Ph.D. Dissertation Project Overview: Quantifying Spatio-Temporal Responses of Marine Ecosystems to Climate Change and Other Anthropogenic Habitat Modifications to Facilitate Adaptive Management Strategies

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1 Summary

My dissertation research is focused on the spatio-temporal responses of the marine ecosystem to climate change to improve forecasts of species distributions and adapt responsive management practices. I am particularly interested in understanding the trade-offs in model architecture and different surveys that affect bias and accuracy in spatio-temporal predictions at various scales. I want to use this information to recommend options for alternative sampling designs and modeling architectures that support adaptive management strategies and future planning efforts.

Currently, I am building a spatio-temporal model of Atlantic menhaden to understand the factors influencing population response at various scales, while comparing model architectures (VAST, R-INLA) and using multiple sources of data. In the future, I will forecast menhaden distribution under various climate change and offshore wind development scenarios.

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2 Background

Marine species are responding to dramatic changes in the marine environment caused by climate change through adaptation, mortality, or movement, and these responses can be tracked by understanding how the spatial distribution of a population may be changing. When we properly characterize the spatio-temporal distribution and abundance of species, we can reveal the underlying ecosystem processes that influence its population and community dynamics. Species distribution models (SDM) that account for unmeasured variables and processes (i.e. latent variables or random effects), including spatial autocorrelation (neighboring samples are more similar to each other than those that are farther apart), can reduce the bias in population models and improve the accuracy of predicting species distributions under future seascape scenarios (e.g., climate change scenarios, offshore wind development). These models can also be used to explore and address situations where species may not be appropriately captured by a fixed survey, either temporally or spatially, as a result of a changing ecosystem. For example, species movements to deeper waters, latitudinal shifts outside a survey region, or shifts in the timing of seasonal migrations.

Forage fish (juvenile fish and small pelagic fishes) are important prey for large pelagic and protected species; their populations are sensitive to environmental conditions, but their spatial distributions are often overlooked. I am currently using Atlantic menhaden, *Brevoortia tyrannus*, as a case study. Menhaden are planktivorous schoolers found in coastal waters from Florida to Nova Scotia and are important prey to fish, birds, and marine mammals (Figure **??**). Menhaden spend the winter off the southeastern US coast and move north in spring. In the summer, they stratify and school by age/size, and older fish move farther north until the late summer when they migrate south again. Following many forage fish population characteristics, menhaden population has cycles of increasing and decreasing abundance. Menhaden abundance peaked in the 1950s and then decreased precipitously, maintaining a relatively low abundance through the 1980s. Since the 1990s, abudance has trended to increase, with abudance in recent years being more similar to the 1950s (Figure 3). Spatially, abundance patterns across the coast are not temporally even, where increased abundance was in the south in the 70s-90s, then in the north in the early 2000s (Buchheister et al., 2016). There is anecdotal evidence that menhaden abundance has increased in the NY Bight region in recent years.

3 Research Questions

1. What drives the distribution and abundance patterns of Atlantic menhaden and other forage fishes?
2. What is the forecasted distribution of Atlantic menhaden and other forage fishes under different climate scenarios and offshore wind development plans, and what are the potential impacts on the ecosystem and management of these fisheries?
3. How could fisheries management adapt to changing distributions? What adaptive management strategies could be considered for future planning (e.g., modeling frameworks, survey designs, time-area closures)?

4 Goals (January 2021 - January 2022)

1. Build a functioning spatio-temporal model in R-INLA and VAST that predicts the distribution of menhaden by depth and bottom temperature to identify drivers of distribution patterns (to complete in September 2020).
2. Compare the bias and accuracy and evaluate tradeoffs between INLA and VAST models to evaluate efficacy and implementation of model frameworks for distribution (to complete in Fall 2020).
3. Acquire and prepare survey data for Atlantic menhaden model (biological survey data and environmental data). Identify procedural pathways and challenges to address (to complete in Fall 2020).
4. Compare the bias and accuracy and evaluate trade-offs in including different survey sources and scales in distribution models to evaluate the value of different data (to complete in Fall 2020).

5 Recent Accomplishments

1. Model of the distribution of Atlantic menhaden 2007-2019 in VAST, by season, covarying with depth and bottom temperature, without an interaction. Data include NEAMAP and unscrutinized NEFSC data.
2. Preparing to present at November AFS meeting.
3. Outlined manuscript for publishing this research.

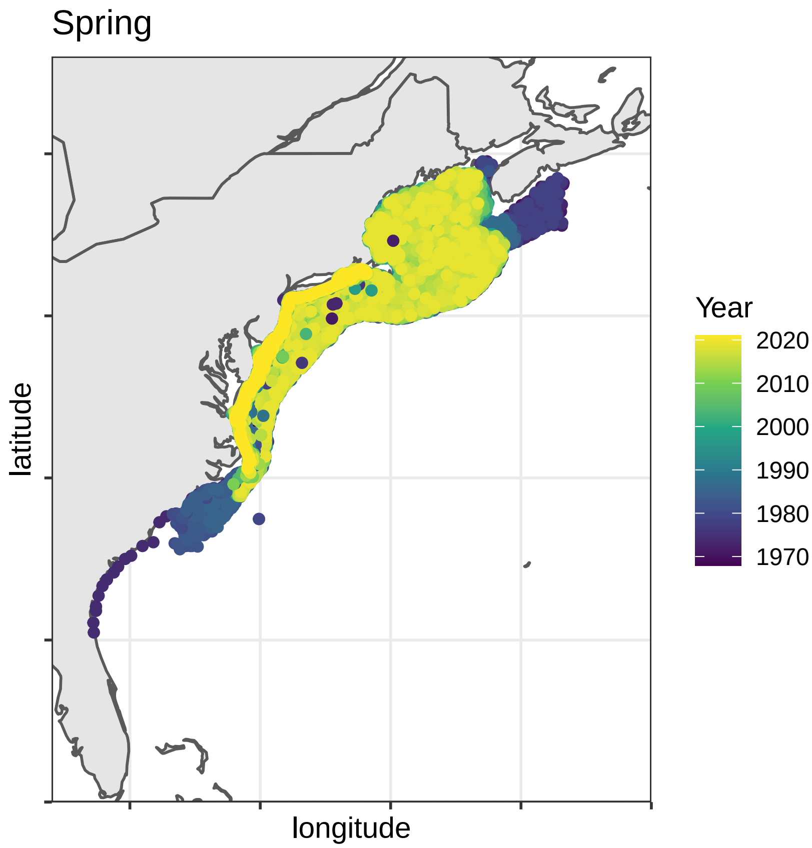

Figure 1: The distribution of sampled menhaden in the NEFSC bottom trawl surveys, 1963-2019, and the NEAMAP bottom trawl surveys, 2007-2020. Note that recent years are plotted on top of past years, which may obscure contractions or expansions of the range in past years.

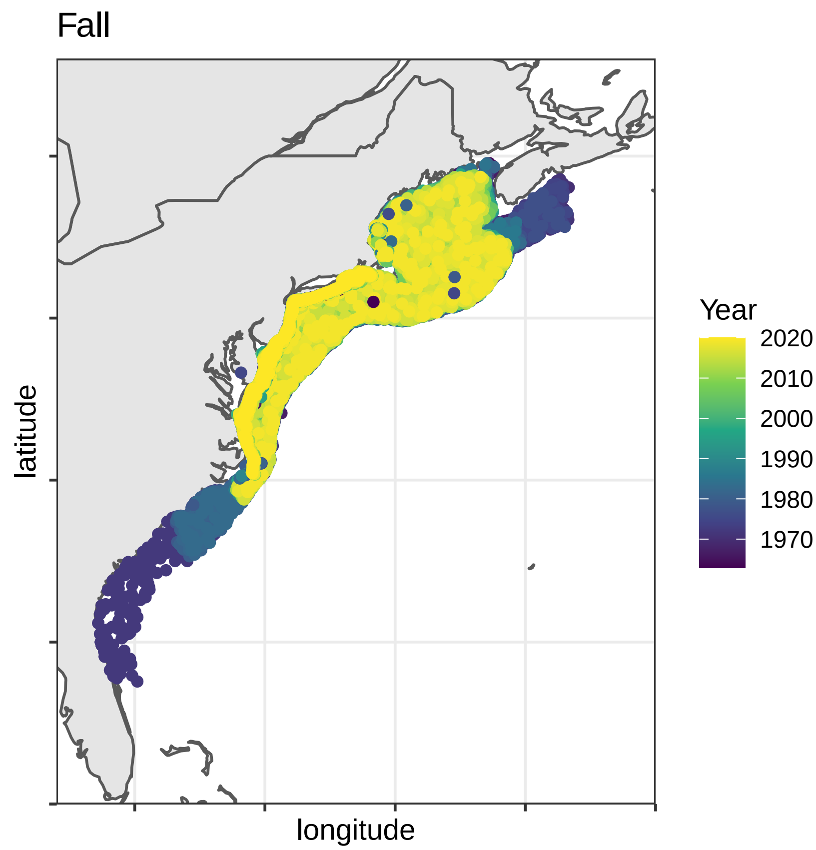

Figure 2: The distribution of sampled menhaden in the NEFSC bottom trawl surveys, 1963-2019, and the NEAMAP bottom trawl surveys, 2007-2020. Note that recent years are plotted on top of past years, which may obscure contractions or expansions of the range in past years.

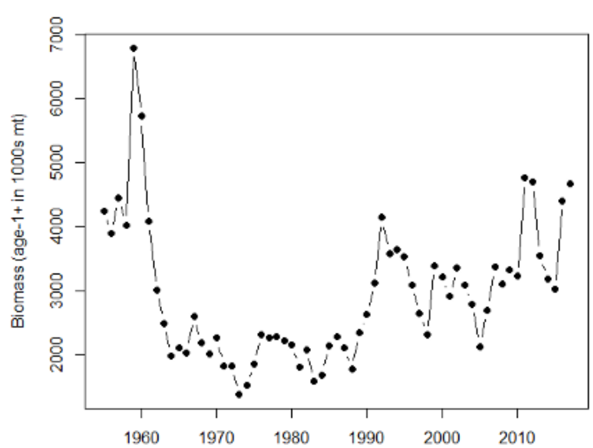

Figure 3: **Biomass of age 1+ Atlantic menhaden stock, 1955-2017. Reproduced from SEDAR (2020).**

6 VAST Model of Distribution

The model built in VAST is an index of abundance model that predicts the abundance as average catch over years and locations. This model uses data from the Northeast Fisheries Science Center (NEFSC) spring and fall bottom trawl surveys, 1963-2019, and the Northeast Area Monitoring and Assessment Program (NEAMAP) near shore trawl, 2007-2020. For this model, the data are limited to overlapping years, 2007-2019.

The biomass of menhaden varies over the years (Figure **??**)

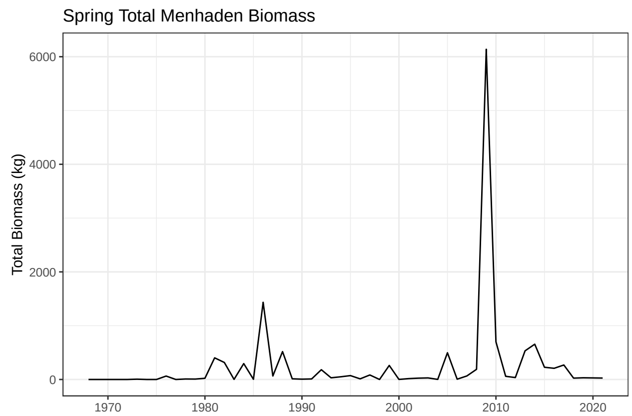

Figure 4: Total biomass of Atlantic menhaden NEFSC bottom trawl surveys, 1963-2019, from the Spring survey.

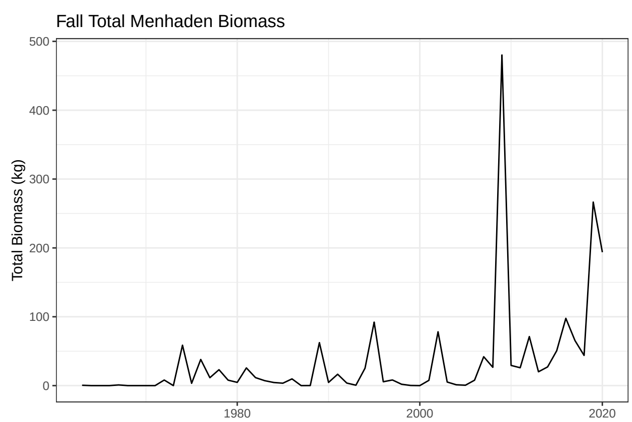

Figure 5: Total biomass of Atlantic menhaden NEFSC bottom trawl surveys, 1963-2019, from Fall survey.

The estimates of abundance and distribution are made over the extrapolation grid that encompasses the sampled area (Figure 6). The knots (red dots) are used as computational points (Figure 6).

For each sampled year of the NEFSC bottom trawl survey, 1963-2019, the Atlantic menhaden abundance is estimated across the sampled area. Note that these data are not verified as including all appropriate years and survey sites, and these data are pooling the spring and fall surveys into a single year. Thus, these results should be interpreted only as a preliminary understanding of the model output and should not be considered a representation of the actual ecology of menhaden. Given these caveats, in general, the distribution has changed periodically, with years of low abundance or absence in the north (Figure 8). Menhaden are most abundant along the coast, with localized abundance offshore around Georges Bank and a localized absence in the NY Bight. More work is needed to examine this.

To quantify the change in the distribution of species, there are a few metrics that VAST calculates by default. The first is center of gravity, which is the mean spatial location of the sampled population, weighted by

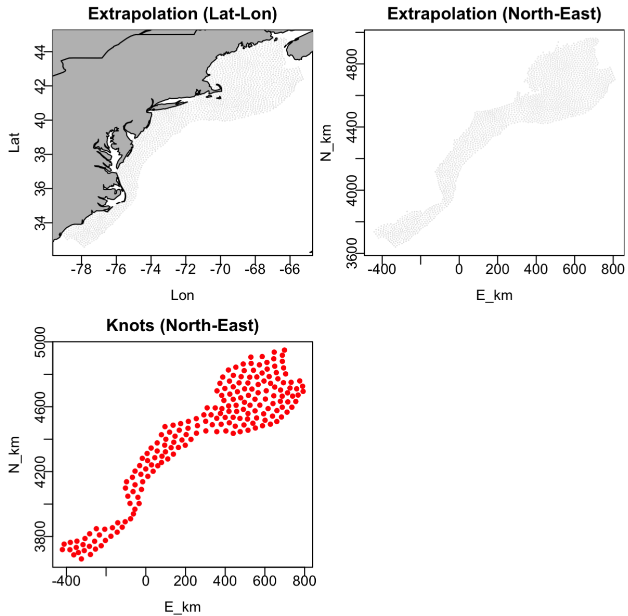

Figure 6: **Area the abundance is being predicted over and the number of knots used to calculate over the surface.**

biomass (Figure 10). This measure is most effective at assessing change over time if the distribution across the range is more homogenous and so it is unclear if this measurement is the most appropriate for this population. However, looking at the trend in recent years, there may be some movement more west and north, which could be interpreted as more coastal towards the north.

The second metric is the distributional range edge, which, for marine species along the US Atlantic coast, has been moving northward in relationship to warming ocean temperatures. VAST provides a calculation of the latitudinal and longitudinal range edge, or by northing and easting, respectively, by default. In the default figure format, the northern (BLUE) and southern (RED) range edges of Atlantic menhaden, along with the centroid (GREEN), appear to be static or stable (Figure 12). However, when comparing the centroid in Figure 10 to the centroid in Figure 12, there may be detail of patterns of change that are lost in the scale of the range edge figure (Figure 12). Additionally, the range edges are near the survey extents, so the NEFSC survey may not fully capture the extent of menhaden distribution.

Longitudinal range edge for Atlantic menhaden follows a similar static or stable trend (Figure **??**), with the same caveats as with the latitudinal range edge figure. Additionally, longitudinal range edge is limited by the shoreline and the shape of it, and has less biogeographical theory support than poleward changes, so longitudinal range edge may not be as informative.

7 Upcoming Activities

1. Understanding the detailed output of VAST.
2. Generate informative figures for presentation.
3. Prepare AFS presentation.
4. Replicate model in R-INLA and compare with VAST. .

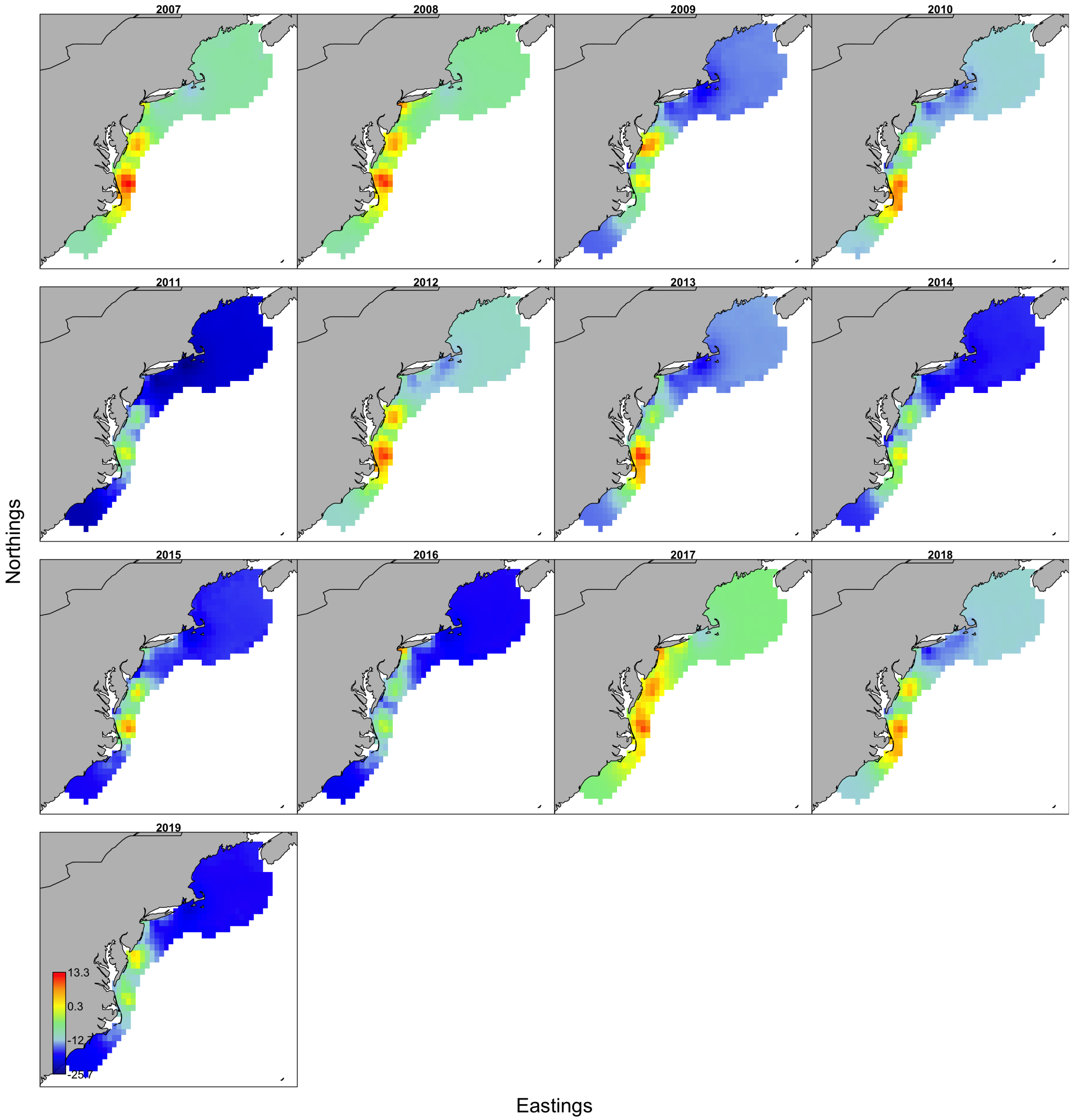

Figure 7: **Estimated spatio-temporal distribution of Atlantic menhaden, 2007-2019, in Spring. Blue = 0-low abundance, red = high abundance.**

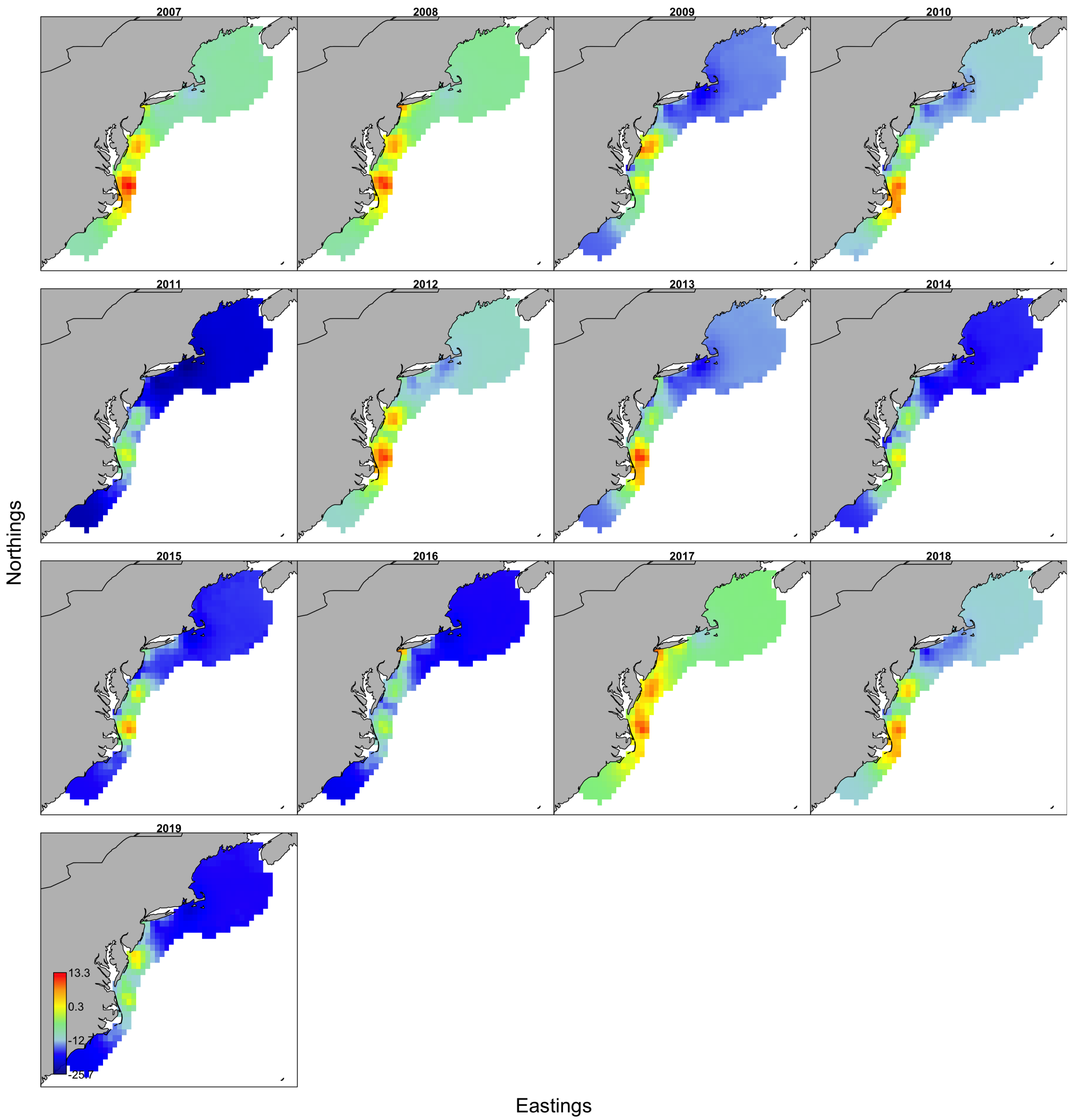

Figure 8: **Estimated spatio-temporal distribution of Atlantic menhaden, 2007-2019, in Fall. Blue = 0-low abundance, red = high abundance.**

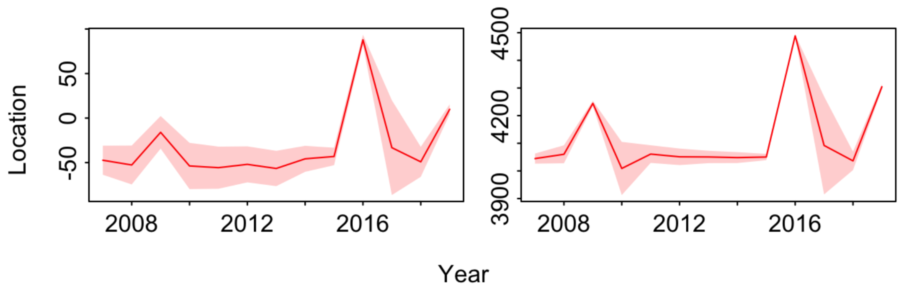

Figure 9: **The center of gravity of the Spring population (left graph = easting, right graph = northing). Refer to Figure 5.1 for a geographic easting and northing reference.**

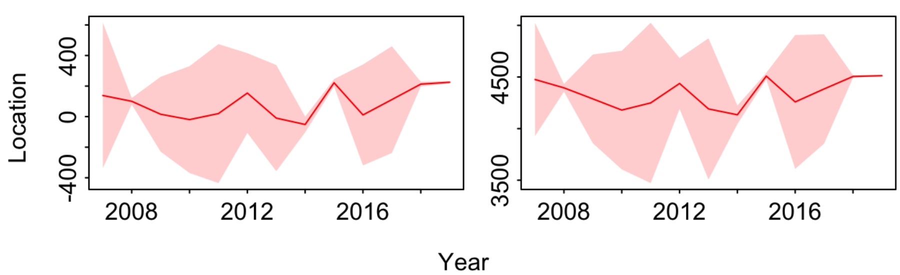

Figure 10: **The center of gravity of the Fall population (left graph = easting, right graph = northing). Refer to Figure 5.1 for a geographic easting and northing reference.**

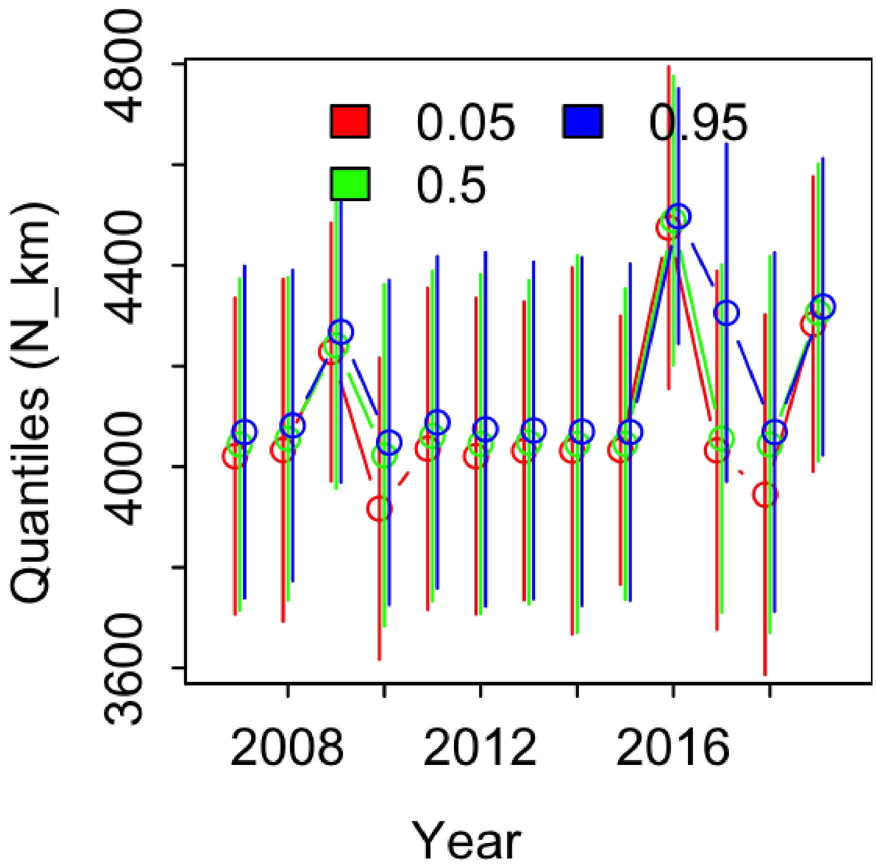

Figure 11: **Latitudinal (in northing, N__km) range edge. The northern edge is BLUE (0.95 = 95% biomass) and the southern edges is RED (0.05 = 5% biomass). The centroid is GREEN (0.5 = 50% of biomass).**

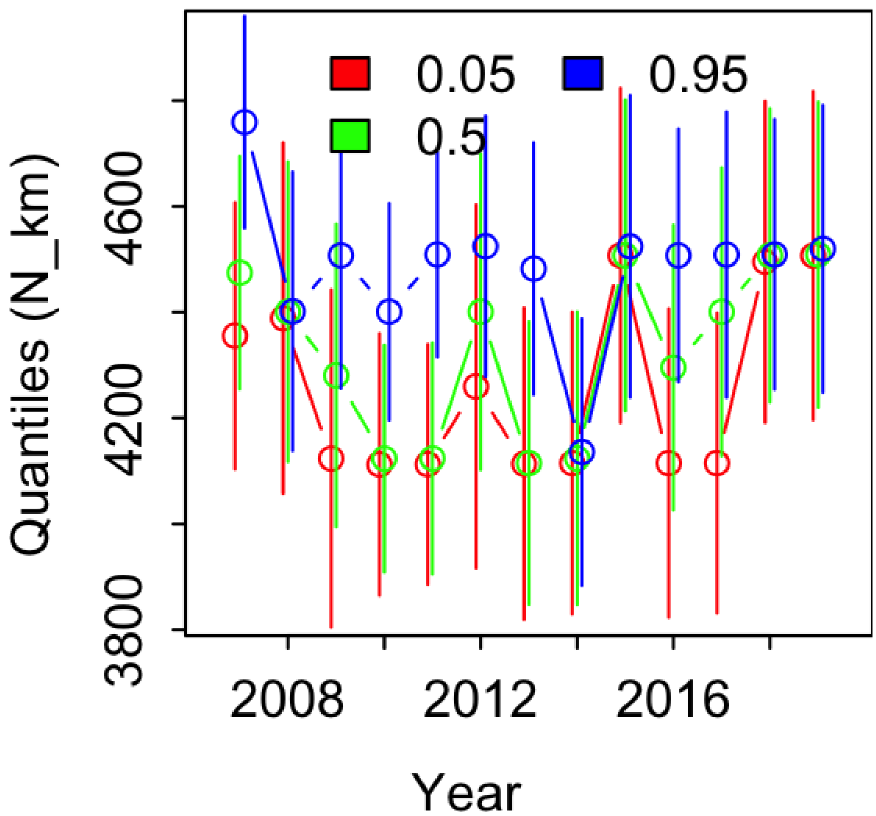

Figure 12: **Latitudinal (in northing, N__km) range edge. The northern edge is BLUE (0.95 = 95% biomass) and the southern edges is RED (0.05 = 5% biomass). The centroid is GREEN (0.5 = 50% of biomass).**