Climate-influenced shifts in a highly migratory species recreational fishery

Running Title: Shifts in HMS recreational fishery

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Ethics approval

Not applicable

Data availability statement

The Large Pelagics Survey data used in this study are publicly available. The sea surface temperature dataset is publicly available from the sources identified in the manuscript as well as the other explanatory variables. R statistical code from this study can be available upon request to the corresponding author.

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Abstract

The distribution of marine species is changing as a direct result of climate change. Large pelagic highly migratory species (HMS), like tunas, billfishes, and sharks are particularly sensitive to environmental change due to their migratory nature and use of large scale ocean features. These temporal and spatial shifts are likely reflected in the Atlantic HMS recreational fishery and could have downstream effects on coastal communities. We utilized dockside intercept data from the Large Pelagics Survey (LPS) from 2002-2019, which conducts sampling from June to October and spans Maine to Virginia, U.S.A. We assessed how species catch composition has changed and developed spatiotemporal models to understand latitudinal and temporal shifts in the recreational catch of 12 HMS groups. Latitudinal shifts were significantly affected by Northeast Shelf SST for 11 of the 12 HMS groups and ranged from 3 ± 1 km $°C^{-1}$ for the large bluefin tuna to 40 ± 1 km $°C^{-1}$ for the blue shark. In addition, the estimated day of the year when the first 25% of bigeye tuna intercepts occurred, happened over 50 days earlier in 2019 compared to 2002, suggesting the initial catch is happening earlier in recent years. These results suggest that changes in species distribution and phenology are affecting where and when HMS recreational catch occurs. Understanding these shifts would allow managers to be more responsive and promote flexibility in the fishery, while helping communities prepare for changes, whether it be a switch to a new species or shifts in the fishing season.

Key words: climate change, Large Pelagics Survey, spatiotemporal models, pelagic sharks, tunas, billfishes, fisheries management

Introduction

Marine species distributions have been shifting due to the impacts of climate change on the ocean (Rose 2005; Sunday et al. 2012; Kleisner et al. 2016). Marine species are primarily thermal-range conformers, therefore their latitudinal range and depth distributions are driven by their thermal tolerance and the tight connection between temperature and their underlying physiology (Pörtner and Knust 2007; Sunday et al. 2012; Pinsky et al. 2020). This connection has led to the poleward edge of marine species' range to expand an average of 72 km dec^{-1} poleward (Poloczanska et al. 2013). These shifts are expected to continue and will likely be an important way species cope with climate change (Robinson et al. 2015; Morley et al. 2018; McHenry et al. 2019; Hastings et al. 2020; Pinsky et al. 2020; Champion et al. 2021). Such spatio-temporal shifts may have complex effects on marine ecosystems and fisheries that rely on accessibility to these resources (Kerr et al. 2009; Townhill et al. 2019), including altered food web dynamics (Du Pontavice et al. 2020) and the opportunities that fishermen have to target specific species (Champion et al. 2022).

Large pelagic highly migratory species (HMS) of fishes such as tunas, billfishes, and sharks are particularly reliant on ocean conditions due to their large scale movements and use of major ocean features, which are often driven by temperature (e.g., Gulf Stream). In addition, marine species migrations are often cued by environmental conditions like temperature (Kerr et al. 2009; Jansen and Gislason 2011; Brown et al. 2016). This reliance makes HMS susceptible to changes in the ocean due to climate change. For example, on average from 1958 to 2004, tuna habitat distributions in the northern hemisphere shifted poleward 6.5 km dec^{-1} (Erauskin-Extramiana et al. 2019). These shifts are expected to continue particularly for temperate tuna species as oceans continue to warm (Erauskin-Extramiana et al. 2019). North Atlantic albacore and eastern Atlantic bluefin tuna have also experienced phenology shifts, where feeding migrations into the Bay of Biscay have occurred 2 and 5.6 days earlier per decade, respectively (Dufour et al. 2010). Poleward shifts are also predicted to occur in pelagic shark species, such as blue and mako sharks along the eastern coast of Australia (Birkmanis et al. 2020) and thresher and blue sharks in the northeast Pacific (Cheung et al. 2015).

Shifting HMS distributions and migratory phenology are likely directly influencing the Atlantic HMS recreational fishery, which operates from Maine to Florida and throughout the Gulf of Mexico. Particularly along the U.S. Northeast Shelf, climate change has and will continue to warm (Saba et al. 2016). For example, sea surface temperature over the U.S. Northeast Shelf has increased between 0.25-0.50°C dec^{-1} since 1982 (Chen et al. 2020). The recreational fishery targeting Atlantic HMS has grown in recent years from 23,614 private and for-hire permitted vessels in 2016 to 26,672 in 2021 (NMFS 2017; NMFS 2021b). An economic assessment of the Atlantic HMS recreational fishery conducted in 2016 estimated it contributes \$510 million annually to the U.S. economy between fishing tournaments, private and for-hire angling trips, and expenditures on durable items such as fishing vessels and gear (Hutt and Silva 2019). Annual expenditures on private Atlantic HMS recreational fishing trips were found to be the highest in the South Atlantic (\$20.5 million) followed by the Mid-Atlantic (\$10.7 million), Gulf of Mexico (\$10.1 million), and New England (\$5.2 million) (Hutt and Silva 2019). However, as species shift their distribution and phenology we would expect to see a shift in where and when HMS are caught by recreational fishermen (Kerr et al. 2009; Townhill et al. 2019). This could lead to fishermen from a given geographic location catching a different mix of species or catching the same species but earlier in the year or at different locations over recent decades. Such long-term shifts could have variable socioeconomic impacts (e.g., fishing effort and expenditures shifting to different coastal communities), depending on the vulnerability of affected fishing communities (Jepson and Colburn 2013; Colburn et al. 2016). Examination of recreational fishing and catch data may reveal how fishermen are adapting to changing conditions and provide insight into how catch may change in the future (Kerr et al. 2009; Townhill et al. 2019). Although there have been many studies understanding the impacts of climate change on important recreational marine species (Muhling et al. 2017; Crear et al. 2020b; Slesinger et al. 2021), very few have directly examined how these changes trickle down and affect the recreational fishery itself, particularly, the HMS recreational fishery.

To better understand the potential impacts of climate change on the HMS recreational fishery we used data from the Large Pelagics Survey (LPS) to investigate whether the composition, location, and timing of HMS catches have shifted over time and with sea surface temperature (SST). The examination of this fishery-dependent dataset is expected to yield novel insights into climate change effects on HMS distributions and phenology, as well as how these valuable fisheries are responding to such shifts.

Methods

Large Pelagics Survey Data

The current design of the LPS was implemented in 2002 to collect recreational catch and effort data on tunas, swordfish, billfishes, sharks and other important pelagic species and represents one of the only standardized recreational datasets on HMS in the United States (NMFS 2021a). The survey spans from Maine (44.5° N lat) to Virginia (36.6° N lat), targets sites where boats are known to travel offshore and target HMS, and runs from June to October. The LPS conducts three surveys to address its overall goal, the Large Pelagics Intercept Survey (LPIS), the Large Pelagics Telephone Survey (LPTS), and the Large Pelagics Biological Survey (LPBS). The LPIS interviews private and for-hire vessels at dockside after completed trips that targeted large pelagic species. These intercept surveys collect catch-per-trip information, such as catch for each species, target species, latitude and longitude of fishing effort, number of lines in the water, other gear information, and length and weight data on landed fish. The LPTS conducts telephone interviews from HMS Angling and Atlantic Tunas General permit holders to collect fishing effort data, while effort data for HMS Charter/Headboat permit holders is collected by the general For-hire Survey (FHS). The LPBS is another dockside sampling program which collects biological samples on landed pelagic species for age and genetic analyses. The survey effort is allocated by the level of fishing and the number of access sites by state. Sampling assignment allocation has increased for some states across years and the amount of sampling assignments increased over the early years since the inception of current LPIS design in 2002. The increase in sampling assignments in some states compared to others was an attempt to obtain the consistent number of intercepts relative to the predetermined intercept targets across years. In addition, the increases in sampling assignments across years occurred similarly in each month. As a result of these efforts, the number of vessels intercepted from the sampling assignments remained consistent for each state across years and for each month across years (see Supplemental Material Figures 1-4). Because the trends in vessel intercepts occurred similarly for states and months across years, it is unlikely the composition, location, and timing of HMS catch were impacted by the changes in sampling assignments in LPIS. Typically, the data collected are used to generate estimates of total catch and fishing effort and are published on a monthly basis (NMFS 2022b). These estimates are then used for national and international stock assessments for various HMS and are provided to managers who monitor landings and catch against quotas.

For this study, intercept data from the LPIS were used from 2002 to 2019. Data prior to 2002 were collected following different survey protocols and were therefore not included in this study. Each row consisted of an intercept for a specific trip where a unique species was interacted with, either kept or released. For example, if during a trip, five yellowfin tuna and one blue shark were interacted with, then there would be two unique rows or intercepts for that trip, one for yellowfin tuna and the other for blue shark. Latitude and longitude of fishing location were listed when known.

We only focused on HMS because they consist of the main species targeted and caught by fishermen who are interviewed by the LPS. Eleven HMS species (12 total groups) were analyzed in this study where 10 species were defined as each species group and one species was split into two sizes classes. Atlantic bluefin tuna (*Thunnus thynnus*) are managed differently based on individuals that are less than or greater than 185.4 cm (73 in) curved fork length (CFL). Therefore two Atlantic bluefin tuna categories were generated; large Atlantic bluefin tuna (either giant or large medium size class; 185.4 cm or greater CFL) and small Atlantic bluefin tuna (all other classes <185.4 cm CFL, including small medium, large school, school, and young school). The 10 remaining species that were not split into size classes included albacore tuna (*Thunnus alalunga*), bigeye tuna (*Thunnus obesus*), skipjack tuna (*Katsuwonus pelamis*), yellowfin tuna (*Thunnus albacares*), blue shark (*Prionace glauca*), shortfin mako shark (*Isurus oxyrinchus*), Atlantic common thresher shark (*Alopias vulpinus*), Atlantic blue marlin (*Makaira nigricans*), swordfish (*Xiphias gladius*), and white marlin (*Kajikia albida*). Any intercepts where the bluefin tuna size class or species was not clearly indicated were removed prior to any analyses.

Explanatory Covariates

Daily SST data were downloaded from NOAA's National Centers for Environmental Information Optimum Interpolation SST product over 2002-2019 at a 0.25° resolution using the package rerddap (Chamberlain 2021) in R v.3.6.1. SST data were rasterized and data along the Northeast Shelf were isolated. SST values were then averaged across the shelf each day to represent the daily Northeast Shelf temperature. SST values were then matched to the intercept data based on the date of the intercept. SST at the location and date of the intercept was considered, however, the wide range of temperature on a daily basis across the spatial extent (i.e., as cold as <10°C in Maine compared to as warm as >25°C in Virginia) was greater than the increase in SST that has occurred overtime due to climate change (i.e., <2°C). Therefore, to understand how increasing regional SST impacted where the HMS recreational fishery was occurring we selected the average across the study region as a proxy for the warming trend occurring along the Northeast Shelf.

Other covariates were also included because of their likelihood to affect the catch and intercept of HMS. Annual Atlantic bluefin tuna quotas for the Angling and General categories were compiled from 2002-2019 because in the HMS recreational fishery bluefin tuna availability is a major driver of fishing effort. The number of HMS permits were included in each state for each year for the three permit categories; Atlantic Tuna General category, HMS Charter/Headboat category, and HMS Angling category where each category was a separate level. We also included the number of HMS tournaments that occurred in each state in each year, as well as whether the completed trips, intercepted by the survey, were part of a tournament or not. Lastly, the annual LPS catch estimates were included for each species group (https://www.fisheries.noaa.gov/data-tools/recreational-fisheries-statistics-queries). All covariates were added to the intercept data and matched based on the year, state where the intercept occurred, and species caught for a given trip. All data analyses described below were conducted in R v.3.6.1 (R Core Team 2021).

Data Analysis

Catch and Target Species Composition

To investigate whether species catch composition has changed over time and with SST, we employed a multivariate approach. Region was assigned to each intercept based on the state where the intercept occurred. Three regions were defined where the northern region consisted of the states Maine, New Hampshire, and Massachusetts; the middle region consisted of the states Rhode Island, Connecticut, New York, and New Jersey; and the southern region was made up of Delaware, Maryland, and Virginia. States were assigned to their respective regions based on their latitude and the geography of the east coast of the United States. The number of intercepts was tabulated for each species across region and year, and zeros assigned where no intercepts occurred. These tabulations were put in a matrix. Mean annual SST along the Northeast Shelf was calculated from daily SST for the duration of the survey (June 1-Oct-31) to provide a general idea of how the annual temperature trend influenced catch composition. Mean annual SST was assigned to the corresponding year within the matrix regardless of region. Using the vegan package in R v.3.6.1 (Oksanen et al. 2020) a Wisconsin double standardization was conducted on the matrix, Bray-Curtis dissimilarities were calculated among all species compositions, and non-metric multidimensional-scaling (nMDS) was used to understand relative similarity among species compositions (Clarke and Warwick 2001; Kendall et al. 2021). nMDS plots were generated where circle size was scaled to year and color was either scaled to region or annual mean SST to visualize if similar species catch compositions trended with year, region, or SST. Analysis of similarity (ANOSIM) was initially used to determine if there was a significant difference in catch community among the region. If there was a significant difference among region then the BIO-ENV procedure was done to determine if year and/or SST correlated with the catch community structure within region using a Pearson correlation and Euclidean distances (Clarke and Ainsworth 1993; Oksanen et al. 2020).

To identify whether target species composition has changed over time and with SST, we employed a similar multivariate approach as described above. In addition to the 12 HMS groups focused on in this study, other species or species groups could be indicated as being targeted during the LPS intercept, therefore other species groups were developed for instances when other species were targeted. The other target species groups were ‘bluefin any’ (any bluefin tuna was targeted), ‘tuna any’ (any tuna species was targeted), ‘other teleost’ (another particular teleost species was targeted; e.g., dolphinfish, *Coryphaena hippurus* & little tunny, *Euthynnus alletteratus*), ‘shark any’ (any shark was targeted), and ‘other sharks’ (another particular shark species was targeted; e,g., porbeagle shark, *Lamna nasus* & blacktip shark, *Carcharhinus limbatus*). The number of intercepts where a species or group was targeted was tabulated for each of the 17 target species or species groups across region and year, and put in a matrix. Wisconsin double standardization was done on the matrix, followed by Bray-Curtis dissimilarities among all target species compositions. nMDS was conducted to determine relative similarity among target species compositions. To visualize target species compositions trends nMDS plots were created. ANOSIM was initially used to determine if there was a significant difference in target species composition among the region. The BIO-ENV procedure was done if there was a significant difference to determine if year and/or SST correlated with the target species composition structure within region using a Pearson correlation and Euclidean distances.

Spatial Shifts

A series of linear models using generalized least squares were developed to understand whether the latitude at which fishermen have been catching various HMS was related to year (as a temporal variable) and shelf SST. Intercept data where latitude and longitude was unknown were removed from this analyses. A separate data set was created for each HMS where only intercepts or trips where that species was caught (kept or released) were isolated. Then a linear model using generalized least squares from the nlme package in R (Pinheiro et al. 2013) was developed for each of the 12 species groups where the latitude of catch was the response. Year and daily shelf SST were the two main covariates of concern. However, to account for other factors that may impact the latitude of catch, we also included annual quotas for the Atlantic bluefin tuna Angling and General categories, the number of HMS permits purchased in each state per year for each of the three permit categories (Atlantic Tunas General category, HMS Charter/Headboat category, and HMS Angling category), the number of HMS tournaments that occurred in each state per year, whether the trip was part of a tournament or not, and the annual LPS catch estimates of that species. The number of trips by intercept state for each year were assessed to ensure there were not simply more intercepts in northern states in later years than in earlier years. Collinearity was assessed for each species data set and when present, one of the collinear covariates were excluded from the model. A continuous first-order autoregressive (CAR1) correlation structure was used to account for the temporal autocorrelation present in the data where the time covariate was the date and time of when the intercept occurred and the grouping factor was the state where the intercept took place. Temporal autocorrelation was either completely removed or reduced based on the species using auto-correlation function (acf) plots. Diagnostic plots of model residuals were used to check for homogeneity and normality. When heterogeneity was present we used various variance structures to account for it in the model. Once all assumptions were met, the final model was run and significance of year and daily shelf SST on latitude of catch was determined at $\alpha = 0.05$.

For species where year or daily shelf SST significantly affected the latitude of catch, the slope of significant trends were converted to kilometers shifted per year and kilometers shifted per °C increase to better understand these shifts. In addition, predicted latitudes of catch over the range of daily shelf SST were estimated using marginal means (Searle et al. 1980).

Temporal Shifts

To identify if recreational fishermen were catching species earlier in the year over the time series (2002-2019), a linear model using generalized least squares were developed using all available data (i.e., with or without latitude and longitude information). A separate data set was created for each HMS where only intercepts or trips where that species was caught (kept or released) were isolated (i.e., positive trips only). Preliminary analysis indicated that over the time series the mean day of year of catch across most HMS did not shift. However, the impacts of climate change on species distributions and phenology may differ among individuals within a species due to variation in physiological tolerances (Somero 2010). We therefore also tested whether the day of year when the first 25% of the intercepts had occurred for a given species was happening earlier over the time series. We found this metric useful because if true, it would suggest that recreational fishermen are catching those individuals of a particular species that are migrating earlier at an earlier time of year. The day of year when 25% of the intercepts had occurred for a given species (herein referred to as 'day-of-year') was aggregated by year and the state where the intercept occurred. For example, if a species was intercepted at least once in seven states each year across the 18 year time series then there would be 126 day of year calculations. A separate linear model using generalized least squares was developed for each species. The response variable was day-of-year, while an interaction between year and intercept state were the main covariates. However, to account for other factors that may impact the timing of catch, we also incorporated other covariates including annual quotas for the Atlantic bluefin tuna Angling and General categories, the number of HMS permits purchased in each state per year for each of the three permit categories, the number of HMS tournaments that occurred in each state per year, and the annual LPS catch estimate of that species. Lastly, to account for variability in the number of intercepts across years and state, the total number of intercepts for all species for each state within each year was also considered as a covariate for the models. To ensure model convergence, intercepts of a particular species were required to occur in at least 14 years for a particular state. If this did not occur then the day-of-year calculations for that state were removed. The value of 14 was selected because when less than 14 years were used the models had a more difficult time converging. Collinearity was assessed for each species data set as well as homogeneity and normality and when present, one of the collinear covariates were excluded from the model. Temporal autocorrelation was not present in these data. When heterogeneity was present we used various variance structures to account for it in the models. Once all assumptions were met, the final model was run and significance of year and intercept state on day of year was determined at $\alpha = 0.05$.

Further post-hoc analyses were conducted for species where the interaction between year and intercept state or just year significantly affected the day of year. Species where just year was significant, the shift in day-of-year with year was determined and predicted day-of-year values over the time series were estimated using marginal means (Searle et al. 1980). For species where a significant interaction occurred between year and intercept state, individual slopes of day-of-year for each state was tested to determine significance from zero using the R package emmeans (Lenth 2021). For states where slopes were significantly different from zero, predicted day-of-year over the time series were estimated using marginal means.

HMS Tournament Trends

It was expected that the latitude and timing of recreational catch would be driven by where and when HMS tournaments occurred. This is particularly important because over 20% of intercepts with latitude and longitude occurred during tournaments. To ensure potential spatial and temporal shifts in HMS recreational catch were not attributed to spatial and temporal shifts of HMS tournaments a qualitative assessment was done. Specifically, to indicate the trends in HMS tournaments overtime the mean latitude and day of year of the tournaments when each of the HMS species were targeted were plotted over years. Tournaments targeting any of the pelagic sharks were grouped together and large and small bluefin tuna were treated as one.

Results

After post processing the data, of the 96,606 recorded intercepts (total number of unique combinations of trip and species), consisting of 53,698 unique trips from 2002 through 2019 (Fig. 1), 54% intercepted one of the 12 HMS focused on in this study. The number of intercepts for a given HMS ranged from 615 for swordfish to 14,326 for yellowfin tuna (Table 1). The top five target species or species group were yellowfin tuna (22% of intercepts), giant bluefin tuna (12%), any tuna species (12%), white marlin (11%), and shortfin mako shark (9%). Latitude and longitude was recorded for 77% of the HMS intercepts (Table 1).

Catch and Target Species Composition

The nMDS multivariate analysis was conducted to investigate species catch composition differences across years (2002-2019) and annual shelf SST. Distances between points indicate relative similarity in species catch composition, meaning points that are closer together have a greater similarity in species catch compositions than those that are farther apart. Stress for the nMDS was 0.09. ANOSIM results indicated that species catch composition was significantly different among regions ($R = 0.91$, $p < 0.001$), with the middle region showing the greatest within region similarity, followed by the southern region, and the northern region (Fig. 2a). In the northern region, blue shark and large Atlantic bluefin tuna often dominated the catch, while in the southern region, white marlin, yellowfin tuna, and small Atlantic bluefin tuna dominated. The middle region largely consisted of a mix of those abundant species in the other regions and shortfin mako shark. Within region, species catch composition did correlate with year, where earlier years were closer together and later years were closer together (Table 2; Fig. 2a). Although not as correlated as year, shelf SST correlated with species catch compositions in the southern region and partially in the middle region, where species catch compositions had a greater similarity during warmer years versus cooler years and vice versa (Table 2; Fig. 2b).

A separate nMDS analysis was done to understand target species composition differences across years (2002-2019) and annual shelf SST. Stress for the nMDS was 0.15. Similar to species catch composition, target species composition ANOSIM results indicated that composition was significantly different among regions ($R = 0.58$, $p < 0.001$), with the most similarity occurring in middle region, then the southern region, and then the northern region. Fishermen targeted primarily the other teleost group, followed by large Atlantic bluefin tuna and blue sharks in the northern region, while the other teleost group, yellowfin tuna, and white marlin were highest target species groups in the southern region. In addition to the target species above, the fishermen in the middle region also often targeted shortfin mako shark. Within the northern and southern regions in particular, target species composition correlated year where earlier years were more similar, while later years were more similar (Table 2; Fig. 2c). Shelf SST correlated with target species composition strongest in the southern region followed by the middle region where target species composition were more similar during warmer years and more similar during cooler years (Table 2; Fig. 2d).

Spatial Shifts

Of the 12 HMS groups, year significantly affected the latitude of catch of 10 species (Table 1). Year did not significantly affect the latitude of catch for blue sharks and swordfish. Spatial shifts (all northerly) with year ranged from 1 ± 1 km year^{-1} (mean ± standard error) for blue marlin to 10 ± 1 km year^{-1} for the small bluefin tuna. Other species with rates greater than 3 km year^{-1} included large bluefin tuna, shortfin mako, and thresher shark. Spatial shifts over years (2002-2019) are also clear in the raw data (annual median of catch) for all HMS (Fig. 3). For example, substantial shifts were observed going northeast over the time series for small bluefin tuna (Fig. 3d), shortfin mako shark (Fig. 3h), and thresher shark (Fig. 3i).

Daily shelf SST significantly affected the latitude of catch of 11 of the 12 HMS (Table 1). The only species where SST did not significantly affect the latitude of catch was white marlin. Significant spatial shifts (all northerly) ranged from 3 ± 1 km °C^{-1} for the large bluefin tuna to 40 ± 1 km °C^{-1} for the blue shark. Other species with rates greater than 10 km °C^{-1} included bigeye tuna, shortfin mako, and thresher shark. When examining the marginal means across the range of daily shelf SST, predicted mean latitude of catch of blue and thresher sharks would occur off Delaware during the coldest temperature and off Massachusetts during the warmest (Fig. 4). Predicted mean latitude of bigeye tuna catch would occur in waters from Virginia to Delaware, when spanning from the coldest to the warmest SST, respectively. Whereas although the trends were significant, based on predicted mean latitude of large bluefin tuna catch across the range of SST, catch would primarily occur in waters off Massachusetts (Fig. 4).

Temporal Shifts

The day of year where the first 25% of intercepts occurred was significantly affected by year and state for a handful of species. Because it is likely that the day of year would differ among states regardless of climate change, we did not further examine models where only intercept state was significant. Species where neither year nor the interaction between year and intercept state was significant included, albacore tuna, swordfish, thresher shark, white marlin, and yellowfin tuna. Regardless of state, year significantly impacted the day of year for both bigeye ($t_{(66)} = -4.97$, $p < 0.05$) and skipjack tuna ($t_{(87)} = -3.02$, $p < 0.05$), where for bigeye (Fig. 5a), for every one year increase, day of year would occur 4 (± 1) days earlier and for skipjack (Fig. 5d), for every one year increase, day of year would occur 3 (± 1) days earlier. Models for the remaining species, bigeye tuna, large and small bluefin tuna, blue shark, blue marlin, shortfin mako, and skipjack tuna, indicated a significant interaction between year and intercept state. All trends significantly different from zero decreased as year increased, except for small bluefin tuna intercepted in Virginia (Fig. 5c). The steepest trend occurred for large bluefin tuna intercepted in Massachusetts, where the predicted day of year where 25% of intercepts occurred took place 80 days earlier in 2019 compared to 2002 (Fig. 5b). Other significant trends for other species included a decrease in the day of year of 38 days for small bluefin tuna in New Jersey (Fig. 5c), 66 days for blue sharks in Connecticut (Fig. 5e), 27 days for blue marlin in New York (Fig. 5g), and 21 days for shortfin mako in New York (Fig. 5f) from 2002 to 2019.

Tournament Trends

The mean latitude of tournaments across the majority of HMS for this study started to decline after 2015. Prior to 2015 the mean latitude fluctuated up and down slightly across HMS, but did not trend in either direction (Fig. 6a). In general, pelagic shark tournaments occurred the furthest north, while white and blue marlin tournaments occurred furthest south. The day of the year of HMS tournaments occurred later in the year at the beginning of the time series until 2006, gradually occurred earlier until 2015, sharply occurred later until 2018, and by 2019 tournaments began earlier relative to 2018 (Fig. 6b). Pelagic shark and skipjack tuna tournaments often occurred earlier in the year compared to other HMS.

Discussion

Our analysis indicates that since 2002, there have been significant spatial, temporal, and species composition shifts in HMS recreational fishery catches off the northeast and mid-Atlantic U.S. Specifically, these include changes in catch and target species assemblages over time, poleward shifts in catch locations, and catches occurring earlier in the year for numerous HMS. These shifts are concurrent with regional trends in climate change, specifically increasing SST, which has been documented to be affecting the distribution and phenology of numerous other marine species (Poloczanska et al. 2013; Kleisner et al. 2016; Gervais et al. 2021; Langan et al. 2021; Champion et al. 2022).

Despite the interesting trends observed in the LPS catch data for HMS, some limitations and caveats do exist. A major limitation of using the LPS data in this analysis is that the LPS is designed to monitor the primary recreational fishery for Atlantic bluefin tuna and similar HMS with survey coverage limited to June through October and Maine to Virginia. The lack of information from states south of Virginia suggests the survey is likely missing trends in HMS catch associated with HMS that use habitat in the South Atlantic. Because of this limitation, some of the trends observed in the data may be underestimated, particularly for the more southern species. Expanding coverage of the LPS to include the southeastern U.S. and Gulf of Mexico may help further refine interpretation of the currently available data. An additional limitation is relying on recreational fishermen to correctly identify species that were released, which may lead to small discrepancies in the results. However, we expect species misidentifications to be rare in the LPIS. Participation in the offshore HMS fishery requires a significant financial investment, which generally serves as a barrier to participation by inexperienced or novice anglers that are more likely to misidentify their catch (Hutt and Silva 2019). Furthermore, many of the fishers interviewed by the LPIS are for-hire charter boat captains with years of experience or their crewmembers. Lastly, it is important to note that trends in fishing effort that have occurred since 2002 could influence HMS catch rates. Unfortunately, due to the LPS design, effort data were not collected at a fine enough scale to understand fishing effort change in this study, a common limitation of working with recreational fisheries data. For example, increases in fishing effort in more northern areas over time could potentially lead to an overestimation of the effect of climate change on the fishery shifts. Fishing effort could also change due to shifts in human population or other factors over the time series, which could affect the number of HMS caught in each region. While there is annual variability in total fishing effort estimates, as with all survey based statistical estimates, most states across our study region have seen similar trends in ocean fishing effort over the last two decades, with total annual effort remaining fairly consistent (Supplemental Material Figure 5). Such consistent trends in overall effort help minimize potential biases in our results. To account for some of the annual variability in effort, our spatial models only focused on the latitude of where at least one individual was caught for a particular species and not the number of individuals caught. An additional analytical approach to address uneven effort is to subsample the data to equalize sampling across time periods, however, for rarer species subsampling this is likely not possible (Bates et al. 2015). Therefore, it would be helpful for sampling programs to increase the spatial resolution of effort data when collecting catch and effort data and also consider designing the surveys to have the ability to robustly detect future range shifts.

It is clear that although species catch composition was split primarily by region, there were still trends in species catch composition across years (2002-2019) and shelf SST. The major grouping by region was likely driven by HMS that are primarily caught in specific regions. For example, across all years 96% of large bluefin tuna intercepts occurred in the northern region, while 74%, 67%, and 65% of all white marlin, skipjack tuna, and blue marlin intercepts occurred in the southern region, respectively. This indicates that although there are within group trends across years and shelf SST, HMS and subsequent catch have not shifted enough latitudinally to mix the common community structure in catch that occurred in the spatially broad regions. Nonetheless, the within region grouping by year (for all regions) and SST (southern region) indicate that catch composition has been shifting and will likely continue to shift through time and as the ocean warms. Whether strong enough shifts in catch composition in the future will result in mixing among regions is an interesting follow-up question and will likely be driven by more extreme shifts in species distribution and phenology, as well as a strong enough shift in the species recreational fishermen are targeting. In addition, since anglers traditionally target or use fishing methods and locations for a specific set of species it is possible that there could be a lag in changes in recreational catch reflecting changes in species distributions if changes in fishing behaviors are needed to fish for the new species. Shifts in community composition in response to changing environmental conditions are not uncommon. For example, in coastal marine communities, such as in Narragansett Bay, increase water temperatures led to changes in the nekton community, which likely caused a shift from demersal species to more pelagic species and an increase in warm-water species from 1959 to 2005 (Collie et al. 2008). Along the Northeast Pacific shelf region, the pelagic species assemblages are predicted to shift poleward by 2050, with higher rates of species invasion in more northern areas such as the Bering Sea and higher rates of local extinction along California (Cheung et al. 2015).

Shifts in the latitude of recreational catch of HMS have occurred at significant levels since 2002 and were related to shelf SST. Species catch with large latitudinal shifts related to year or SST are likely attributed to species distribution shifts over years and the direct and indirect reliance of HMS on SST. This is consistent with climate vulnerability assessments and projection modeling suggesting that some HMS have a high likelihood of distribution shifts under climate change (Hazen et al. 2013; Cheung et al. 2015; Hare et al. 2016). Stronger latitudinal shifts in species catch associated with shelf SST compared to year suggests that species are more likely affected by SST than other factors that may trend with year. Although some of the strong SST shifts may be related to when migrations occur, the June to October timeframe (LPS time period) is when many HMS inhabit areas along the northeast shelf (Walli et al. 2009; Goodyear 2016; Kohler and Turner 2019).

The catch of some species displayed strong latitudinal shifts with shelf SST, particularly the pelagic sharks such as shortfin mako, thresher, and blue sharks. It is known that shortfin mako distribution in the northwest Atlantic is more concentrated during the summer and fall seasons, primarily occurring north of the Gulf Stream from the Carolinas, USA to Newfoundland, Canada (Vaudo et al.

2016). Although shortfin mako sharks experience regional endothermy (Carey et al. 1981) and thus may not be as directly impacted by SST, their distributions along with other HMS are likely also driven by prey distribution that are impacted by SST and productivity, all of which are influenced by the Gulf Stream and eddy formation. While no studies have yet examined the impacts of climate change on shortfin mako distribution within the northwest Atlantic, it has been identified that in other regions a significant poleward shift (Birkmanis et al. 2020) and suitable habitat reduction (Hazen et al. 2013) are likely to occur for this species as a result of climate change. Thresher sharks, which like shortfin mako sharks experience regional endothermy (Bone and Chubb 1983; Bernal and Sepulveda 2005) and are distributed along the northeast shelf during summer and fall (Kneebone et al. 2020) are likely experiencing similar impacts. The blue shark which is one of the most common sharks along the northeast shelf particularly during summer and fall (Kohler et al. 2002; Kohler and Turner 2019), and as an ectotherm, experienced a stronger shift in relation to SST. Similar to shortfin mako, blue sharks are expected to shift poleward as a result of climate change (Birkmanis et al. 2020). These distribution shifts observed in pelagic sharks either directly or indirectly related to climate change are likely having a strong influence on the latitude of where recreational fishery catch of these species is occurring.

The wide range of latitudinal shifts in teleost species catch related to year and SST suggests multiple drivers, such as shifts in species distributions and differences in species spatial extent. Significant latitudinal shifts with shelf SST for bigeye tuna and small bluefin tuna, like the pelagic sharks, are related to species distribution shifts. Bigeye tuna are projected to shift poleward (Erauskin-Extramiana et al. 2019), while bluefin tuna in the northwest Atlantic are expected to see a decrease in suitable habitat below 40°N but an increase in the Gulf of Maine (Muhling et al. 2017). These shifts in smaller bluefin tuna may be exacerbated relative to large bluefin tuna due their lesser ability to thermoregulate and their use of more southerly habitat. Smaller latitudinal shifts in large bluefin tuna may be driven by their ability to thermoregulate (Carey and Teal 1969) and that they are primarily available to the recreational fishery in the Gulf of Maine during the LPS. On the other hand, smaller or non-significant latitudinal shifts with shelf SST occurred in more southerly species such as skipjack tuna, yellowfin tuna, blue marlin, and white marlin. These smaller shifts may be an artifact of the LPS southern boundary occurring at Virginia. If the survey extended further south we may have observed a greater shift in catch of these more southern HMS. Meaning some of the estimated shifts in catch with year and SST for some of these species may be underestimated.

The majority of HMS have been caught earlier in the HMS recreational fishery over the last couple decades. Although these trends occur for only the first 25% of the catch, this still indicates the fishery may be starting earlier in the year. This shift in catch is likely attributed to shifts in species migratory phenology. Feeding migrations of albacore and bluefin tuna into coastal habitats in the northeast Atlantic have occurred days earlier per decade (Dufour et al. 2010). Although studies of changing phenology of HMS focused on in this study are limited, migration shifts have been observed or estimated for marine fish species. For example, cobia (*Rachycentron canadum*), a coastal pelagic fish that makes an inshore and northern migration into Chesapeake Bay where they spawn, feed, and are targeted by recreational fishermen, was estimated to migrate into the bay earlier and leave the bay later due to climate change. This shift would increase the duration cobia would spend in Chesapeake Bay by an additional 30 days by 2050 compared to today (Crear et al. 2020a). Phenology shifts of large HMS, in addition to being driven by their physiology, is also likely influenced by prey shifts. A meta-analysis study indicated earlier phenology shifts that were driven by climate change occurred in phytoplankton (6.3 ± 1.6 days dec^{-1}), zooplankton (11.6 ± 2.9 days dec^{-1}), larval bony fish (11.2 ± 1.7 days dec^{-1}), and bony fish (~7 days dec^{-1}) (Poloczanska et al. 2013), demonstrating that multiple trophic levels are impacted by climate change.

HMS recreational catch is often influenced by the timing and location of HMS tournaments. HMS tournaments in recent years indicate the mean latitude of tournament locations have actually occurred further south and that the mean day of the year of tournaments have occurred later in the year. This suggests that some of the estimated latitudinal and temporal shifts of catch may have occurred even further north and earlier in the year had HMS tournaments in recent years followed the average trends. In addition, many of the tuna and billfish tournaments occur later in the LPS time period, further indicating the estimated temporal shifts may be conservative for some HMS.

Results in the present study demonstrate that the HMS recreational fishery is adapting to shifts in species distribution and phenology. It is widely known that fishermen use a handful of environmental conditions to determine where to fish, how to fish, and what species they will be targeting on a day to day basis (Haynie and Pfeiffer 2012; Klemas 2013). Shifts in the composition of target species over years and across SSTs indicate that this behavioral trend can be observed on a broader annual or mean annual SST scale. For example, in the southern region during warmer years and more recent years, small bluefin tuna were targeted less, while more southerly species like white marlin were targeted more. For the northern region, during warmer and more recent years, large bluefin tuna, shortfin mako, the other teleost group, and the other shark group were generally targeted more often. These observations imply that the U.S. Atlantic HMS recreational fishery has some inherent resiliency to the effects of climate change, and can adapt certain elements of fishing behavior to remain sustainable. However, such resiliency likely varies port-to-port, requiring higher resolution exploration of these factors in the future.

The economic implications of spatial shifts in HMS distributions on the recreational fishery are hard to predict. It is possible these shifts will have minimal impact on the overall economic value of the fishery, but they may have severe impacts on the economies of specific coastal communities, both positive and negative. As HMS stocks shift northward, or arrive earlier, coastal communities that currently feature busy HMS for-hire fleets, or popular HMS tournaments, may find the fishery shifting away from them during key times of the year, or bypassing them altogether. Large HMS tournaments can bring hundreds of thousands of dollars to an individual community's economy (Hutt and Silva 2019). However, the losses of some communities have the potential to be the gain of other communities that will have access to new or improved fishing for species that had previously been rare event catches off their coasts.

These shifts in catch are likely occurring in other recreational and commercial fisheries. Countless species, including many that have important recreational and commercial importance, are experiencing changes in their distribution and phenology as a result of climate change (Morley et al. 2018; Pinsky et al. 2020; Champion et al. 2021; Zhou et al. 2021). In the U.S., commercial fishery-dependent data are generally collected through mandatory logbook or census-style programs providing more and more detailed data compared to recreational data, and questions and analyses described in this study could be applied to those data. For example, Pinsky and Fogarty (2012) focused on four commercial fisheries and identified that over the last four decades, although the fisheries are corresponding to northward shifts in species distributions, they shifted just 10-30% as much as their target species. This lag may have been attributed to economic and regulatory constraints.

The Marine Recreational Information Program (MRIP) conducts recreational fishery surveys, similar to the LPS, which produce publicly accessible data, but run for the entire year, span the U.S. east coast and Gulf of Mexico, and capture detailed information on many recreationally important coastal species (NMFS 2022a). HMS are typically rare event species in MRIP, and that survey does not record detailed location data, therefore those data were not included in this HMS focused study. Those data offer an opportunity to capture changes in coastal species catch over time and across other climate related variables.

Conclusions

This study demonstrated latitudinal and temporal shifts in the catch of Atlantic HMS in the recreational fishery. These changes reflect shifts in species distribution and phenology driven by climate change. Although similar trends between species and catch may appear obvious, this connection is often overlooked and has a downstream effect on coastal communities that rely on marine resources. Understanding these shifts can help communities prepare for changes, whether it be a switch from one species to a new species or shifts in the fishing season. These kind of analyses could also help management be more responsive and adaptive, reduce uncertainty, and increase sustainability all of which would promote more flexibility in the fishery. Lastly, this study highlights the importance of publicly accessible data and the power of time series when it comes to understanding climate impacts.

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Tables

Table 1. The number of intercepts in total and with latitude and longitude (LL) for each HMS. The model output for each HMS latitude model, including the t statistic for the covariates of concern (year and NES SST) and the significant trends converted to kilometers per year (± SE) or kilometers per °C (± SE). When year or NES SST did not significantly affect latitude of catch a "-" was put in place of the trend. All significant latitudinal trends occurred in the northern direction.

Species	# Intercepts (Total)	# Intercepts (w/LL)	t Statistic (Year)	Year Rate (km/year)	t Statistic (SST)	SST Rate (km/°C)
Albacore Tuna	2564	1774	3.79	2 (± 1)	6.4	9 (± 1)
Bigeye Tuna	1091	903	3.04	3 (± 1)	7.81	14 (± 2)
Bluefin Tuna (Large)	1870	1515	14.2	4 (± <1)	2.9	3 (± 1)
Bluefin Tuna (Small)	8177	6588	18.15	10 (± 1)	6.61	8 (± 1)
Skipjack Tuna	2071	1679	6.25	3 (± 1)	4.12	4 (± 1)
Yellowfin Tuna	14326	12020	8.31	2 (± <1)	19.36	7 (± <1)
Blue Shark	6979	4103	1.53	-	32.04	40 (± 1)
Shortfin Mako	4382	2651	4.96	4 (± 1)	19.31	22 (± 1)
Thresher Shark	1106	585	4.18	5 (± 1)	16.59	33 (± 2)
Blue Marlin	1526	1249	2.08	1 (± 1)	4.49	7 (± 2)
Swordfish	615	508	-0.13	-	2.01	4 (± 2)
White Marlin	7486	6462	11.06	2 (± <1)	-0.47	-

Table 2. Pearson correlations for both catch composition and target species composition in relation to and year and shelf SST for each region based on the BIO-ENV analyses.

	Catch Composition		Target Species Composition	
Region	Year	SST	Year	SST
North	0.46	0.05	0.86	0.16
Mid	0.62	0.25	0.39	0.31
South	0.51	0.42	0.56	0.58

Figures

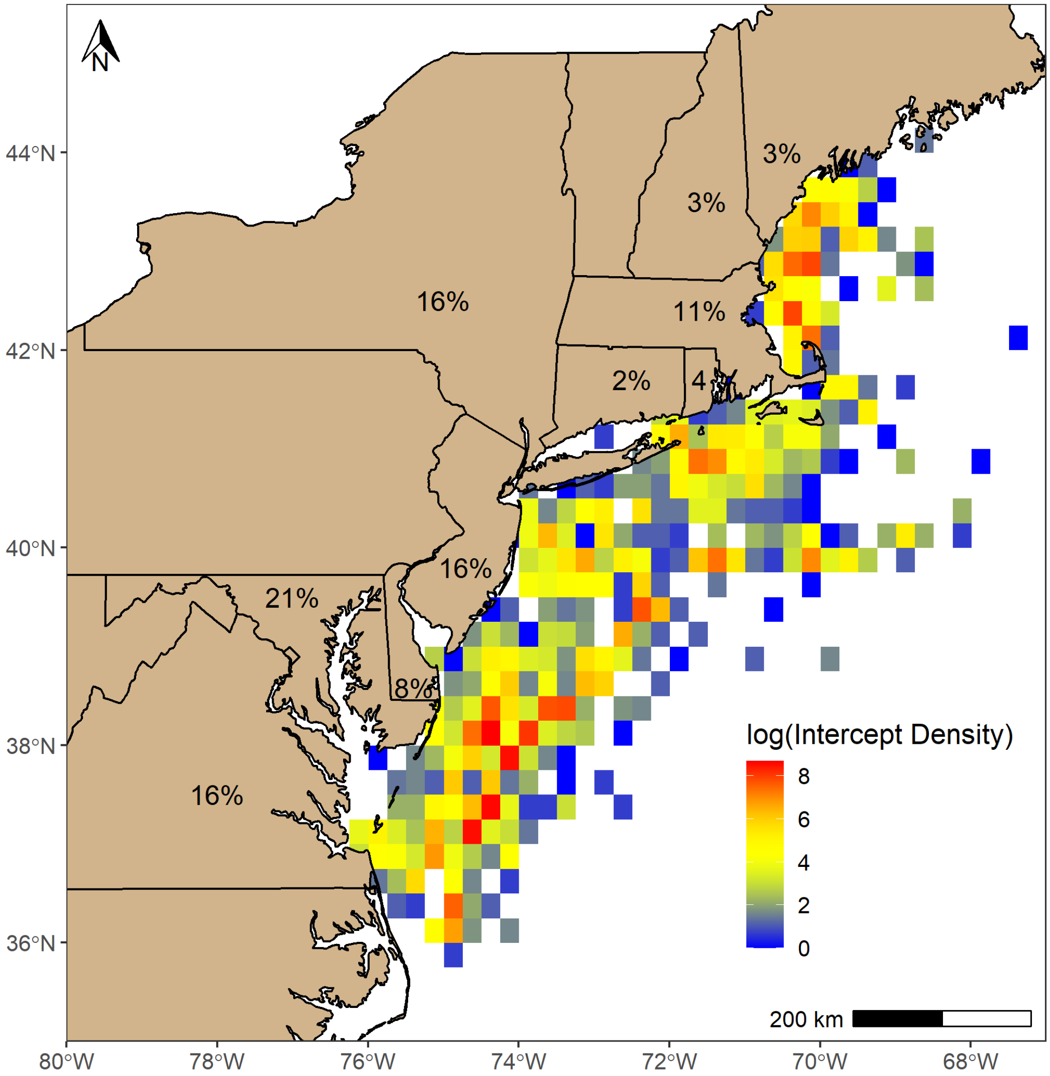

Figure 1. Density of the 75,558 intercepts of the Large Pelagic Survey from 2002-2019 in which latitude and longitude were available (total intercepts: 96,606). Densities were generated for 0.25° grid cells. Densities were log transformed because of the large range. The percentage values over each state represents the percentage of total trips that were intercepted across all years.

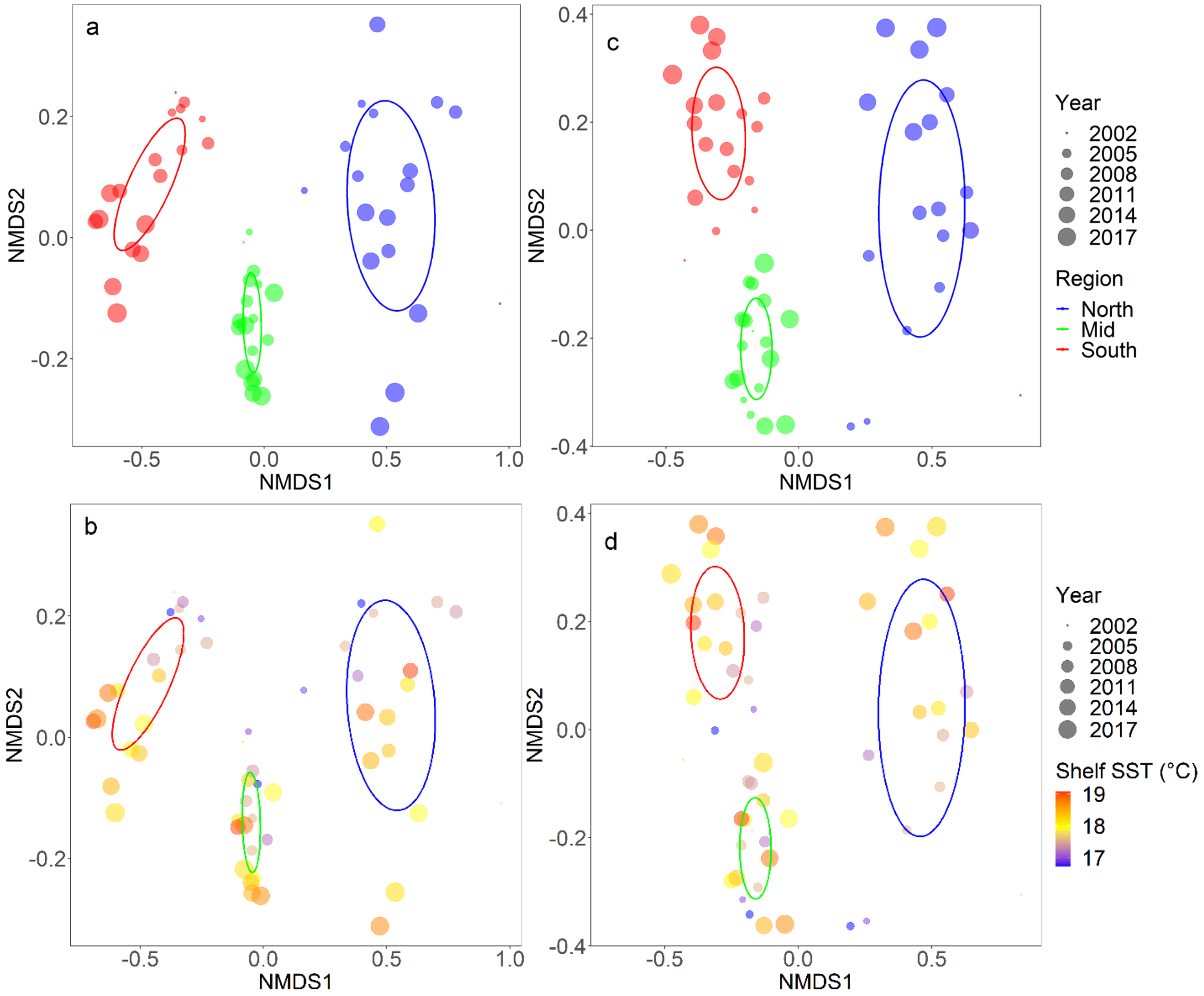

Figure 2. Non multi-dimensional scaling plots of species catch composition (a, b) and target species composition (c, d). Size of the circles is scaled by year. Location of the circles are the same between the two plots per given analysis. (a, c) The color of the circles is based on the region (northern, middle or southern). (b, d) The color of the circles is based on the mean annual NES SST (June-October). Ellipses represent the standard deviation of each region centroid.

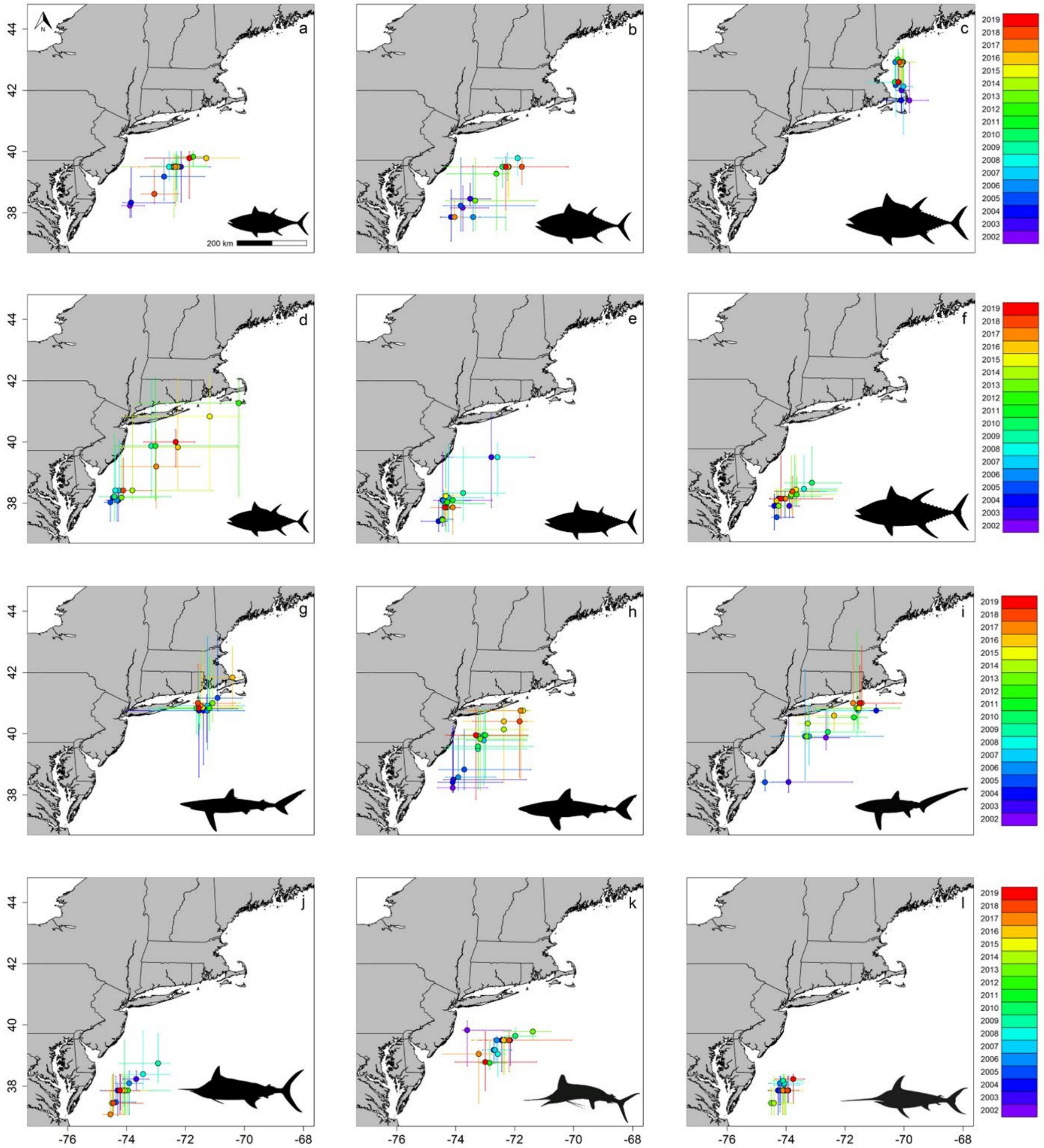

Figure 3. The median location of catch each year for albacore tuna (a), bigeye tuna (b), large bluefin tuna (c), small bluefin tuna (d), skipjack tuna (e), yellowfin tuna (f), blue shark (g), shortfin mako shark (h), thresher shark (i), blue marlin (j), swordfish (k), and white marlin (l). The color of the dot indicates the year and the error bars represent the upper and lower quartiles for a given year. To reduce overlap among median catch locations, a small jitter was added to the median latitude and longitude when appropriate.

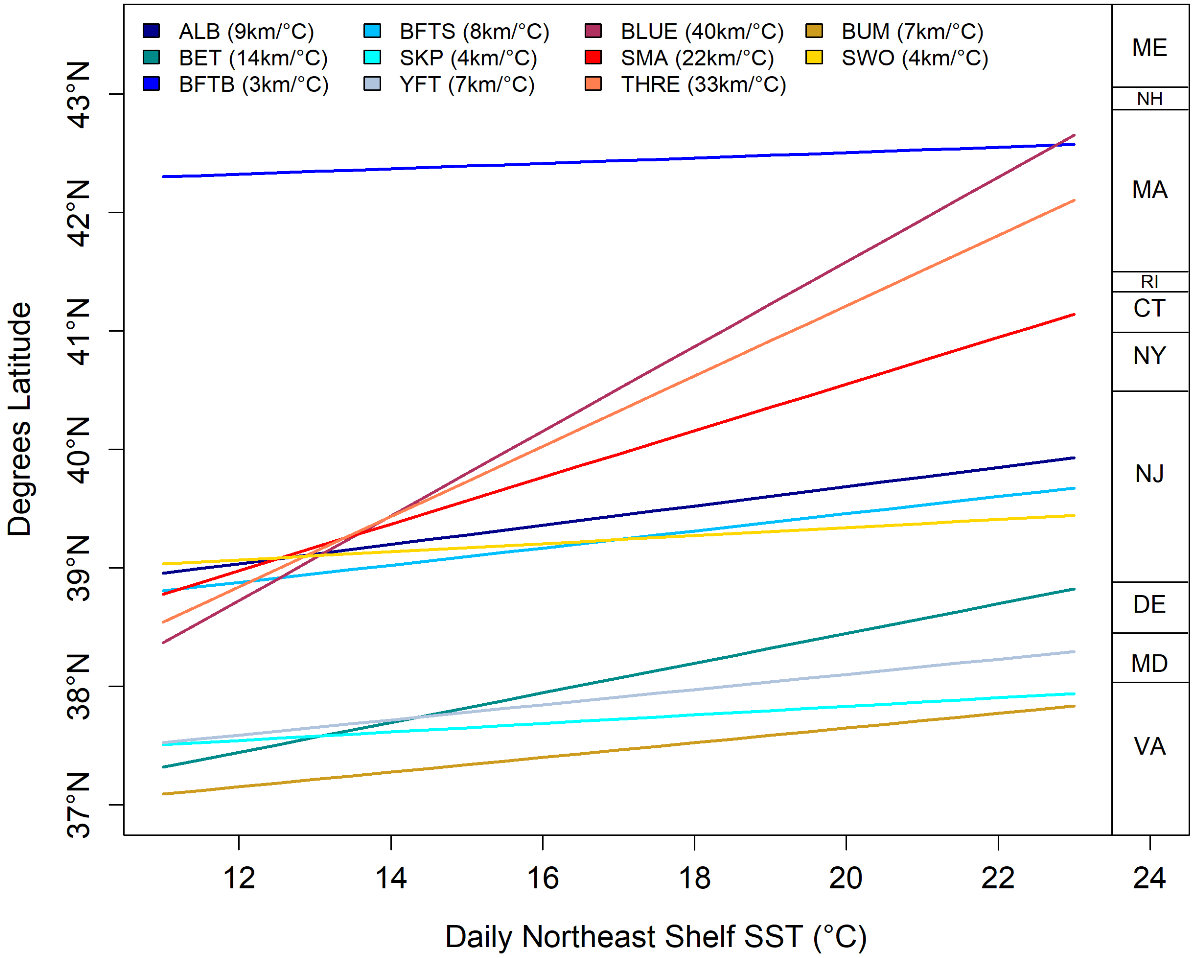

Figure 4. Marginal mean predictions of degrees latitude of catch for the 11 HMS where daily Northeast Shelf SST significantly affected latitude of catch. Corresponding boundaries (matches degrees latitude on the primary y-axis) for the east coast states where the Large Pelagics Survey takes place for reference. The color represents 11 HMS and the rate in the legend indicates the significant trend for each species. Abbreviated HMS are ALB = albacore tuna, BET = bigeye tuna, BFTB = large bluefin tuna, BFTS = small bluefin tuna, SKP = skipjack tuna, YFT = yellowfin tuna, BLUE = blue shark, SMA = shortfin mako shark, THRE = thresher shark, BUM = blue marlin, SWO = swordfish. Abbreviated states are ME = Maine, NH = New Hampshire, MA = Massachusetts, RI = Rhode Island, CT = Connecticut, NY = New York, NJ = New Jersey, DE = Delaware, MD = Maryland, VA = Virginia.

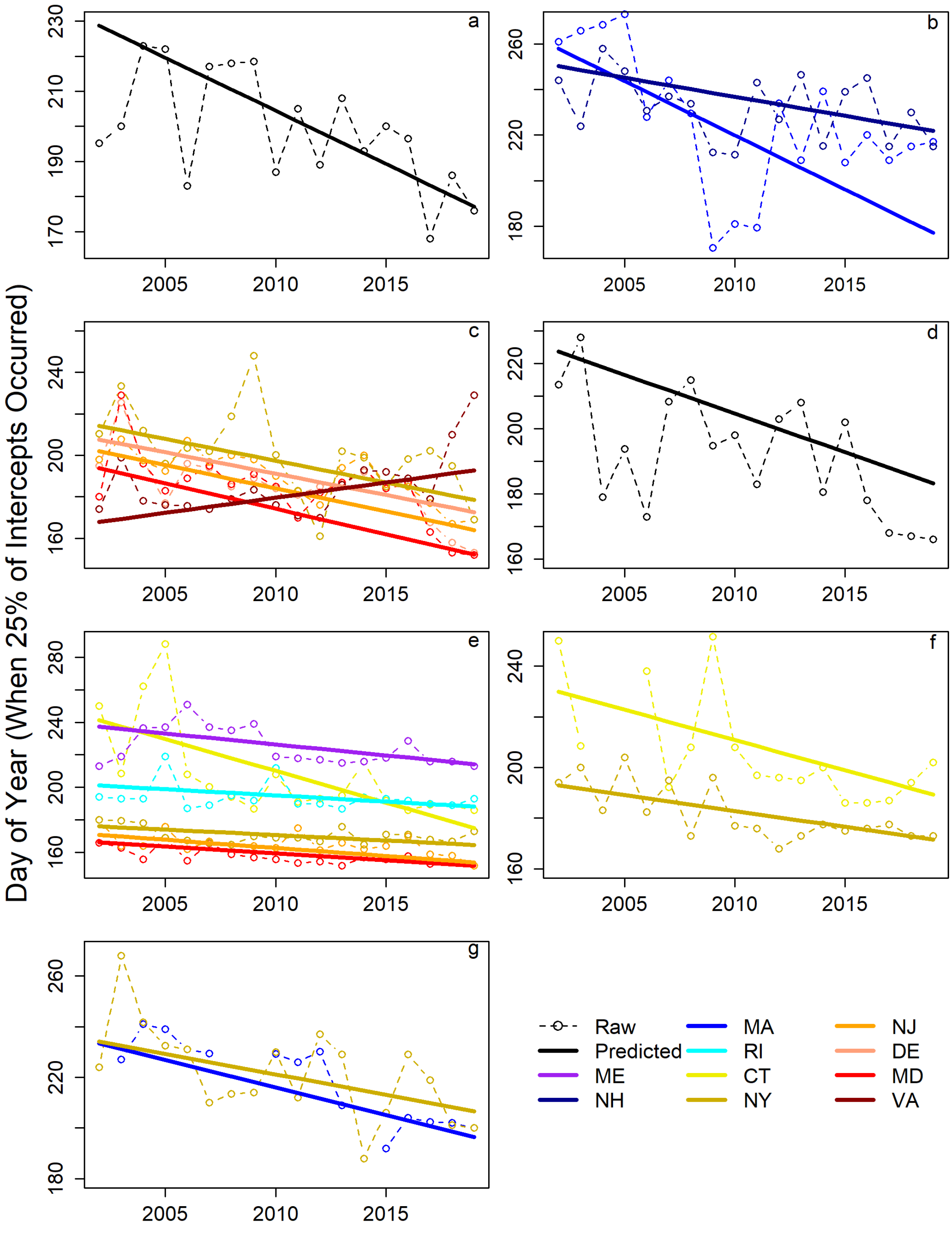

Figure 5. Raw and predicted values for day of year when 25% of intercepts occurred for each year for HMS where year was significant: bigeye tuna (a), large bluefin tuna (b), small bluefin tuna (c), skipjack tuna (d), blue shark (e), shortfin mako (f), and blue marlin (g). Dashed lines indicate raw day of year values each year, whereas solid lines indicate the predicted day of year values. Plots where only black lines exist indicates there was no significant interaction between year and state intercept (a & d). For all other plots, colors represent the raw and predicted day of year values for each state for that species. Abbreviated states are ME = Maine, NH = New Hampshire, MA = Massachusetts, RI = Rhode Island, CT = Connecticut, NY = New York, NJ = New Jersey, DE = Delaware, MD = Maryland, VA = Virginia.

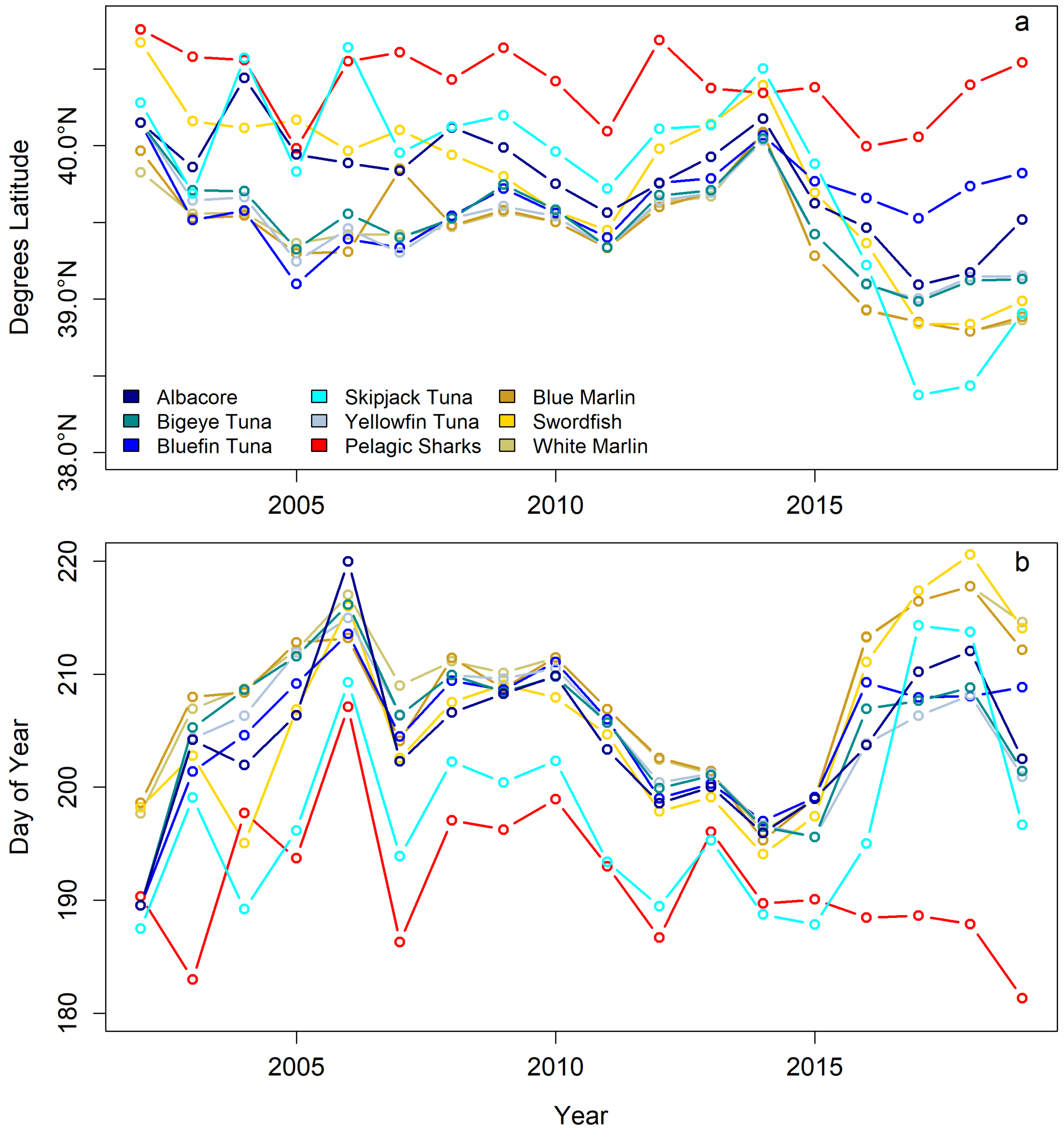

Figure 6. Mean latitude (a) and mean day of year (b) of HMS tournaments targeting HMS that were focused on in this study.

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