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Exploring trends in abundance of Young-of-the-Year, and Age-1 Atlantic Croaker (*Micropogonias undulatus*), Black Drum (*Pogonias cromis*), Spot (*Leiostomus xanthurus*) and Weakfish (*Cynoscion regalis*) in relation to salinity, temperature and large-scale climatic signals in a Mid-Atlantic estuary

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<A>Abstract

Atlantic Croaker (*Micropogonias undulatus*), Black Drum (*Pogonias cromis*), Spot (*Leiostomus xanthurus*) and Weakfish (*Cynoscion regalis*) have shown species-specific varying trends in abundance, despite general declines in commercial landings throughout the Delaware River Estuary. Identifying how environmental factors and climatic processes affect fishes at multiple life stages is needed to enhance the precision of regulatory actions for managed species. Species' area and age specific indices were compared with depth, salinity, temperature, the Atlantic Multidecadal Oscillation (AMO) and the North Atlantic Oscillation (NAO) to explore potential relationships, as well as temporal and spatial parameters. Our results demonstrate that station (15 indices), salinity (14 indices), the AMO and NAO (13 indices each), depth and temperature (12 indices each), served as important components for models of abundance of seventeen species, age, and area specific combination from 1991-2016. Significant time series trends were detected in six of the modelled indices of abundance, including Bay-wide indices of Age-1 Weakfish (decline), and YOY Atlantic Croaker (increase); as well as YOY Atlantic Croaker (increase) and Weakfish (decline) in Delaware, and Age-1 Spot (decline) and Weakfish (increase) in Delaware. Our results demonstrate how multiple fixed station surveys can be combined to quantitatively assess environmental and climatic effects correlated with species-age-area specific levels of abundance, suggesting climatic signals are affecting smaller scale environmental variables that in turn affect relative abundance.

<A>Introduction

Understanding how environmental phenomena affect fisheries is a significant challenge that requires immediate attention to identify how these processes impact managed species. Recognizing the effects of environmental processes on fish stocks at multiple life stages can provide new information to enhance precision of regulatory action and management efforts. Previous studies have suggested that environmental and ecological factors need to be accounted for to better understand the behavior of fish stocks and more accurately assess population levels (Garcia and Cochrane 2005; Lehodey et al. 2006; Methot and Richard 2015). Environmental processes, such as El Niño and La Niña in the Pacific Ocean; the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) in the Atlantic Ocean, vary over large spatiotemporal scales, causing varying responses amongst fish growth rates (Fiedler et al. 1986; Ottersen et al. 2001; Jonsson and Jonsson 2004; Izzo and Zydlewski 2017), predation (Stenseth et al. 2002; Nye et al. 2009; Yasumiishi et al. 2016), recruitment and other population dynamics (Hare and Able 2007; Nye et al. 2009; Large et al. 2013; Edwards et al. 2013; Harris et al. 2014; Nye et al. 2014; Buchheister et al. 2016). Climatic processes have been linked to changing physiochemical properties in estuaries (Irby et al. 2018) which can have confounding effects on the fish species that rely on certain conditions seasonally within estuaries to survive (Barletta et al. 2005). Understanding how components of multiple large-scale environmental phenomena impact marine nekton is critical to address trends in annual variability of recruitment and survival. In the northwest Atlantic Ocean, two large-scale atmospheric processes, the NAO and AMO, are likely influencing the abundance of the Delaware River Estuary fish community in unknown ways.

The NAO is observable in the Northern Hemisphere throughout the year with over one third of sea-level-pressure variance occurring during winter months (December-February) over the North-Atlantic (Hurrell and Deser 2010). The NAO is characteristically defined as an annual index and a winter index due to the significant variances in sea-level-pressure observed in winter months (Jing et al. 2019). The NAO is defined more specifically as a change in pressure differences between the subtropical atmospheric high-pressure zone over the Azores and the atmospheric low-pressure zone over Iceland (Otterson et al. 2001; Durkee et al. 2008). However, NAO indices have been shown to influence many atmospheric and oceanographic conditions such as sea surface temperature (SST), storms and precipitation, cloud cover, hydrographic characteristics, mixed-layered depths, and circulation patterns (Barnston and Livezey 1987; Ostermeier and Wallace 2003; Durkee et al. 2008; Hurrell and Deser 2010). Unlike El Niño/La Niña and the AMO, the NAO has no defined change in periodicity between its warm and cold phases (Otterson et al. 2001; Hurrell and Deser 2010). Warm (positive) phases of the NAO index are defined as an intense Icelandic low and a strong Azores high-pressure gradient, with the pressure difference delivering powerful winter storms crossing the Atlantic Ocean in a northern direction, conversely cold (negative) phases have a weak pressure grade and produce weaker storms that tend to move west to east (Hurrell 1995; Otterson et al. 2001). The NAO influences atmospheric pressures causing variations in precipitation patterns, wind events, storm events and climate fluctuations (Durkee et al. 2008).

The AMO is characterized as varying SST anomalies that encompass the North Atlantic and is considered the dominant pattern of SST variability within the region (Schlesinger and Ramankutty 1994; Dong et al. 2006; Knudsen et al. 2011; Alexander et al. 2014; Harris et al. 2014; Nye et al. 2014). Unlike the NAO, the AMO has oscillating phases that tend to switch every 65-70 years based on approximately 130 years of observed and reconstructed SST data (Nye et al. 2014). The AMO is defined as having warm and cool phases, with warm phases described as having above average ocean temperatures and a shifting of the intertropical convergence zone from the south to the north, where precipitation expands spatially (Enfield et al. 2001; Knudsen et al. 2011; Nogueira et al. 2013; Nye et al. 2014). Warm phases of the AMO typically cause the mixed layer depth to be much shallower and are linked to variations in oceanic pressure gradients, wind speed and direction across the North Atlantic (Nye et al. 2014). Conversely, the cool phase of the AMO is described as causing opposite anomalies as seen with the warm phase respectively (Dijkstra et al. 2006; Alexander et al. 2014).

Successful recruitment of young-of-the-year (YOY) fishes has been linked to environmental processes (e.g. Boehlert and Mundy 1988; Lehodey et al. 2006; Cury et al. 2008). Previous studies have shown that nekton size (Hale & Targett 2018), temperature (Witting et al. 1999; Lankford and Targett 2001; Hare and Able 2007; Carassou et al. 2011; Yasumiishi et al. 2016), salinity (Lankford and Targett 1994; Able et al. 2009), freshwater input (Reist et al. 2006; Carassou et al. 2011), flow (Dunning et al. 2009) and wind speed and direction (Schieler et al. 2014; Nye et al. 2014) can significantly affect transport, growth and survival of multiple life stages of marine nekton. The NAO and the AMO have been linked to trends in fisheries production, distribution, and abundance (Lehodey et al. 2006). The AMO has been correlated with spatial distribution and spawning success for fish species in the Mid- and North Atlantic Ocean including Striped Bass (*Morone saxatilis*; O'Connor et al. 2012) and American Shad (*Alosa sapidissima*; O'Connor et al. 2012); Atlantic Mackerel (*Scomber scombrus*; Overholtz et al. 2011); Atlantic Croaker (*Micropogonias undulatus*; Hare and Able 2007); Atlantic Salmon (*Salmo salar*; Izzo and Zydlewski 2017). Lankford and Targett (2001) found that severe cold winter temperatures were correlated to weak year-class strength of age-0 Atlantic Croaker in estuaries along the Mid-Atlantic Bight. In that study, temperature was found to be a growth-limiting factor in juvenile Atlantic Croaker within the Delaware Bay due to feeding temperature preferences and acute thermal stress leading to significantly increased mortality at temperatures below 5° C. Other environmental factors, including wind patterns, have been found to have a positive correlation with larval fish ingress into estuaries within the Mid-Atlantic Bight. Schieler et al. (2014) found that wind direction and speed were correlated with the ingress of larval fish including Atlantic Menhaden (*Brevoortia tyrannus*), Summer Flounder (*Paralichthys dentatus*) and Atlantic Croaker in Delaware Bay.

The mechanistic link between ocean climatic processes and year-class strength has some regional stock assessment teams beginning to examine effects that atmospheric and oceanographic conditions have on species-specific stock assessments (e.g., Sablefish

(*Anoplopoma fimbria*; Schirripa et al. 2009) and Weakfish (*Cynoscion regalis;* Jiao et al. 2012). Responses of Atlantic Croaker and Weakfish to changing oscillations of the NAO have been observed along the continental shelf between the North Carolina-Virginia border and Cape Canaveral, Florida (Roberts et al. 2019). The findings by Roberts et al. (2019), suggest that the predictability of species distributions potentially shift with phases of the NAO. Along the Eastern US continental shelf, Atlantic Mackerel have been found to occupy different areas annually in response to large scale climatic shifts associated with the phases of the AMO but were historically located in relatively narrow bands of optimal habitat within the Mid-Atlantic region during winter (Overholtz et al. 2011). However, Overholtz et al. (2011) found that overwintering Atlantic Mackerel shifted their distribution much further North and East as they followed their optimal habitat to higher latitudes in response to shifts in environmental conditions over a period of decades. In the Hudson River Estuary, YOY Striped Bass and American Shad were both found to exhibit strong relationships to the AMO; freshwater flow, water temperature, and the AMO explained 46% of the total variance in the species stage specific abundance patterns within the Hudson River Estuary (O'Connor et al. 2012). Juvenile American Shad were negatively correlated with the AMO in the Hudson River Estuary, while Striped Bass were positively correlated with the AMO (O'Connor et al. 2012). A recent study developed indices of Atlantic Menhaden recruitment using independent surveys from the southern region of the Northeast Atlantic and correlated the indices to the AMO (Buchheister et al. 2016). Even though different correlations to the AMO were discovered in Chesapeake Bay and Southern New England regions, results showed that the AMO had been one of the greatest predictors of Atlantic Menhaden recruitment patterns throughout the entire Atlantic coast (Buchheister et al. 2016).

The Delaware River Estuary is a large coastal plain estuary, which borders the states of Delaware, New Jersey, and Pennsylvania in the Mid-Atlantic Bight. The estuary is both an important spawning area for many diadromous and estuarine species, seasonally occupied by a host of species, serving as a nursery ground that contributes habitat services to commercial and recreational fisheries along the eastern United States. Common migratory species inhabiting the Delaware River Estuary include Striped Bass, American Shad, Hickory Shad (*Alosa mediocris*), Alewife (*Alosa pseudoharengus*), and Blueback Herring (*Alosa aestivalis*), and several species of sciaenid including Atlantic Croaker, Black Drum (*Pogonias cromis*), Weakfish, and Spot (*Leiostomus xanthurus*).

Identifying and monitoring environmental influences on successful reproduction, growth, distribution, and recruitment is essential to understand how variable environmental processes may affect populations in the future, especially within dynamic environments, including coastal estuaries. To examine the effect the AMO, the NAO, salinity and water temperature have on managed fisheries in the Mid-Atlantic region, we have compared trends in these variables to multiple indices of abundance for Atlantic Croaker, Black Drum, Spot and Weakfish within the Delaware River Estuary. Annual recreational and commercial landings of Atlantic Croaker, Black Drum, Weakfish and Spot have all generally decreased from 1991-2016 despite significant management measures to restrict or reduce harvest. Management plans have suggested monitoring environmental preferences of Atlantic Croaker, Black Drum, Spot and Weakfish to understand effects on stock size, life histories, and spatial distribution (ASMFC 2017). In order to better understand fluctuations in recruitment we need to better account for the effects of large-scale climatic trends, such as the AMO and NAO, as well as more direct environmental factors including salinity and temperature. Our first objective was to standardize indices of catch among commonly shared variables to generate models of relative abundance, while incorporating significant abiotic parameters associated with the AMO and NAO. Next, we sought to combine multiple indices of abundance to generate Bay-wide composite indices of relative abundance. Finally, we examined significant trends in abundance to determine if state specific, and Bay-wide indices of species, age and area specific abundance significantly varied through time from 1991-2016.

<A>Methods:

Study Area:

The Delaware River Estuary is the second largest estuary on the Atlantic Coast of the USA, and it stretches 213 km from Trenton, NJ to Cape May, NJ on the north and Cape Henlopen, DE on the south (Schieler et al. 2014). The widest part of the estuary extends 45 km just inside the estuary entrance, which is 18 km wide (Janzen and Wong, 2002). The Delaware Bay has a mean depth of 8 m (Aristizábal and Chant 2015) with a shipping channel dredged to maintain 14 m MLLW (Mean Lower Low Water) extending up the estuary to the Delaware River. The estuary is weakly stratified with estuarine circulation variably dominated by wind and buoyancy driven flows impacting species and stage/size specific patterns of early juvenile fish ingress (Epifanio and Garvine 2001; Hale and Targett 2018).

Surveys:

Two data sets of fishery independent samples from the Delaware River Estuary were used in this analysis; one conducted by Delaware's Division of Fish and Wildlife (DFW; Figure 1) and one conducted by New Jersey's Bureau of Marine Fisheries (NJMF). Since 1980, DFW has used a 5.2-m semi-balloon style trawl, equipped with a 1.3-cm knotless stretch-mesh liner to retain juvenile fishes to estimate relative abundance (Greco 2019). Sampling is conducted monthly in Delaware Bay at 33 fixed sites and in Delaware River at 6 fixed sites, from April through October. Tow durations for both surveys are standardized at 10 minutes for both surveys. Catches that yield large numbers are randomly subsampled in DFW's trawl survey for length and age data. In the DFW 5.2-m trawl a randomly selected 30 individual subsample for each species is measured to the nearest half centimeter for fork length (FL), and the remaining individuals are enumerated. Similarly, NJMF has conducted a trawl survey within New Jersey state waters of Delaware Bay since 1991, using a 4.9-m trawl net equipped with a 1.3-cm knotless stretch-mesh liner (Hassall 2019) contributing to indices of relative fish abundance within the estuary. NJMF collects data monthly at 11 fixed stations within the bay, from April through October. NJMF tow durations are standardized at 10 minutes against tide, using optimal weather windows to conduct sampling similar to the DFW survey. NJMF randomly subsamples 50 individual fish for length, which was reported as both FL and total length (TL) for Atlantic Croaker, Black Drum, Spot, and Weakfish. All data were temporally subset to provide overlapping information from 1991-2016 for the purposes of this project. The total number of each species caught per tow was multiplied by the proportion of catch by age based on the observed size distribution for that tow to provide an estimate of the number of YOY and Age-1 individuals captured per haul. Fish less than 13 mm were removed from the models to account for gear saturation. Age at length for YOY and Age-1 Black Drum, Atlantic Croaker, Spot and Weakfish were derived from juvenile recruitment indices. Year classes tend to have lengths centered around frequently occurring size classes after hatching (Michels and Greco 1995; Bonzek et al. 1995). Further the YOY recruits are available to the gear seasonally and spatially in the estuary and only certain months are considered in the length ranges and indices per species. YOY length cutoffs for Atlantic Croaker were designated at 100 mm and under in September and October; Black Drum YOY cutoffs were 300 mm and under in August, September, and October; Spot YOY cutoffs were 170 mm and under in July and 200 mm and under in August, September, and October; Weakfish YOY cutoffs were 110 mm and under in June, 150 mm and under in July, 200 mm and under in August, 235 mm and under in September and 250 mm and under in October. Age-1 length frequencies were developed using literature reviews of YOY to Age-1 cutoffs and Age-1 to Age-2 cutoffs (Atlantic Croaker; Liao et al. 2019, Michels and Greco 1995, Bonzek et al. 1995, ASMFC 2017b); Black Drum; Liao et al. 2019, Michels and Greco 1995, Bonzek et al. 1995); Spot; Liao et al. 2019, Michels and Greco 1995, Bonzek et al. 1995); Weakfish; Liao et al. 2019, Michels and Greco 1995, Bonzek et al. 1995, ASMFC 2006, Lowerre-Barbieri 1995). Age-1 length cutoffs for Atlantic Croaker were determined to be 201 – 260 mm; Black Drum Age-1 fish were considered at 330 – 455 mm; Spot Age-1 fish were considered at 201 – 224 mm; Weakfish Age-1 fish were considered at 254 – 275 mm.

Statistical Analyses:

Environmental data including surface water temperature (°C) and salinity (ppt) collected at each net set/haul, as well as the monthly values of two climatic indices including the AMO (https://psl.noaa.gov/data/timeseries/AMO/), and NAO (www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao_index.html) were used to explore how these parameters influenced the species, age and area specific indices of catch. Both the DFW 5.2 m and the NJMF 4.9 m surveys were standardized using a generalized additive model framework where tow specific catch was modelled as a function of

$$\text{Catch} \sim \text{factor(Year)} + \text{factor(Month)} + s(\text{Station}) + s(\text{Temp.}) + s(\text{Salinity}) + s(\text{Depth}) + s(\text{AMO}) + s(\text{NAO})$$

using a negative binomial error distribution, Poisson error distribution and zero-inflated Poisson error distribution for each index through time where Year and Month are fitted as fixed effect factors, while Station was treated as a random effect, Temperature, Salinity, Depth, monthly values for the AMO and NAO are fitted as smooth terms with thin plate regression splines as the basis and *k*, is the number of basis functions to use for each smooth term before any identifiability constraints are applied to estimate an index using the “gam” function in the “mgcv” package in R 3.5.2 (R 2008) for each survey, species and age combination (Drexler and Ainsworth 2013). Indices of abundance were each fit using this model formulation to standardize according to year, and fixed station, as well as to account for variation in depth and month between surveys while measuring if environmental and climatic variables affected catch. The estimation method applied was restricted maximum likelihood (REML). Similarly, Bay-wide, composite indices of abundance were modelled using the same approach, with the incorporation of an additional factor to account for variability associated with the two state surveys with tow specific catch was modelled as a function of

Catch ~ factor(Year) + factor(State) + factor(Month) + s(Station) + s(Temp.) + s(Salinity) + s(Depth) + s(AMO) + s(NAO) + s(Year*State)

using a negative binomial error distribution (NBGAM), Poisson error distribution (PGAM) and zero-inflated Poisson error distribution (ZIPGAM) for each index. For all of the candidate GAMs, the best model (initial error distribution (NBGAM, PGAM, ZIPGAM) and final model selection) was determined with an information-theoretic approach using the Akaike information criterion or AIC score (Burnham and Anderson 2002; Bucheister et al. 2016). After determining the optimal error distribution among three similar, global models, the "dredge" function in the "MuMIn" package of R 3.5.2 (R 2008) was used to automatically test and find the most parsimonious model formulation of potential covariates for each species, area (DE, NJ), and age (YOY, Age-1) specific model, as well as for Bay-wide composite indices (CI) which included an interaction between Year and State. The "predict" function in the "car" package of R 3.5.2 (R 2008) was used to generate estimates of annual mean catch using the tow specific standardized models of catch. A likelihood ratio test was used to compare models with a null model for each index to determine goodness of fit. Standardized indices of abundance for each species (Atlantic Croaker, Black Drum, Spot and Weakfish), age (YOY, Age-1) and survey (Composite Indices, DFW 5.2 m, NJMF 4.9 m) were then fit with Autoregressive Integrated Moving Average (ARIMA) models using an iterative approach of 1,000 bootstrapped runs to estimate a median ARIMA fit for each index using the "surveyfit" and "surveyref" functions in the "fishmethods" package of R 3.5.2 (R 2008). ARIMA models are commonly used to examine trends in a population relative to a given reference point, such as survey quartiles or terminal years in managed species (e.g. Atlantic Sturgeon, ASMFC 2017a) providing a mechanism to assess the relative abundance of each species-area-age combination through time. The terminal year value generated from the median ARIMA was then compared to both the first quartile and the survey start year to estimate a probability of the terminal year being greater than 25% of the time series and the survey start year using a statistical level of confidence of $\beta = 0.80$ with a Holm-adjusted probability of rejecting the null hypothesis regarding normality of model residuals (Box and Jenkins 1976; Helser and Hayes 1995; ASMFC 2017a). Then, we used a Mann-Kendall trend test to analyze monotonic trends in the median ARIMA indices using the "mk.test" function in the "trend" package of R 3.5.2 (R 2008), after correcting for family-wise error rates in the statistical *p*-values using the Holm method. Finally, length frequencies of each species were developed to compare the relative size distributions of Atlantic Croaker, Black Drum, Spot, and Weakfish caught between the two trawl surveys from 1991-2016 (Ogle 2014; Emmanuel 2017).

<A>Results

Trends in the AMO index are evident between positive and negative phases over a time series of reconstructed and observed sea surface temperature (SST) data at 65-70-year intervals (Knudsen et al. 2011). Within our available 26-year time series, shifts from cool to warm years are evident in both the NAO and the AMO. From 1991-1994, the AMO index remained in a cool phase and has remained in a warm phase from 1997 through 2016 (Figure 2). Conversely, the NAO had demonstrated greater variability between years than the AMO. Slightly more than half (53.8 %) of the years from 1991-2016 were represented by a warm year for the NAO index with reversals experienced at a frequency of one to four year intervals (Figure 2).

All species and age combinations were not equally represented between the two locations when compared to the total number of individual fish collected for each species, age and area. Higher numbers of all YOY were observed in Delaware. Between 79 – 92 % of all the YOY observed for the four species were collected in Delaware compared to New Jersey. However, a higher number of Age-1 Weakfish was observed in New Jersey. When examining the total number of fishes caught with all covariate data present, 122,077 individuals were collected in Delaware, whereas 25,202 individuals were collected in New Jersey across all species and ages combined (Table 1). More than 61 % of the total number of individuals collected in Delaware were comprised of YOY Weakfish. Similarly, more than 58 % of the total number of individuals collected in New Jersey were attributed to YOY Weakfish. Age-1 Atlantic Croaker and Spot were both collected in Delaware, at two orders of magnitude less when compared to YOY for both of those species. Conversely, no Age-1 Atlantic Croaker or Spot were documented in New Jersey from 1991-2016 (Table 1). However, Age-1 Weakfish were present at both locations.

Of the seventeen possible combinations where we had enough data to generate base models of catch that included all model covariates, the negative binomial error distribution was the lowest scoring AIC value of the global models in thirteen of the indices (Table 1). ZIPGAMs were chosen as the final model in all three indices of YOY Black Drum indices. And a PGAM was selected for in the Age-1 Atlantic Croaker index in Delaware. All final model configurations were highly significant when compared to null models without covariates (p-value < 0.001). The deviance explained by the final models for all species, area, and age combinations ranged from 23.1 – 89.2 % depending upon the model, with all dispersion values less than 2.4 for all indices, suggesting reasonable levels of variance were present for all final models (Table 1).

Many of the environmental and climatic variable smoothing parameters were found to be significant in the final models. However, the year and state interaction term included in three of the five composite indices which combined data from Delaware and New Jersey was not significant in any model (Table 2). Station was found to act as a significant smoothing parameter in all the fifteen models in which that parameter was selected for inclusion in the final model. The AMO, NAO, salinity and surface temperature collected at each tow were significant smoothing parameters in twelve of the seventeen final models. While depth was found to be significant in ten of the seventeen final models. Residuals were not normally distributed for six of the seventeen ARIMA model fits. However, for the remaining eleven ARIMA models, residuals were normally distributed (Table 3). All the normally distributed median ARIMA model fits, but the Bay-wide, composite index of Age-1 Weakfish had a higher probability (P > 51 %) of being greater than the first quartile for each time series, while four of the indices had a higher probability (P > 51 %) of being less in 2016 when compared to the survey start year of 1991 (Table 3).

Peaks in YOY Atlantic Croaker abundance were observed in New Jersey from 1996-2011 over the course of the time series with peaks in YOY Atlantic Croaker observed in Delaware from 2001-2005 and again in 2010 and 2014 (Figure 3). The Bay-wide composite index of YOY Atlantic Croaker had seven peaks in abundance throughout the course of the time series. However, peaks in abundance of Age-1 Atlantic Croaker are present only at the beginning of the time series in Delaware from 1991-1994 (Figure 3). GAM indices of Atlantic Croaker abundance explained between 38.5 – 60.1% of the deviance for the two surveys (Table 1). The smooth term for salinity was included in all three final YOY models, and significant in both the Delaware and composite indices. Similarly, the AMO and the NAO were significant smoothing parameters included in all three final YOY models. While a significant smooth term for depth was included in the final YOY NJMF 4.9 m survey only. Station was also identified as significant smoothing parameters in the YOY DFW 5.2 m and composite indices. All the smoothing parameters included in the YOY DFW 5.2 m index were included in the Age-1 DFW 5.2 m index, in addition to depth (Table 2). Median fit ARIMAs for the YOY DFW 5.2 m and composite index for Atlantic Croaker (Figure 3) demonstrated an increasing trend from 1991-2016 with normally distributed error terms and a high probability of an increase in abundance relative to the first quartile for each survey ($P \geq 99$ %; Table 3). Median fit ARIMA models of both the YOY NJMF 4.9 m and Age-1 DFW 5.2 m indices were not normally distributed. Atlantic Croaker ranged in size from 15 – 175 mm FL in the DFW-5.2 m survey and 13 – 173 mm FL in the NJMF 4.9 m survey (Figure 7) throughout the time series.

For Black Drum, YOY were the only encountered age group in the two surveys with matching covariate data. Peaks in the DFW 5.2 m survey were observed from 1993 to 2013. Whereas a single large peak in abundance was observed in the NJMF 4.9 m survey in 2007 (Figure 4). GAMs of Black Drum abundance explained between 42.1 – 89.2 % of the deviance for each of the three surveys (Table 1). Depth was the only significant smoothing variable included in all three surveys. Depth and the NAO were the only smoothing parameters included in the YOY, NJMF 4.9 m GAM. The AMO, depth, NAO, salinity, station, temperature were significant smoothing parameters in the YOY models for the DFW 5.2 m survey, and the Bay-wide composite index (Table 2). Additionally, the interaction term between Year and State was also included in the final model of the YOY composite index. The ARIMA of the YOY DFW 5.2 m Black Drum index had a high probability ($P \geq 76$ %, Table 3; Figures 4), that the index value in 2016 was both greater than the first quartile, as well as the survey start year. However, the residuals from the YOY NJMF 4.9 m survey and the composite index were not normally distributed (Table 3) suggesting that the data representing the population were not normally distributed and results inferred from those analyses should be ignored or used with caution. Further, no significant trend in YOY Black Drum abundance was identified in the DFW 5.2 m index (Table 3). Black Drum ranged in size from 75 – 435 mm FL in the DFW-5.2 m survey and 27 – 320 mm FL in the NJMF 4.9 m survey (Figure 7).

Spot like Atlantic Croaker, and Black Drum had a much higher likelihood of being observed as YOY, when compared to the total number of Age-1 individuals (Table 1). Peaks in YOY Spot abundance were asynchronous throughout time between the two states (Figure 5). GAMs of abundance explained between 38.7 – 63.2 % of the deviance for each of the four models (Table 1). Station as a random effect was the only significant smoothing parameter included in the YOY NJMF 4.9 m survey. While all the smoothing parameters were both significant and included in the YOY DFW-5.2 m survey, except for salinity which was dropped from the final model. Additionally, all the smoothing variables of the final YOY composite index were included in the final model formulation. However, the AMO and the interaction between year and state, while included in the final model were not statistically significant smoothing parameters in the YOY composite index. Depth, the NAO, salinity, and station were all significant smoothing parameters in the Age-1 DFW-5.2 m survey index (Table 2). In 2016, the median fit ARIMA of YOY Spot from the DFW 5.2 m and composite index had a 91 % probability of being higher than the first quartile for the time series and lower than the value observed in 1991. However, Age-1 Spot from the DFW 5.2 m index had a 77 % probability of being greater than the first quartile (Table 3). No significant trends in abundance were detected for any median ARIMA fit YOY Spot index. However, Age-1 Spot from the DFW-5.2 m survey were found to have declined since 1991. Spot ranged in size from 15-250 mm FL in the DFW-5.2 m survey and 14-224 mm FL in the NJMF 4.9 m survey (Figure 7).

Similar to all three of the other species explored, YOY weakfish were more frequently encountered by both surveys when compared to the proportion of the total number observed of Age-1 Weakfish within each survey (Table 1). YOY Weakfish had a period of relatively higher abundance from 1999-2012 in the NJMF 4.9 m index; whereas YOY Weakfish were generally higher in relative abundance in the DFW 5.2 m survey from 1991-2000 with peaks after that period in 2007, 2011 and 2015 (Figure 6). Relative abundance was higher for the Age-1 DFW 5.2 m survey from 1992-2000, when compared to the rest of time series. Conversely, the Age-1 Weakfish index from the NJMF 4.9 m had more peaks toward the end of the time series from 2000-2015 (Figure 6). The Bay-wide, composite index of Weakfish appeared to be more like the DFW 5.2 m index with a cluster of higher values observed from 1991-1997, however all of the Age-1 annual means were less than 1. GAMs of Weakfish abundance explained between 23.1 – 60.5 % of the deviance in the data for the six indices (Table 1). The AMO, station as a random effect and temperature, were all significant smoothing parameters included in the final models for all YOY Weakfish indices. Depth was included in all three final models, as well, but not significant in the YOY DFW 5.2 m Weakfish index. While the NAO and salinity were significant smoothing variables for the DFW 5.2 m and the composite indices, but not included in the final YOY NJMF 4.9 m index. All smoothing variables present in the final model formulation were significant in the Bay-wide GAM of Age-1 Weakfish. Additionally, the interaction between year and state was included in the final YOY composite index (Table 2). Salinity and station as a random effect were all significant smoothing parameters in all three of the Age-1 Weakfish indices. The AMO was a significant smoothing parameter in both the DFW 5.2 m and composite index, but not included in the final Age-1 NJMF 4.9 m index. Temperature was a significant smoothing parameter in the Age-1 NJMF 4.9 m and composite index, but not included in the final model of the Age-1 DFW 5.2 m index. Finally, the NAO was a significant smoothing parameter in the Age-1 NJMF 4.9 m index, but not present in either of the final models for the other two Age-1 indices (Table 2). The 2016 terminal time series year estimate from the median fit ARIMA had a high likelihood ($P \geq 75$ %) of being greater than the first quartile for each YOY Weakfish time series. However, the likelihood of the terminal year being greater than the survey start year in 1991 was much lower in most of the YOY and Age-1 Weakfish indices. Also, the Bay-wide Age-1 Weakfish composite index had a higher likelihood of being less than the first quartile ($P = 57$ %; Table 3). No significant trends were detected in the YOY Weakfish for either the Bay-wide composite index or the NJMF 4.9 m index. However, the YOY Weakfish DFW 5.2 m GAM was found to have declined through time. Residuals from the Age-1, NJMF 4.9 m survey were not normally distributed suggesting that the data representing the population are not normally distributed and results inferred from those analyses should be ignored or used with caution for that index. However, the median fit ARIMA Age-1 Weakfish index for the DFW 5.2 m survey was increasing, while the composite index was found to be declining through time (Table 3). Weakfish showed a range in lengths between 13-250 mm FL in the DFW 5.2 m survey for YOY and Age-1, and 13-250 mm FL in the NJMF 4.9 survey for YOY and Age-1 (Figure 7).

<A>Discussion

Sciaenid species showed varying patterns in abundance through time within the Delaware River Estuary from 1991-2016 demonstrating significant trends and associations with both environmental covariates and larger, regional climatic indices. Each of the four species experienced shifts in abundance at different time intervals within the modelled time series, suggesting that underlying factors are likely affecting species-age-area specific trends in abundance within the estuary. Of the environmental processes affecting abundance, temperature and salinity were both consistently found to smooth GAM fits for multiple species-age-area specific models of abundance for these species. Similarly, we consistently observed relationships between climatic indices including the AMO and the NAO, and modelled abundance, demonstrating that long term climate has a correlation between smaller scale processes like water temperature, that affect the species examined in this study at multiple ages. Of the eight potential composite indices (YOY & Age 1; Atlantic Croaker, Black Drum, Spot, Weakfish) that might allow us to examine how environmental drivers may affect relative abundance for Sciaenids on an estuary wide scale, only five of the indices had enough data to generate GAMs of abundance, and only two of the indices had normally distributed, measurable trends in abundance including the YOY Atlantic Croaker and Age-1 Weakfish composite indices. Of those two, YOY Atlantic Croaker have increased, while Age-1 Weakfish have decreased from 1991-2016. Therefore, we have demonstrated a method to aggregate data across spatial areas, standardize catch, evaluate trends within an area through time and make comparisons relative to time series reference points that may serve as a management guideline, and make broader assessments across a larger spatial region to examine how abundance varies through time.

We have considered the limitations of our data and analyses in the interpretation of these results. Our study used catch data across two historical fixed-station time series of unequal survey sites, limiting the catch variability and inducing potential spatial bias within the sampling routines. However, due to heavy maritime shipping traffic in the estuary and spatial designations by each state limiting the bounds at which each survey can operate, combining fixed station data became a viable option for analyzing a time series of relative abundance in the Delaware River Estuary. Further, daily weather patterns, gear type, trawl speed and boat captain may have all affected the concentration of individuals within a given species for each survey (Misund et al. 1999). Additionally, there was a higher number of stations sampled within the Delaware survey when compared to the New Jersey survey, which likely skewed our results, particularly in the construction of Bay-wide composite indices. Our attempt to build a composite index may reflect this disparity between the number of sampling stations, as the composite models often behaved similar to those from the DFW surveys. We used the most optimal GAM we could identify for each individual survey and species-age-area-specific index of relative abundance so that we could standardize annual catches of each species without assuming linear relationships among covariates and build individual models that accounted for covariates including station and interactions between year and state for composite indices. GAMs apply a series of smoothing functions in an iterative approach to fit linear or nonlinear relationships between individual predictors and dependent variables simultaneously (Hastie and Tibshirani 1986). As an example, GAMs were found to better estimate catch when compared to GLMs because of the nonlinearity associated with covariates and catch in the Alaskan Sablefish (*Anoplopoma fimbria*) longline fishery (Mateo and Hanselman 2014). Overlap in ages at length was also considered within our analysis, especially within the Age-1 to Age-2 cutoffs for Weakfish where large variations of length at age have been observed within these age groups (Lowerre-Barbieri et al. 1995). However, we believe that the estimates of catch we derived are likely a conservative approximation for the true proportion at age being captured.

Combining each of the two surveys into a single composite index through time allowed for a Bay-wide model of species-specific relative abundance by combining multiple surveys throughout the estuary standardized by a similar suite of potential covariates. Abundance data vary annually, reflecting population level fluctuations, survey sampling variability, and variable catchability (Pennington 1986; ASMFC 2017a). We utilized ARIMAs to filter measurement error from process variability to identify trends in relative abundance (Box and Jenkins 1976; Helser and Hayes 1995; ASMFC 2017a) for individual surveys, and Bay-wide composite indices, and generate comparisons with those filtered data with environmental variables. Finally, the AMO and NAO vary at multi-decadal frequencies, so attempting to compare trends in relative abundance with 26 years of data may fail to adequately capture the effect these climatic processes have on Sciaenid abundance through time. However, we were fortunate enough to have data that spanned positive and negative phases of both the AMO and NAO, allowing for an exploration of how the AMO and NAO affect relative abundance. Despite the limitations of our data and the assumptions associated with our methods, we have managed to estimate relative abundance for four species at two ages, using standardized indices of abundance, generate statistically significant Bay-wide trends in relative abundance for four species, and make comparisons of a subset of those trends to large scale, climatic drivers and environmental variables including temperature and salinity.

The abundance of Atlantic Croaker was related to the AMO, depth, the NAO, salinity, station as a random effect, temperature and an interaction between year and state within the Delaware River Estuary. These results suggest climatic, and environmental processes are correlated to fluctuations in abundance at both ages. Further, our results demonstrate that the two fixed station surveys asynchronously capture peaks in abundance, suggesting that Atlantic Croaker may be utilizing different areas within the bay through time based on active habitat selection, physical processes affecting their ingress into the estuary or a combination of biophysical transport processes (Hale & Targett 2018). Trends in species abundance based on statistics for the Mann-Kendall trend tests of median fitted ARIMAs for each index demonstrate an increasing trend in abundance of YOY Atlantic Croaker in Delaware Bay. Additionally, we found that multiple environmental variables and climatic phenomena were correlated to modelled abundance through time including temperature, salinity, depth, station, the AMO and the NAO depending upon the survey.

The connection between environmental variables that are controlled by large scale climatic signals and abundance in Atlantic Croaker has been previously observed. Data from Lankford and Targett (2001) suggested that Atlantic Croaker have an optimal temperature window at age-0 in Delaware Bay, with substantial mortality when exposed to prolonged water temperatures below 5°C. Similarly, work conducted in the Gulf of Mexico suggested that Atlantic Croaker distribution can be influenced by abiotic factors, such as hypoxia and water temperature, causing spatial disturbances within the species' preferred niche and dispersing Atlantic Croaker to cooler offshore waters where growth was limited due to reduced growth energy (Craig and Crowder 2005). Witting et al. (1999) found that in the Little Egg Harbor, NJ, temperature affected the annual phenology and duration of seasonal larval fish assemblages, with Atlantic Croaker being most abundant as part of the fall assemblage. Similarly, our findings suggest that the AMO, which is directly related to SST (Edwards et al. 2013; Large et al. 2013), affects YOY Atlantic Croaker abundance within the Delaware River Estuary (Lankford and Targett 2001; Miller et al. 2003). Previous work, including a study by Hare and Able (2007) correlated 'outbursts' of recruitment and year class strength of juvenile Atlantic Croaker with above average minimum winter temperatures and the wintertime NAO index across several Mid-Atlantic States, demonstrating that warm winters provide an increase in optimal Atlantic Croaker habitat in Mid-Atlantic estuaries. Our findings, much like previous studies, show an increase in Atlantic Croaker abundance during warm temperatures within Delaware Bay. Our findings with the AMO and NAO index suggest that physical mechanisms controlling SST, wind driven flows and precipitation (Enfield et al. 2001) are correlated to juvenile abundance, based on reported size at maturity and landings (ASMFC 2010; ASMFC 2017b) in the estuary. Similarly, larval Atlantic Croaker were previously suggested to be reliant upon physical forcing mechanisms at early life history stages to promote ingress into Delaware Bay (Hale and Targett 2018) suggesting that environmental processes are acting throughout life history on this species in a compounding manner with behavioral modification to enhance or depress survival.

Comparable to Atlantic Croaker, we found that multiple climatic drivers and environmental variables significantly affected models of abundance of YOY Black Drum in Delaware, and at an estuarine scale. Other researchers have similarly identified links between climatic signals and Black Drum. Zimmerman (2016) found a strong positive correlation with the AMO and Black Drum landings, with significant lags occurring at 9 years prior to a given year, suggesting that increased catches were linked with positive AMO phases nearly a decade prior. Although the study by Zimmerman (2016) dealt with adult Black Drum primarily, the findings do show that the species has some likely relationship with the AMO. Despite the relatively brief time series we have available (26 years) compared to the 65-year time series examined by Zimmerman (2016) coupled with the longevity of the species (maximum age = 67 years, ASMFC 2015) we still identified the AMO as a significant smoothing parameter of YOY Black Drum in the composite index and Delaware. However, the AMO was not correlated to the YOY Black Drum index in New Jersey suggesting that some difference exists between the two data series. Further, Black Drum were the lowest encountered of the four species explored. Juvenile Black Drum use of salt marshes and tidal creeks as nursey habitat (Odell et al. 2017), as compared to more open habitat accessible to the trawl surveys may be a cause of the low interaction rates observed in our study, due to the lack of sampling in these areas by the two surveys. Further, the two surveys may have differences in how they trawl, that affect catch rates, which we failed to account for in our models of abundance. Differences such as area sampled, depth, number of stations, equipment, and operational variations between the two surveys likely impact catch rates. However, we attempted to control for these parameters by including station and an interaction between year and state where applicable. Similar to the results of our study, Thomas and Smith (1973) examined Black Drum YOY and suggested that factors such as bottom type, current, and temperature are more important for suitable nursery habitat than salinity alone in tidal creeks in the upper Delaware Bay. Further, Black Drum chorusing activity associated with spawning has been correlated with water temperatures offshore of North Carolina and Georgia suggesting that water temperature may affect spawning behavior (Rice et al. 2016) and the subsequent presence of YOY. Black Drum were significantly correlated to dissolved oxygen levels during associated spawning runs in Louisiana, where supersaturated environments were found to have large aggregations of spawning adults (Saucier & Baltz 1993). Additionally, Saucier and Baltz (1993) suggested that the highly oxygenated environments may be sought after because of the size of the Black Drum eggs and the need for higher concentrations of dissolved oxygen to assist in diffusion through the egg envelope. During different phases of the AMO there may be an influx or decrease of freshwater (Enfield et al. 2001; Nye et al. 2014), and variability within SST, which can influence the amount of dissolved oxygen within a given area, changing the physiochemical properties of the water (Irby et al. 2018), and potentially causing Black Drum to search for suitable habitat for spawning or juvenile periods of residency.

A Bay-wide, composite index of YOY Spot included smoothing parameters for all of the environmental variables and climatic phenomena tested, similar to the Bay-wide composite index of Black Drum. In fact, all smoothing variables, except for the AMO and the interaction between year and state were significantly related to the modelled abundance of Spot in Delaware Bay and all but, salinity were correlated between YOY Spot collected in Delaware. Conversely, YOY Spot collected in the New Jersey survey were best explained by salinity and station as a random effect without the inclusion of other environmental or climatic variables. However, the total number of YOY Spot was an order of magnitude lower between Delaware and New Jersey, again suggesting that there is variability in the collection of a species by area, like what was found with Black Drum. However, it is again worth nothing, that a greater number of stations were sampled in Delaware when compared to the New Jersey survey. Our findings demonstrate that YOY Spot abundance in Delaware Bay is significantly correlated to temperature, salinity, depth, and the

NAO. Like the results of our study, Spot in Chesapeake Bay were positively associated with increased temperature and salinity (Schaffler et al. 2013; Love and May 2007).

Models of Weakfish abundance were significantly related to environmental and climatic processes depending upon the age of the fish and the survey area. Bay-wide indices of abundance demonstrate associations among temperature, salinity, station, an interaction between year and state, and the AMO for YOY and Age-1 ages and the NAO for YOY. The AMO was a significant smoothing variable in five of the six final models of Weakfish abundance, suggesting that this climatic phenomenon is correlated to Weakfish abundance. Previous studies have found similar associations between climatic indices and Weakfish abundance, as well as Weakfish mortality. Both the AMO and the NAO have been previously correlated to Weakfish natural mortality for ages 1-6 using data from Connecticut to North Carolina (Jiao et al. 2011). However, the AMO (annual average) was linearly related to natural mortality (Jiao et al. 2011). The last negative phase of the AMO, which occurred from the late 1950s into the 1980s, was linked with higher total catches of Weakfish, most notably in the 1980s. However, the AMO moved into a warm, positive phase in the early 1990s, remaining positive through recent time with associated record low total catch rates (ASMFC 2009). A similar trend was observed through historical catch records in the Delaware Bay from 1880-1933, where catches of Weakfish were high into 1929 followed by decline through 1933 (Nesbit 1954). Higher catches of Weakfish coincide with the negative phase of the AMO during this time period within Delaware Bay, with lower catches correlated with the warm AMO phase starting in the early 1930s (Nesbit 1954).

In addition to large scale climatic drivers, smaller scale, environmental variables have been found to affect Weakfish concentration as well. Weakfish studied in Great Bay, NJ, utilized areas of higher salinities and water temperatures during summer suggesting those environmental factors may influence their habitat selection (Turnure et al. 2015). Temperature may have an influence on male Weakfish disturbance call duration during spawning which may help female Weakfish find a suitable mate and discriminate males based on size (Connaughton et al. 2000). Based on our results, we believe that juvenile Weakfish abundance may be significantly influenced by the AMO through the effect of the AMO on water temperature. Feeding behavior of juvenile Weakfish has been correlated to temperature, salinity and prey interaction rates within Delaware Bay (Grecay and Targett 1996), with results demonstrating these physiochemical attributes can significantly affect growth rates and induce a stress response if high temperatures and lower salinities are encountered (Lankford and Targett 1994). Hare et al. (2016) suggested that Atlantic Croaker, Spot and Weakfish all had the same moderate levels of climatic vulnerability, but the relative degree of certainty according to the standard error of the index was much less for Weakfish compared to the other two species. The relative significance of the environment could be tied to both natural factors, including trends in early life history and natural mortality, as well as confounding anthropogenic factors, including a depleted population status and subsequent interactions between those natural (e.g. mortality, competition) and anthropogenic factors (destruction of environment and environmental conditions).

Beyond the findings for these species in Delaware Bay, the results of previous analyses suggest that fish species are affected by large-scale environmental processes across broad geographic areas, with species being affected at different life stages, and altering attributes associated with trophic ecology. Environmental processes have been correlated with changes in predation patterns (Yasumiishi et al. 2016), growth of marine nekton (Charnov and Gillooly 2004; Yasumiishi et al. 2016; Izzo and Zydlewski 2017) and success of year classes among nekton in freshwater (Reist et al. 2006) and marine ecosystems (Lankford and Targett 2001; Brander and Mohn 2004; Hare and Able 2007). In the Pacific, greater oceanic recruitment and growth rates of juvenile Sockeye Salmon (*Oncorhynchus nerka*) have been positively correlated with SST before entering oceanic waters along the eastern Bearing Sea during warming events, allowing Sockeye Salmon to reach adult maturity more rapidly, aiding in survival (Yasumiishi et al. 2016). Further, survival of nekton is greatly affected by feeding and feeding encounter rates of different prey species (Chao and Musick 1977) with annual variability generated by physical environmental conditions including water column stability (Carassou et al. 2011). In addition, environmental variables and climatic processes have been found to generate variance in the patterns of spatial distribution among marine species due to habitat preferences and potentially overlapping concentrations of prey (Overholtz et al. 2011; Sagarese et al. 2011).

The AMO and NAO have been correlated to recruitment and life stages of many species in the Atlantic Ocean. Specifically, Buchheister et al. (2016) found that an Atlantic Menhaden recruitment index in Delaware showed a significant positive relationship when correlated to a lagged AMO. Our results suggest the AMO's influence on the Delaware River Estuary ecosystem has the potential to alter individual year classes, and subsequently affect population abundance which in turn affects the potential productivity of a fishery of an individual species, generating ecological implications for other species and fisheries. Similarly, the NAO also has been linked to trends in the production, distribution, and abundance of fishes. The NAO has been found to broadly affect anadromous (e.g. Striped Bass, O'Connor et al. 2012) and catadromous (e.g. American Eel (*Anguilla rostrata*), Friedland et al. 2007) species, as well as impact multiple life history stages of other species including the larval stages of Blueback Herring, American Eel, Weakfish, Spot, Atlantic Croaker, and Black Drum (Love et al. 2009) and adult stages of Alewives, Blueback Herring, Atlantic Herring (*Clupea harengus*), and Atlantic Mackerel (Turner et al. 2017). Similarly, Hare and Able (2007) found that increased catches of adult Atlantic Croaker in the 1950s, 1970s, and 1990s were significantly correlated with the warm phase of the NAO index showing the effect of the NAO on Atlantic Croaker recruitment. North Atlantic Cod (*Gadus morhua*) recruitment was positively correlated to the NAO in three cod stocks in the North Sea, Baltic Sea, and Irish Sea, but had a negative correlation in Iceland (Brander and Mohn 2004).

Understanding how environmental variables affect the relative abundance of managed fishes is important to improve the characterization of population variability and assess stock status. We successfully documented species-age-area specific relationships that suggest temperature, salinity, and climatic drivers that impact those variables including the NAO and the AMO can have measurable effects on the abundance of four Sciaenid species at multiple points through time at variable spatial scales. Bay-wide composite indices of abundance provide insight into how environmental variables impact abundance in juvenile fishes across a broader area. Nonlinear relationships exist between catch, temperature and salinity for YOY Atlantic Croaker, Black Drum, Spot, Weakfish, and Age-1 Weakfish in Delaware Bay (Supplemental Figures) which generate variable points in time and space that can alter juvenile survival and growth in an estuary. These age and species-specific responses to environmental and climatic variables occur within an optimum band to produce elevated levels of abundance within a range of observed values for a suite of covariates. We suggest that long term climatic conditions are generating smaller scale environmental fluctuations that present unique physiochemical water conditions that vary in spatial and temporal scale, generating species, age and area specific responses in the abundance of marine fishes observed in Mid-Atlantic estuaries. Further, we have demonstrated a need to explore relationships between environmental factors and fishes, so that stock assessments and management action can incorporate or at least consider incorporating climatic variability and respond accordingly to changes in environmental conditions, thus more accurately portraying natural variability of trends in abundance.

<A>Figures

Table 1. Species, area, age, n (total number of fish observed with matching covariate data), delta AIC scores for similar base models to determine optimal error structure, the final model selection with deviance explained and dispersion from 1991-2016.

Table 2. Associated p-values for the smoothing parameters of AMO, depth (m), NAO, salinity (ppt), station, temperature (°C), and an interaction between Year * State for each species, area, and age specific final model with significant variables highlighted in yellow, unused covariates from the final model formulation were left blank.

Table 3. Summary statistics for median ARIMA results and the Mann-Kendall trend tests of median fitted ARIMAs for each index by species, area and age. W = Shapiro-Wilk statistic for normality, adj. p-value= Holm-adjusted probability of rejecting the null hypothesis regarding normality of model residuals, (θ) = moving average parameter, SE = standard error of theta, σ^2_c = variance of index, P(2016 < 25^{th} pctl) = the probability that the terminal year index value observed in 2016 was less than the first quartile for the time series, P(2016 < 1991) = the probability that the terminal year index value observed in 2016 was less than the survey start year in 1991, S = Kendall Score, σ^2 = variance of Kendall Score, τ = Kendall's tau statistic, adj. *p*-value = the Holm-adjusted probability of the Mann-Kendall time series trend being significant, Trend= trend result (increasing, decreasing or n.s.= not significant). ARIMA fits with non-normally distributed residuals are highlighted in yellow.

Figure 1. A map of Delaware Bay and Delaware River. Trawl station coordinates are marked with symbols and each trawl survey is denoted by color within the estuary.

Figure 2. The annual AMO, annual NAO indices by year (1991-2016) with the standard error of the mean for each index.

Figure 3. Standardized (GAM) indices of abundance for Atlantic Croaker by age, survey (DE-DFW 5.2 m; NJ-NJMF 4.9 m; CI-composite index) and year from 1991-2016, with the error bars representing the 95 % Confidence Interval for each annual mean in the upper four panels. While the lower four panels represent the corresponding median fitted ARIMA of standardized indices

of abundance by species, year and survey for the standardized index immediately above. In the lower plots, the dots represent the ln(index + 0.01), and the gray line represents the ARIMA index, while the red line represents the first quartile for the time series for each ARIMA.

Figure 4. Standardized (GAM) indices of abundance for YOY Black Drum by survey (DE-DFW 5.2 m; NJ-NJMF 4.9 m; CI-composite index) and year from 1991-2016, with the error bars representing the 95 % Confidence Interval for each annual mean in the upper three panels. While the lower three panels represent the corresponding median fitted ARIMA of standardized indices of abundance by species, year and survey for the standardized index immediately above. In the lower plots, the dots represent the ln(index + 0.01), and the gray line represents the ARIMA index, while the red line represents the first quartile for the time series for each ARIMA.

Figure 5. Standardized (GAM) indices of abundance for Spot by age, survey (DE-DFW 5.2 m; NJ-NJMF 4.9 m; CI-composite index) and year from 1991-2016, with the error bars representing the 95 % Confidence Interval for each annual mean in the upper four panels. While the lower four panels represent the corresponding median fitted ARIMA of standardized indices of abundance by species, year and survey for the standardized index immediately above. In the lower plots, the dots represent the ln(index + 0.01), and the gray line represents the ARIMA index, while the red line represents the first quartile for the time series for each ARIMA.

Figure 6. Standardized (GAM) indices of abundance for Weakfish by age, survey (DE-DFW 5.2 m; NJ-NJMF 4.9 m; CI-composite index) and year from 1991-2016, with the error bars representing the 95 % Confidence Interval for each annual mean in the upper six panels. While the lower six panels represent the corresponding median fitted ARIMA of standardized indices of abundance by species, year and survey for the standardized index immediately above. In the lower plots, the dots represent the ln(index + 0.01), and the gray line represents the ARIMA index, while the red line represents the first quartile for the time series for each ARIMA.

Figure 7. A. Length frequency of Atlantic Croaker by survey and across all years from 1991-2016. DFW - Mean: 44 mm, Median: 25 mm. NJMF - Mean: 31 mm, Median: 23 mm.

B. Length frequency of Black Drum by survey and across all years from 1991-2016. DFW - Mean: 171 mm, Median: 170 mm. NJMF - Mean: 166 mm, Median: 165 mm.

C. Length frequency of Spot by survey and across all years from 1991-2016. DFW - Mean: 137 mm, Median: 140 mm. NJMF - Mean: 129 mm, Median: 130 mm.

D. Length frequency of Weakfish by survey and across all years from 1991-2016. DFW - Mean: 96 mm, Median: 80 mm. NJMF - Mean: 70 mm, Median: 57 mm.

Supplemental Figures:

Supplemental Figure 1. A plot of the NBGAM, YOY Atlantic Croaker composite index (CI) component smooth functions including AMO, NAO, salinity (ppt), station as a random effect and temperature (°C) with two standard errors above and below the estimate of the smooth expressed as dashed lines.

Supplemental Figure 2. A plot of the ZIPGAM, YOY Black Drum composite index (CI) component smooth functions including AMO, depth (m), NAO, salinity (ppt), station as a random effect, temperature (°C) and the interaction between Year and State (labelled as Year) with two standard errors above and below the estimate of the smooth expressed as dashed lines.

Supplemental Figure 3. A plot of the NBGAM, YOY Spot composite index (CI) component smooth functions including the AMO, depth (m), NAO, salinity (ppt), station as a random effect, temperature (°C) and the interaction between Year and State (labelled as Year) with two standard errors above and below the estimate of the smooth expressed as dashed lines.

Supplemental Figure 4. A plot of the NBGAM, YOY Weakfish composite index (CI) component smooth functions including the AMO, depth (m), NAO, salinity (ppt), station as a random effect, temperature (°C) and the interaction between Year and State (labelled as Year) with two standard errors above and below the estimate of the smooth expressed as dashed lines.

Supplemental Figure 5. A plot of the NBGAM, Age-1 Weakfish composite index (CI) component smooth functions including the AMO, depth (m), salinity (ppt), station as a random effect and temperature (°C) with two standard errors above and below the estimate of the smooth expressed as dashed lines.

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Figure 1.

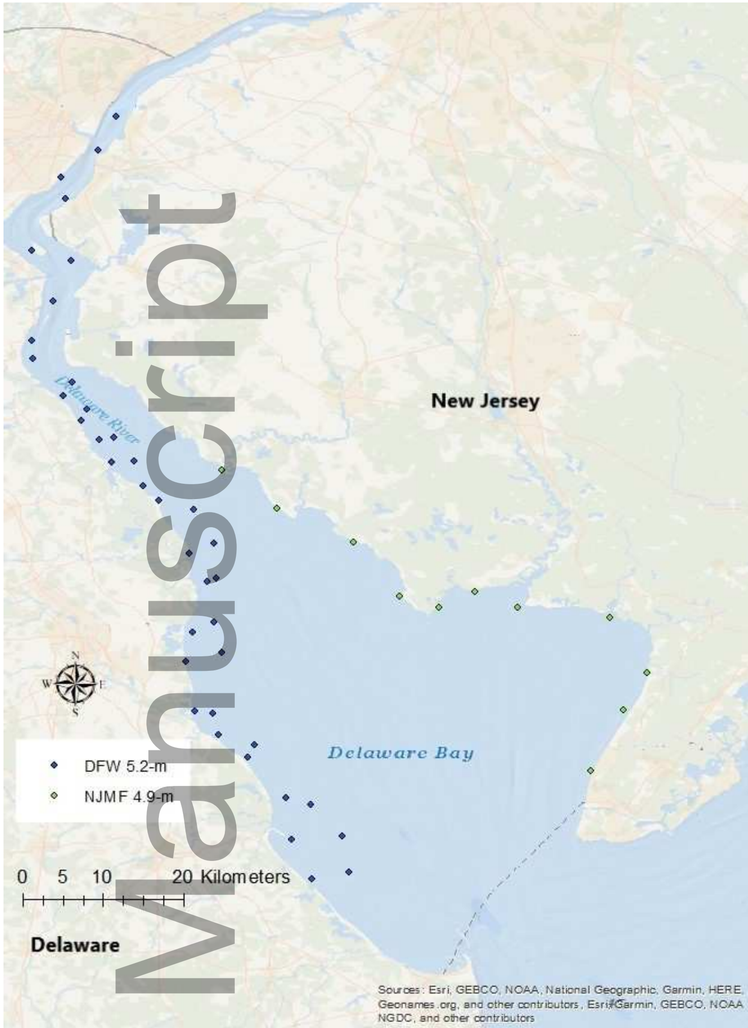
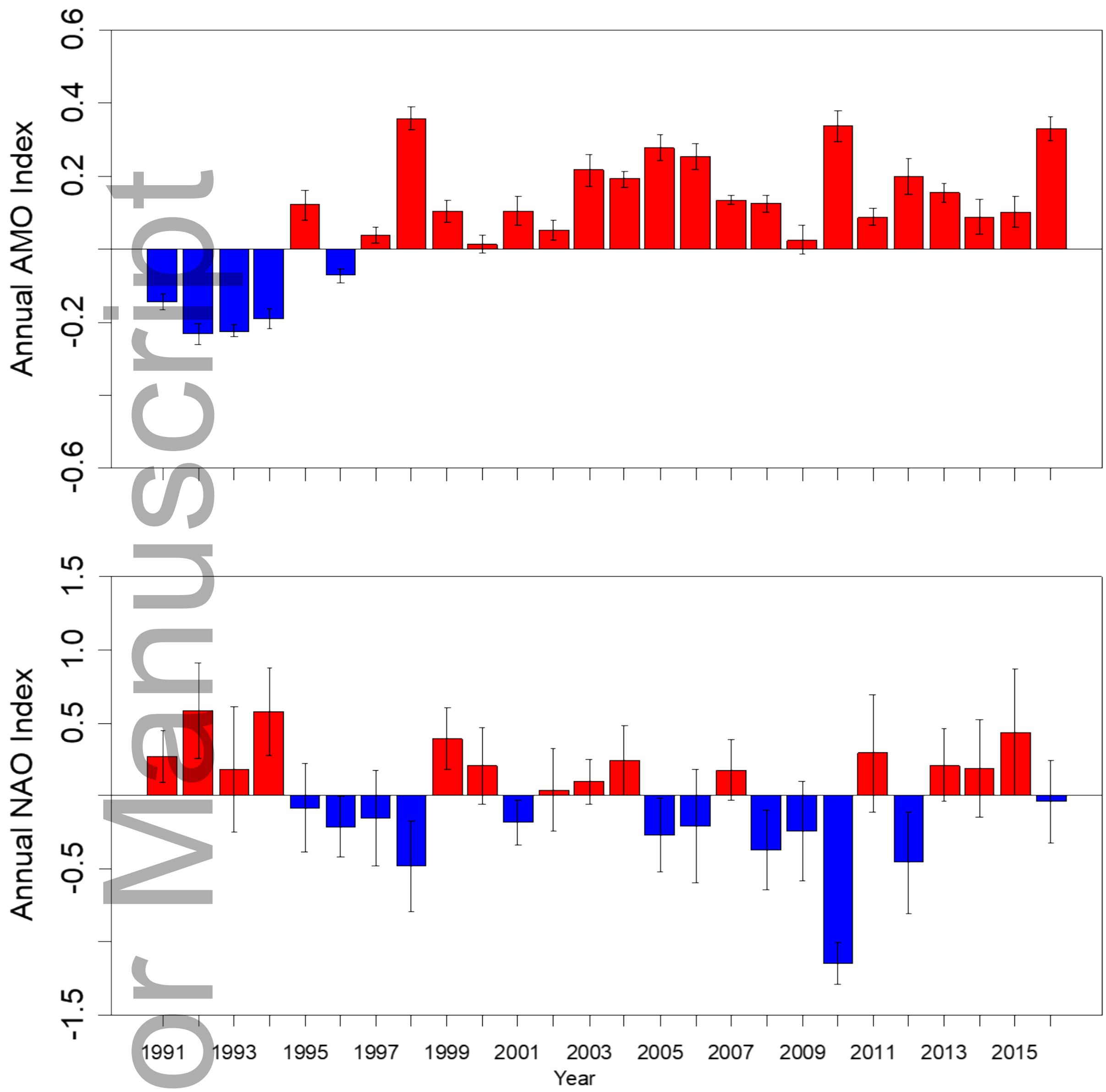

New Jersey
Delaware River
Delaware Bay
DFW 5.2-m
NJMF 4.9-m
0 5 10 20 Kilometers
Delaware
Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors, Esri, Garmin, GEBCO, NOAA NGDC, and other contributors

Figure 2.



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1189 Figure 3.

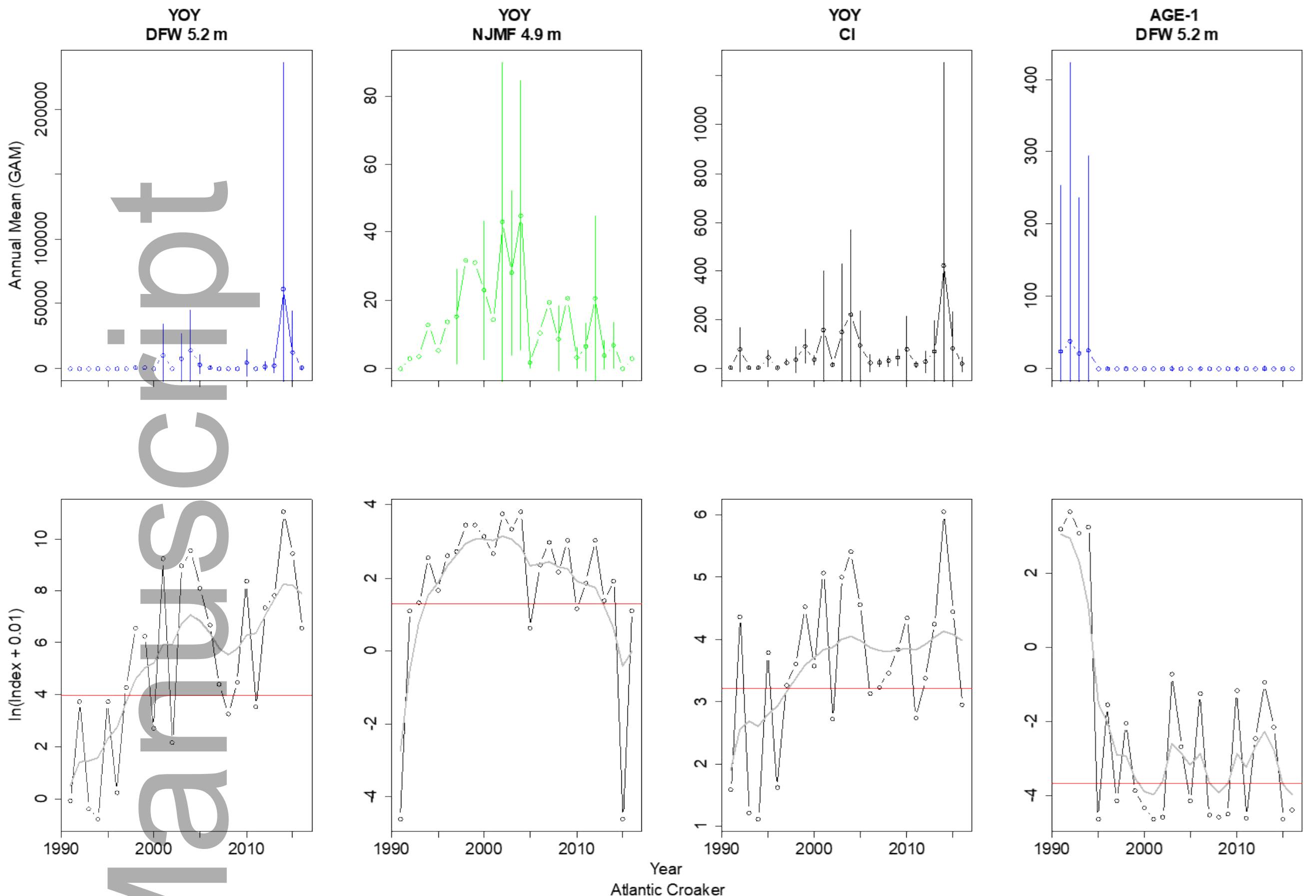

YOY
DFW 5.2 m
YOY
NJMF 4.9 m
YOY
CI
AGE-1
DFW 5.2 m
Annual Mean (GAM)
ln(Index + 0.01)
Year
Atlantic Croaker

Figure 4.

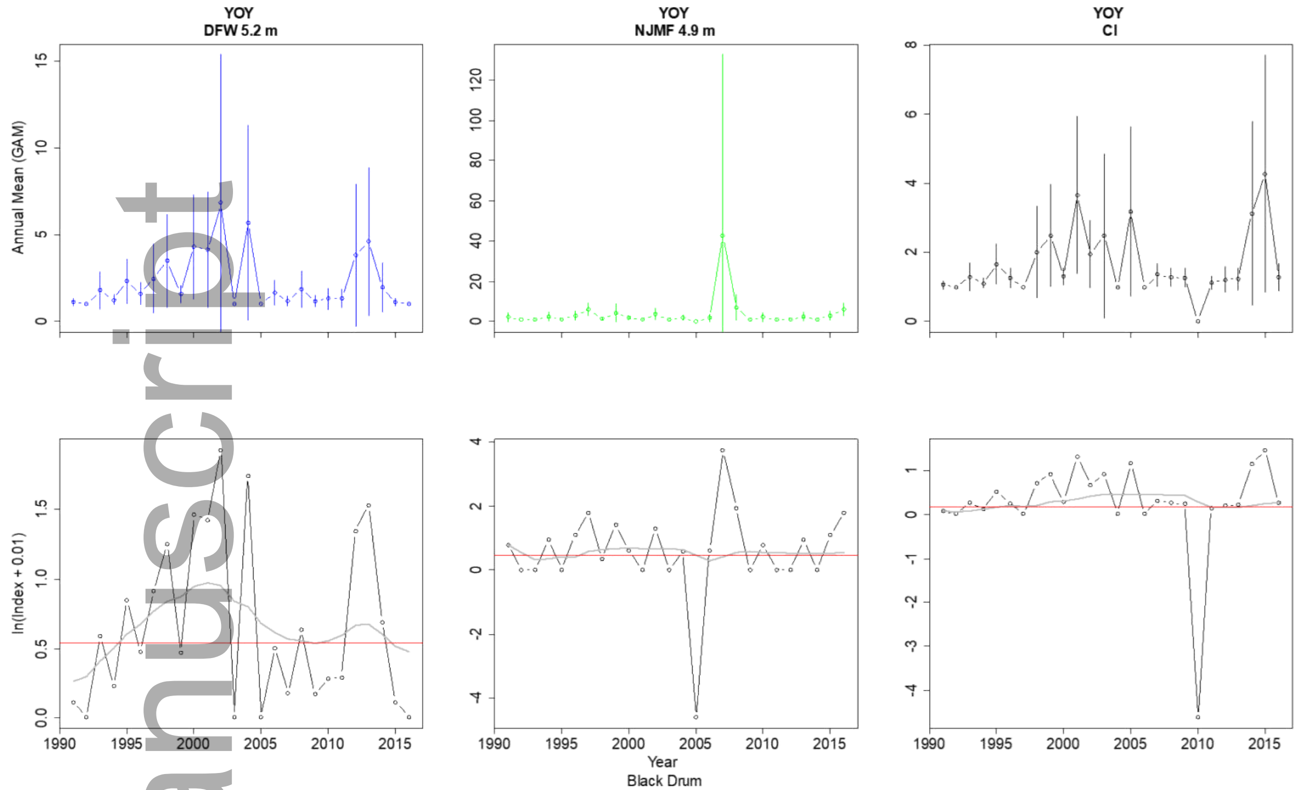
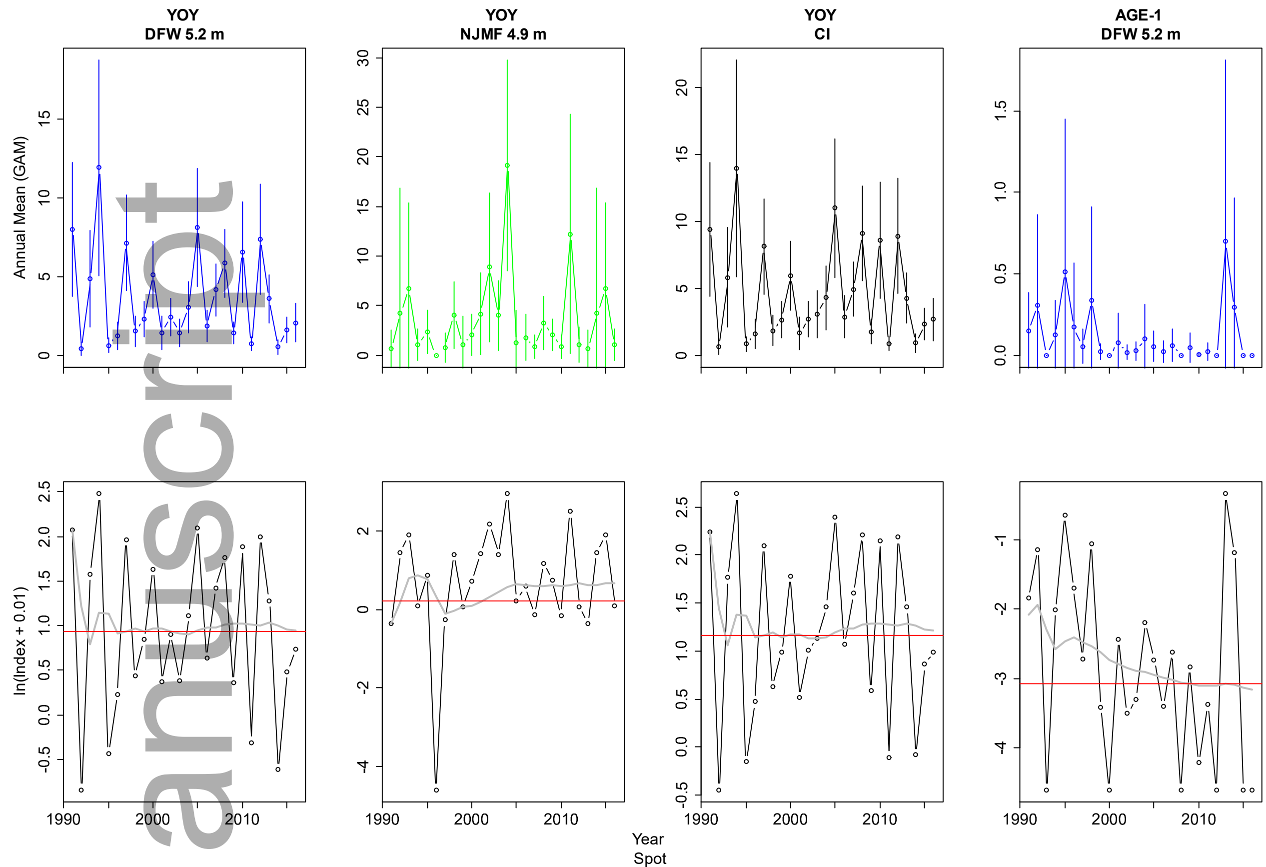

YOY
DFW 5.2 m
YOY
NJMF 4.9 m
YOY
CI
Annual Mean (GAM)
ln(Index + 0.01)
Year
Black Drum

Figure 5.


YOY
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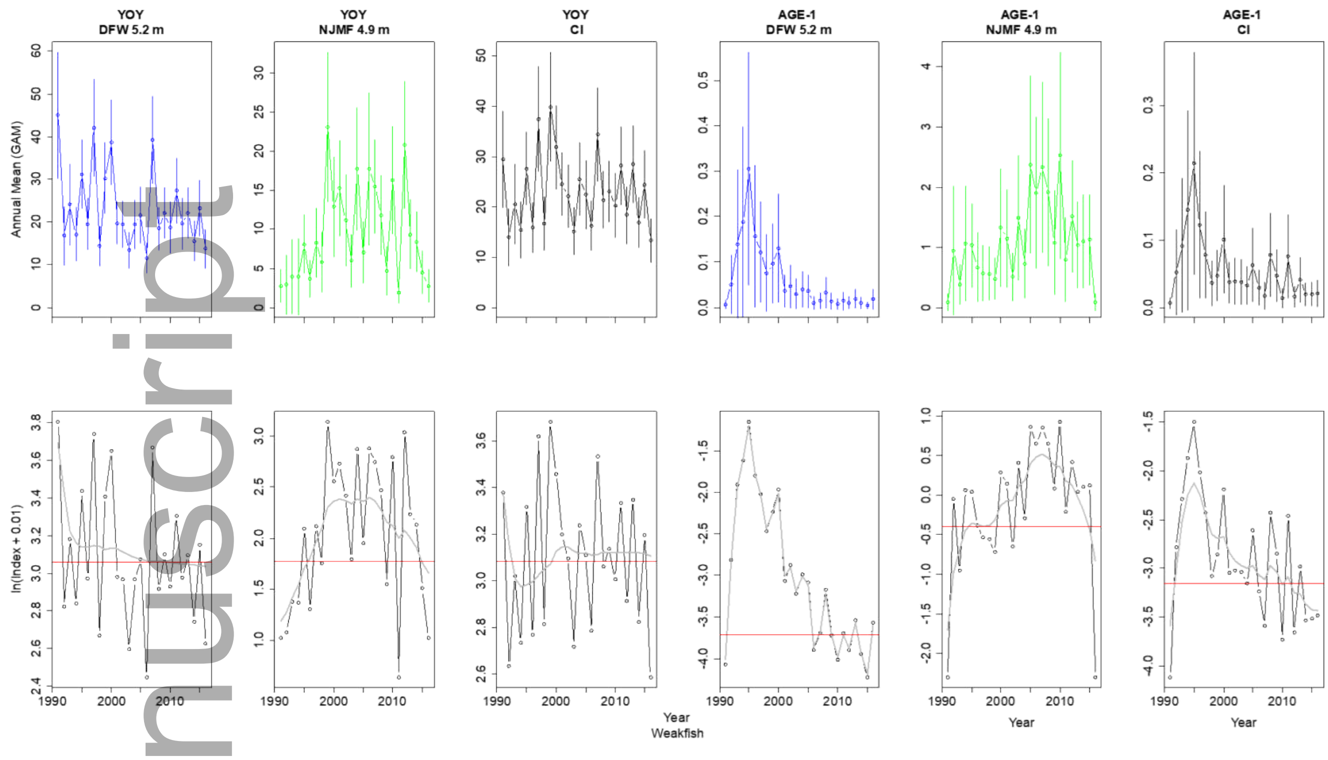
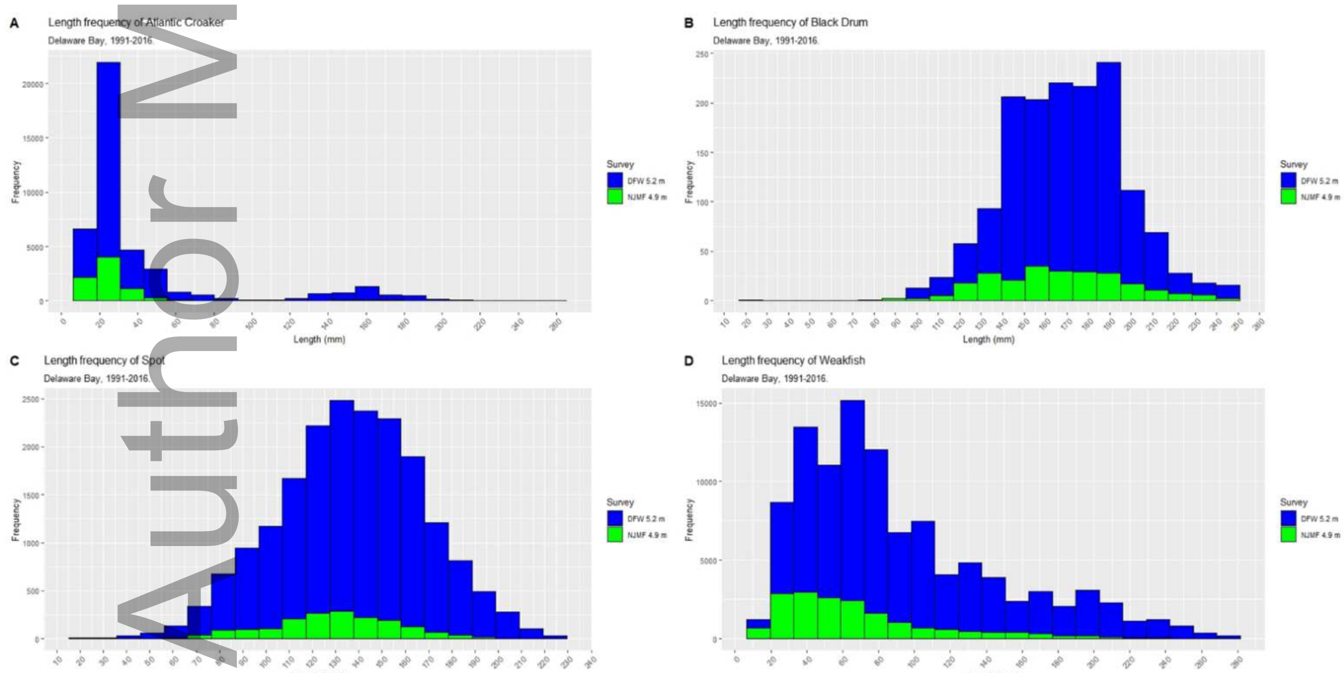
YOY
NJMF 4.9 m
YOY
CI
AGE-1
DFW 5.2 m
Annual Mean (GAM)
ln(Index + 0.01)
1990
2000
2010
Year
Spot

Figure 6.

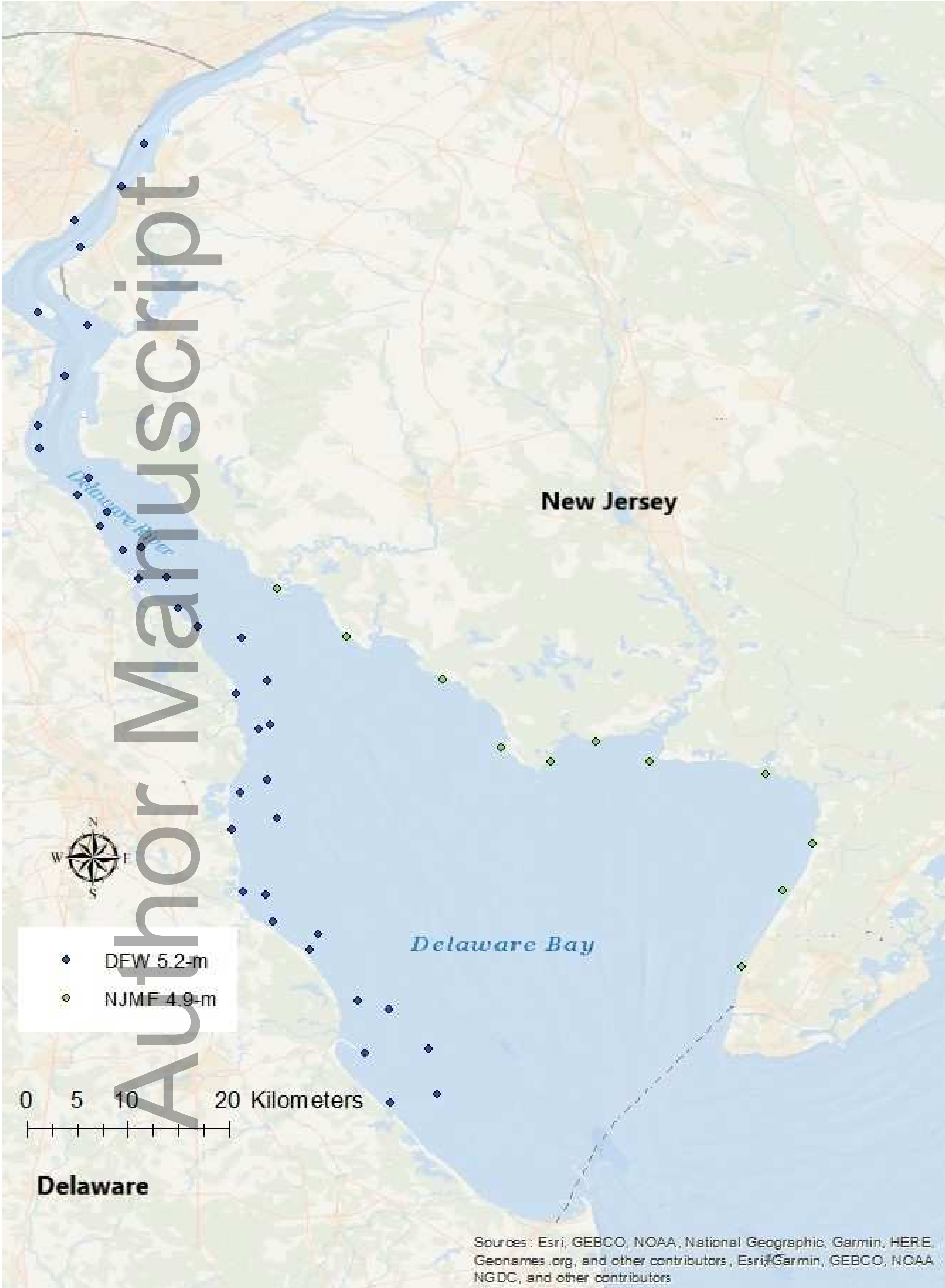


YOY
DFW 5.2 m
YOY
NJMF 4.9 m
YOY
CI
AGE-1
DFW 5.2 m
AGE-1
NJMF 4.9 m
AGE-1
CI
Annual Mean (GAM)
ln(Index + 0.01)
Year
Weakfish
Year
Year

Figure 7.



A
Length frequency of Atlantic Croaker
Delaware Bay, 1991-2016
B
Length frequency of Black Drum
Delaware Bay, 1991-2016
C
Length frequency of Spot
Delaware Bay, 1991-2016
D
Length frequency of Weakfish
Delaware Bay, 1991-2016
Frequency
Length (mm)
Survey
DFW 5.2 m
NJMF 4.9 m



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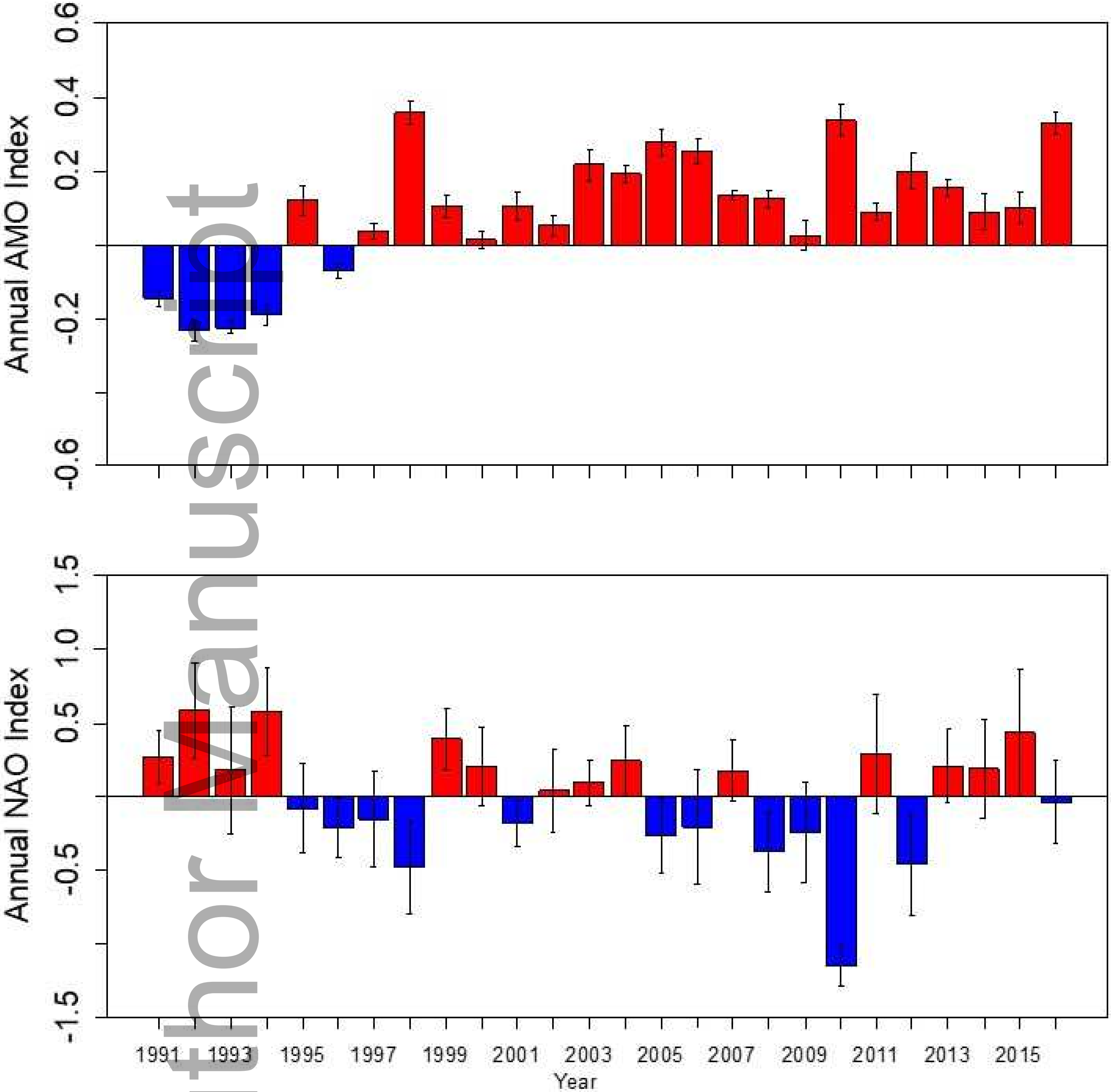

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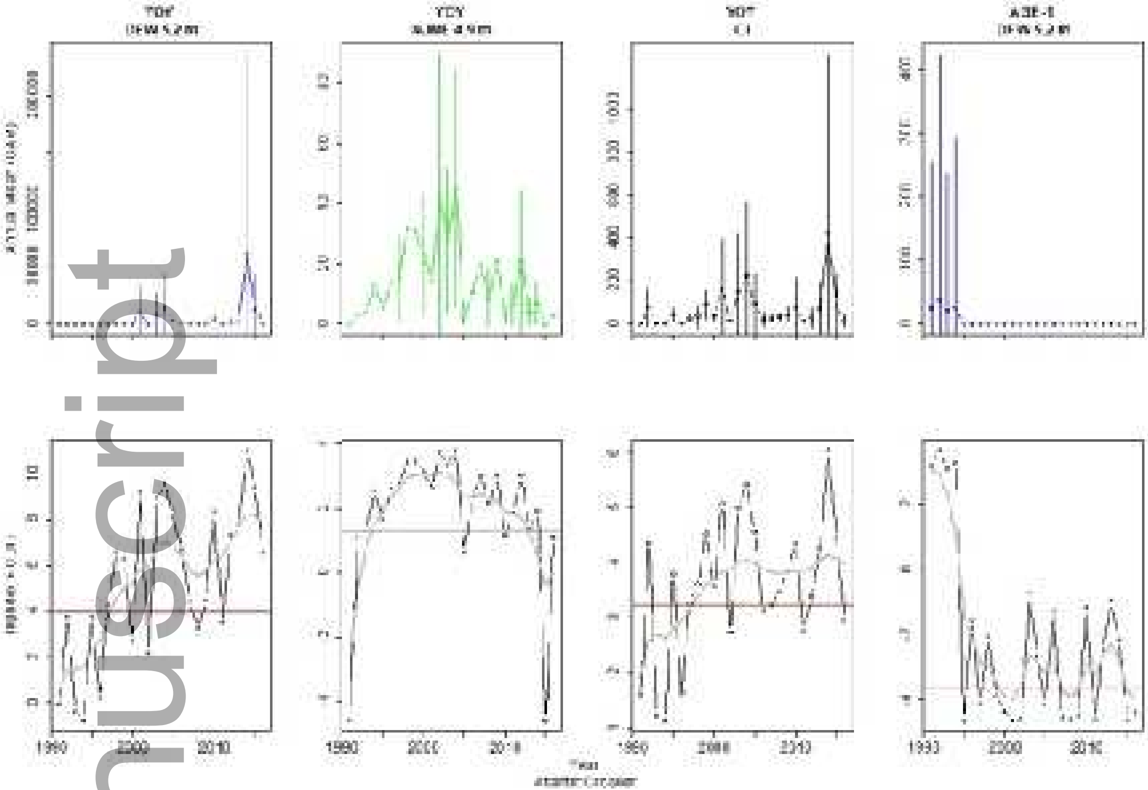

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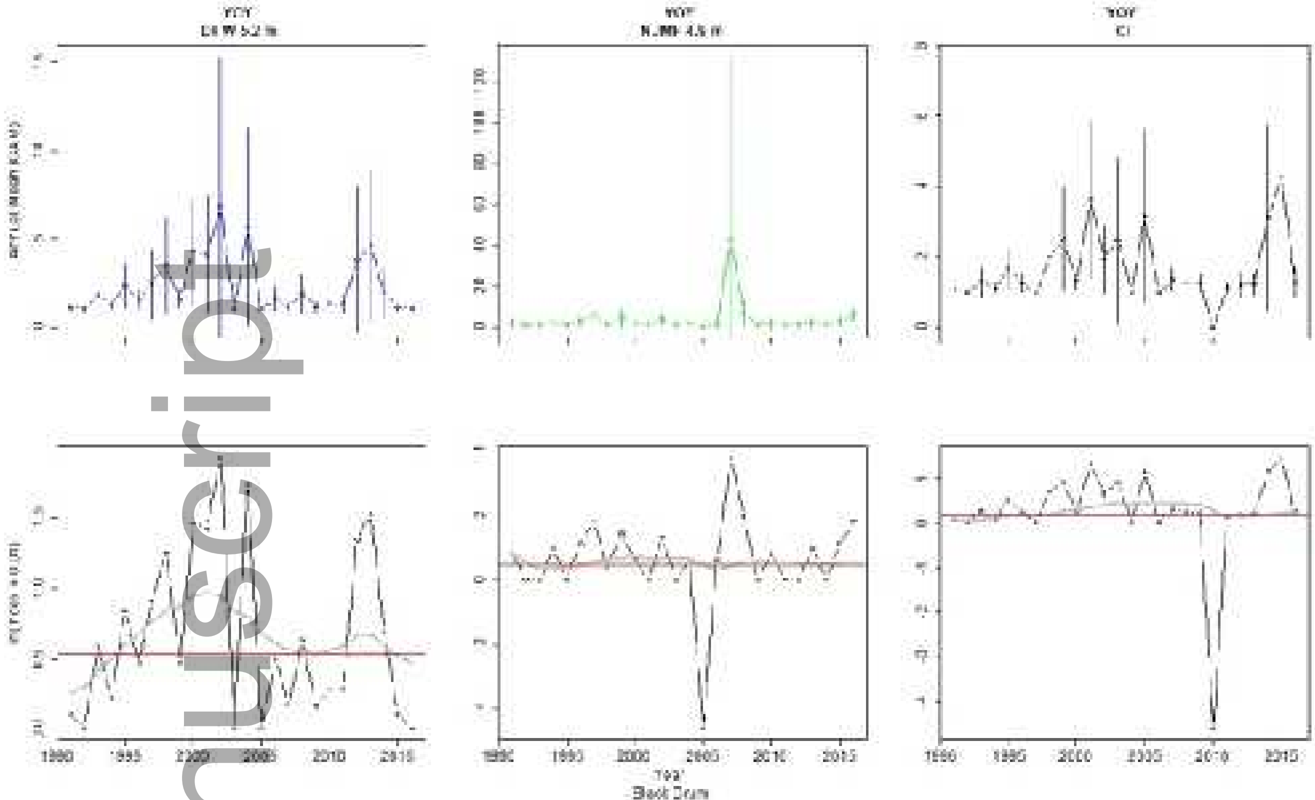

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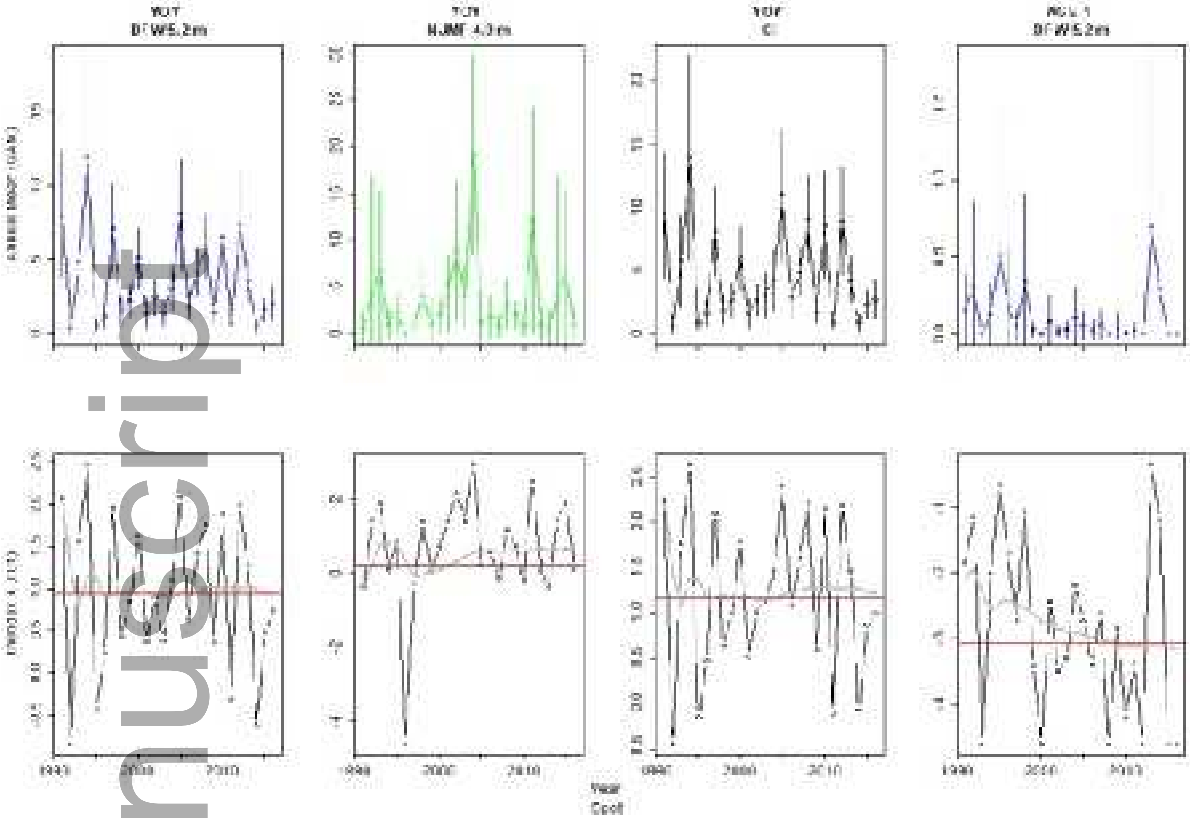

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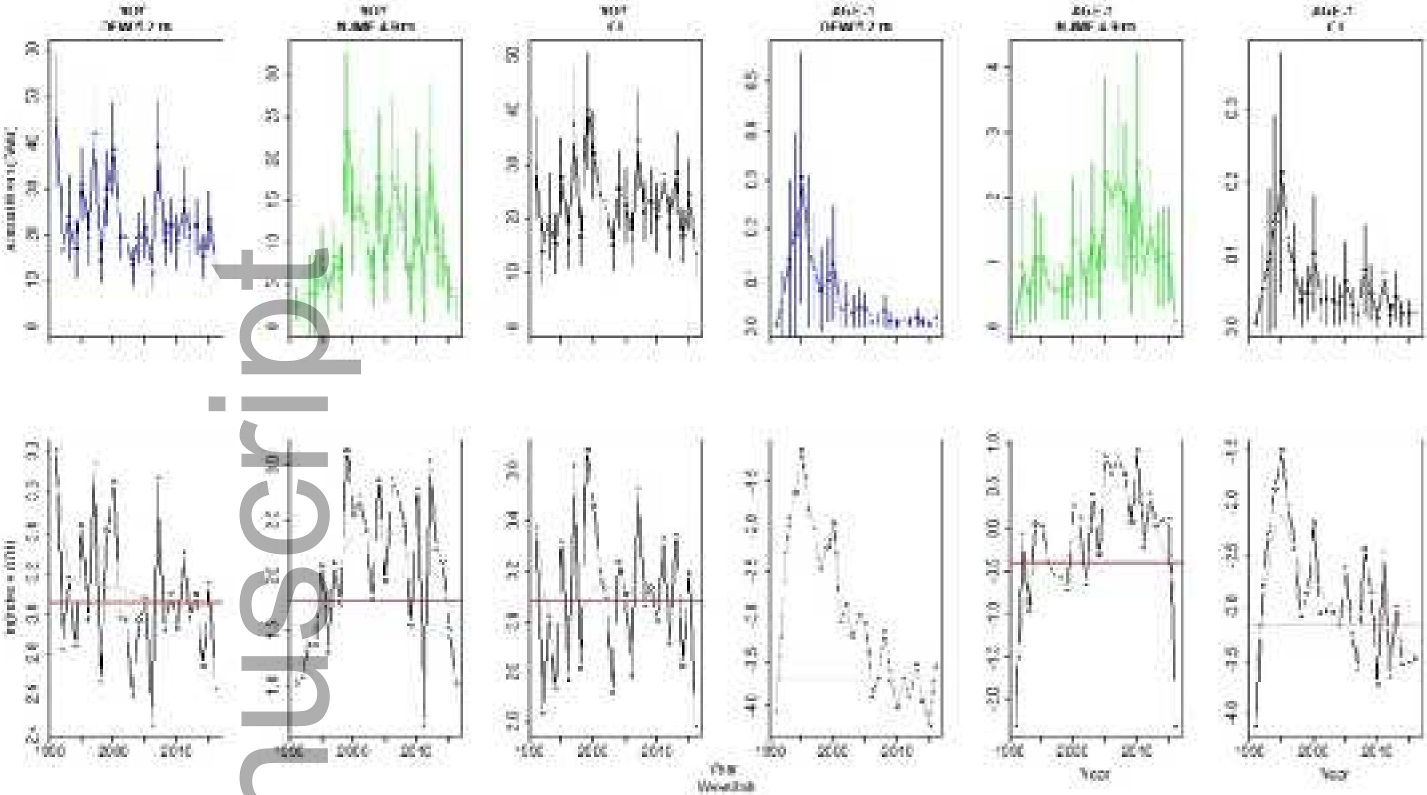

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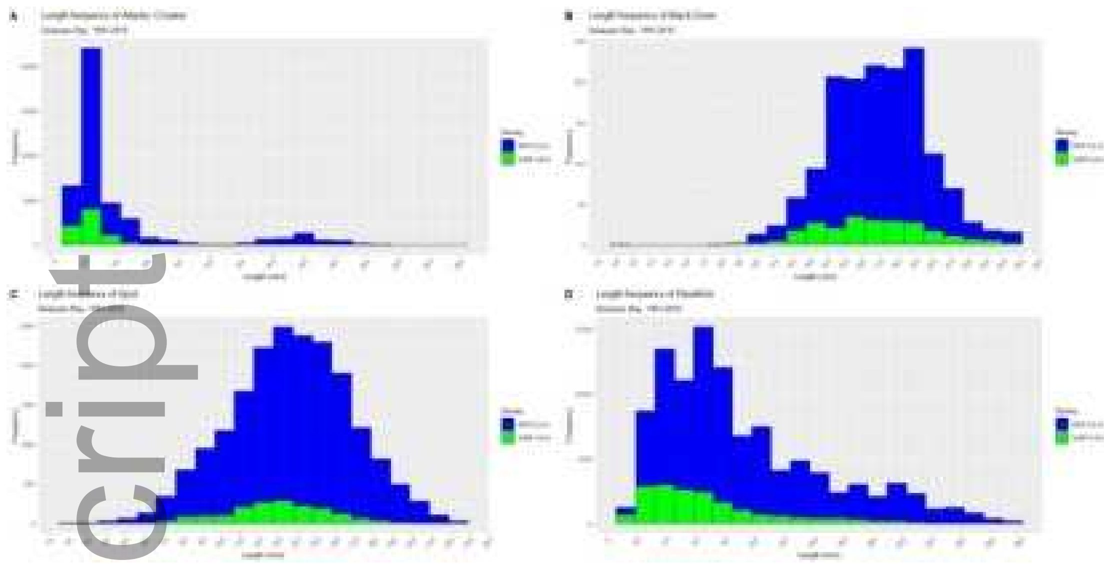

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