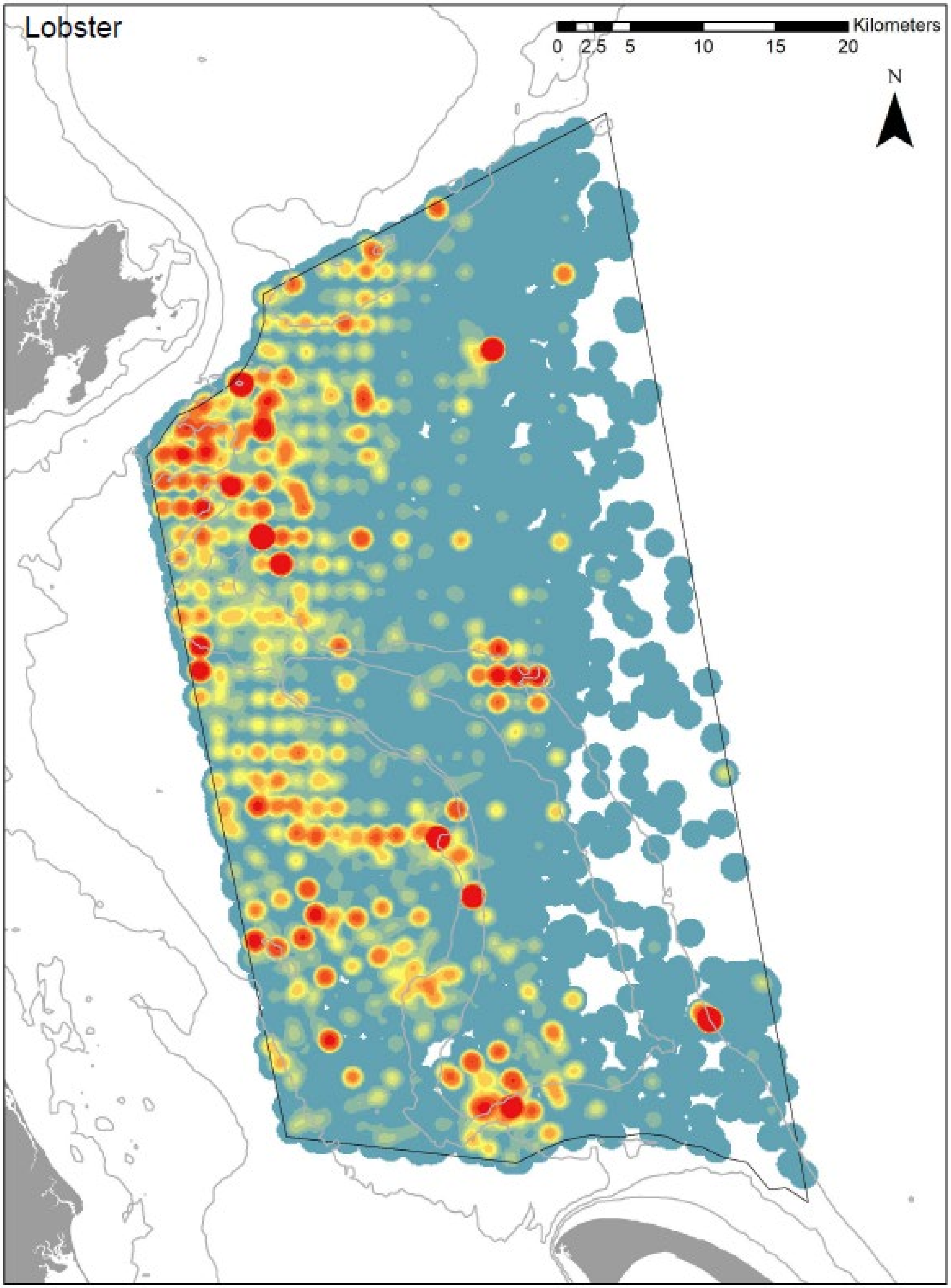

Figure B-11. Catch data summaries for lobster 2007–2016 in SBNMS from VTR data

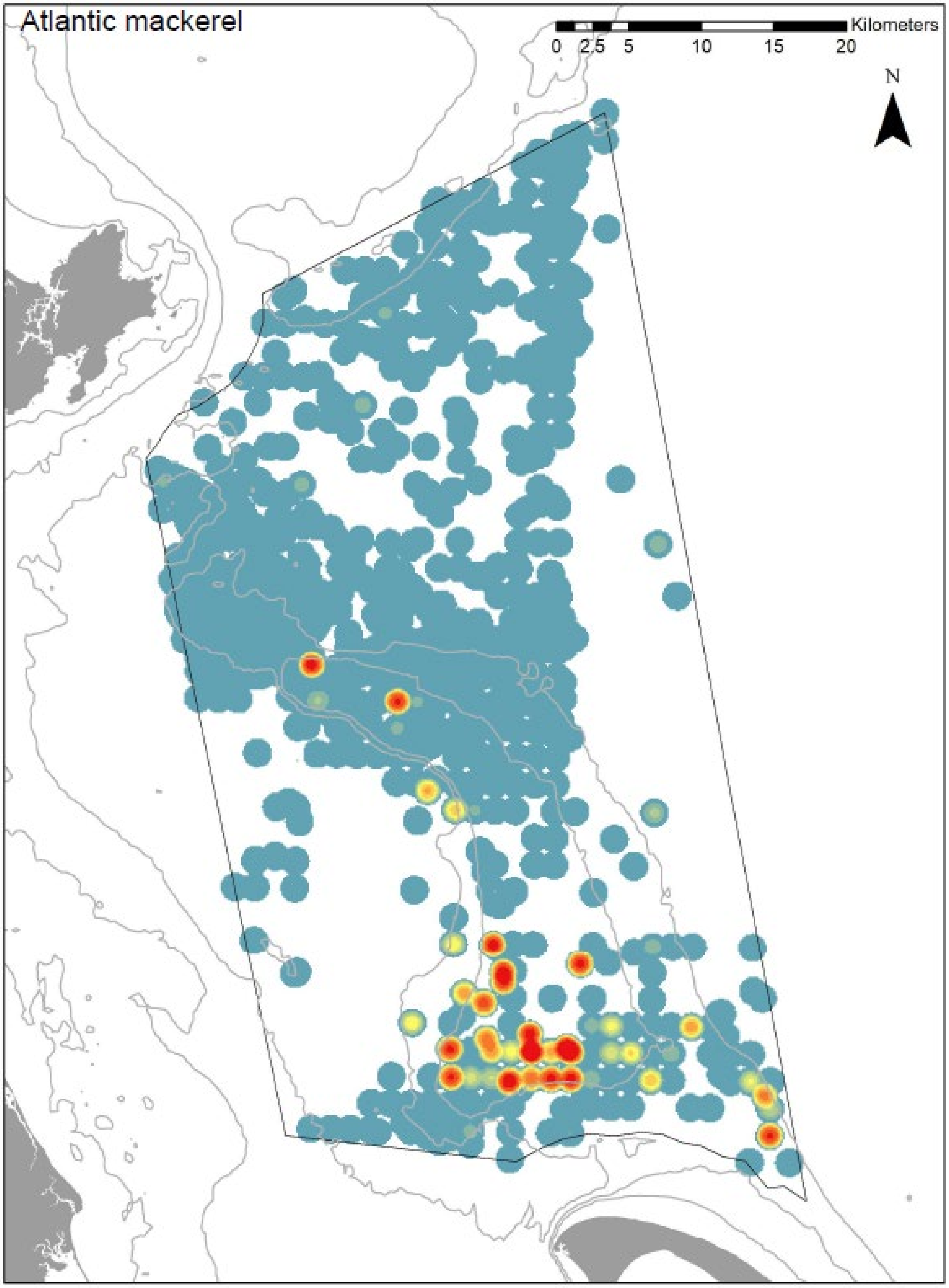

Figure B-12. Catch data summaries for Atlantic mackerel 2007–2016 in SBNMS from VTR data

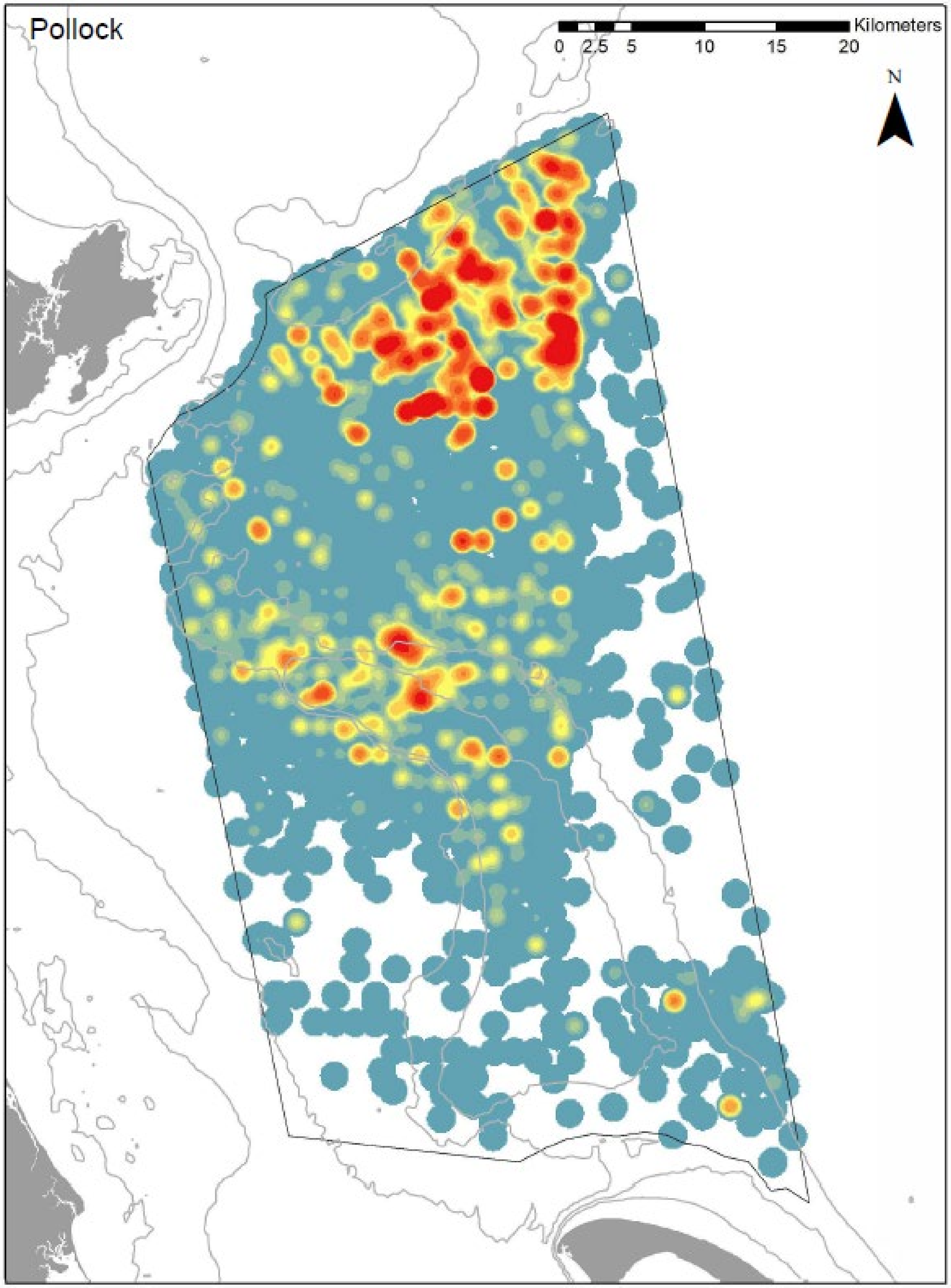

Figure B-13. Catch data summaries for pollock 2007–2016 in SBNMS from VTR data

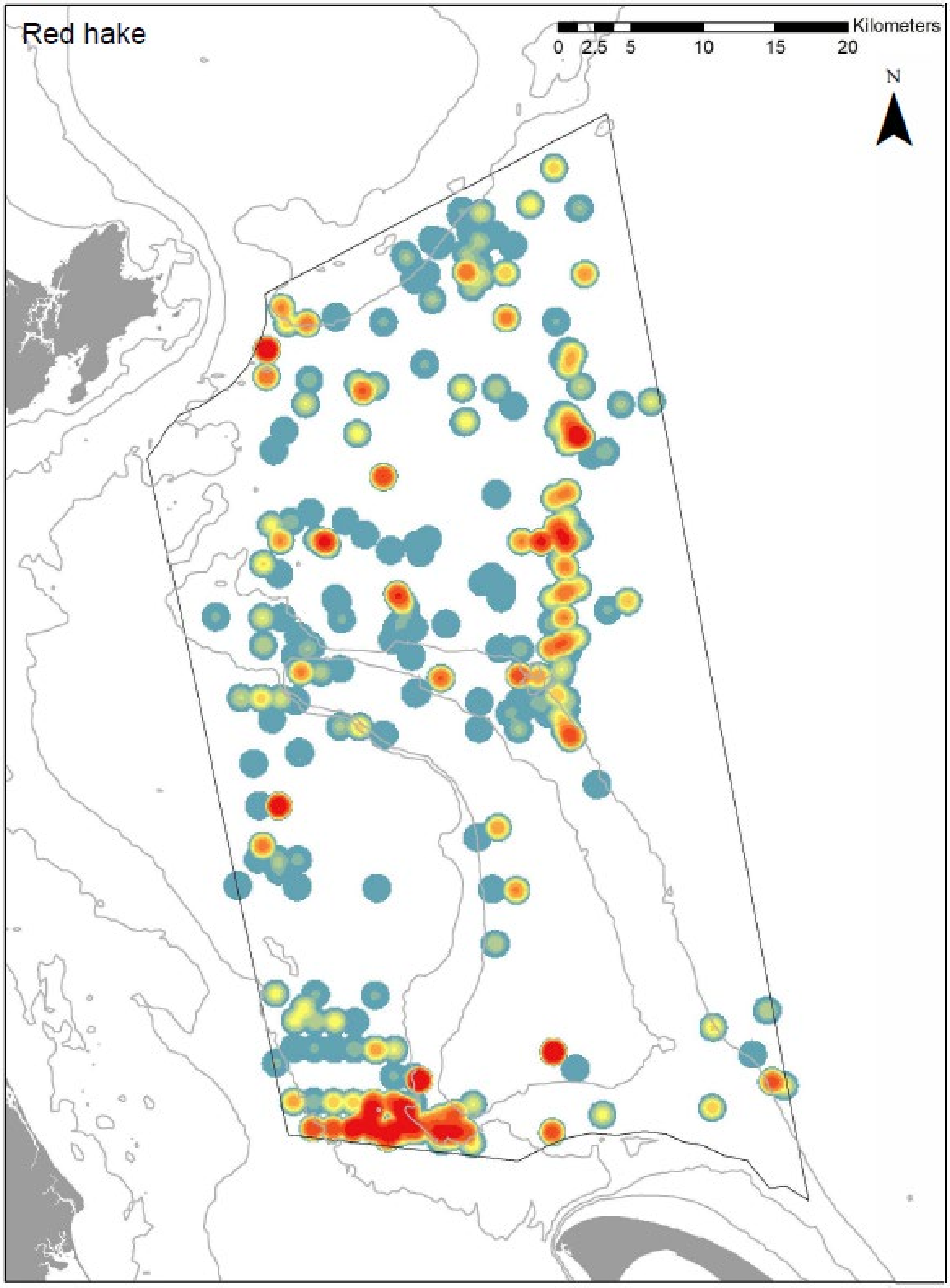

Figure B-14. Catch data summaries for red hake 2007–2016 in SBNMS from VTR data

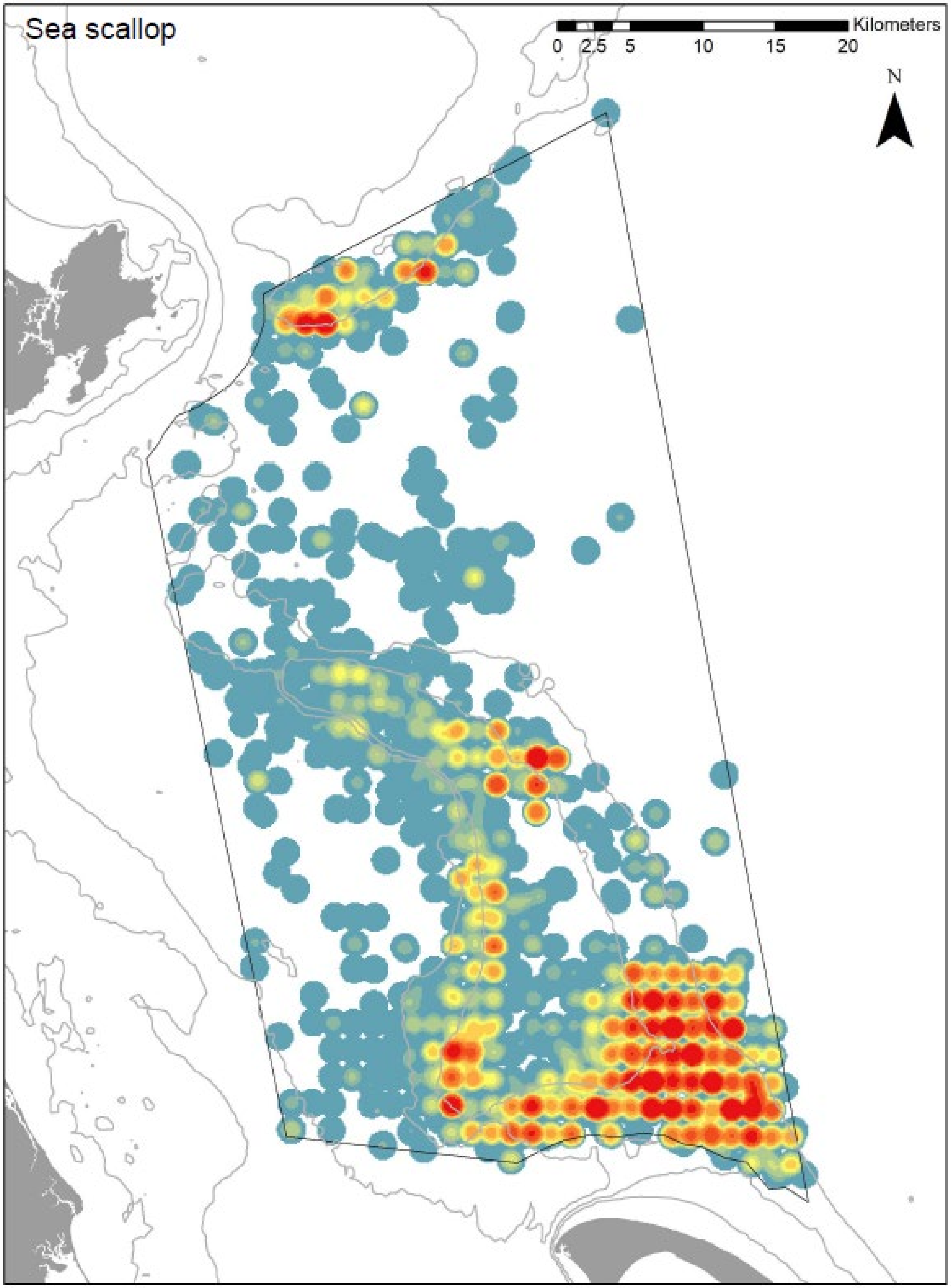

Figure B-15. Catch data summaries for sea scallop 2007–2016 in SBNMS from VTR data

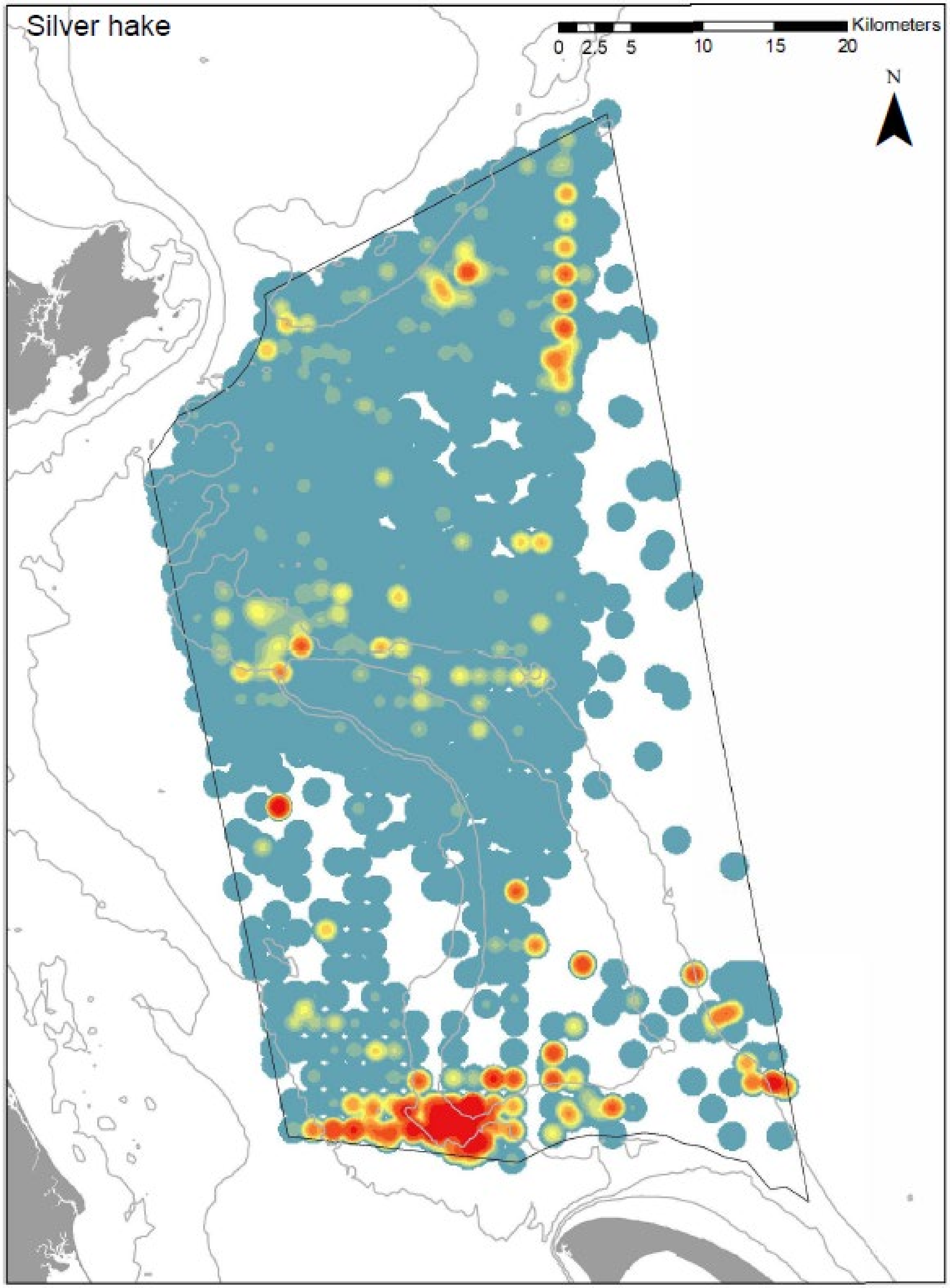

Figure B-16. Catch data summaries for silver hake 2007–2016 in SBNMS from VTR data

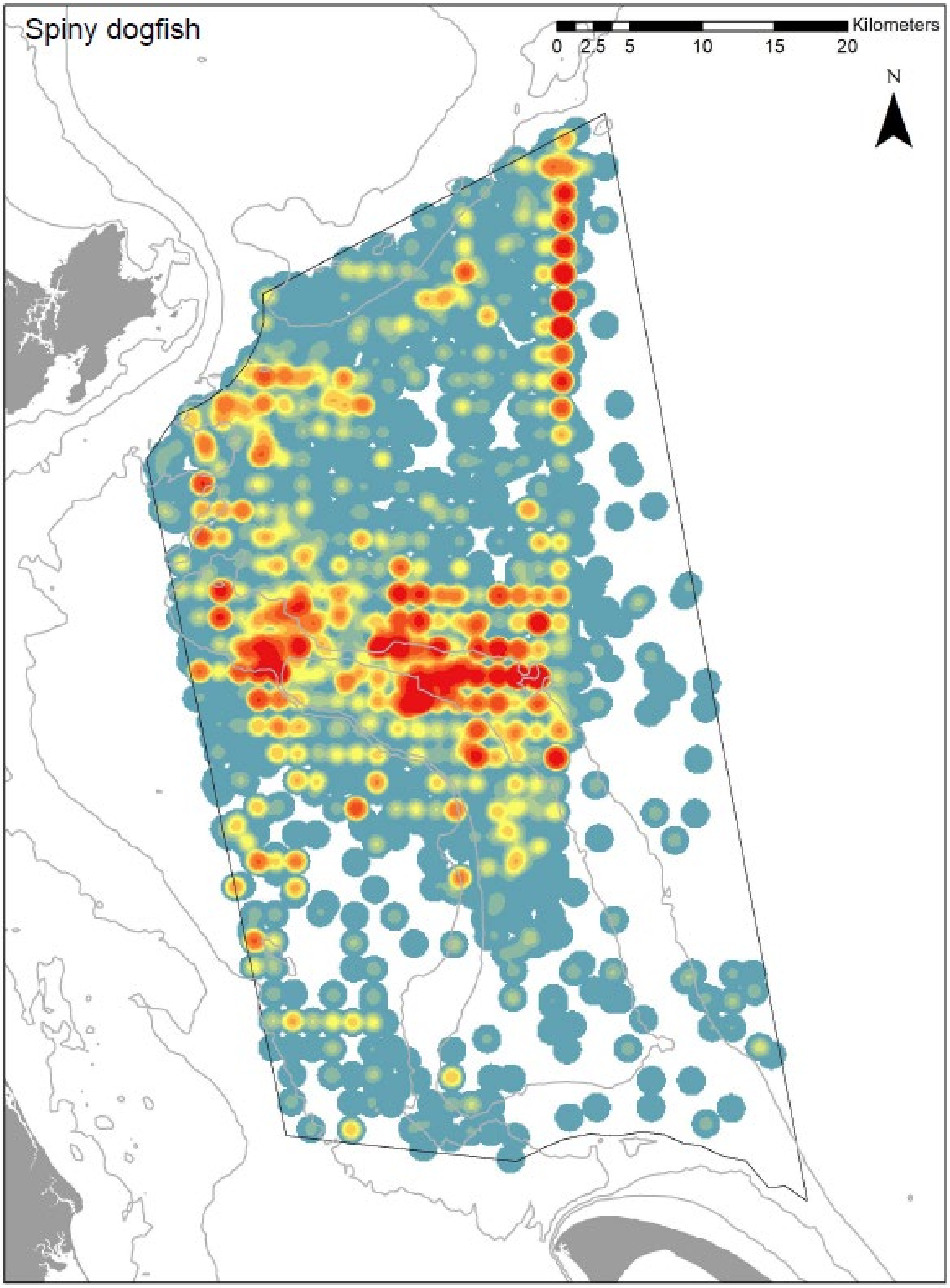

Figure B-17. Catch data summaries for spiny dogfish 2007–2016 in SBNMS from VTR data

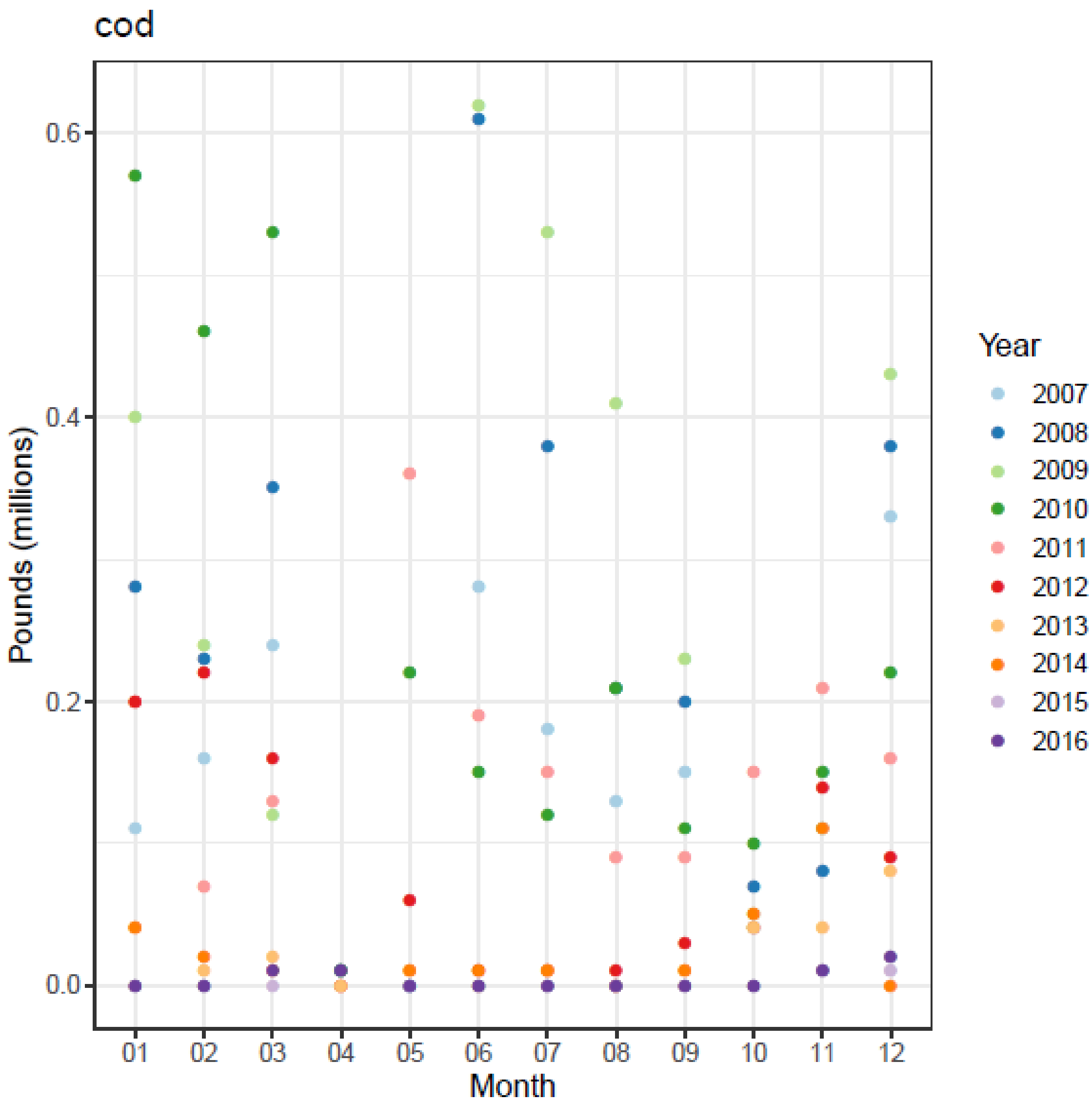

Figure B-18. Catch data summaries for cod 2007–2016 in SBNMS from VTR data by month

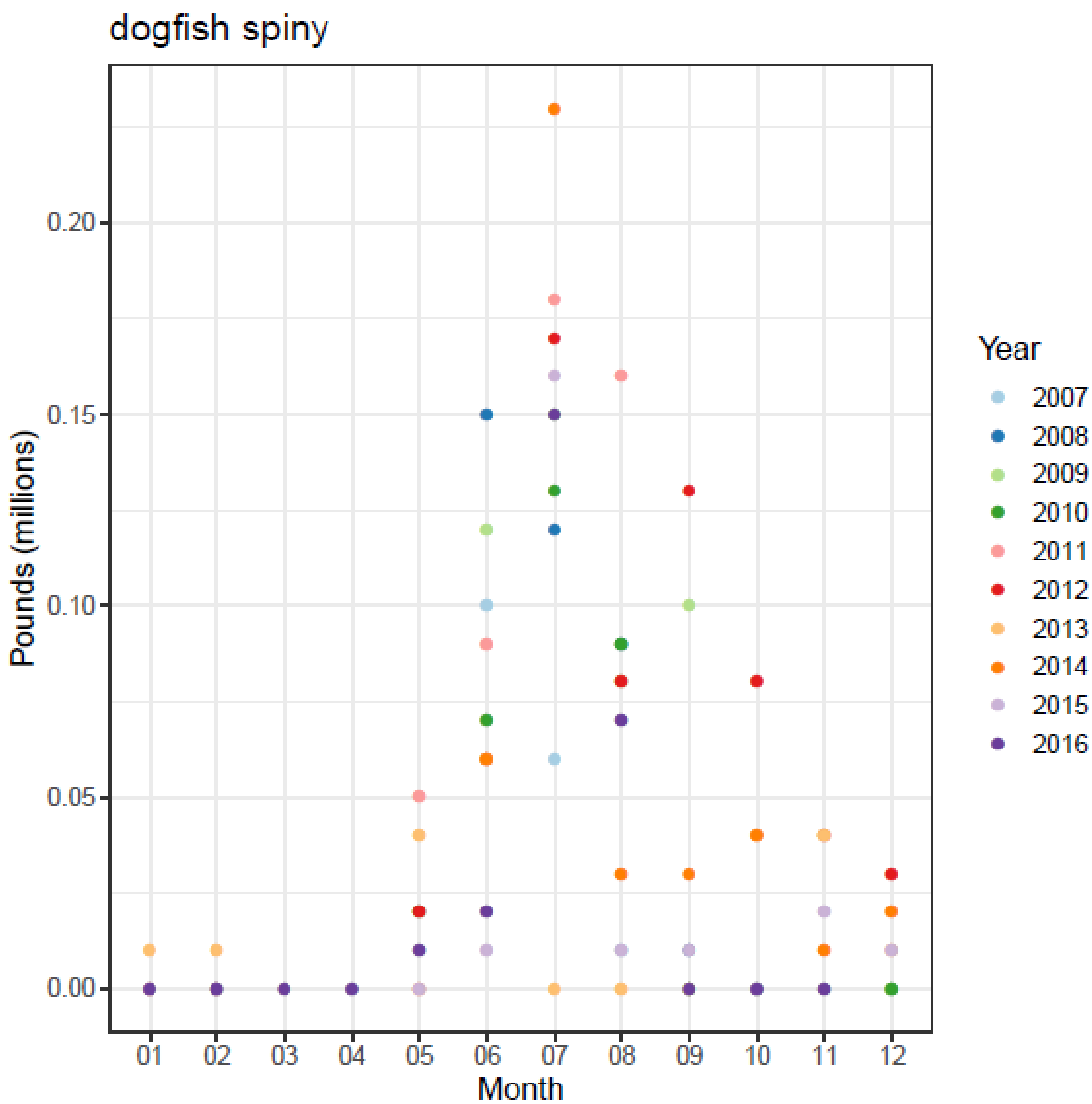

Figure B-19. Catch data summaries for spiny dogfish 2007–2016 in SBNMS from VTR data by month

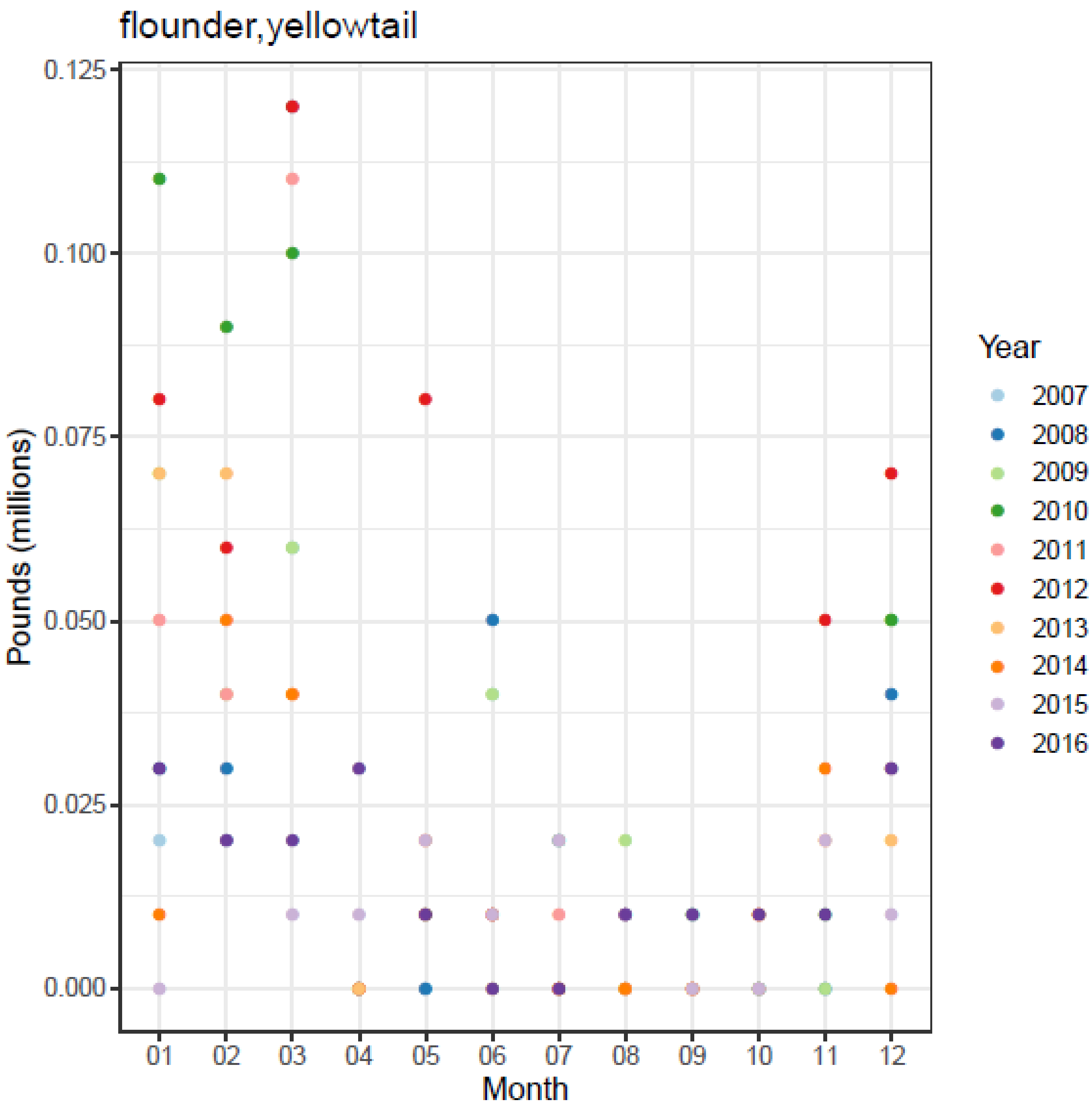

Figure B-20. Catch data summaries for yellowtail flounder 2007–2016 in SBNMS from VTR data by month

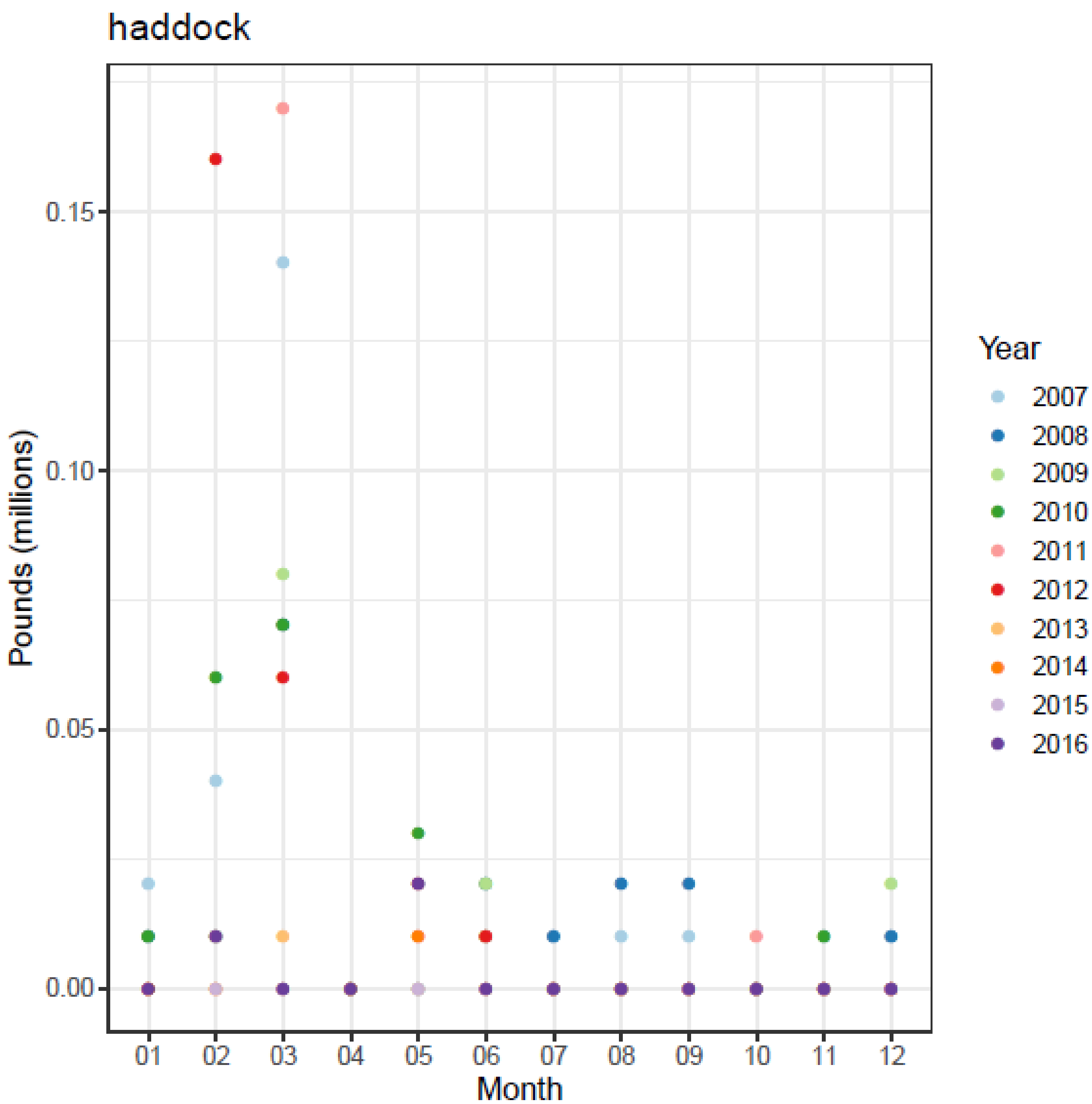

Figure B-21. Catch data summaries for haddock 2007–2016 in SBNMS from VTR data by month

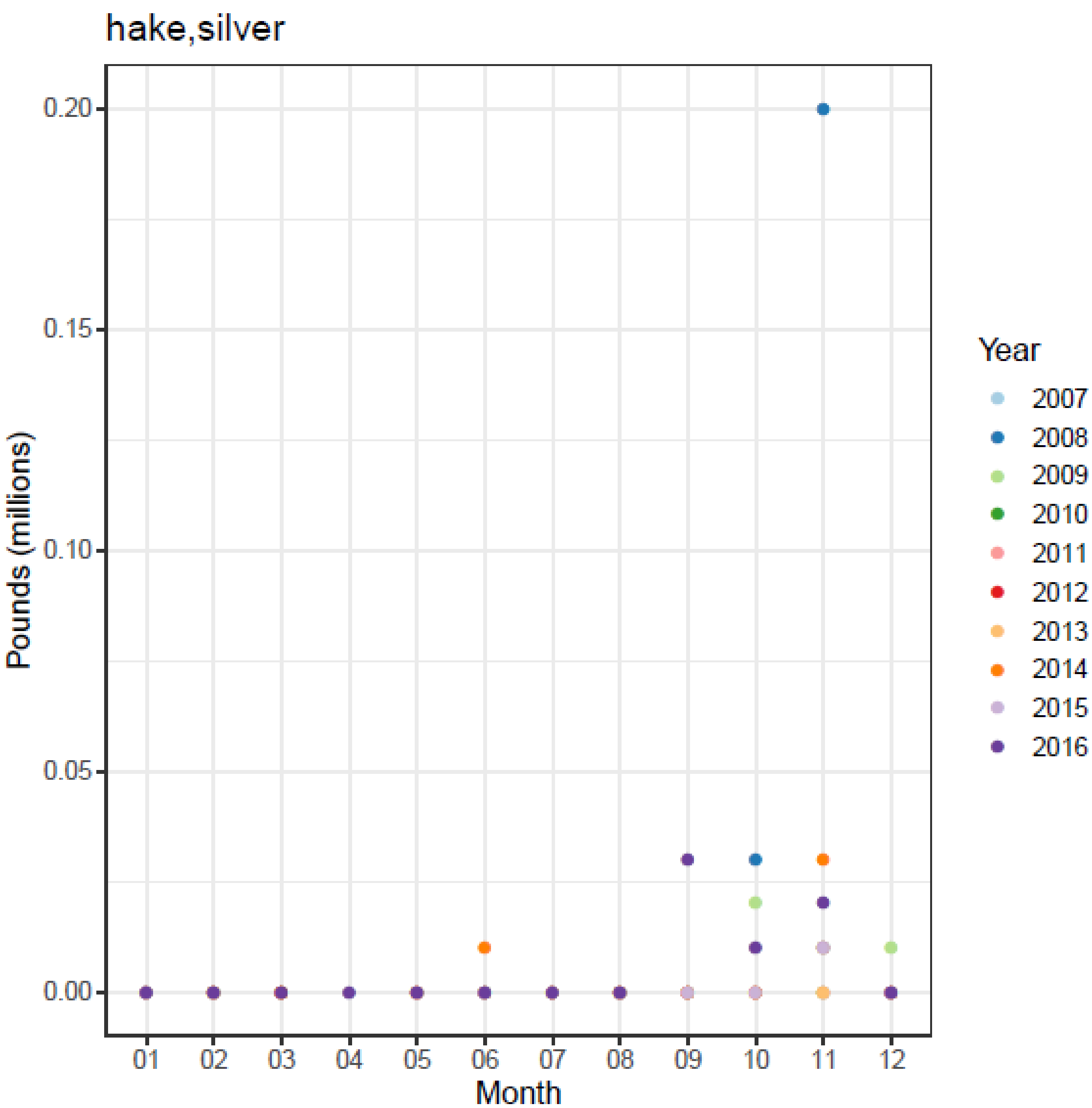

Figure B-22. Catch data summaries for silver hake 2007–2016 in SBNMS from VTR data by month

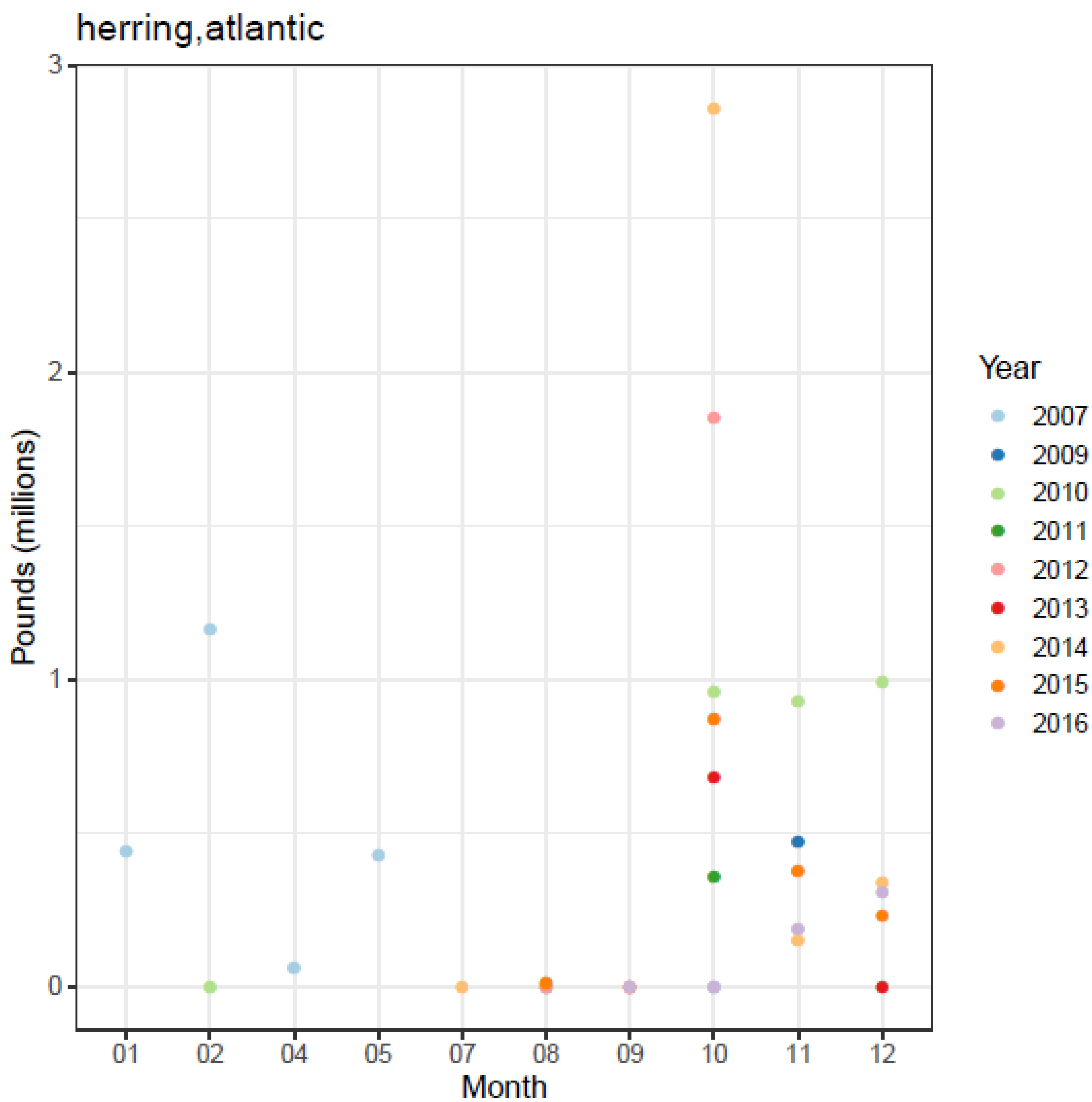

Figure B-23. Catch data summaries for Atlantic herring 2007–2016 in SBNMS from VTR data by month

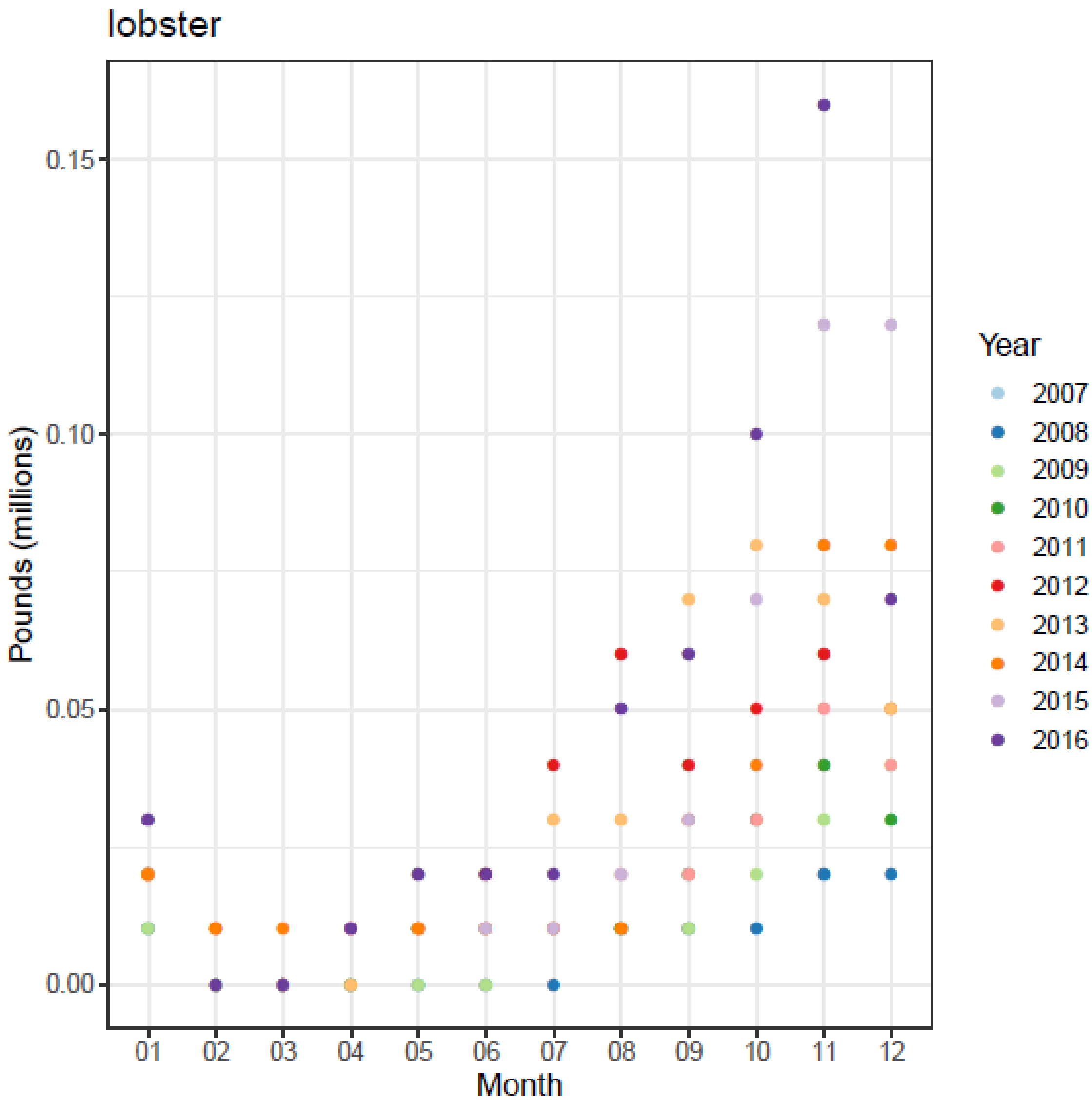

Figure B-24. Catch data summaries for lobster 2007–2016 in SBNMS from VTR data by month

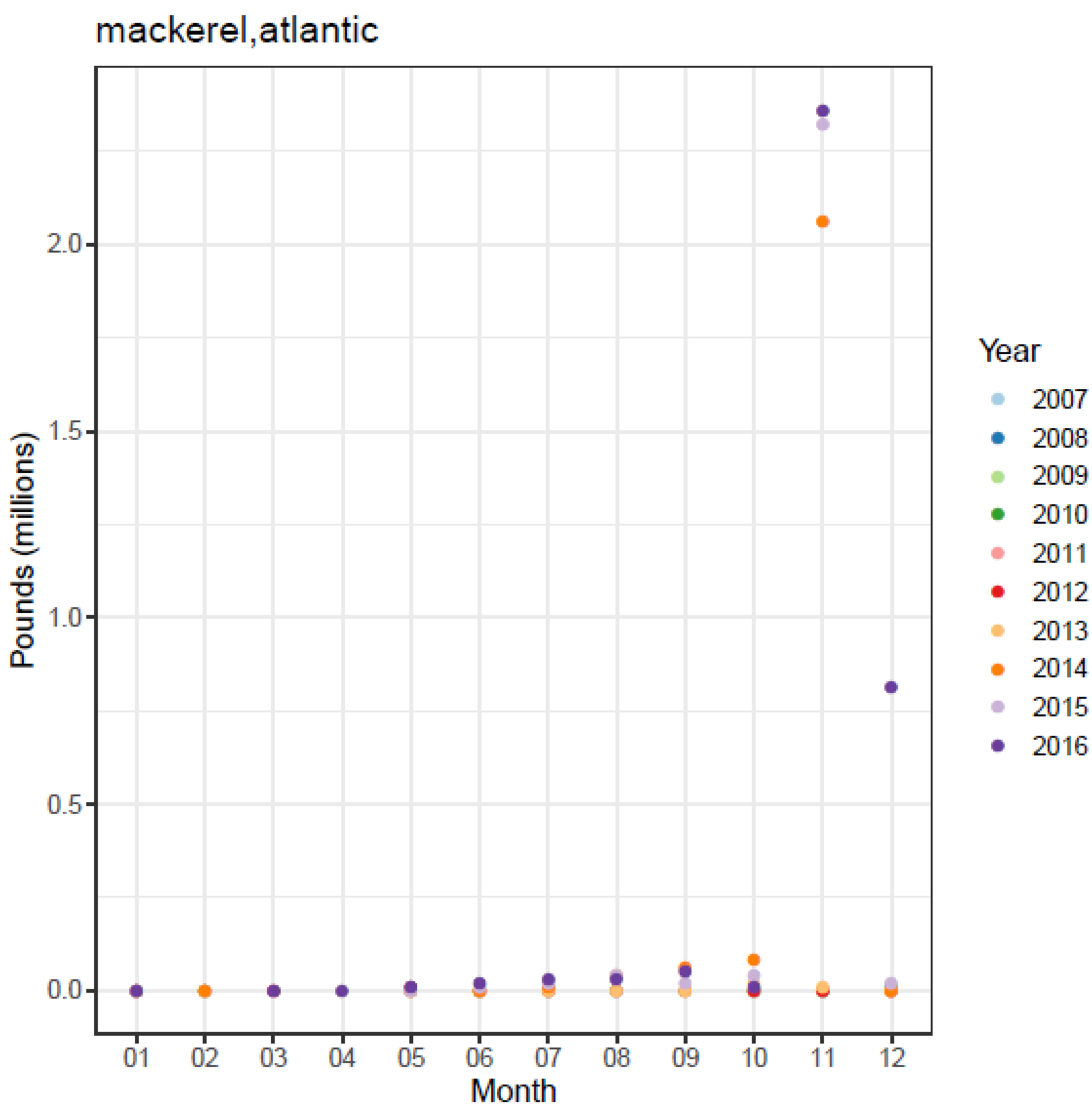

Figure B-25. Catch data summaries for Atlantic mackerel 2007–2016 in SBNMS from VTR data by month

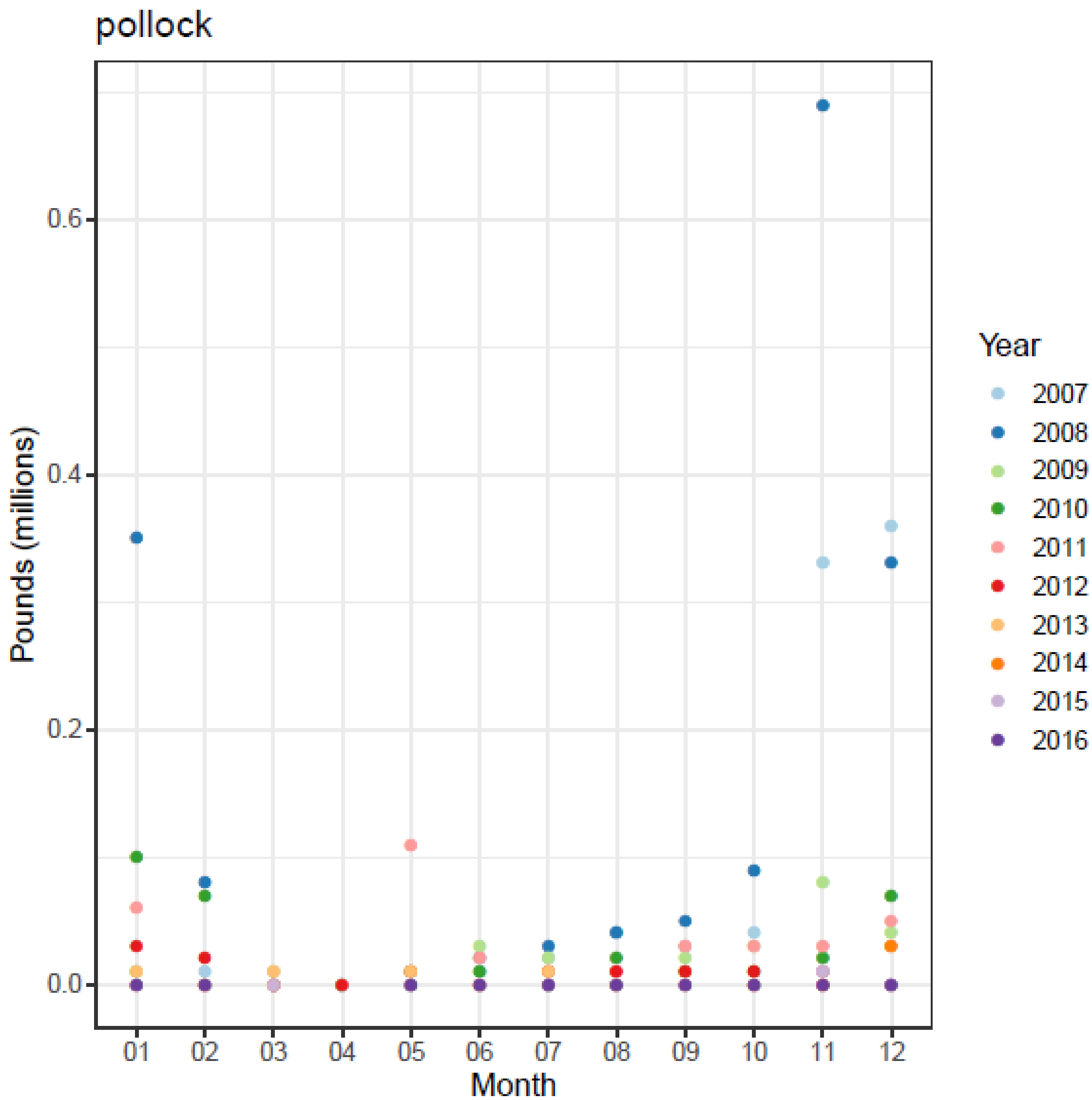

Figure B-26. Catch data summaries for pollock 2007–2016 in SBNMS from VTR data by month

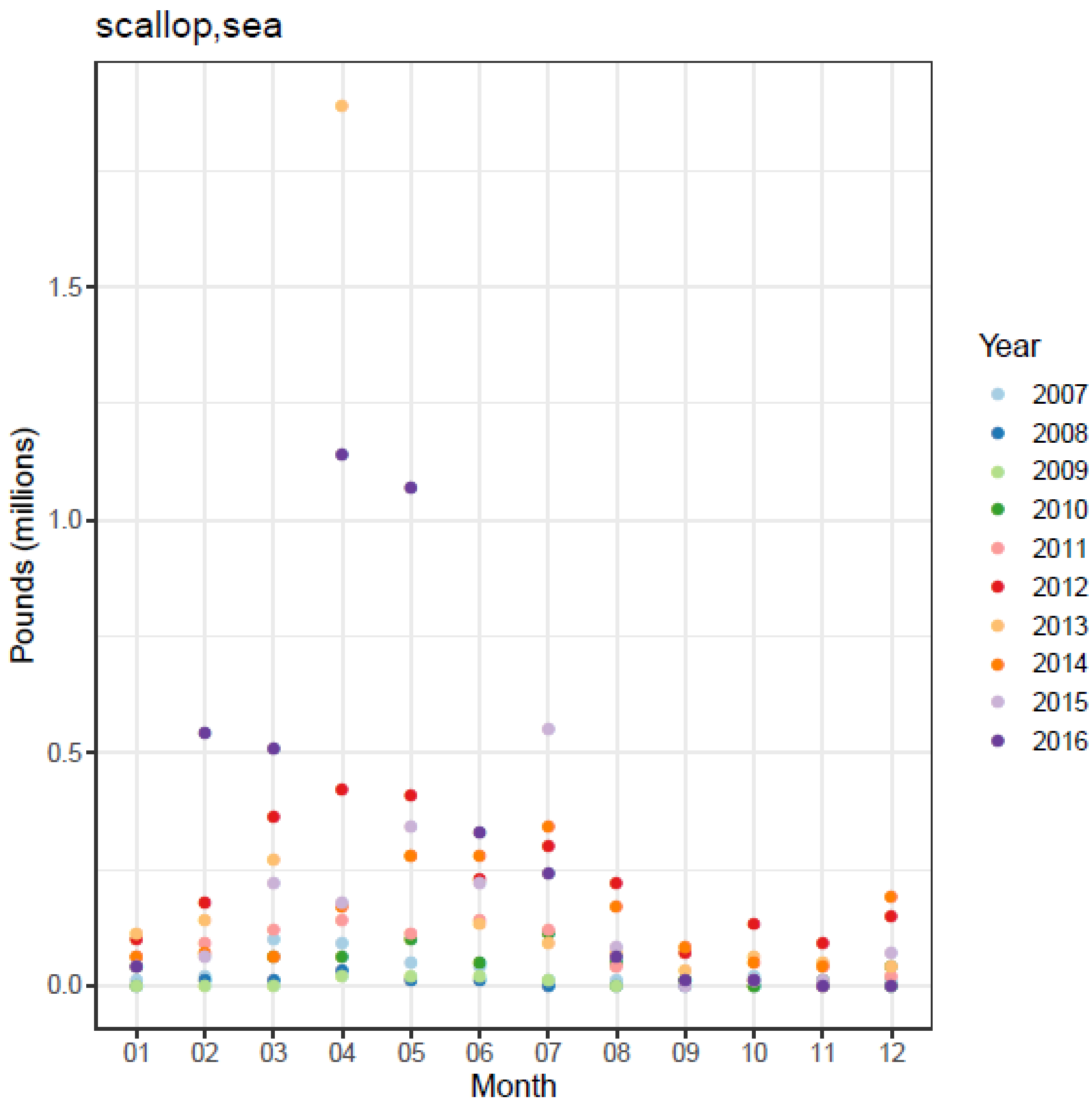

Figure B-27. Catch data summaries for sea scallop 2007–2016 in SBNMS from VTR data by month

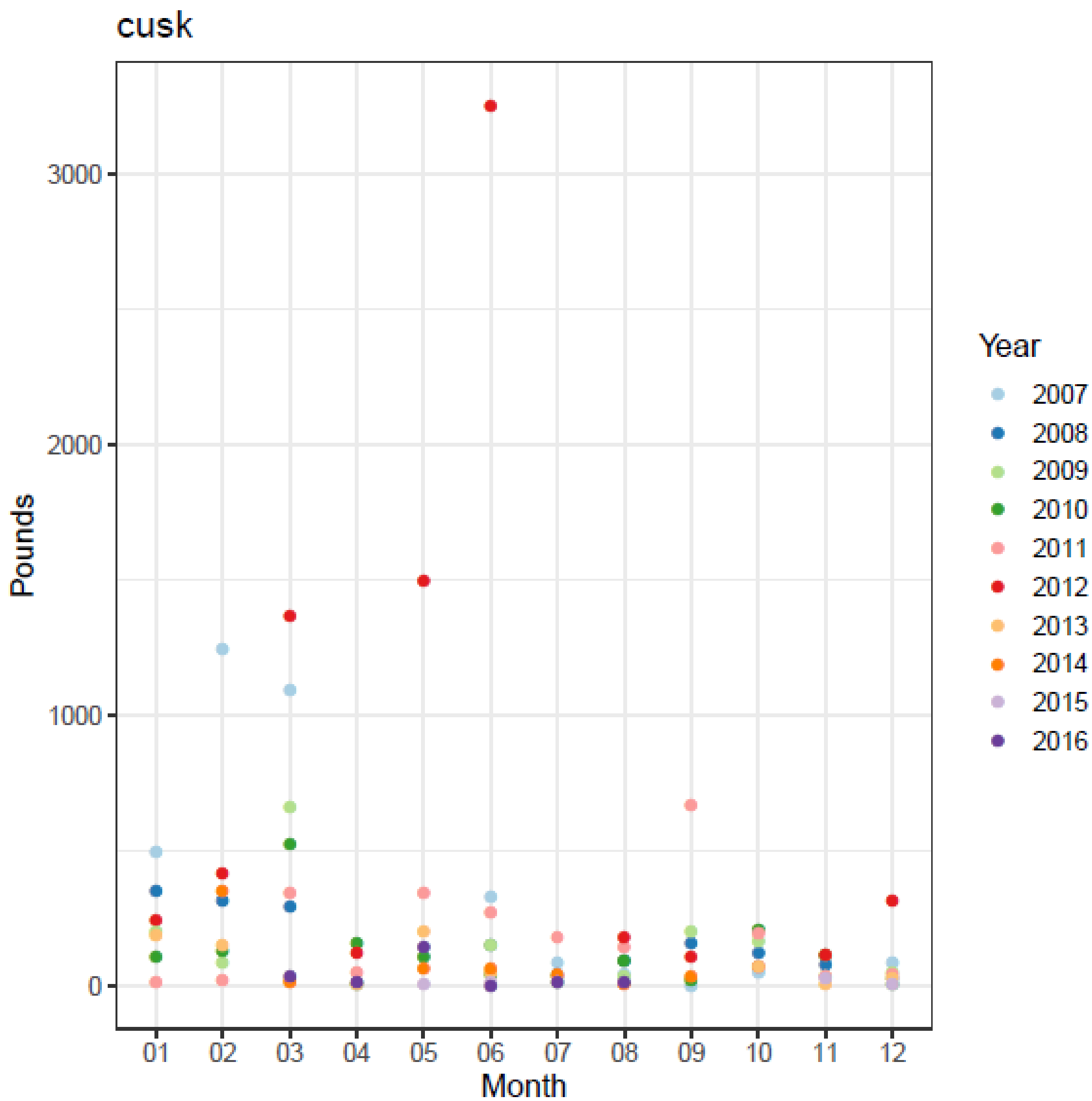

Figure B-28. Catch data summaries for cusk 2007–2016 in SBNMS from VTR data by month

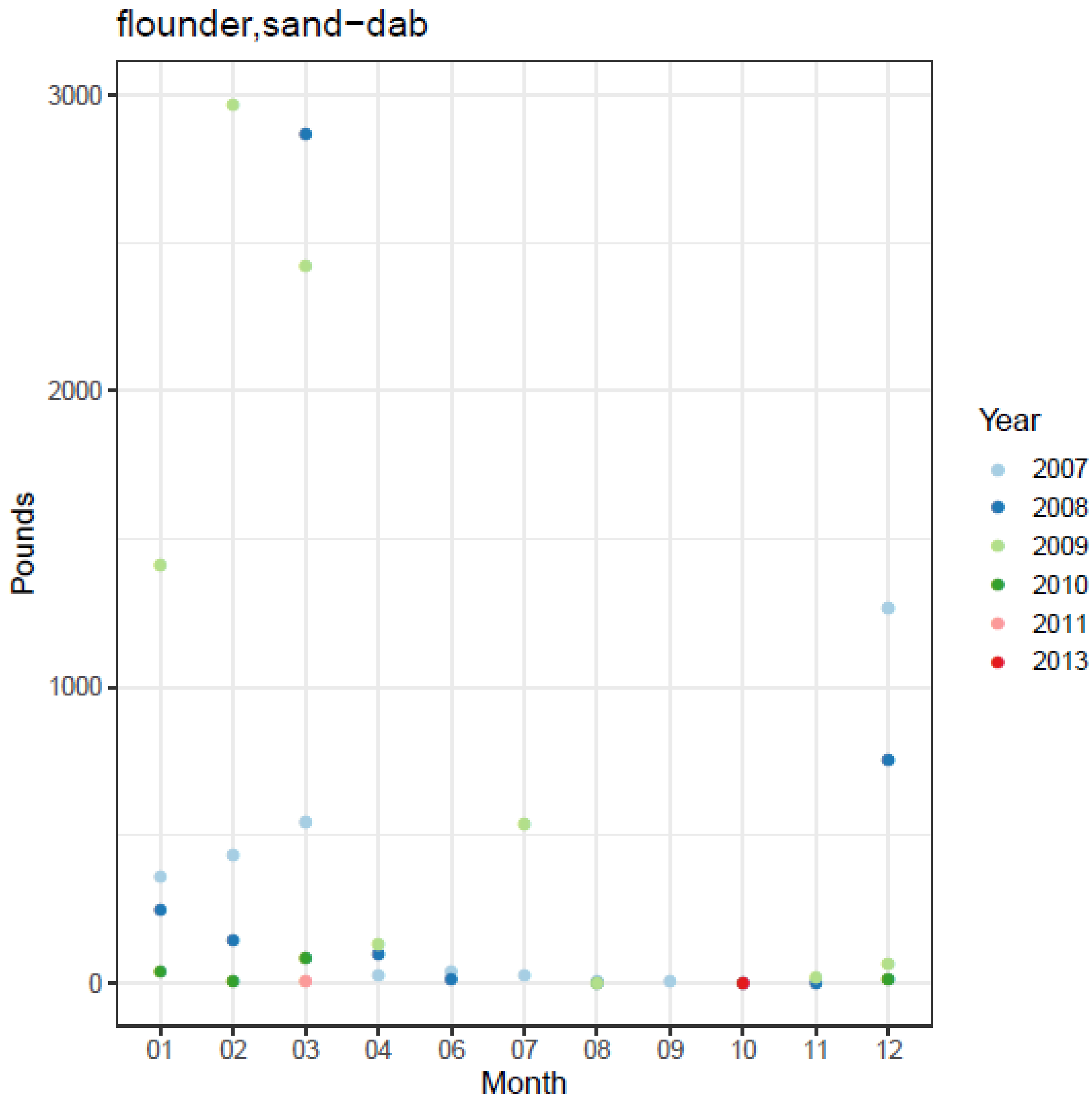

Figure B-29. Catch data summaries for sand-dab flounder 2007–2016 in SBNMS from VTR data by month

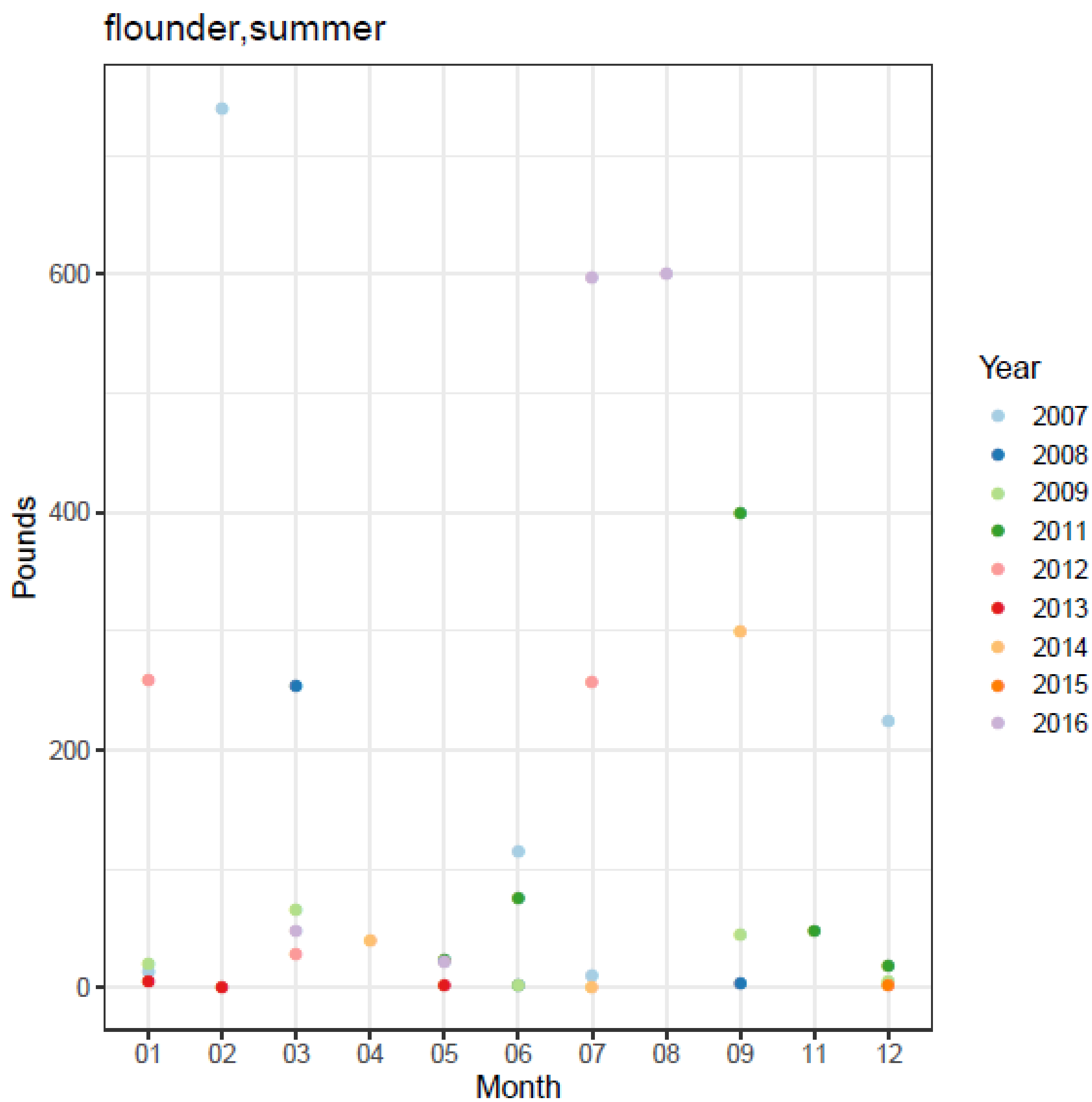

Figure B-30. Catch data summaries for summer flounder 2007–2016 in SBNMS from VTR data by month

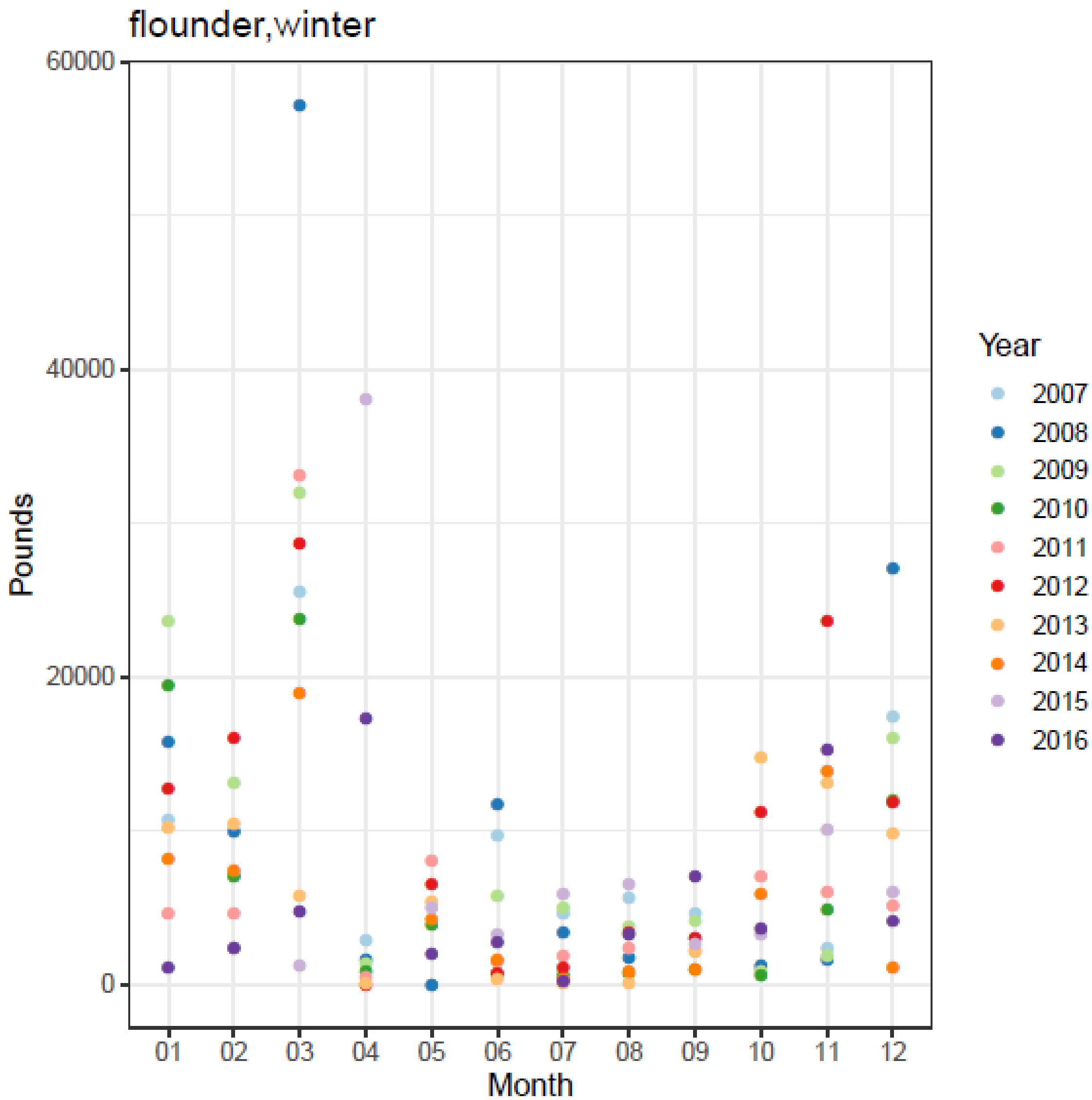

Figure B-31. Catch data summaries for winter flounder 2007–2016 in SBNMS from VTR data by month

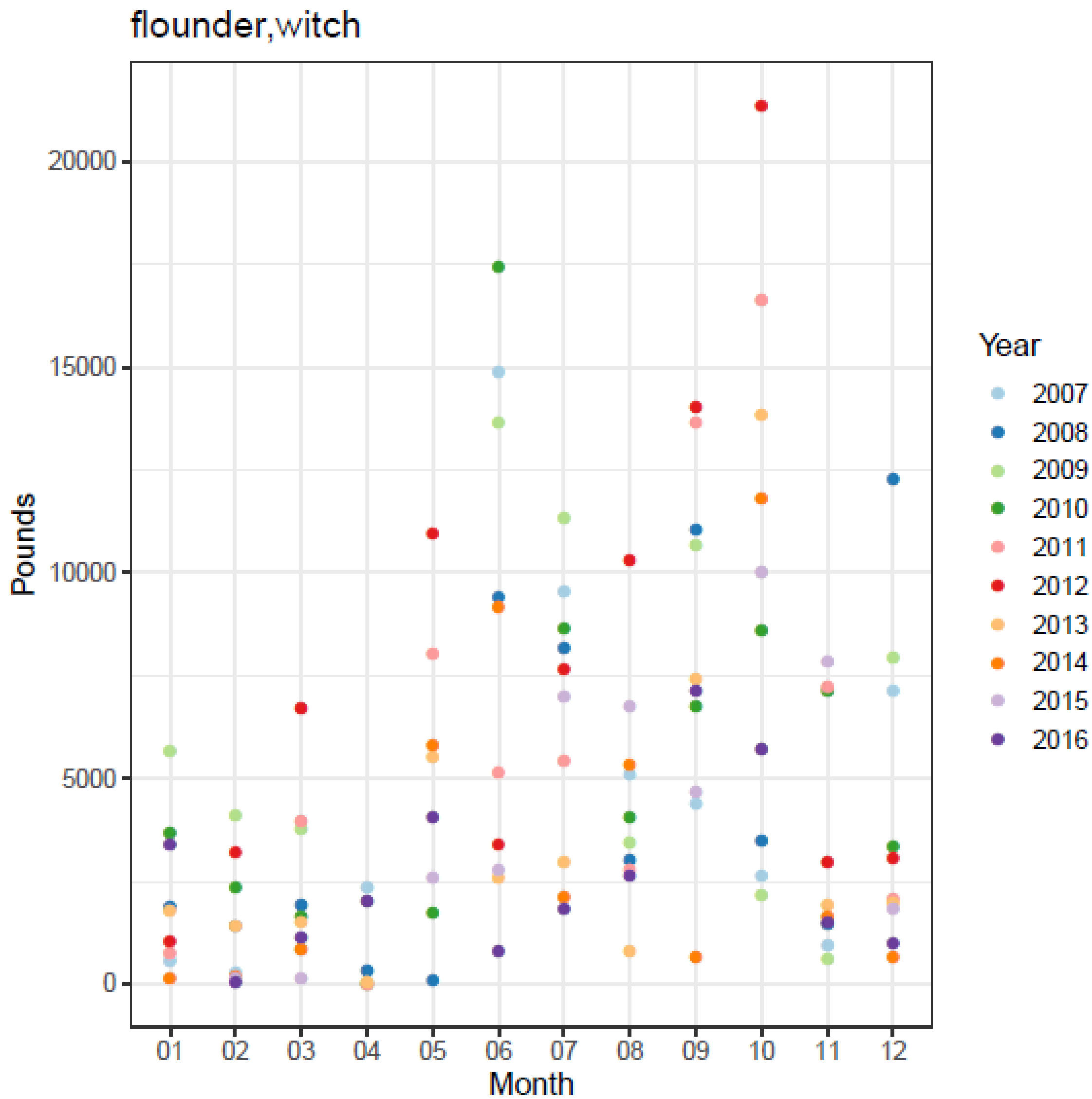

Figure B-32. Catch data summaries for witch flounder 2007–2016 in SBNMS from VTR data by month

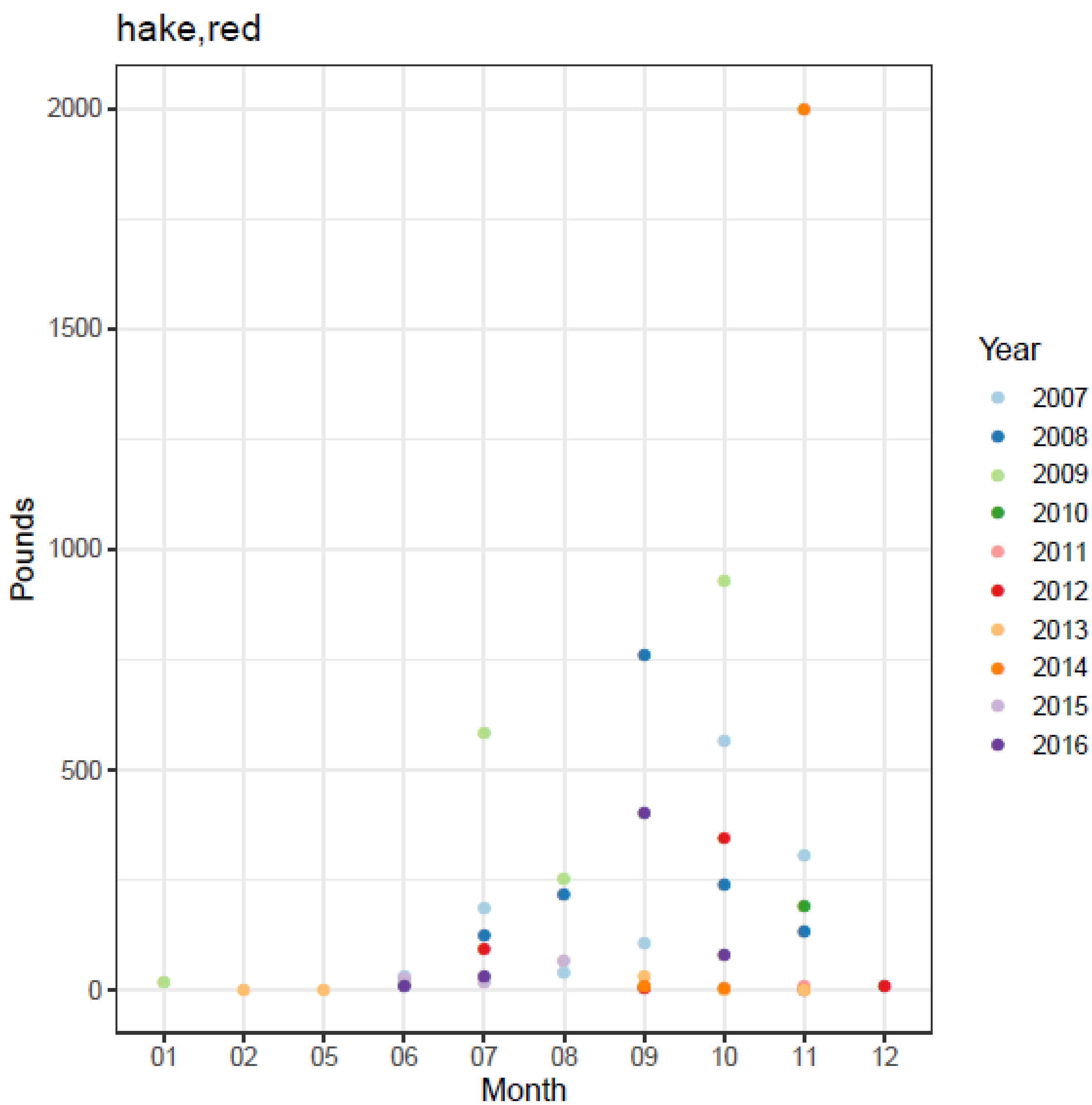

Figure B-33. Catch data summaries for red hake 2007–2016 in SBNMS from VTR data by month

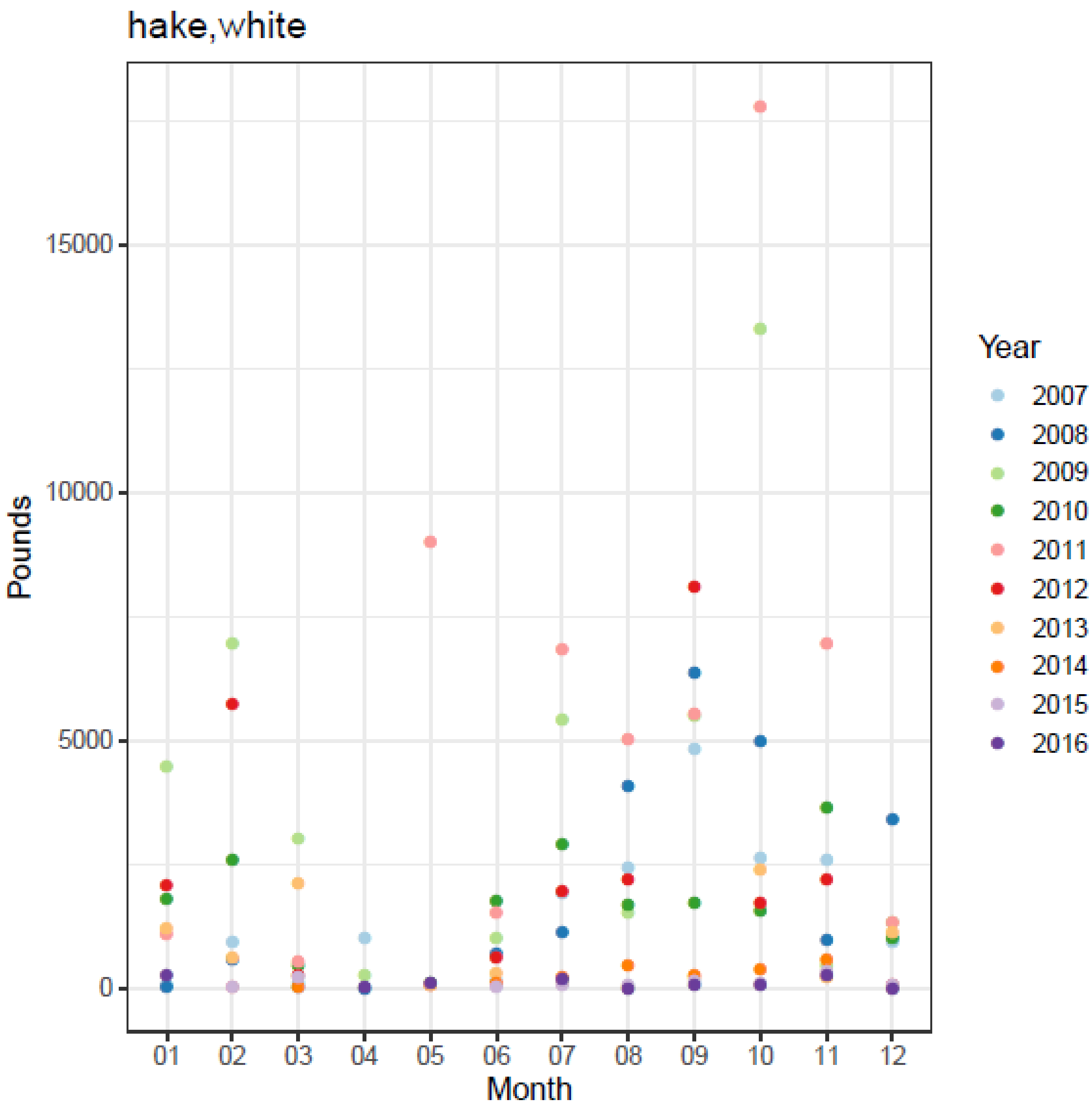

Figure B-34. Catch data summaries for white hake 2007–2016 in SBNMS from VTR data by month

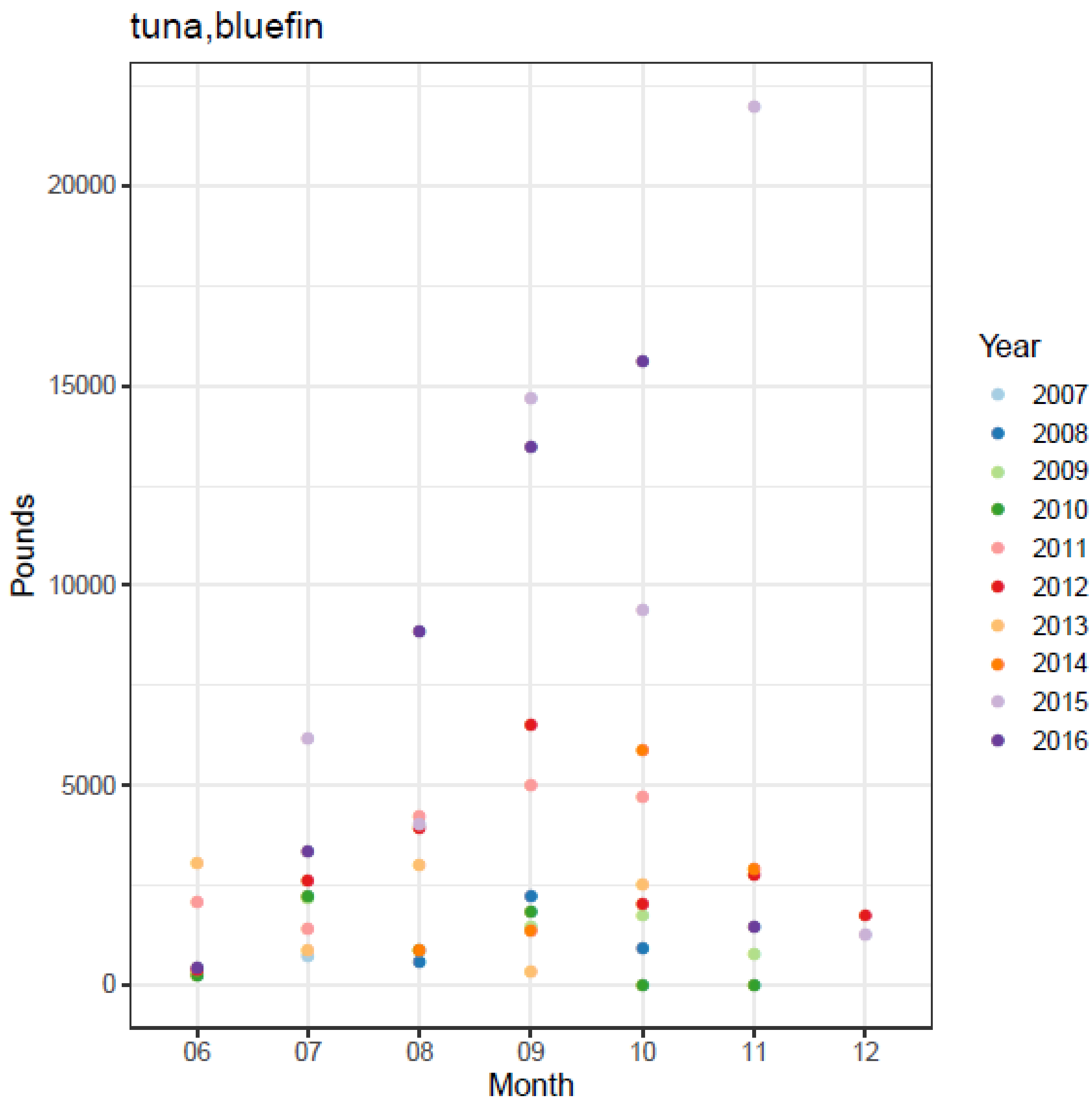

Figure B-35. Catch data summaries for bluefin tuna 2007–2016 in SBNMS from VTR data by month

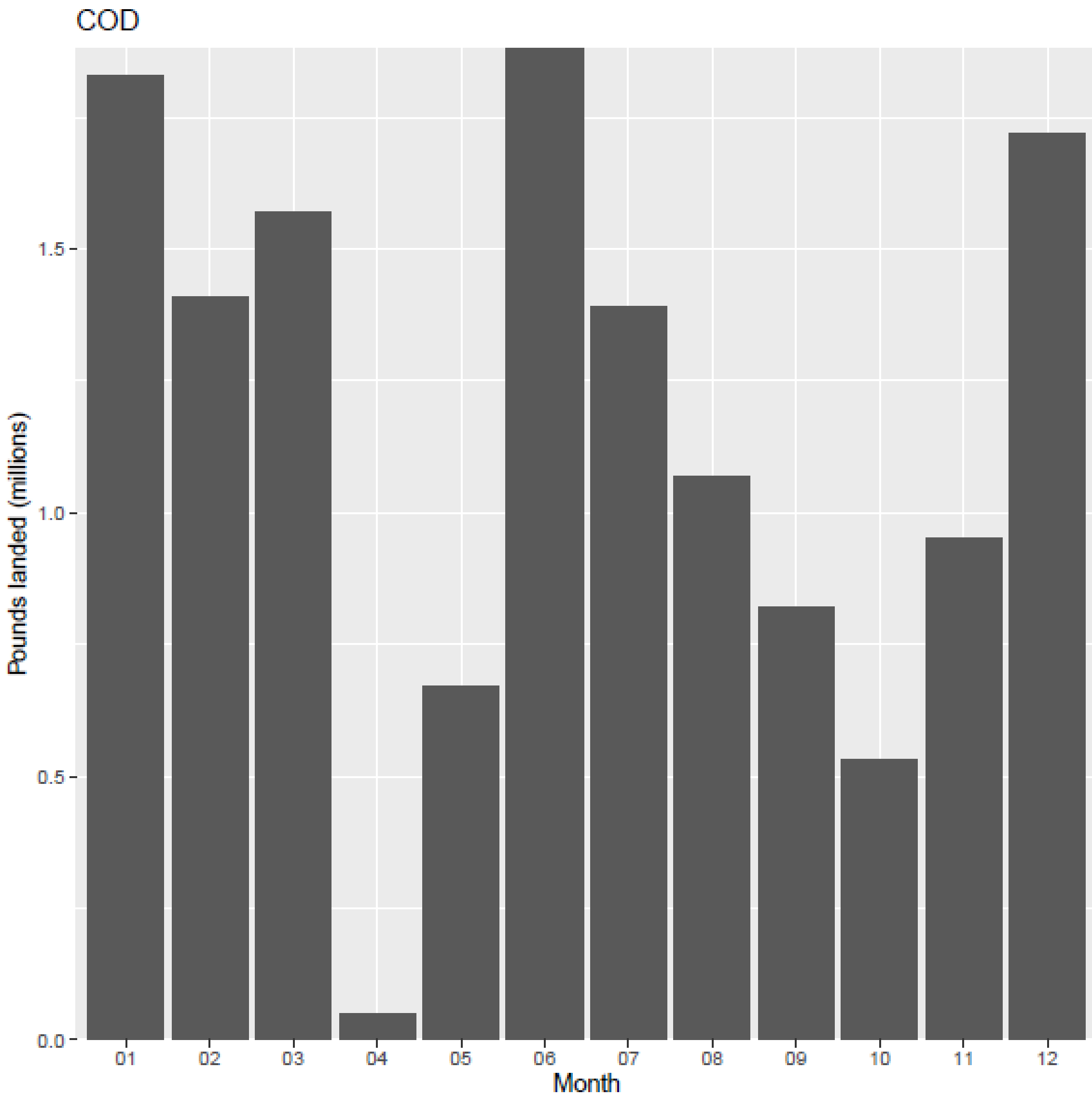

Figure B-36. Millions of pounds of cod caught by month in SBNMS from 2007–2016

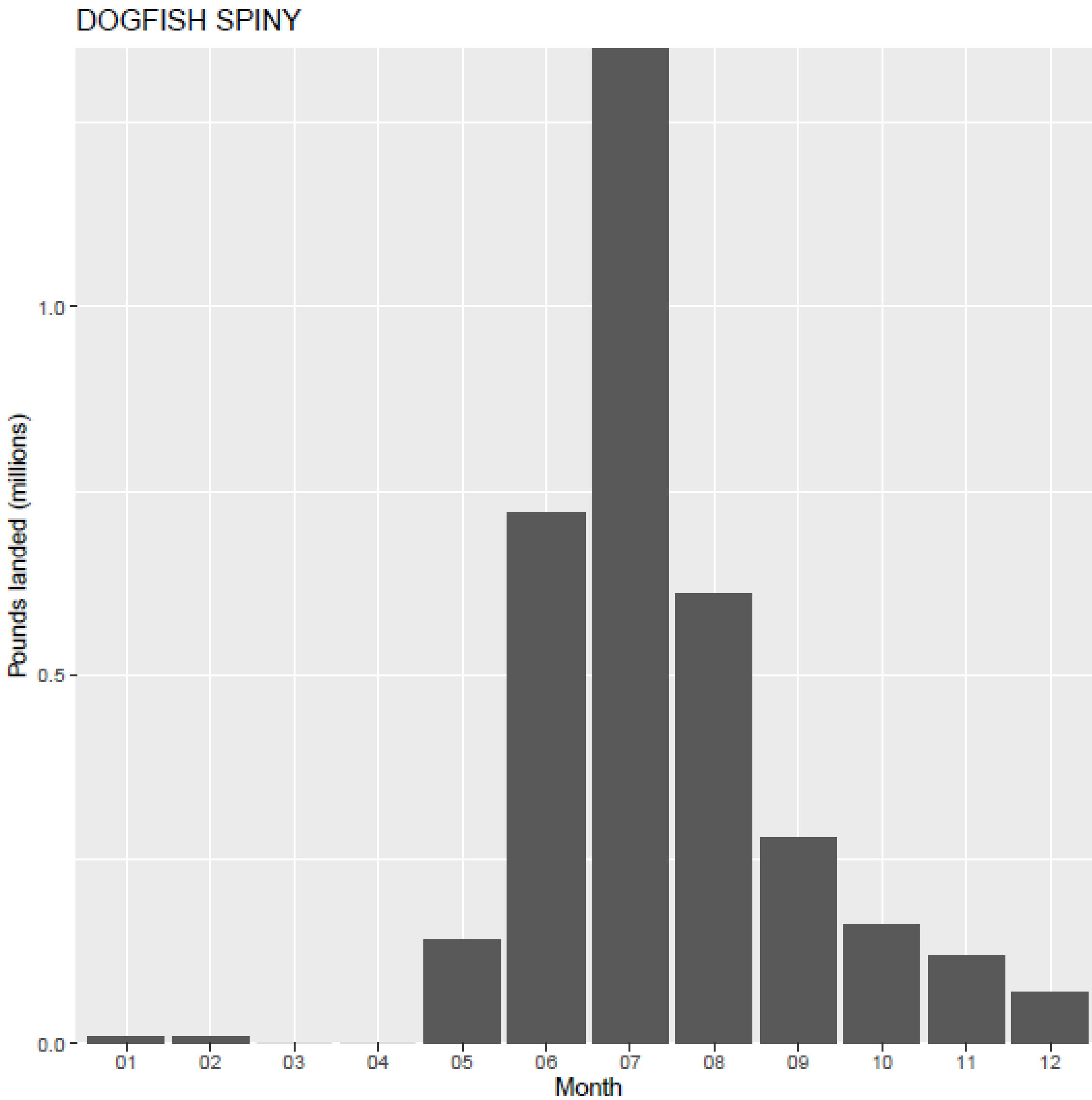

Figure B-37. Millions of pounds of spiny dogfish caught by month in SBNMS from 2007–2016

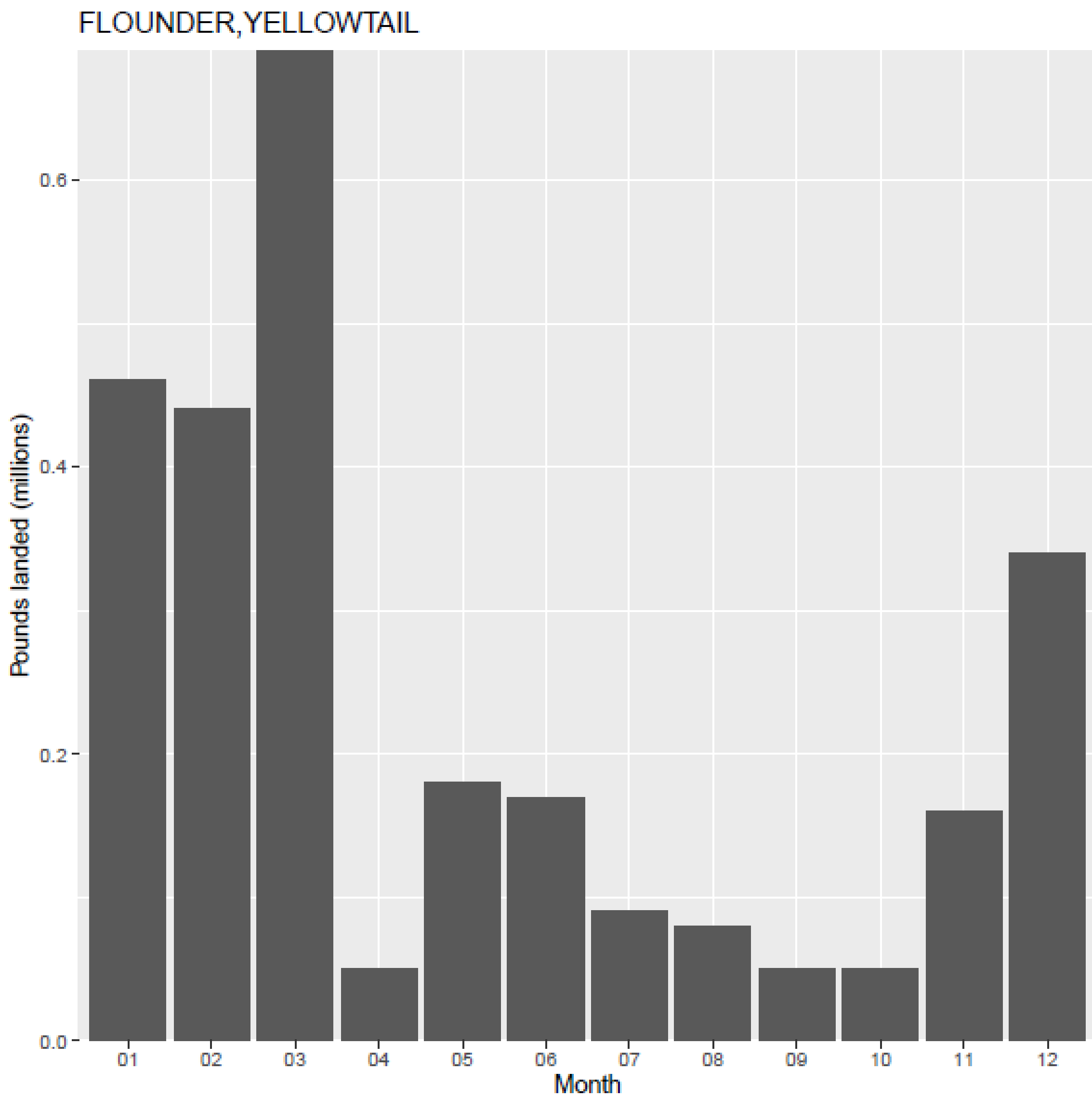

Figure B-38. Millions of pounds of yellowtail flounder caught by month in SBNMS from 2007–2016

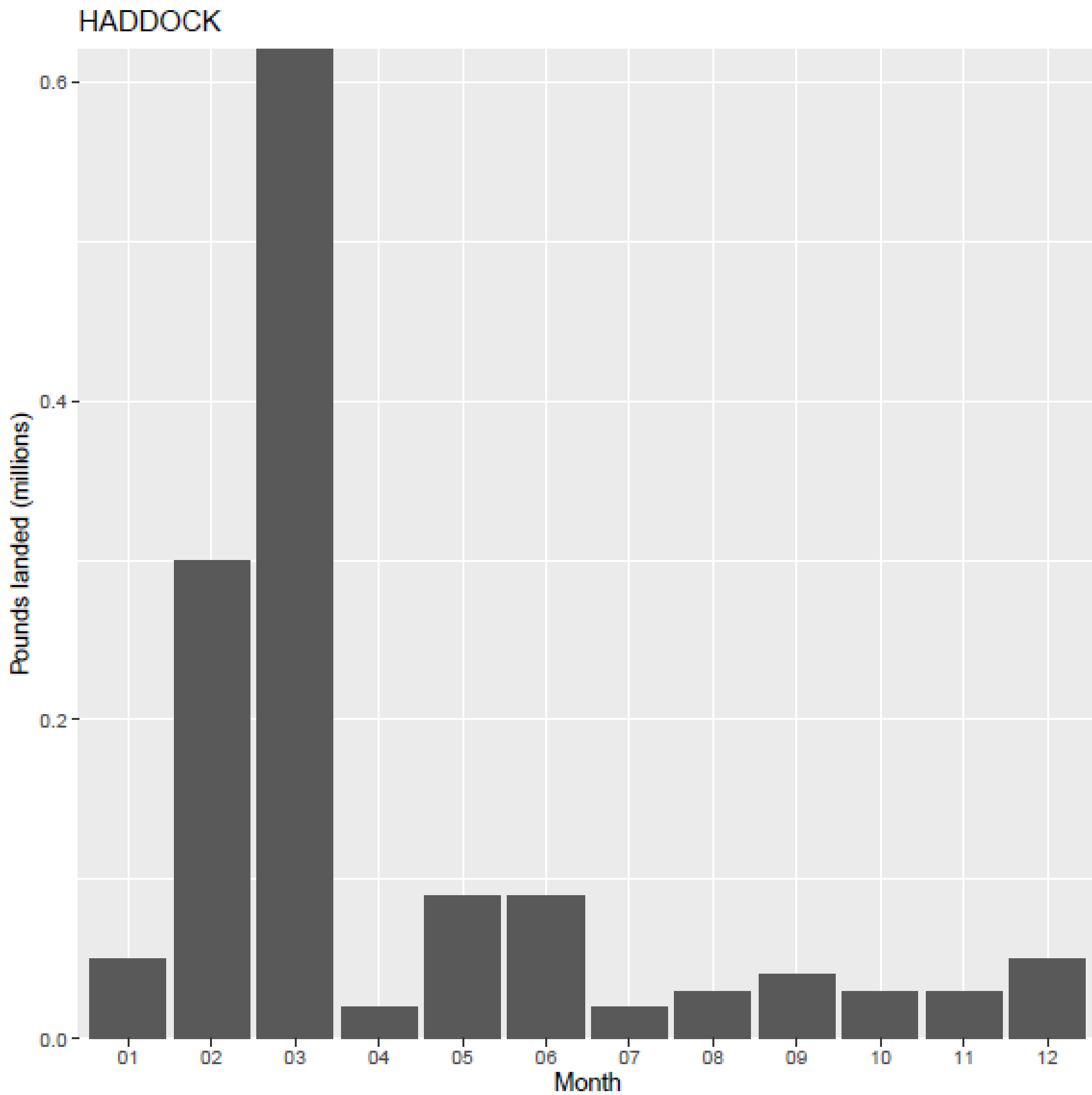

Figure B-39. Millions of pounds of haddock caught by month in SBNMS from 2007–2016

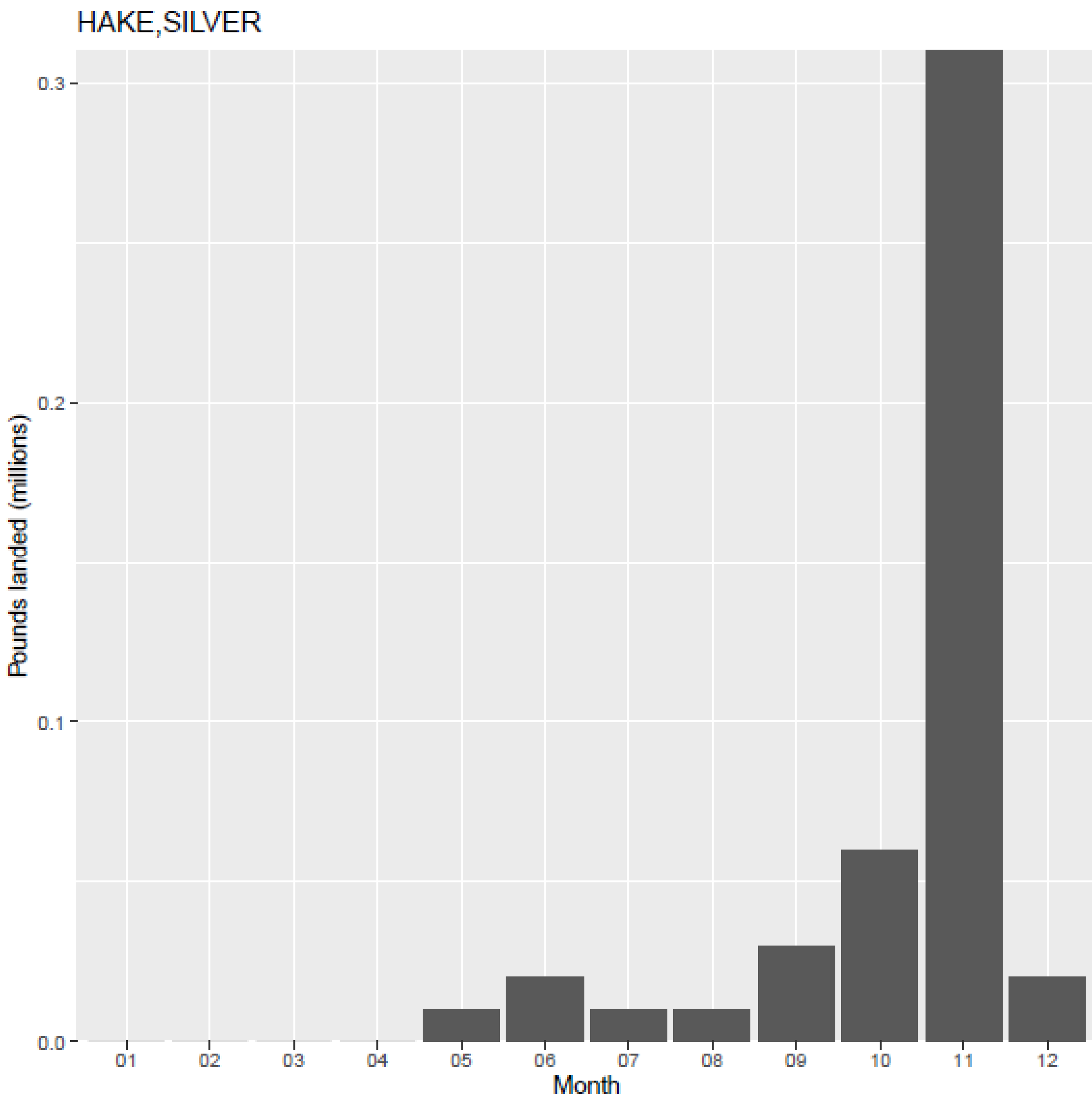

Figure B-40. Millions of pounds of silver hake caught by month in SBNMS from 2007–2016

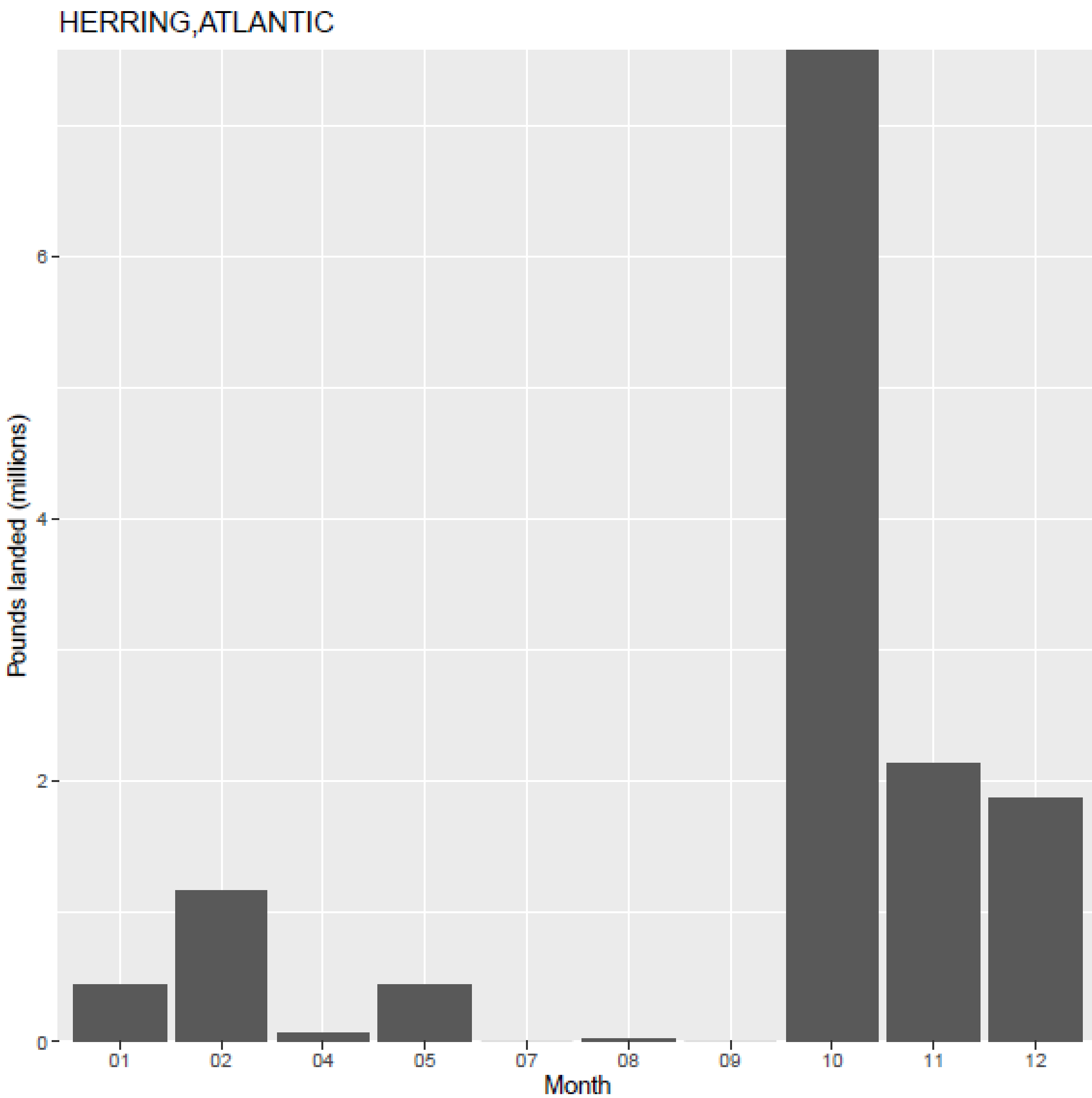

Figure B-41. Millions of pounds of Atlantic herring caught by month in SBNMS from 2007–2016

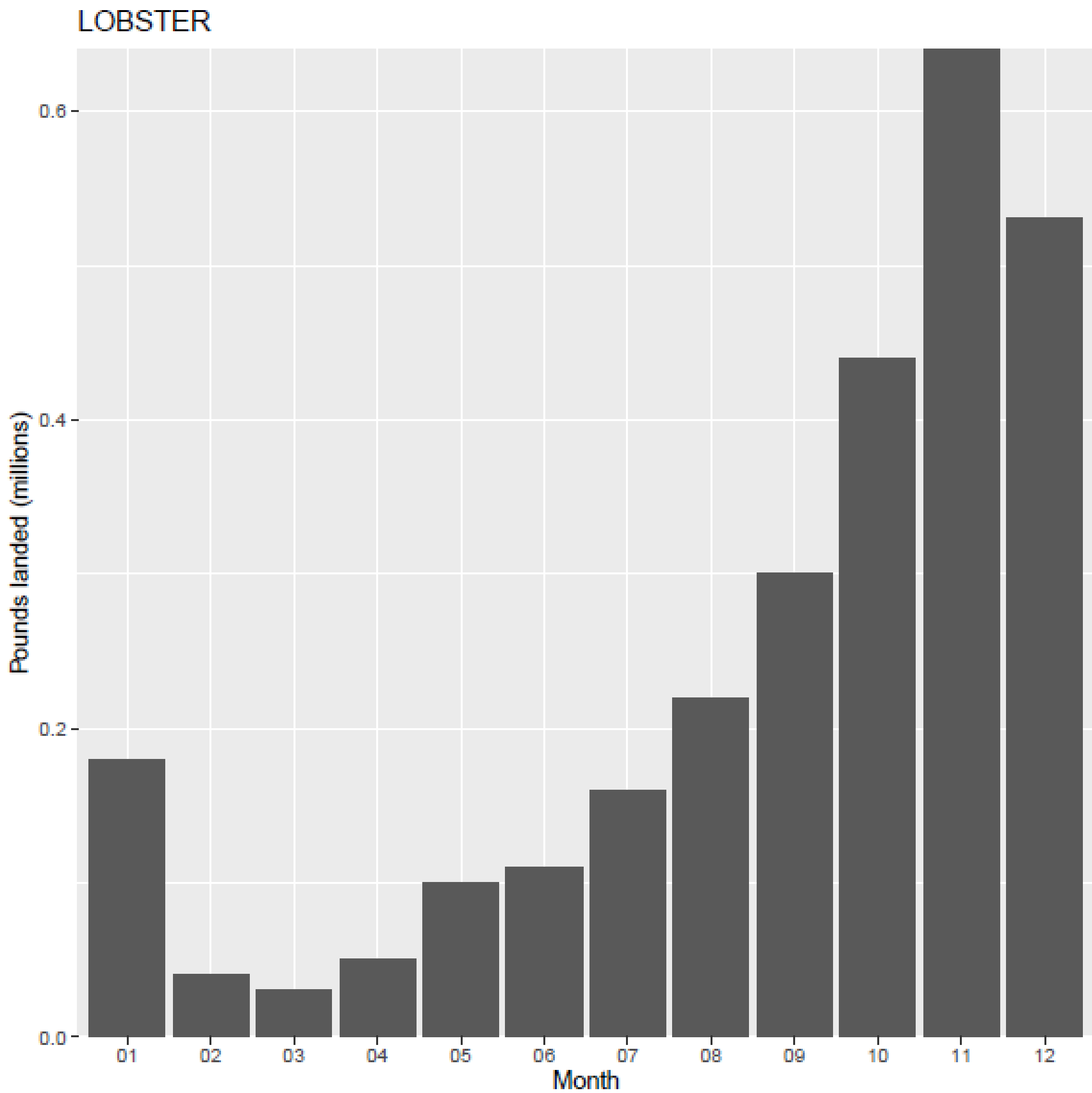

Figure B-42. Millions of pounds of lobster caught by month in SBNMS from 2007–2016

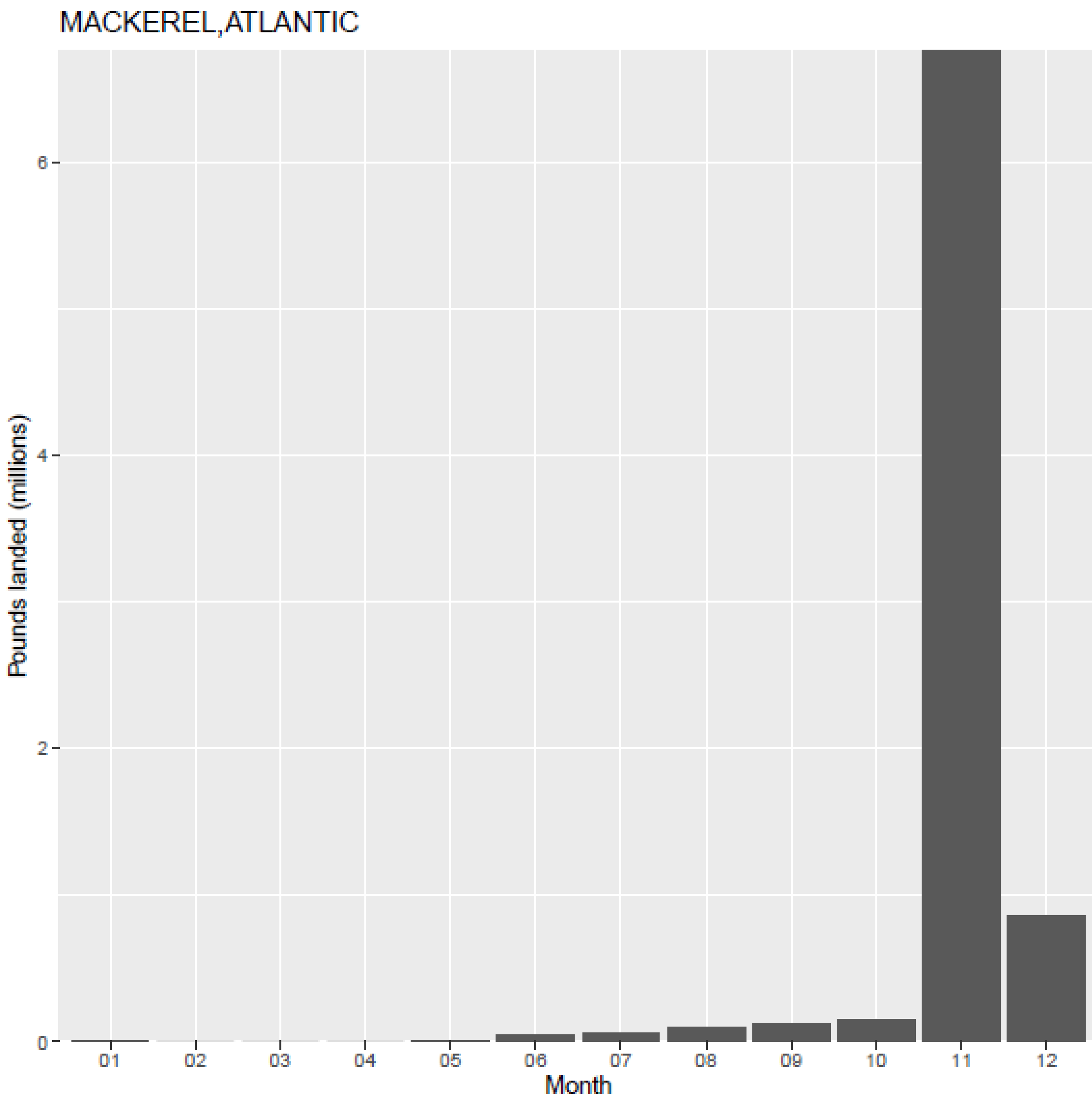

Figure B-43. Millions of pounds of Atlantic mackerel caught by month in SBNMS from 2007–2016

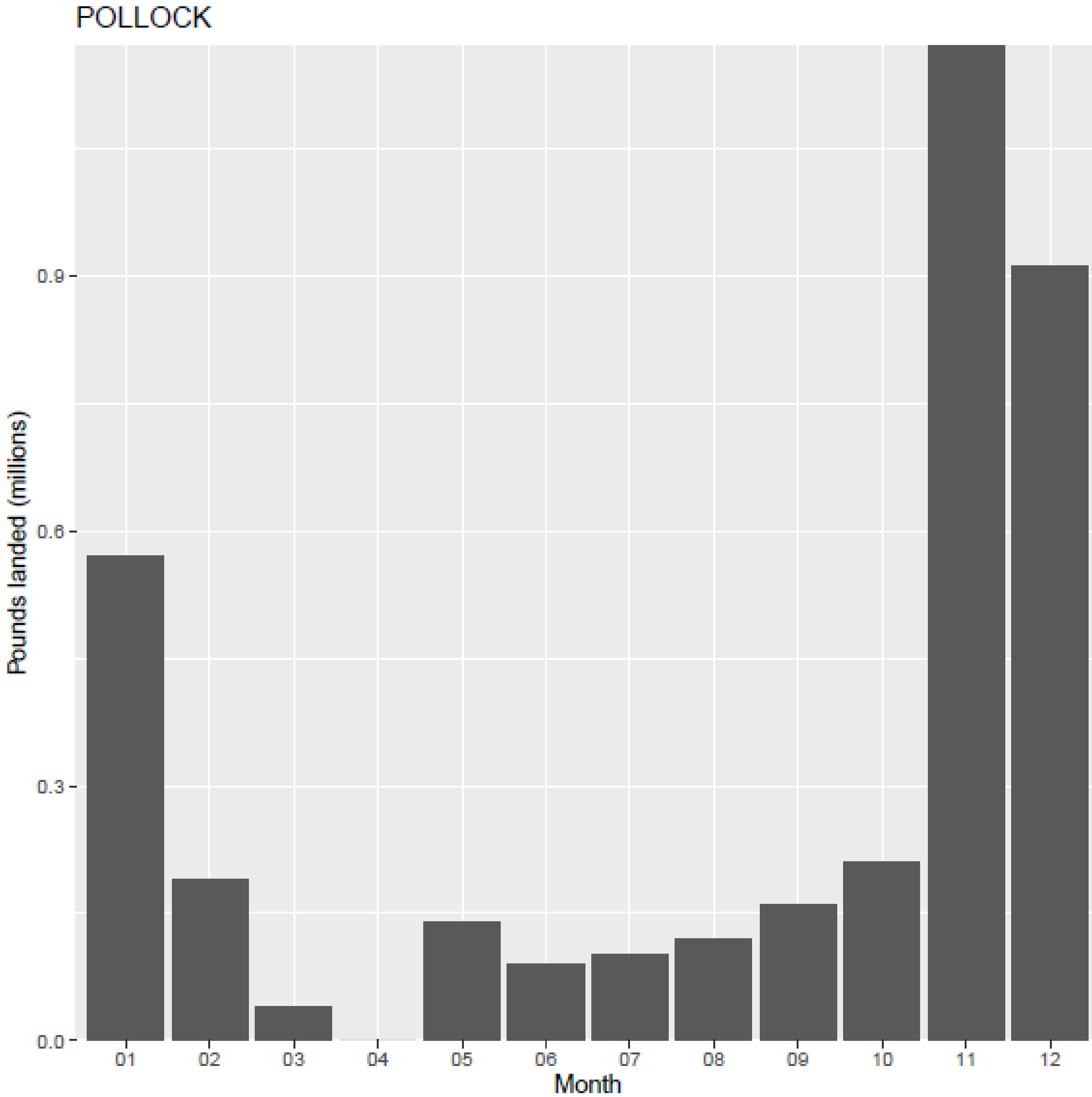

Figure B-44. Millions of pounds of pollock caught by month in SBNMS from 2007–2016

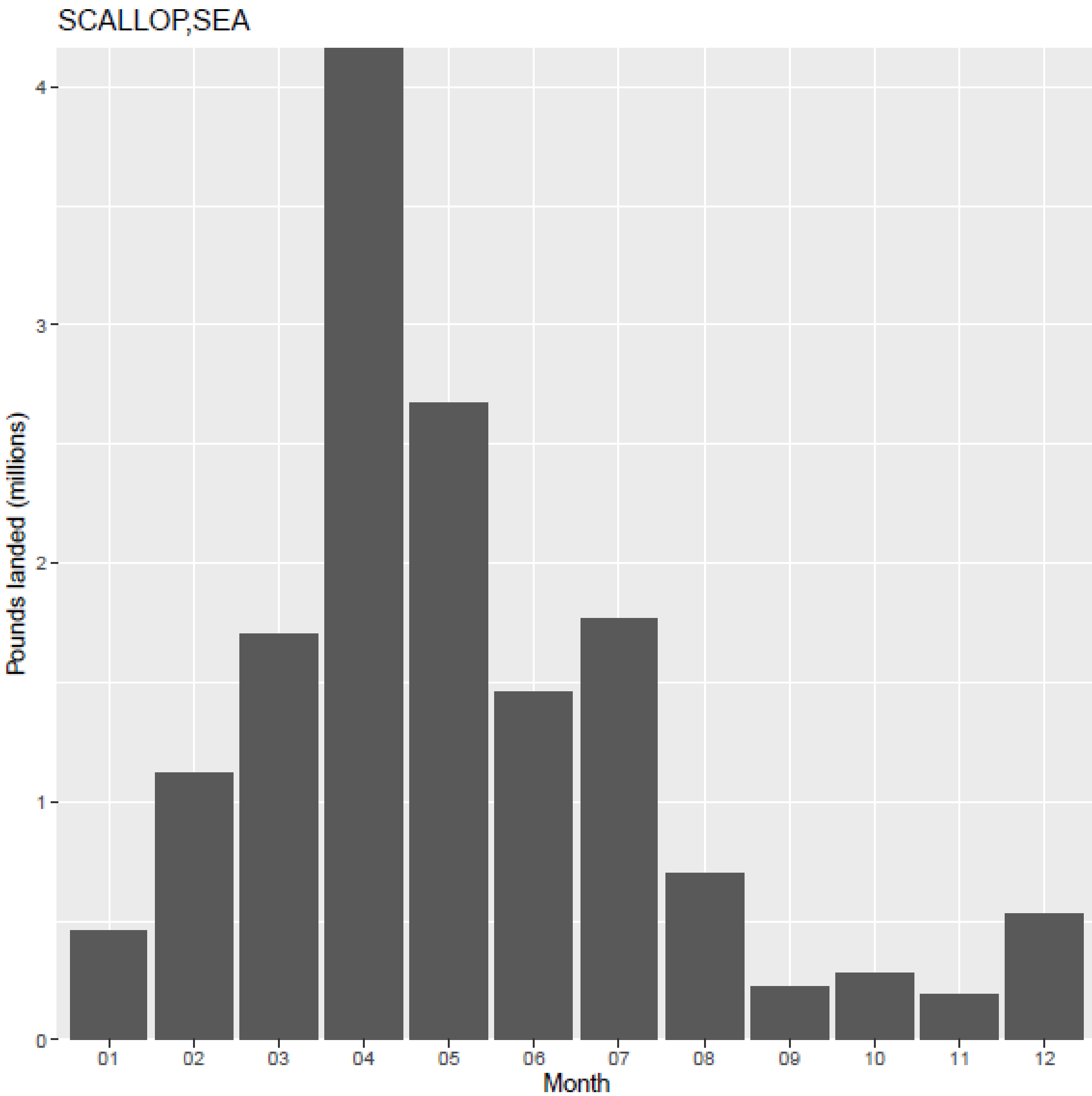

Figure B-45. Millions of pounds of sea scallop caught by month in SBNMS from 2007–2016

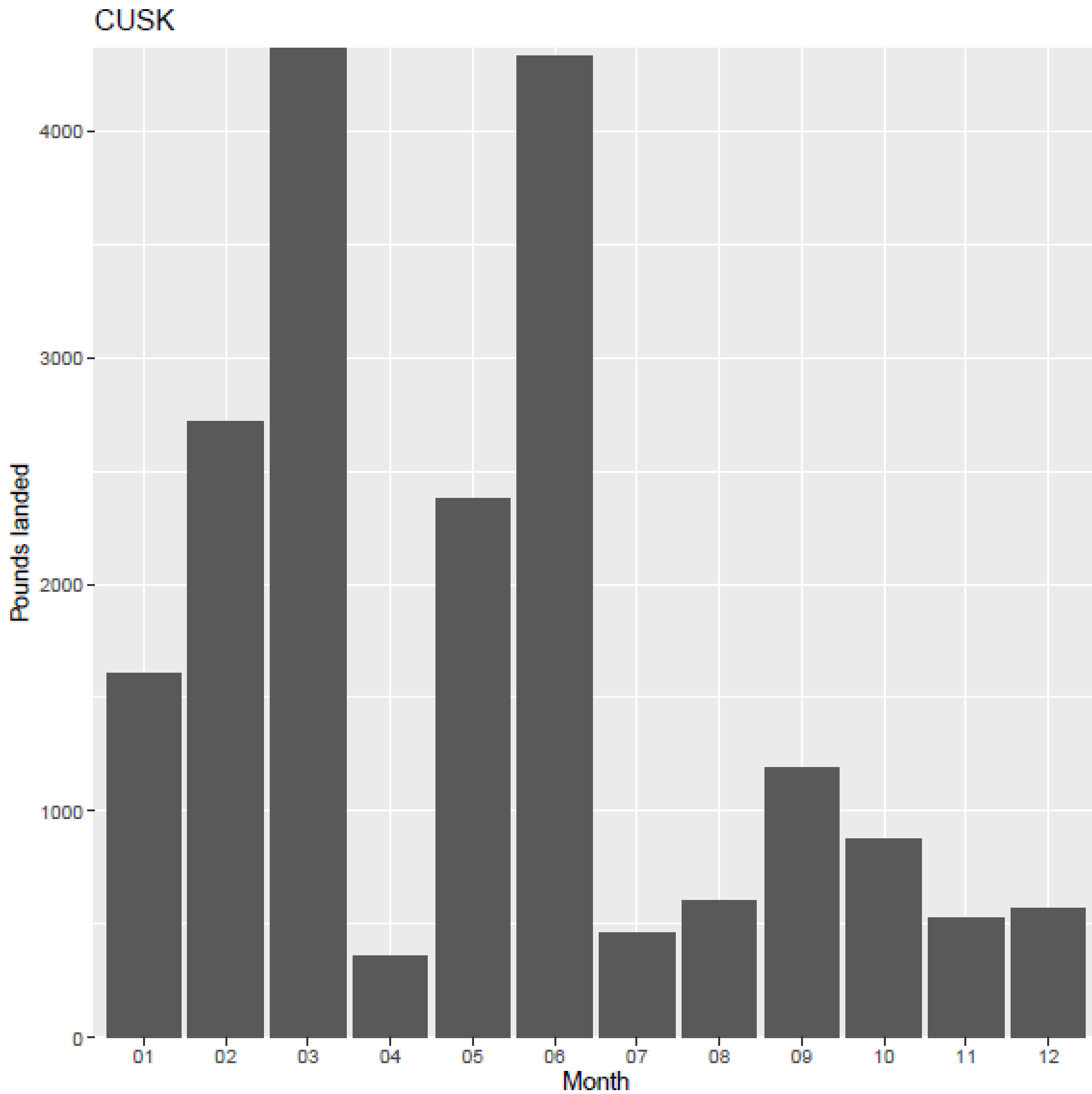

Figure B-46. Millions of pounds of cusk caught by month in SBNMS from 2007–2016

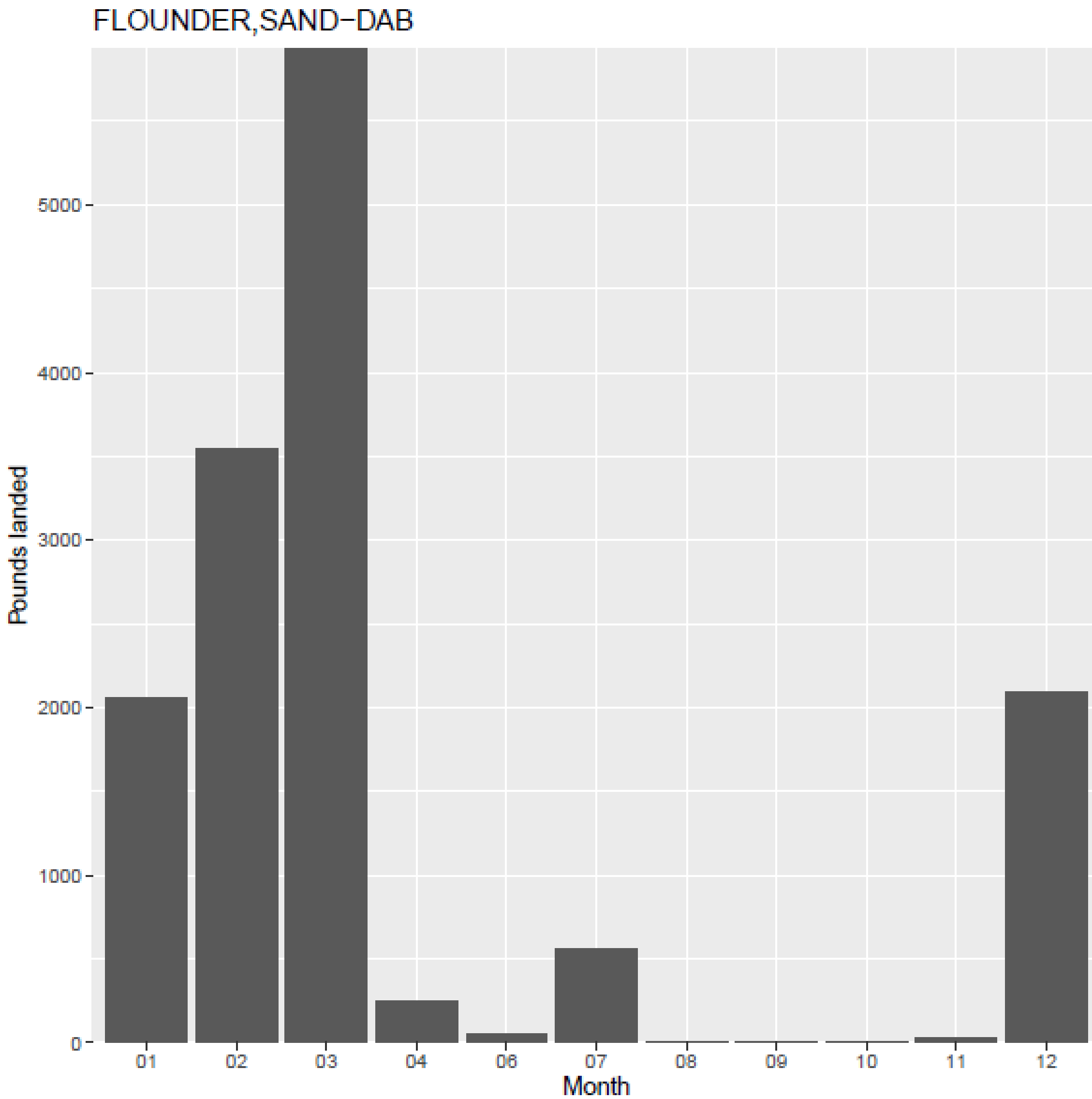

Figure B-47. Millions of pounds of sand-dab flounder caught by month in SBNMS from 2007–2016

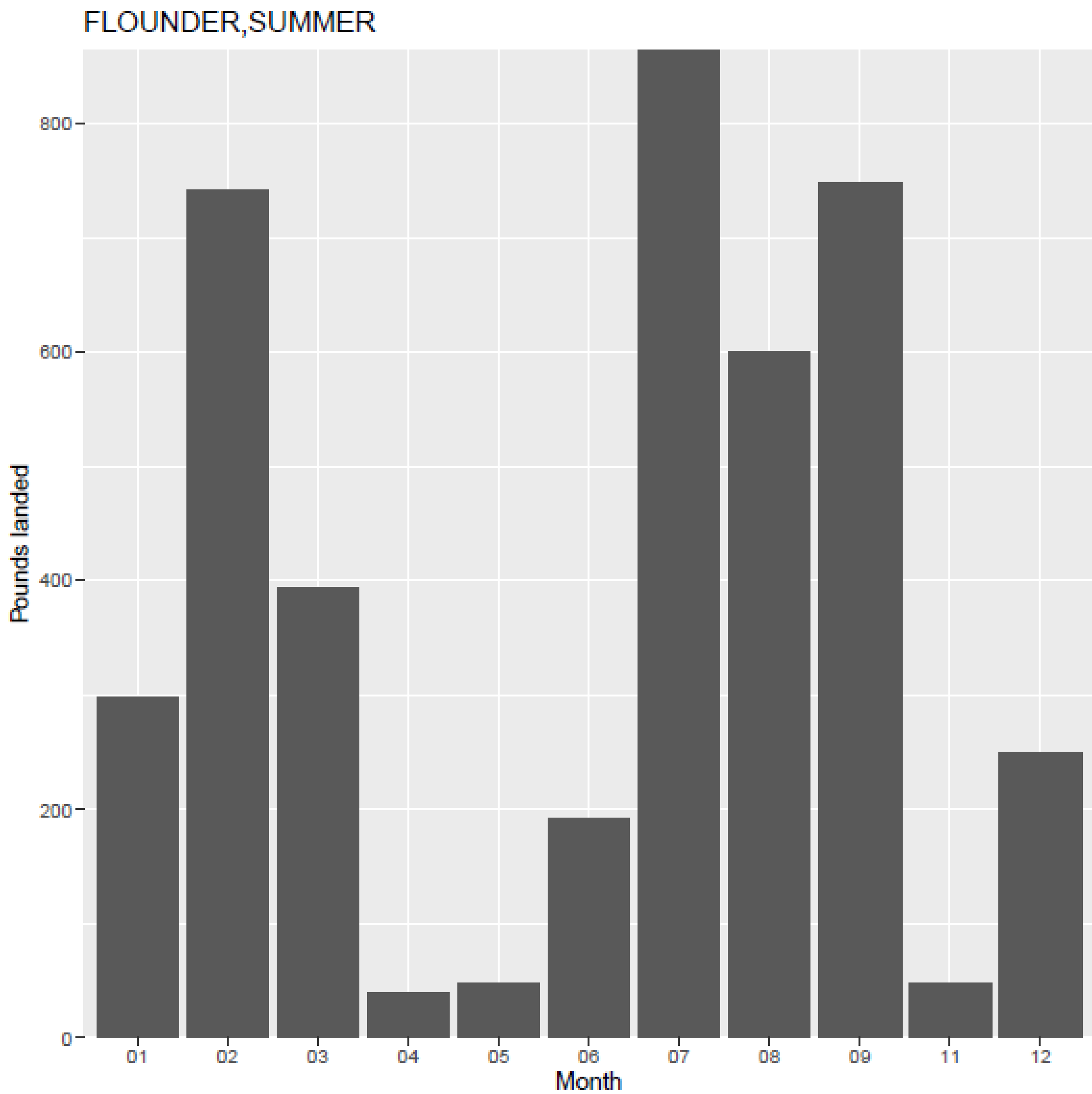

Figure B-48. Millions of pounds of summer flounder caught by month in SBNMS from 2007–2016

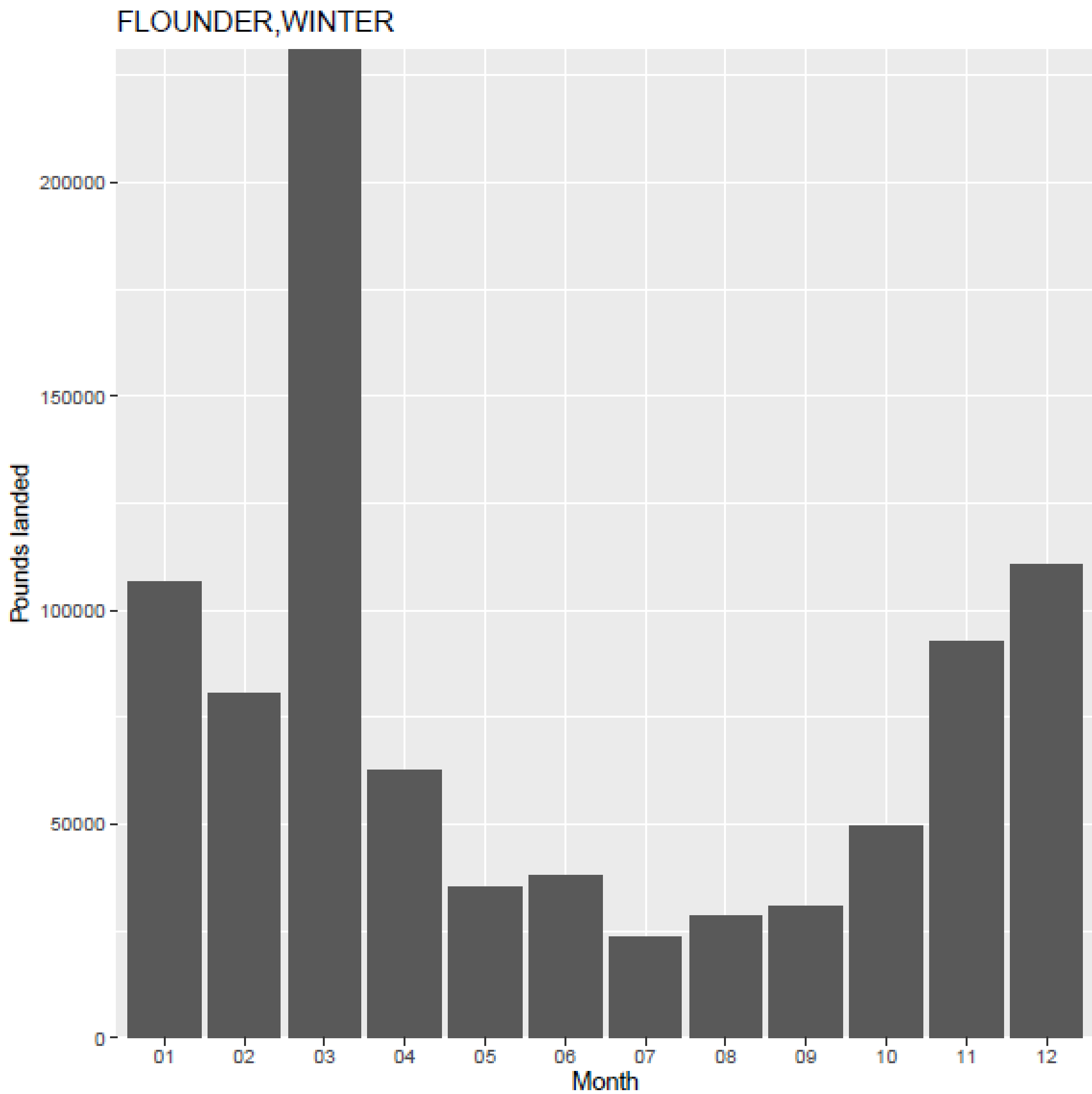

Figure B-49. Millions of pounds of winter flounder caught by month in SBNMS from 2007–2016

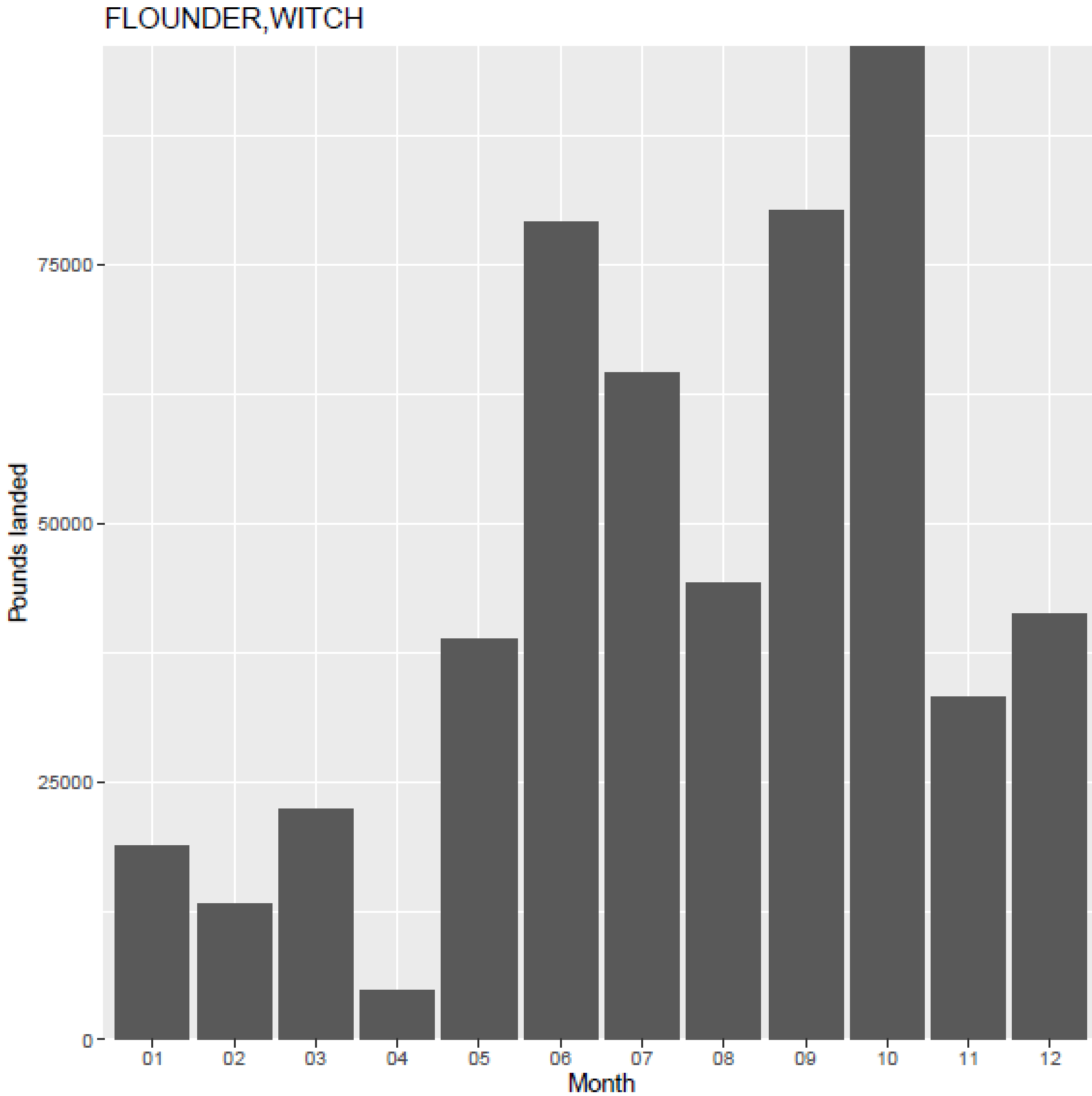

Figure B-50. Millions of pounds of witch flounder caught by month in SBNMS from 2007–2016

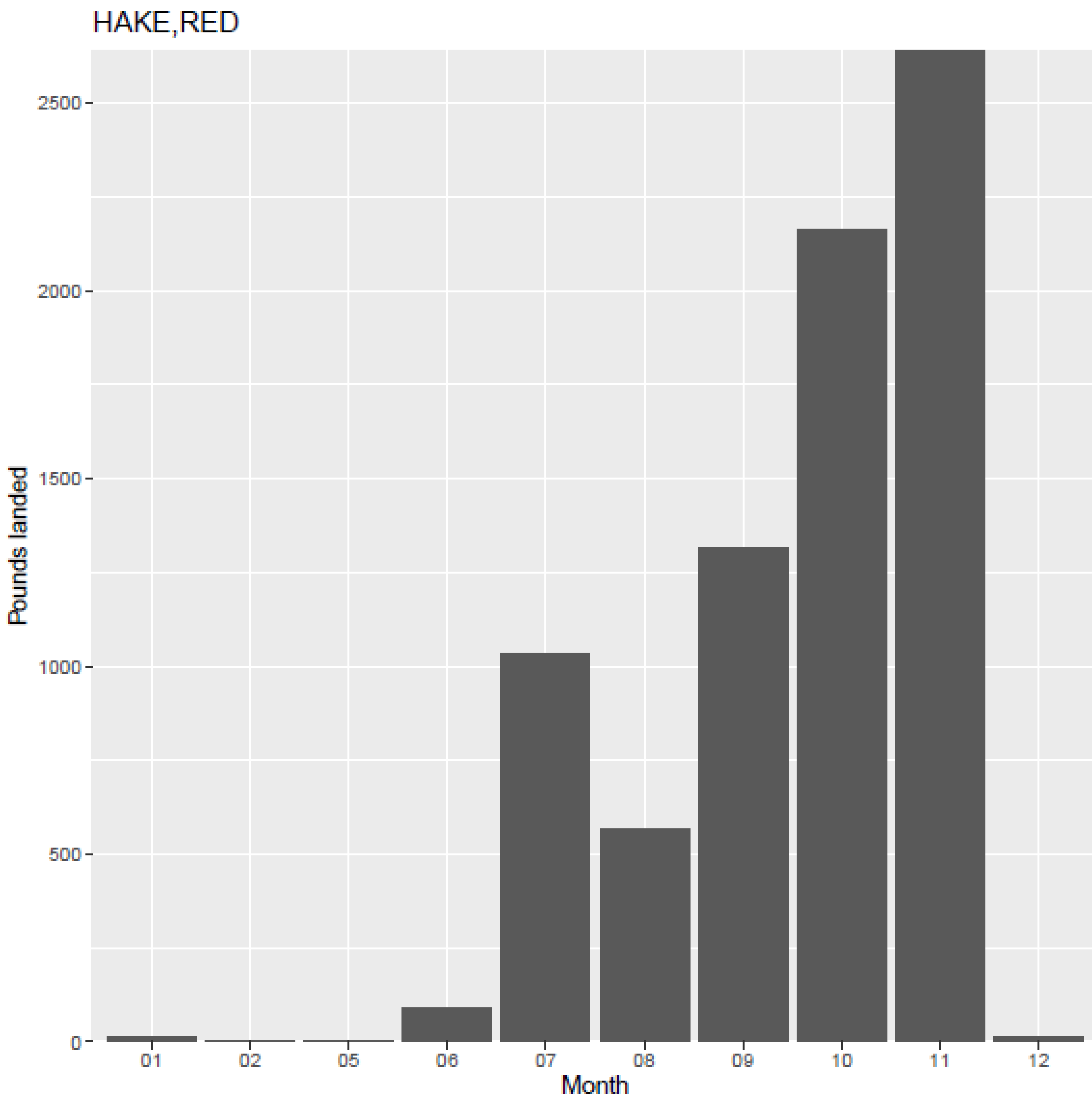

Figure B-51. Millions of pounds of red hake caught by month in SBNMS from 2007–2016

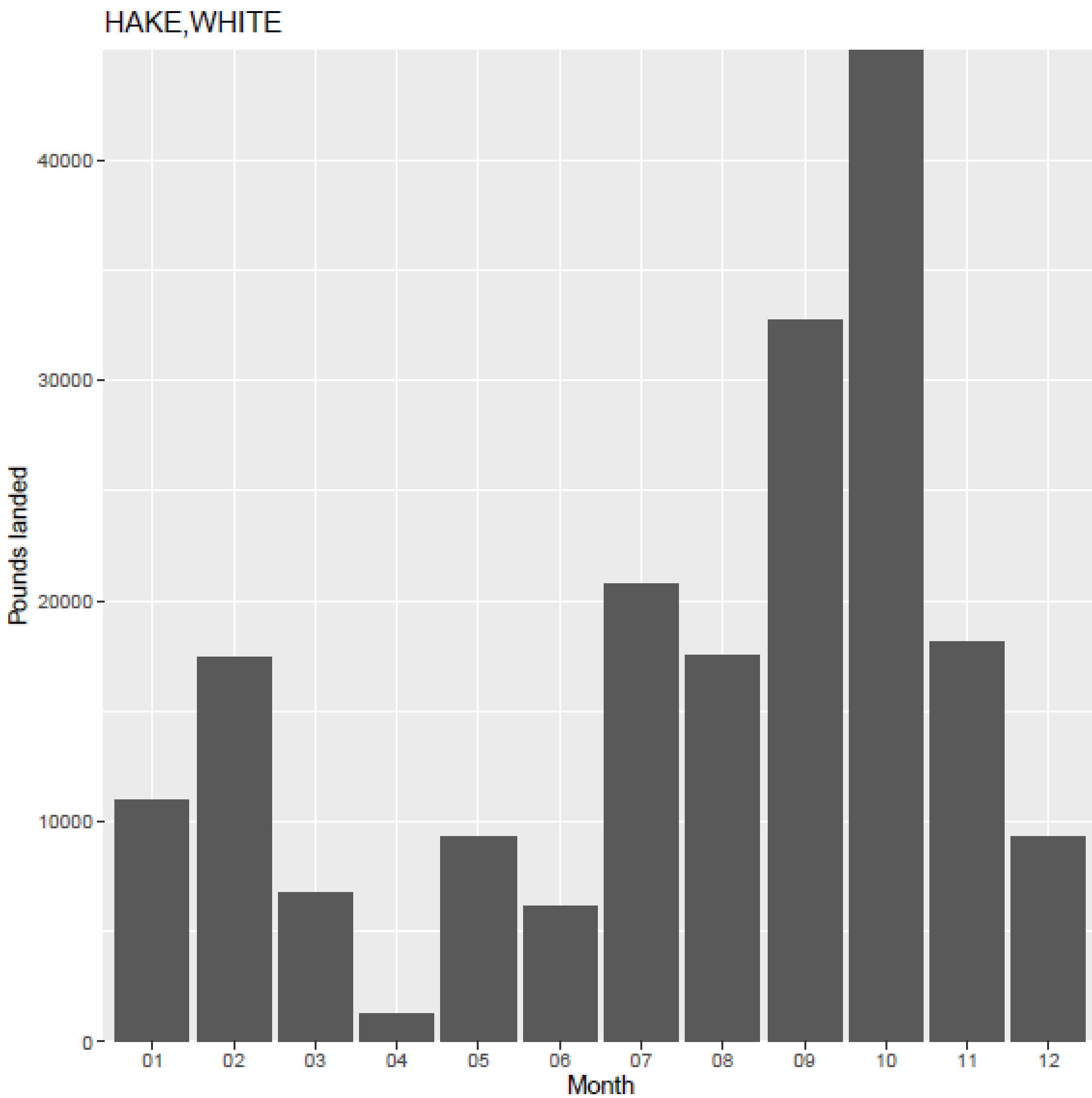

Figure B-52. Millions of pounds of white hake caught by month in SBNMS from 2007–2016

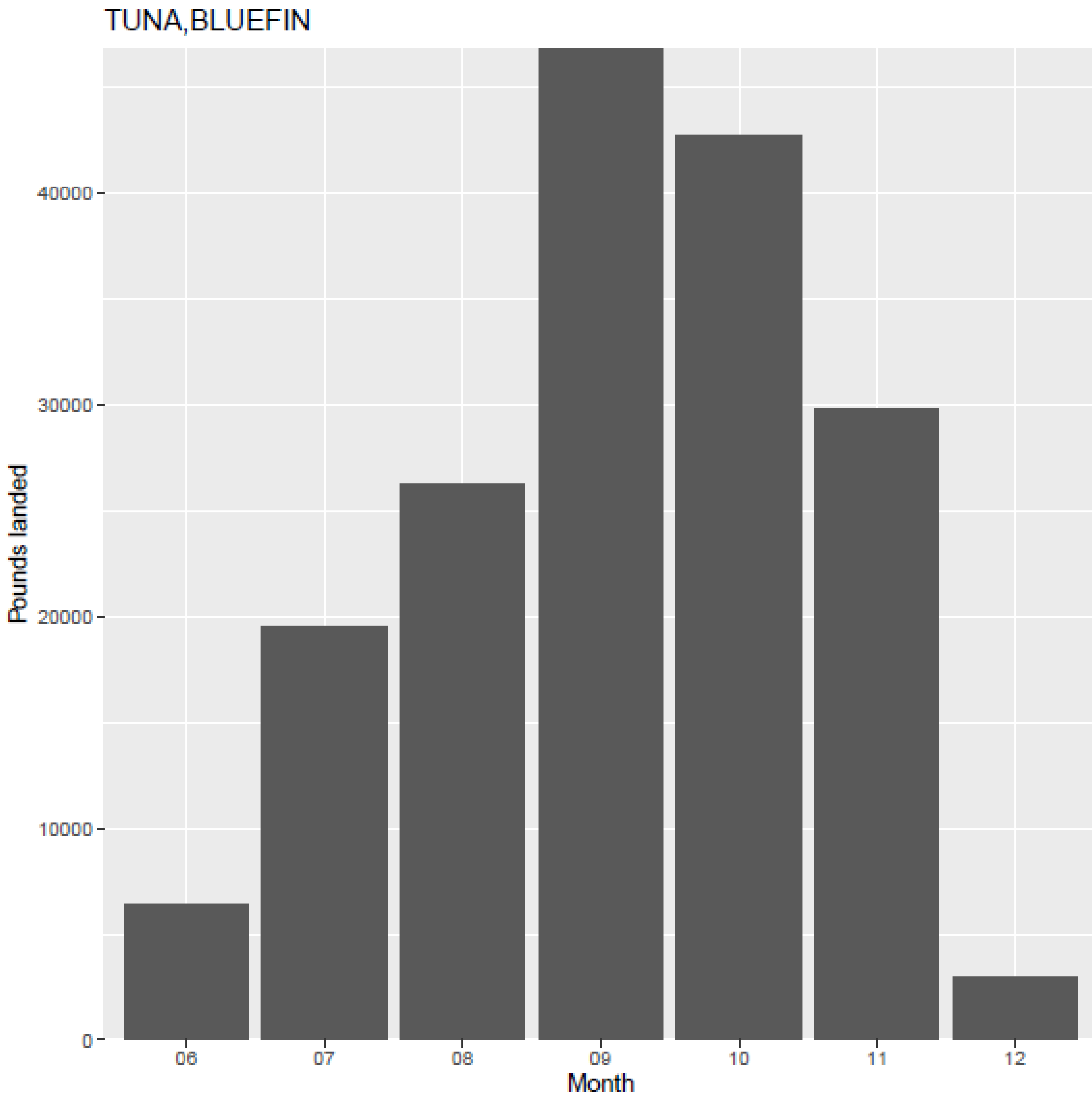

Figure B-53. Millions of pounds of bluefin tuna caught by month in SBNMS from 2007–2016

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